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Assessment of Security of Water Supply for Benissa Municipality, Spain Employing the Shannon-Weaver Model

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1. Introduction

A water supply system is a set of devices that operate closely together, namely water intakes, raw water transmission pipes, water treatment plants, retention tanks and water mains distribution pipes and related accessories.

As these elements belong to a city's critical infrastructure and play a key role in their operation, in addition to technical, technological, and economic criteria, reliability criteria must be formulated. Given that critical infrastructure protection is one of the priorities facing state authorities, the importance of tasks related to critical infrastructure not only constitute protection against threats but ensure any damage and disruption in its functioning is as short as possible, easy to remove, and does not cause additional losses to citizens and the economy.

By reliable operation of Collective Water Supply Systems (CWSS) one means the probability of supplying drinking water in the correct quantity, of a quality in accordance with accepted standards, under the required pressure at a convenient time for the consumer, and at a socially acceptable price per cubic meter (Rak 2008).

Depending on the size of the city, an external water supply system can operate in conditions in which it is within range of several water intakes, with different capacities and carrying water reserves accumulated in a tank, connected to collected water source and distributing it in a specific systematic way in terms of the water supply.

Although water supply systems are biotechnological devices with a specific structure, they stand out from other systems by being susceptible to the random nature of events which affect the functioning of a dynamic system, namely through work parameters (efficiency, pressure).

The basis for an analysis of the reliability of water supply systems, subsystems, or individual elements, depends on one's knowledge of the parameter values (estimators) from a quantitative description of their horizontal values (Wieczysty 1990). An example of assessing the one-parameter reliability of a water supply taking into account the diversification of water resources is a generalized indicator of determined *Ku* values. It is recommended to specify the required value of water shortage and the stage of completion of the system's requirements when determining the efficiency standard.

In this study, an attempt will be made to assess the security of the water supply for the coastal municipality of Benissa, Spain, as well as to determine the factors for the diversification and allocation of CWSS resources serving the municipality.

2. Analysis

Benissa is located in the province of Alicante within Valencia region on the Costa Blanca (Figure 1). The town has 10,768 inhabitants (2018 census) with a territory of 69.71 km^2 (Instituto Nacional de Estadistica 2018). Benissa's drinking water supply and sanitation network belong to the Municipal Water Supply Council of Benissa.

Fig. 1. Municipality of Benissa, Spain (City Counsil of Benissa)

The urban area presents a diverse orography in which the following landforms stand out: a four-kilometer coastal strip, characterized by cliffs and small bays; and a mountainous area featuring Sierra de Oltá (586 m), Solana (652 m), Mallá Verda and Sierra de Bernia (1,129 m).

Benissa, like most coastal municipalities, is characterized by a dispersed population living in several urbanizations located along the coast, with a higher population density (50.11%) concentrated in the administrative area of the town located in its northern part.

There are no significant industries in the community. Although in 2012 the population of Benissa was approx. 13,808 inhabitants, in the summer months the number increased by 73%, reaching 23,935 inhabitants (Pro Aquas Costa Blanca S.A. 2013). The seasonal increase in the number of inhabitants is caused by an increase in tourist traffic and the temporary occupation of homes during the summer holidays.

Between the winter period and the summer months, there is a significant difference in the quantity of drinking water distributed. Indeed, this amount can double from approx. 4,000 m^3/d to 8,000 m^3/d.

To supply water, the area has six deep wells (the use of two of which were discontinued in 2017 and nowadays constitute a reserve source), located in the mountain river valleys outside the community. The water is supplied under pressure by a pump to overflow tanks located in the hills. From here, it is directed by gravity through the distribution system with a mains diameter of 300-700 mm to three retention tanks.

Additionally, the location of three river basins, namely the: Gorgos, Girona, Bararanc de la Garganta; and two separate water divisions, are separated by the hills of Llosa de Camacho.

The total water recovered from the Water Intake System travels a distance of 11.9-16.2 km to reach the retention tanks As this helps to improve its quality, the intakes do not require pretreatment. The water is stored in three tanks whose names and capacities are as follows: Salvador 2,500 m^3, Ibiza 5,000 m^3, Europe 10,000 m^3. Located in the same facility as each other, the tanks are hydraulically connected at the same level of the water table for everyone. The water is protected against secondary contamination by dosing it with chlorine gas at the tank inlet.

The distribution of the water is carried out by gravity from three retention tanks, located at an altitude of 309.9 m.s.l. to the receivers which provide pressure to the in-line supply system with a range of up to 26 atm. The pressure of the water in the network is variable due to varying levels of consumption during the year, with a decrease in its consumption being observed during the winter by houses occupied on a seasonal basis. Changes in pressure during periods of higher temperatures from spring to fall create more major failures in the ductile iron piping system.

The water intakes have a cyclical variability in terms of the dynamic level of the water table, with this value fluctuating by approximately 100 m. The periodic water demand does not show any decrease during the rainy period from May to September, which contributes to the water table. The average immersion depth of a submersible pump during the summer months increases to an immersion depth of approximately 250 m below ground.

The "cold drop" (literally translated from the Spanish *gota fría* as "cold water drop") is a well-known phenomenon in the Marina Alta area. This climatic anomaly occurs when, at the end of summer, there is a contrast between the temperature of the sea and cold polar air. Consequently, the hot air rises rapidly to form a low-pressure, humid mass or high-altitude cyclone that moves in line with the topography and when cooled, causes this phenomenon.

In the Marina Alta area, the mountains create a barrier when the rainstorms occur along the coast. The porosity of the earth helps rainwater quickly reach the aquifers and thus the "cold drop" recovery of water levels is spectacular. Apart from causing floods, the *gota fría* usually generates strong winds of up to 150 k.p.h. provoking damage inland to trees and buildings. The phenomenon also causes storms at sea with waves that damage beaches, promenades, and boats moored in the ports (Carmen 1991, Water Office of Benissa 2020).

As the water supply system analyzed here has many variable factors in various conditions which affect its proper operation, the system requires its operators to make constant efforts to increase its reliability.

The quantity of water distributed from each water supply source in the years 2016-2019 is shown in Figure 2.

The data presented highlights the cyclically increased values of water distribution to its recipients in the summer months, July-August, and a decrease in demand in the winter months.

The percentage of water received by individual intakes has been variable during the last four years (Fig. 3), due to the exhaustion of two local wells called Canor and Benimallunt. However, these inlets remained in the water supply system as a backup in times of crises. In subsequent years, similar amounts were obtained from the exploitation of other water sources, with an increase in the share of the Corrales intake.

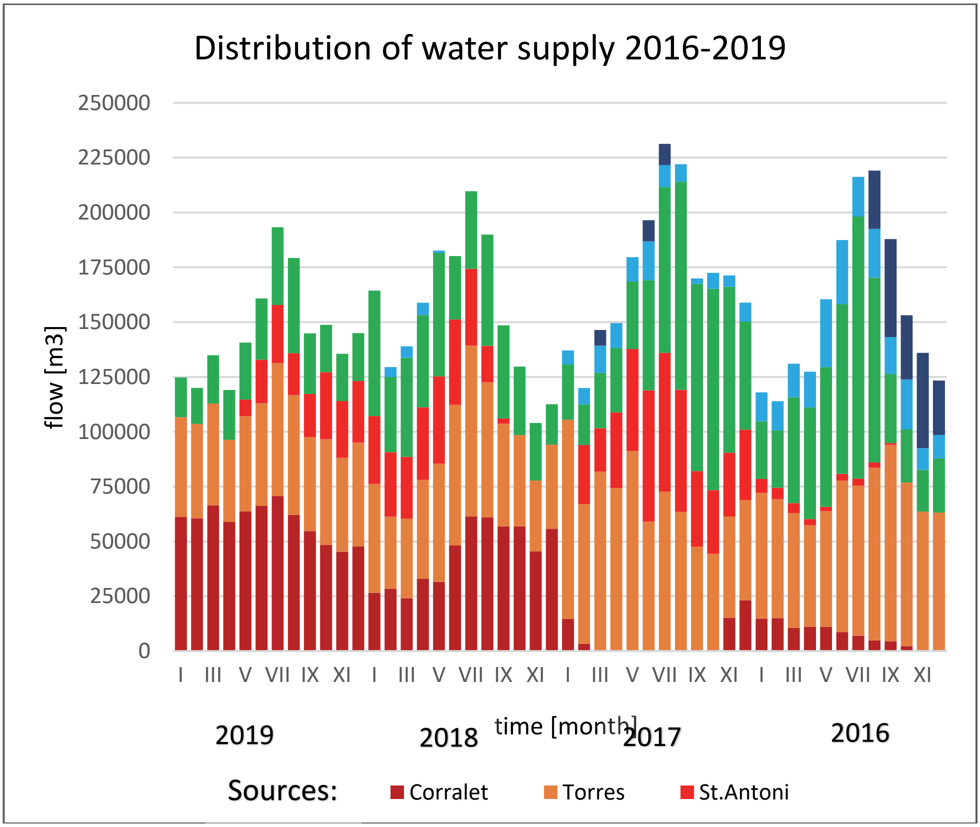

Fig. 2. Distribution of water supply 2016-2019 year (author)

3. Methods, calculations and results

The main point of this work is the calculation of the water diversification index, which is described below: The data from the collected flow tanks were analyzed using the Shannon-Weaver model.

Claude Elwood Shannon was an American mathematician and electrical engineer who laid the theoretical foundations for digital circuits and information theory, a mathematical model of communication. In 1948, Shannon published a paper entitled "A Mathematical Theory of Communication". He established the basic results of information theory such a comprehensive way that its framework and terminology are still used.

Shannon's information theory and its formulae were immediately accepted by communications engineers and continue to prove useful (Piore 1979).

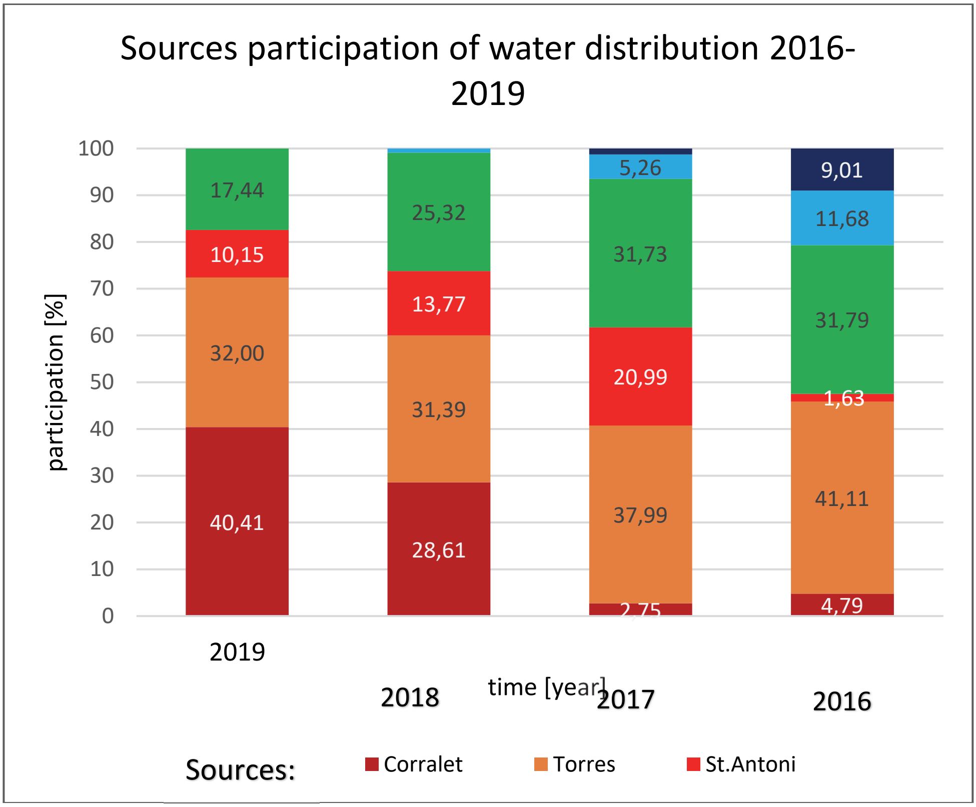

Fig. 3. Sources' share of water distribution 2016-2019 year (author)

Warren Weaver was an American scientist and administrator. He is widely recognized as one of the pioneers of machine translation and as an important figure in building support for science in the United States (Shannon 1948).

The resulting mathematical theory was later known as the Shannon-Weaver communication model or "the mother of all models". It also inspired many attempts to apply information theory in other areas, such as cognition, biology, linguistics, psychology, economics, and physics.

The diversification rate was derived from the joint work of Shannon and Weaver (Rak 2017, Shannon 1948, Shannon 1962).

The Shannon-Weaver index was determined in relation to the diversity of water intakes (d_{SWQ}) and the volume of water in networked reservoirs (d_{SWV}), i.e. a two-parameter method for assessing the diversification of water resources.

$$d_{SW} = d_{SW\,Q} + d_{SW\,V} \tag{1}$$

where:
$d_{SW\,Q}$ – an indicator of diversification of water resources,
$d_{SW\,V}$ – an indicator of water volume diversification in water tanks.

The diversification indicator according to the Shannon-Weaver model is equal to:

$$d_{SW}=\sum_{i=1}^{m}(u_i)\cdot(\ln(u_i)) \tag{2}$$

where:
u_i – share of the operating efficiency of the i-th Water Supply Subsystem (WSS) in the total water supply/ share of the volume of the i-th tank in relation to the total volume of the tanks in the network,
m – number of (WSS) tanks / network.

In this analysis, the assessment category of diversification of the CWSS in the municipality of Benissa was based on studies by Professor J. Rak. The categorization and evaluation scale of the degree of diversification of water resources for the *Shannon-Weaver* index is presented below for a one-parameter diversification shown in Table 1, while a two-parameter diversification shown Table 2.

Table 1. Category of one-parameter diversification (Rak & Boryczko 2017)

Category of diversification	Degree of diversification
fail	$d_{SW} = 0$
small	$0 < d_{SW}\ 0.325$
medium	$0.325 < d_{SW} < 0.690$
advanced	$0.690 < d_{SW} < 1.390$
very satisfactory	$d_{SW} < 1.390$

Table 2. Category of two-parameter diversification (Rak & Boryczko 2017)

Category of diversification	Degree of diversification
fail	$d_{SW} = 0$
small	$0 < d_{SW}\ 0.65$
medium	$0.65 < d_{SW} < 1.38$
advanced	$1.38 < d_{SW} < 2.78$
very satisfactory	$d_{SW} < 2.78$

The calculations for the Benissa CWSS took into account the variable number of water intakes (WSS) and their efficiency in the analyzed period, i.e.:

m = 6, in 2016-2017,
m = 5, in 2018,
m = 4, in 2019.

The values of the Shannon-Weaver index in relation to the diversity of water intakes (d_{SWQ}) are as follows:

$d_{SWQ(2019)} = -(0.40 \cdot \ln 0.40 + 0.32 \cdot \ln 0.32 + 0.10 \cdot \ln 0.10 + 0.17 \cdot \ln 0.17) = 1.27$

$d_{SWQ(2018)} = -(0.29 \cdot \ln 0.29 + 0.31 \cdot \ln 0.31 + 0.14 \cdot \ln 0.14 + 0.25 \cdot \ln 0.25 + 0.01 \cdot \ln 0.01) = 1.38$

$d_{SWQ(2017)} = -(0.03 \cdot \ln 0.03 + 0.38 \cdot \ln 0.38 + 0.21 \cdot \ln 0.21 + 0.32 \cdot \ln 0.32 + 0.05 \cdot \ln 0.05 + 0.01 \cdot \ln 0.01) = 1.37$

$d_{SWQ(2016)} = -(0.05 \cdot \ln 0.05 + 0.41 \cdot \ln 0.41 + 0.02 \cdot \ln 0.02 + 0.32 \cdot \ln 0.32 + 0.12 \cdot \ln 0.12 + 0.09 \cdot \ln 0.09) = 1.41$

The diversification rates received are very similar in each year, and values are high (Table 3).

Table 3. Calculation of degree of diversification by sources (author)

	Corralet	Torres	St. Antoni	Sanet	Canor	Benima-llunt		
year	u_1	u_2	u_3	u_4	u_5	u_6	d_{SW}	Degree of diversification
2019	0.40	0.32	0.10	0.17	0.00	0.00	1.27	**advanced**
2018	0.29	0.31	0.14	0.25	0.01	0.00	1.38	**advanced**
2017	0.03	0.38	0.21	0.32	0.05	0.01	1.37	**advanced**
2016	0.05	0.41	0.02	0.32	0.12	0.09	1.41	**very satisfactory**

The highest rate was obtained in 2016 and was associated with the distribution of global performance into a larger number of intakes. In 2019, despite the closing down of two intakes, the diversification index slightly decreased compared with the maximum value from 2016. The level of the indicator value depends on both the number of intakes and the performance of individual shares. In the case of the system under consideration, in 2019 the number of deep wells decreased from 6 to 4, while the 2 closed wells are wells with a very low efficiency rate throughout the system.

The water supply system of the community of Benissa analyzed here, consists of three primary network tanks for WSS: m = 3. The water allocation indicator in the water tanks is:

$$d_{SW} = - (14.29 \cdot \ln 14.29 + 28.57 \cdot \ln 28.57 + 57.14 \cdot \ln 57.14) = 0.96$$

Table 4. Calculation of degree of allocation by retention tanks (author)

	Salva-dor	Ibiza	Europa
	u_1	u_2	u_3
Capacity, m^3	2,500	5,000	10,000
Participation, %	14.29	28.57	57.14

The allocation rate of the water supply system obtained is classified as *advanced* (Table 5). Three retention tanks with a gradually varying total capacity ensure a high level of diversification of water resources.

In addition, its hydraulic interconnection provides a guarantee of continuity of water supply in times of crisis with a total quantity of less than 17,500 m^3, which will ensure its delivery to customers in the winter for 3-4 days, and in the summer months for 2 days.

Finally, the two-parameter category of diversification of water resources for Benissa CWWS for each year are as follows:

$$d_{SW(2019)} = 1.27 + 0.96 = 2.23$$
$$d_{SW(2018)} = 1.38 + 0.96 = 2.34$$
$$d_{SW(2017)} = 1.37 + 0.96 = 2.33$$
$$d_{SW(2016)} = 1.41 + 0.96 = 2.37$$

Table 5. Calculation of degree of two-parameter diversification (author)

year	$d_{SW\,Q}$	$d_{SW\,V}$	d_{SW}	Degree of diversification
2019	1.27	0.96	2.23	**advanced**
2018	1.38		2.34	**advanced**
2017	1.37		2.33	**advanced**
2016	1.41		2.37	**advanced**

The results of the diversification indicator represent the *advanced* category (Table 5) at its upper thresholds. A high level of diversification is a component of the high value of the diversification index of the intake and allocation of water resources.

4. Conclusions

The area described here is one dependent on tourism while having variable water consumption. In the municipality of Benissa there is a great need for water at the height of the tourist season which is, in addition, a period of no rainfall. When, during the winter season, this need decreases, rainfall is sporadic. Weather anomalies, the so-called *gota fría*, are becoming more common, featuring heavy precipitation, storms causing the raising of the water table, as well as, unfortunately, the destruction of existing infrastructure. The technical solutions applied to sources of water allow one to adapt the depth of pumps to the significant seasonal changes in ground water levels. Moreover, variable water consumption has an impact on variations in the pressure of the distribution system.

Despite the impact of so many variable factors, a high level of reliability of water supplies is maintained by the system analyzed here. This result is influenced by the large amount of water sources, as well as their separate location in three different river basins. The amount of water collected in active sources possesses a similar proportion of that delivered to the system. This system has three retention tanks of significant capacity built into its structure which ensure there is a high water distribution buffer.

The water distribution system constitutes the application of a system for delivering water to the municipality in variable tourism, weather and hydrological conditions. The structure of the CWSS guarantees a high level of diversification and water supply.

The obtained Shannon-Weaver indicators present values concerning the significant diversification of water sources and the allocation of their resources.

The obtained result of the diversification of water sources in 2019 (2.32) is lower than that of previous years by a very small amount. The previous year, work was halted on two sources, evenly adjusting the constituent parts of the efficiency of the remaining deep-well pumps into the most beneficial position, obtaining similar values in the total daily production of water as in previous years.

This expanded system offers a high level of reliability in adverse local conditions. In addition, it guarantees a continuous supply of water at the required pressure, at the required standard of quality (Markowsky 2020) and at a socially acceptable price (Water Office of Benissa 2020). It should be noted that such diversification and allocation of water resources is a continuous process and has to be constantly supervised.

Regarding the dynamic development of the settlement analyzed here, Benissa's Water Works are currently being expanded to include a new intake, in the form of new well reaching 400 meters underground or 100 m below sea level. Only at this depth can geologists find water of the required quality.

A final definition of the factors influencing the security of water supplies in Spain requires knowledge of the factors in the diversification and allocation of water resources for systems serving settlements with changeable and varied conditions. Further studies by the authors will be aimed in this direction.

The authors would like to express their gratitude to the Municipal Service of Drinking Water Supply of the Town of Benissa for their cooperation and help in putting this article together. In addition, we express a special acknowledgement to its director, Rubén Macho, for his commitment, dedication and sharing his valuable experience in this field.

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Abstract

This publication is a presentation of the methodology to determine the degree of diversification and allocation of water resources in water supply systems; with a differentiated level of need based on the example of the municipality of Benissa Spain.

The article shows a frequency of the changes and factors that affect the functioning of the water supply system. Moreover, its presents the calculation of the diversification indices for the selected water supply system while the methodology offers the possibility of evaluating the diversification of water resources in two parameters according to an adapted form of the Shannon-Weaver index.

Keywords:
diversification, allocation, resources, water supply, tanks, distribution, flow, capacity

Ocena bezpieczeństwa dostawy wody dla gminy Benissa z wykorzystaniem wskaźnika Shannona-Weavera

Streszczenie

Publikacja przedstawia metody wyznaczenia współczynnika dywersyfikacji i alokacji zasobów wodnych dla systemu zbiorowego zapotrzebowania wody cechującego się zróżnicowanym jej zapotrzebowaniem na przykładzie miasta Benissa w Hiszpanii. W pracy przedstawiono obliczenia stopnia dywersyfikacji zasobów wodnych, metodą dwu-parametryczną, wg zaadaptowanego wskaźnika Shannona-Weavera.

Słowa kluczowe:
dywersyfikacja, alokacja, zasoby, system wodny, zbiorniki, dystrybucja, przepływ, pojemność

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Influence of the Light Source on the *Chlorella vulgaris* Biomass Growth in the Culture Medium Supplemented with Anaerobic Digestate

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1. Introduction

The way of providing light is one of the most important elements affecting the effectiveness of production of algae biomass directly. In many studies, it was proven that the type of the light source, wavelength and exposure method affect not only the yield of microalgae production, but also the formation of the taxonomic structure and the chemical composition of the obtained biomass (Schulze et al. 2014). The photosynthetic activity of most microalgae species increases in the range of light intensity at the level of 200-400 μmol E/m^{2}s (Ogbonna & Tanaka 2000), which corresponds to about 10% of the amount of light they can receive directly from the sun. The amount of light needed for microalgae growth is slightly lower than for terrestrial plants. For example, Chlorella vulgaris microalgae can grow under exposure of 50-100 W/m^2, which corresponds to a value of 232 to 465 μmol E/m^2·s of the PAR range. For many algae species, the optimal light exposure conditions range from 5000 lx (90 μmol/m^2·s) to 13000 lx (230 μmol/m^2·s), and a temperature of 17-20°C (Schulze et al. 2014).

Sunlight is undoubtedly the best type of the light source enhancing the growth of microalgae cultures. However, the solar energy is available only during the cloudless days, and in the middle latitudes the intensity of natural sunlight also varies significantly depending on the season. In turn, in the hours around noon when the radiation intensity increases even to 4000 μmol E/m^2·s, a photoinhibition is observed. According to Zhu et al. (2008), photoinhibition of different algae species may occur at a photon flux density ranged from 200 to 800 μmol/m^2·s. Photoinhibition of photosynthesis is very likely to occur in starter cultures with low concentration of microalgae cells exposed to strong sunlight, where no cellular self-shading is observed (Goksan et al. 2003).

In the closed systems, photoinhibition can be reduced by choosing the proper type and intensity of light, as well as by increasing the contact surface of microalgae cells with light (Torzillo et al. 2003). The best way to eliminate the drawbacks of sunlight for microalgae cultivation is using the hybrid lighting systems in combination with LEDs (Szwaja et al. 2016).

Another method applying molecular tools is genetic reducing of the size of the chlorophyll antennas in microalgae cells. As a result, the efficiency of light energy adsorption is reduced, which allows for the proper and stable process of photosynthesis at a higher light intensity (Melis et al. 1999). In order to ensure the continuous microalgae biomass synthesis, a stable supply of the light energy should be ensured around the clock or in the established photoperiod required by some species of microalgae. Absence of light and inhibition of photosynthesis create anaerobic conditions in photobioreactors, contributing to reducing the rate of biomass growth and concentration of microalgae cells. Thus, in intensive microalgal production, artificial light sources are commonly used.

In the light of the above considerations, there is a need to find technological solutions ensuring optimal lighting conditions for technologically and economically effective production of microalgae biomass. The aim of the study was to determine the influence of the light source on the productivity of *Chlorella vulgaris* biomass cultivating on anaerobic digestate.

2. Materials and methods

2.1. Microalgae inoculum, cultivation in photobioreactors and study organization

The inoculum was a culture of *Chlorella vulgaris* originated from UTEX 2714 Culture Collection of Algae (University of Texas, Austin, USA).

Liquid algal culture was grown photoautotrophically in closed, vertical, tubular photobioreactors with an active volume of 2.5 L (inner diameter 76 mm and 550 mm height) made of transparent plexiglass. An initial concentration of the algae biomass in the photobioreactors was 250±22 mg total solids (TS)/L. Compressed air was delivered continuously at 200 L/h from the bottom of the reactors upwards by peristaltic pumps (Mistral 200). This ensured appropriate mixing of the culture medium, homogeneity of conditions in the entire reactor volume and introduction of atmospheric CO_2 to the culture. The temperature of the culture was maintained at 23.0±2.0°C.

The nutrient medium for *Chlorella vulgaris* cultivation was the mixture of liquid anaerobic digestate, tap water and synthetic medium. The digestate was obtained from an agricultural biogas plant operated in a technical scale feeding with maize silage and distillery stillage. The concentration of anaerobic sludge in reactor was maintained at the level of 5 g TS/L, the temperature was 40°C and organic loading rate was 2.4 kg of volatile solids (VS)/L·d. Before using as a nutrient medium, digestate was centrifuged (MPW-251 Donserv, 10 min, 5000 rpm) and then autoclaved (30 min, 90°C). The chemical characteristics of anaerobic digestate is shown in Table 1. Due to a high color and the content of organic compounds, the digestate constituted 20% of the active volume of the photobioreactors in series 1 and 10% in series 2. The remaining part of the culture medium was tap water with synthetic medium composed of: $NaNO_3$ 25 g/L, $CaCl_2 \cdot 2H_2O$ 2.5 g/L, $MgSO_4 \cdot 7H_2O$ 7.5 g/L, $K_2HPO_4 \cdot 3H_2O$ 7.5 g/L, KH_2PO_4 17.5 g/L, NaCl 2.5 g/L, VB12 1.0 mL/L, VB1 1.0 mL/L, microelements 6.0 mL/L, Na_2EDTA 0.75 g/L, $FeCL_3 \cdot 6H_2O$ 97.0 g/L, $MnCl_2 \cdot 4H_2O$ 41.0 g/L, $ZnCl_2$ 5.0 g/L, $NaMoO_4 \cdot 2H_2O$ 4.0 g/L, $CoCl_2 \cdot 6H_2O$ 2.0 g/L. The characteristics of the culture medium is shown in Table 2.

Table 1. Characteristics of anaerobic digestate used in the experiment

Parameter	Unit	Concentration	
		Raw digestate	Digestate after centrifugation
Total solids	mg/L	12700±2400	350±34
COD	mg O_2/L	10200±730	7950±370
BOD_5	mg O_2/L	5600±310	3700±190
TN	mg N/L	2750±190	1805±91
N-NH_4	mg N-NH_4/L	2210±130	1300±73
TP	mg P/L	185±22	124±14
P-PO_4	mg P-PO_4/L	158±14	71±9
pH	–	6.9±0.4	7.0±0.2

The photobioreactors were placed in a chamber covered with aluminium foil and were illuminated continuously by different light sources. The experiments in both series were divided into eight variants. The criterion used was the applied light source. Organization of the experimental variants is shown in Table 3.

Table 2. Characteristics of the culture medium used in the experiment

Parameter	Unit	Concentration	
		Series 1	Series 2
Total solids	mg/L	71±21	29±14
COD	mg O_2/L	1590±210	780±113
BOD_5	mg O_2/L	741±39	390±27
TN	mg N/L	361±42	172±35
$N\text{-}NH_4$	mg $N\text{-}NH_4$/L	257±29	129±21
TP	mg P/L	19±6	10±3
$P\text{-}PO_4$	mg $P\text{-}PO_4$/L	12±3	7.1±1.6
pH	–	7.2±0.3	7.1±0.2

Table 3. Organization of the experimental variants depending on the light source used

Vari-ant	Light source	Wavelength (λ) [nm]	Electric power of the light source [W]
1	Fluorescent tube – warm light	Colour temperature: 3000 K	100
2	LED – Warm light	2 local maximum at: 450 nm and 580 nm, colour temperature: 6500K	
3	LED – Red and Blue	640 nm and 470 nm	
4	Fluorescent tube – cold light	Colour temperature: 6500K	
5	LED – Blue	470 nm	
6	LED – Red	640 nm	
7	Daylight	Mean colour temperature: 5900K	Exposed to daylight
8	High pressure sodium lamp	Essential spectrum: 570-620 nm, Colour temperature: 2700K	100

2.2. Analytical methods

The cultivation of the microalgae was carried out for 10 days. After the cultivation process was ended, the obtained algae biomass was concentrated, separated and dehydrated by initial sedimentation and then by centrifugation for 10 min at 5000 rpm (MPW-251, Donserv). Determinations of TS and VS in the solid fraction were carried out by gravimetric analysis. In the supernatant, the concentration of ammonia nitrogen ($N-NH_4$) was determined with cuvette tests using a DR 5000 spectrophotometer (Hach-Lange, Germany) with an HT 200s mineralizer (Hach-Lange, Germany). At the beginning and end of the experiment, the digestete and the cultivation medium were analyzed for biochemical oxygen demand (BOD_5) with the Oxi-top control system (WTW, Germany) as well as chemical oxygen demand (COD), the concentrations of orthophosphates ($P-PO_4$), total phosphorus (TP), total nitrogen (TN) with cuvette tests using a DR 5000 spectrophotometer (Hach-Lange, Germany) with an HT 200s mineralizer (Hach-Lange, Germany). The pH value was determined by a digital pH-meter (1000L, VWR). The taxonomic identification of microalgae biomass was conducted at microscope magnifications of: 1.25x10x40 or 1.25x10x100, and with algae analyzer (BB Moldanke, Germany). The light intensity supplied to the photobioreactors was measured using a luxometer NL-100 (Hanna).

2.3. Statistical methods

Each experimental variant was conducted in three replications. Statistical analysis of the obtained results was carried out using the Statistica 12.0 PL package (Statsoft, Inc.). Hypothesis on the distributions of the individual studied variables was verified based on the Shapiro-Wilk test. In order to ascertain the significance of the differences between the variables, an analysis of variance (ANOVA) was carried out. Variance homogeneity in groups was confirmed using the Levene test. In order to determine the significance of the differences between the analysed variables, the HSD Tukey test was used. In the tests, a significance level was assumed as $p = 0.05$.

The formulas that can predict the biomass concentration depending on medium characteristic were developed during the study. A multiple regression model using a stepwise progressive regression algorithm was used to identify the relevant predictor variables in the formulas, among the investigated variables by Statistica 12.0 PL package (Statsoft, Inc.). Then, the residual analysis were carried out to validate the regression models.

3. Results and discussion

3.1. Biomass concentration

According to the literature, light-emitting diodes (LEDs) may become the most important light sources around the world and their application in the intensive algal production systems should to be carefully considered. It has been proven, that using the LEDs as a light source in photobioreactors improve the productivity of microalgal biomass. However, only a balanced mix of wavelengths enhanced the growth of algae depending on the photosynthetic pigments composition and concentration found in the cells (Schulze et al. 2014). For this reason, our experiments studied the influence of the light source on the *Chlorella vulgaris* biomass growth. Due to the low photosynthetic quantum yield in natural systems, there is a need to optimize the regime of the light exposition in microalgal biotechnology (Abu-Ghosh et al. 2016, Zhao et al. 2013). The excess of light energy has an adverse impact on photosynthetic apparatus, thus microalgae have some strategies to control the surplus sunlight energy absorbed in photosystems (Wobbe et al. 2016). The photosynthetic conversion process, and hence also the biomass productivity are strongly dependent on the source and amount of light during the culturing (Pruvost et al. 2015, Moheimani et al. 2013).

During the study, the highest concentrations of *Chlorella vulgaris* biomass averaged 1810±77 mg TS/L and 1640±201 mg TS/L were observed in series 2 in variants 1 and 2, respectively (Fig. 1-3). In other variants significantly lower ($p = 0.05$) biomass productivity ranged from 1110±137 mg TS/L in variant 3 to 730±71 mg TS/L in variant 7 were observed (Fig. 1, Fig. 3). In series 2 the lowest biomass production of 440±93 mg TS/L in variant 8 was noted with the high pressure sodium lamp light source (Fig. 1, Fig. 3).

The similar tendency is found in series 1 (Fig. 1, Fig. 2). In variants 1 and 2, the highest biomass concentrations of 1420±159 mg TS/L and 1230±112 mg TS/L were respectively obtained (Fig. 1). The productivity of *Chlorella vulgaris* biomass in other variants was statistically comparable ($p = 0.05$) to obtained in series 2, and the concentration of biomass ranged in the narrow range from 920±21 mg TS/L to 730±77 mg TS/L. Only in variant 8, it was achieved 412±83 mg TS/L (Fig. 1, Fig. 3).

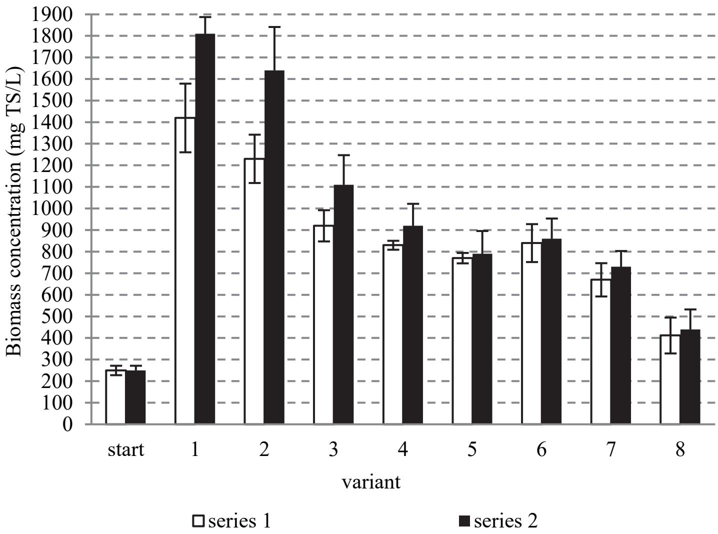

Fig. 1. Final biomass concentration of *Chlorella vulgaris* depending on the experimental variant

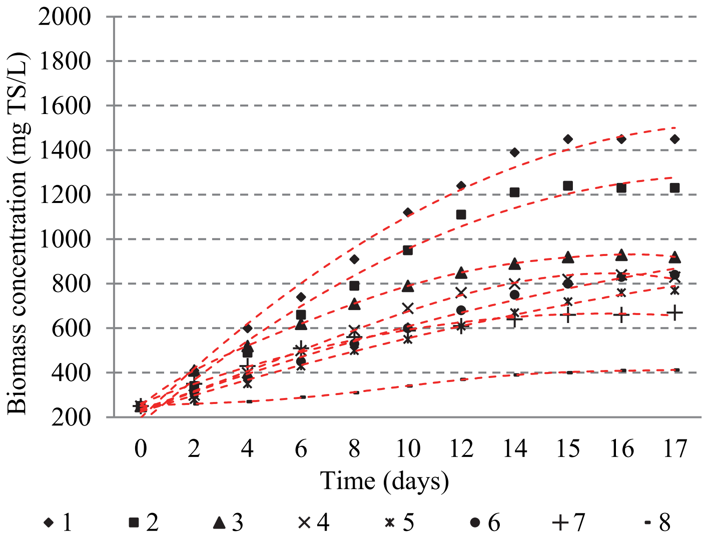

Fig. 2. Changes in biomass concentration of *Chlorella vulgaris* in series 1 depending on the experimental variant

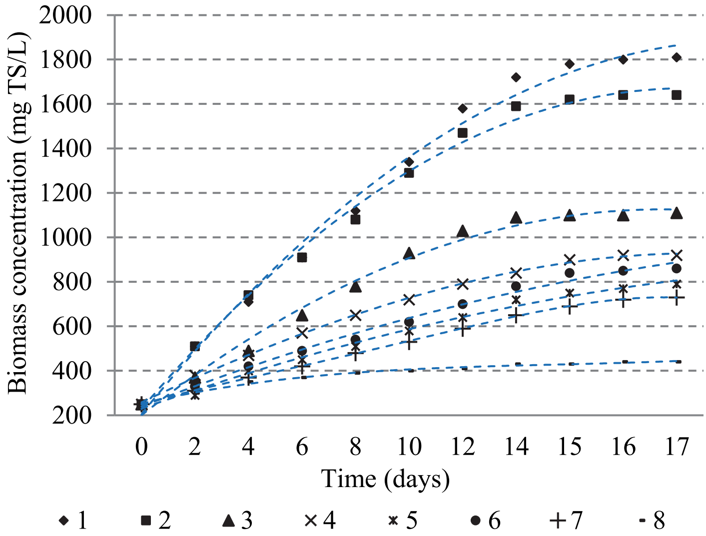

Fig. 3. Changes in biomass concentration of *Chlorella vulgaris* in series 2 depending on the experimental variant

3.2. Organic compounds and nutrient removal from the culture medium

Light spectral quality and intensity significantly influence the microalgal growth, thus it should be considered when choosing a source of light in intensive biomass production and nutrients removal from the culture medium (Wobbe et al. 2016, Baer et al. 2016, Teo et al. 2014). Our studies also confirmed this relationship. The light absorption by microalgae is closely dependent to their chemical composition. The intensity of light should be delivered uniformly to photobioreactors providing a sufficient amount of energy to the cells in the culture (Baer et al. 2016, Teo et al. 2014).

Type of the light source significantly affected the efficiency of COD removal from digestate in series 1 (Fig. 4). The lowest COD concentration at the end of experiment of 903±55 mg O_2/L was noted in variant 1, and the highest of 1610±21 mg O_2/L in variant 8. These values were significantly different (p = 0.05) from those obtained in other experimental variants, in which the COD concentration ranged from 1070±230 mg O_2/L to 1273±112 mg O_2/L. In series 2, the concentrations of COD were statistically comparable regardless of the type of light, and they ranged from 519±31 mg O_2/L in variant 1 to 710±91 mg O_2/L in variant 4 (Fig. 4). The lowest BOD_5 concentration in the culture medium was observed in variant 1 and 2, irrespective of its initial concentration in the culture medium (Fig. 5). In other variants, the concentrations of BOD_5 were significantly higher than those recorded in variant 1 and 2, and amounted to 260±19 mg O_2/L in variant 4 to 330±22 mg O_2/L in variant 5. In series 1, the highest BOD_5 concentration of 699±73 mg O_2/L was found in variant 8 (Fig. 5).

The efficiency of nitrogen removal was directly related to the biomass productivity. The lowest concentrations of N-NH_4 (below 50 mg/L) and TN in the culture medium at the end of experiment were observed in variants 1 and 2, irrespective of the series (Fig. 6-7). In variants 3 to 8 significantly ($p = 0.05$) higher concentrations of N-NH_4 were noted (Fig. 6). In series 1, they ranged from 121±26 to 182±32 mg N-NH_4/L, while in series 2 from 72±5 to 94±21 mg N-NH_4/L (Fig. 6). A similar tendency was observed for TN removal (Fig. 7). In series 1, the lowest TN concentrations of 73±39 mg TN/L in variant 1 and 117±21 mg TN/L in variant 2 were recorded ($p = 0.05$). In other variants, TN concentration was about 250 mg TN/L. In series 2, the lowest TN concentration of 21±9 mg/L was obtained in variant 1, which was significantly higher by 66±19 mg TN/L than noted in series 2. In other variants, the amount of TN was above 100 mg/L (Fig. 7).

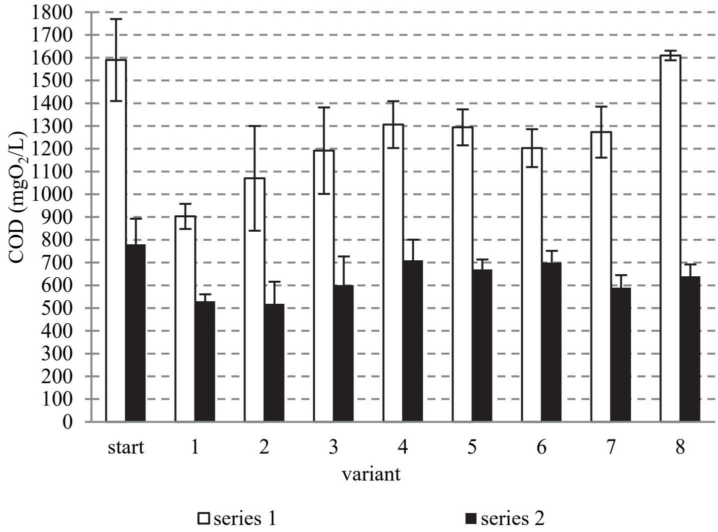

Fig. 4. Final COD concentration in the culture medium depending on the experimental variant

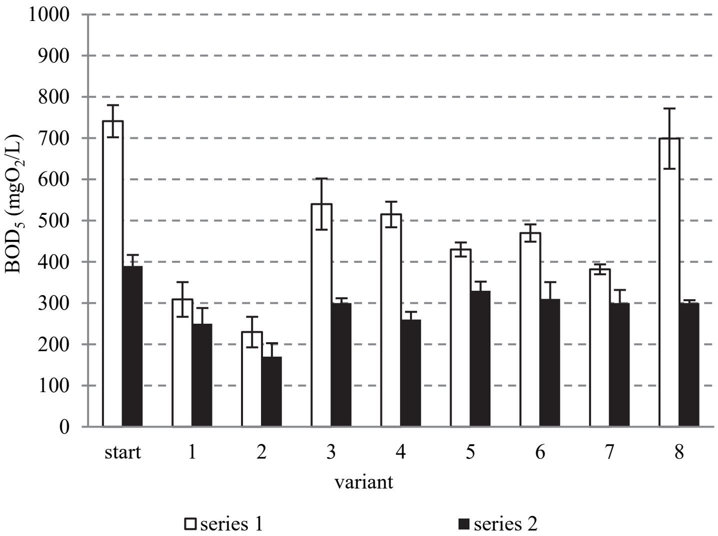

Fig. 5. Final BOD_5 concentration in the culture medium depending on the experimental variant

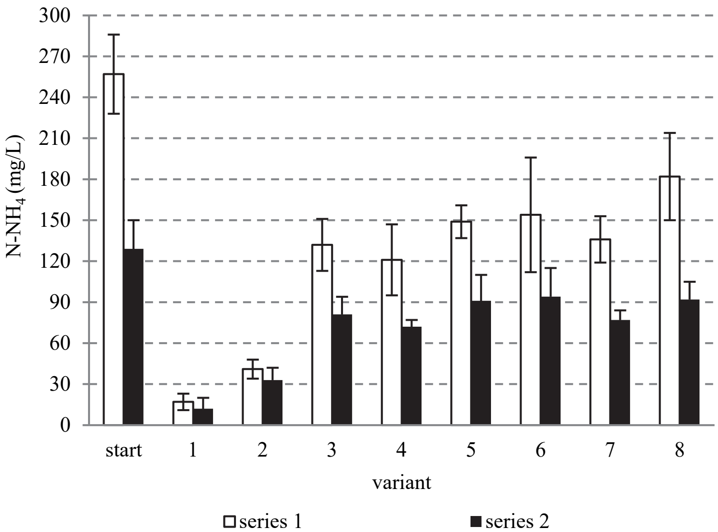

Fig. 6. Final $N\text{-}NH_4$ concentration in the culture medium depending on the experimental variant

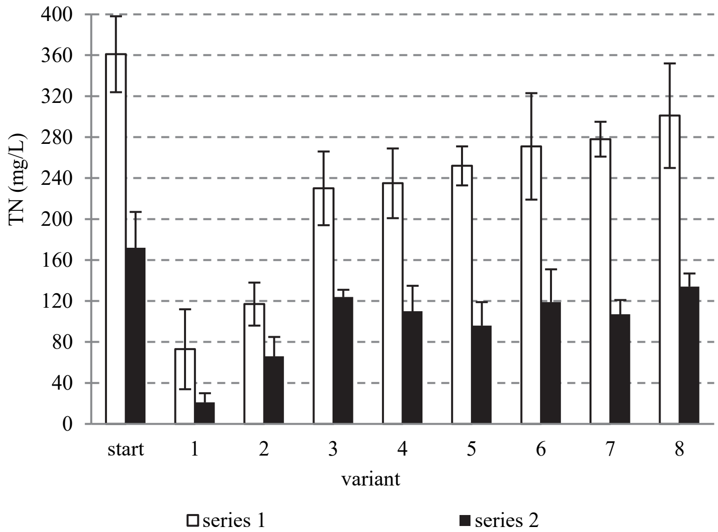

Fig. 7. Final TN concentration in the culture medium depending on the experimental variant

The most important advantages of using artificial light sources are stability and easy controlling, as well as simply incorporation into photobioreactors design. According to the literature, microalgae biomass production efficiency and organic compounds removal from the culture medium were greater with using artificial light sources comparing to sunlight (Wobbe et al. 2016, Baer et al. 2016, Kim et al. 2014, Hashimoto et al. 2015). The presented studies also confirmed this dependence.

Regardless of the experimental series and variant, the effective phosphorus removal from the culture medium was observed. The initial concentrations of phosphates in series 1 and 2 were respectively 12±3.0 mg P-PO_4/L and 7.1±1.6 mg P-PO_4/L, while total phosphorus concentrations were 19±6.0 mg TP/L in series 1 and 10±3.0 mg TP/L in series 2 (Fig. 8-9). In series 1, phosphates concentration at the end of the experiment ranged from 0.9±0.2 mg P-PO_4/L in variant 1 to 2.4±0.3 mg P-PO_4/L in variant 5, while in series 2, it was in the range of 0.7±0.3 mg P-PO_4/L in variant 1 to 1.4±0.3 mg P-PO_4/L in variant 6 and 7 (Fig. 8). The lowest concentration of TP was noted in variant 1, series 1 (2.6±0.7 mg/L) and in variant 1, series 2 (0.8±0.1 mg/L), (Fig. 9).

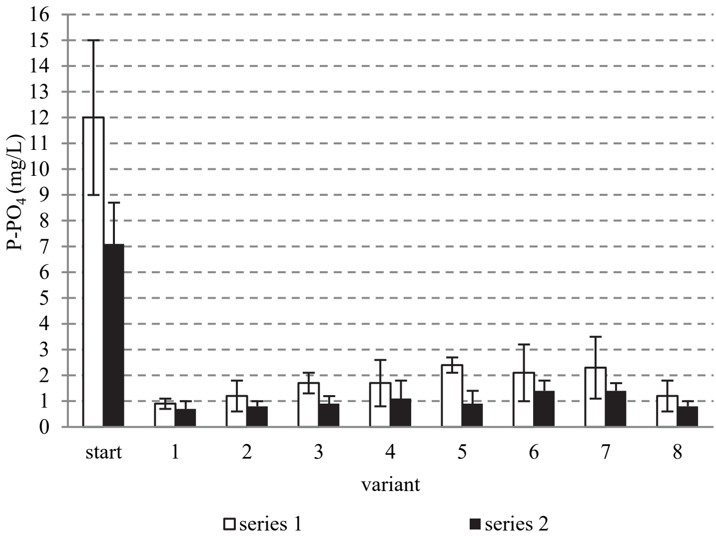

Fig. 8. Final $P\text{-}PO_4$ concentration in the culture medium depending on the experimental variant

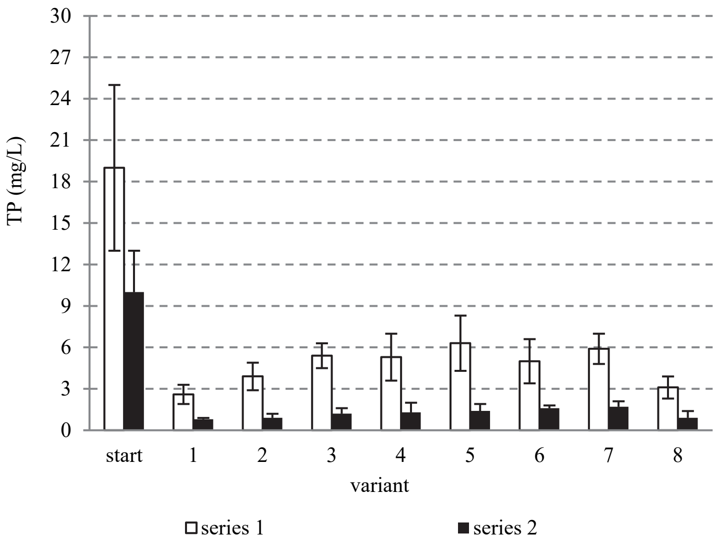

Fig. 9. Final TP concentration in the culture medium depending on the experimental variant

It has been found, that the quantity of direct and diffused light irradiation significantly affect microalgal biomass productivity. However, the light energy limitation is one of the main problems in outdoor photobioreactors exploitation (Pawar 2016, Pruvost 2016). In the intensive microalgal cultivation, maximizing the light absorbed by the cells is a critical factor, because low light conditions may lead to inhibit the biomass growth. The highest biomass productivity can be achieved through continuous algal cultivation in photobioreactors exposed to the constant artificial lighting (Pruvost 2016, Vitova 2015). However, the continuous supplying of light is energy intensive (Wobbe et al. 2016, Kim et al. 2014, Wang et al 2014). Light emitting diodes (LEDs) have been widely used as an alternative to conventional fluorescent and halogen lamps (Liu et al.2017, Wobbe et al. 2016, Singh et al. 2016, Baer et al. 2016) and they are characterized by narrow-band emission spectrum (Vadiveloo et al. 2015, Baer et al. 2016). It has been proved that microalgae cultivated under blue or red monochromatic light enhanced their growth rates as compared to cultures grown under multi-chromatic white light (Liu et al. 2017, Vadiveloo et al. 2015, Baer et al. 2016).

The multiple regression models were developed to indicate variables statistically significantly affecting the microalgae biomass production, and analysis showed that they are COD, N-NH_4 and P-PO_4 concentrations. The estimated values of biomass productivity in the equations in relation to the results obtained in the experimental works are very high, which indicates the correctness of the assumptions made and the practical value of the optimization procedure. The regression formulated models equations for the estimation of biomass production, with their determination coefficients and standard errors are presented in Table 4.

Table 4. Regression equation for the estimation of *Chlorella vulgaris* biomass concentration (BC) with determination coefficient (R^2) and standard error (SE)

Variant	Formula	R^2	SE
1	$BC = 1{,}042COD - 13{,}241N - NH_4 + 100{,}218P - PO_4 + 1994{,}013$	0,9634	28,744
2	$BC = 1{,}186COD - 15{,}080N - NH_4 + 114{,}137P - PO_4 + 1849{,}570$	0,9377	24,989
3	$BC = 0{,}550COD - 6{,}988N - NH_4 + 52{,}893P - PO_4 + 1207{,}118$	0,9155	19,555
4	$BC = 0{,}2604COD - 3{,}3103N - NH_4 + 25{,}0545P - PO_4 + 966{,}0033$	0,9267	16,792

Table 4. cont.

Variant	Formula	R^2	SE
5	$BC = 0{,}0579COD - 0{,}7356N - NH_4 + 5{,}5677P - PO_4 + 800{,}2230$	0,9274	12,772
6	$BC = 0{,}0579COD - 0{,}7356N - NH_4 + 5{,}5677P - PO_4 + 870{,}2230$	0,9441	15,716
7	$BC = 0{,}1736COD - 2{,}2068N - NH_4 + 16{,}7030P - PO_4 + 760{,}6689$	0,9252	10,593
8	$BC = 0{,}0810COD - 1{,}0299N - NH_4 + 7{,}7947P - PO_4 + 454{,}3121$	0,9389	7,554

BC – biomass concentration [mg/L]
COD – initial COD concentration in the culture medium [mg O_2/L]
$N - NH_4$ – initial $N - NH_4$ concentration in the culture medium [mg/L]
$P - PO_4$ – initial $P - PO_4$ concentration in the culture medium [mg/L]

4. Conclusions

The studies proved that the light source significantly enhanced the efficiency of *Chlorella vulgaris* growth on anaerobic digestate. The highest biomass production was observed in variants with the fluorescent tube-warm light (color temperature 3000K) and the LED-warm light with 2 local maximum at 450 nm and 580 nm (color temperature 6500K). In variants with the pressure sodium lamp with the essential spectrum 570-620 nm (color temperature 2700K), the production of microalgae biomass was the lowest.

The efficiency of organic compounds expressed as COD and BOD_5 removal, as well as $N\text{-}NH_4$ and TN removal was dependent on the final concentration of microalgae biomass in the culture medium. In variants with the highest *Chlorella vulgaris* biomass production, the lowest concentrations of these indicators in the culture medium were observed at the end of the experiment. In turn, phosphorus compounds were removed effectively irrespective of the light source used and the concentration of microalgae biomass.

It was found, that anaerobic digestate characteristics influenced the efficiency of *Chlorella vulgaris* growth. Higher amount of digestate in the culture medium (20% by volume) significantly reduced biomass productivity. It was associated with increasing in color intensity, turbidity and suspension solids concentration in the culture medium, which reduced light penetration. The multiple regression analysis showed that the initial concentrations of COD, $N\text{-}NH_4$ and $P\text{-}PO_4$ statistically significantly affected the biomass production efficiency.

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Abstract

Many studies have proven that the type of light source and the lighting regime have significantly influenced the efficiency of microalgae biomass production and the taxonomic composition of the cultivated biomass, as well as its chemical composition. The aim of the study was to determine the influence of the light source on the productivity of *Chlorella vulgaris* biomass cultivating on anaerobic digestate. The criterion for dividing experiment into variants was the light source used.

It was found that the light source significantly influenced the *Chlorella vulgaris* growth. The highest biomass production was observed in variants with the fluorescent tube-warm light (color temperature 3000K) and the LED-warm light with 2 local maximum at 450 nm and 580 nm (color temperature 6500K). In variants with the pressure sodium lamp with the essential spectrum 570-620 nm (color temperature 2700K), the production of microalgae biomass was the lowest.

The removal efficiency of organic compounds expressed as COD and BOD_5 as well as ammonium and total nitrogen were dependent on the final concentration of biomass in the culture medium. In variants with the highest biomass production, the lowest concentrations of these indicators in the culture medium were observed. Phosphorus compounds were removed effectively from the culture medium regardless of the light source and the concentration of microalgae biomass.

Keywords:
microalgae, light source, anaerobic digestate, biomass production

Wpływ źródła światła na wzrost biomasy *Chlorella vulgaris* w medium hodowlanym opartym na wykorzystaniu odcieków pofermentacyjnych

Streszczenie

W wielu badaniach udowodniono, iż zastosowany rodzaj źródła światła i sposób oświetlenia ma wpływ na wydajność produkcji mikroglonów oraz na kształtowanie się składu taksonomicznego populacji, skład chemiczny i właściwości uzyskiwanej biomasy. Celem badań było określenie wpływu rodzaju stosowanego światła na efektywność przyrostu biomasy mikroglonów z gatunku *Chlorella vulgaris* w medium hodowlanym opartym na wykorzystaniu odcieków pofermentacyjnych. Kryterium podziału prac badawczych na warianty stanowiło zastosowane źródło światła.

Przeprowadzone prace badawcze udowodniły istotny wpływ stosowanego źródła światła na proces przyrostu biomasy *Chlorella vulgaris*. Najwyższą efektywność przyrostu biomasy *Chlorella vulgaris* obserwowano w wariantach, w których źródło światła stanowiły świetlówki z ciepłym światłem (3000K) oraz diody LED (ciepłe światło o długości fali 450 nm i 580 nm, 6500K). Najniższe efekty technologiczne związane z przyrostem biomasy mikroglonów obserwowano w wariancie, w którym fotobioreaktory oświetlane były wysokoprężną lampą sodową o długości fali 570-620 nm (2700K).

Efektywność usuwania związków organicznych wyrażona wskaźnikami ChZT i BZT_5 oraz azotu amonowego i całkowitego były zależne od końcowego stężenia biomasy mikroglonów w medium hodowlanym. W wariantach, gdzie populacja *Chlorella vulgaris* przyrastała najwydajniej obserwowano najniższe stężenia tych wskaźników w medium hodowlanym na zakończenie cyklu produkcyjnego. Związki fosforu usuwane były skutecznie niezależnie od stosowanego źródła światła oraz koncentracji biomasy mikroglonów w układzie technologicznym.

Słowa kluczowe:
mikroglony, źródło światła, odcieki pofermentacyjne, produkcja biomasy

MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

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The Attitudes of Managers Towards the Concept of Sustainable Development in Polish Food Industry Enterprises

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1. Introduction

Progressive degradation of the natural environment and the growing social problems created by the economic activity of modern enterprises require a change in the concept of management to a more responsible and adapted to existing threats. Food businesses also have a negative share in this proceeding (Martinez 2013). The food industry belongs to the branch of the national economy that deals with the acquisition and processing of natural resources. It is one of the links in the food economy, which consists of many components closely related to each other. It distinguishes basic, auxiliary and service modules. The basic elements include food production, dominated by agriculture; food processing, in which the food industry plays a major role; food trade and food consumption (Obiedzińska 2013). The food industry is one of the most important economic sectors in our country due to the fact that it determines the Polish nourishment and is a major exporter of beverages and food on international markets (Firlej & Szymański 2012).

An important factor influencing the sustainable economic activity of food industry enterprises in Poland is the attitude of managers responsible for the functioning of the organisation. Medium and high-level employee staff creates organisational behaviours of a food company focused on environmental protection, and therefore the implementation of economic activities based on the principles of sustainable development depends on their attitude. The production of safe, healthy and ecological food products in the processes of clean production is the basic idea on which the group of highly qualified employees is based, who understand and apply the principles of sustainable development. However, taking into account the scale of enterprises, it should be noted that activities focused on sustainable management are characteristic for large enterprises than those from the SME group (Trojanowski 2020).

The implementation of sustainable business is not only about seeking to maximize the profits of a food company, but also depends on environmental and social aspects (Kasperska 2015). Production companies, including those from the food sector, need legitimacy and acceptance of their business on the part of clients, employees, contractors, suppliers as well as social and governmental organisations. The perceived pressure from market participants significantly affects the change of attitudes among managers, which translates into more sustainable activities in the sphere of management, production, work organisation and marketing.

The purpose of the article is to define the attitudes of management staff towards the concept of sustainable development, while striving to achieve financial results in the business operations of food industry enterprises.

2. Theoretical background

Excessive exploitation of natural resources, consumption of fuels, energy and water, generation of more waste and harmful substances along with the progressive increase in the number of the world's population – contribute to irreversible degradation of the natural environment and deterioration of the quality of life of societies (Govindan 2018). Degradation of the natural environment negatively affects the health condition of modern societies, and also reduces the chances of future generations development.

To meet the emerging problems, more attention should be paid to the attitudes and behaviour of managers responsible for the business operations of food companies. High-level employee staff making strategic decisions in an enterprise should be aware of the importance of matching management functions to the requirements of sustainable development ideas. The way and degree of implementation of sustainable production management will have a significant impact on the functioning and success of the company on the market in the changing economic environment of the organisation (Fjeldstad, Snow, 2018). Creating high-level pro-environmental behaviours and practices in the company, based on the concept of sustainable development, will certainly positively influence the behaviour of other employees at lower positions (Ottman 2013, Pape et al. 2011).

Managers responsible for activities leading to the achievement of the company's financial goals are facing a difficult task. This difficulty lies in balancing between the economic goals of the company and social and environmental goals. The triad of goals presented in literature as a triple bottom line (Emery 2012, Glavas & Mish 2015, Muñoz-Pascual, Curado, Jesús & Galende 2019) is not a universally dominant business model in manufacturing enterprises due to the need to maintain a balance between the three indicated areas (Hall & Wagner

2012, Schaltegger, Hansen & Lüdeke-Freund 2016). Striving to maximize profits from the sale of food products, increasing market share by food enterprises and acquiring an ever larger group of customers allow us to guess that financial goals become superior to social and environmental goals. That is why it is so important to balance production, organisational, marketing and sales activities. The economic development of food enterprises should also guarantee the improvement of other elements of social well-being, including the necessary structural changes in the economy and society (Klonowska-Matynia & Radlińska 2018).

The food industry companies must constantly provide customers with consistent values and benefits. This is connected with continuous improvement of the product offer, so that it is attractive and strengthens customers in the belief that the products they purchase are manufactured in a sense of responsibility for the natural environment and are not the cause of social problems (Reisch, Eberle & Lorek 2013, Lang & Heasman 2016, Becot, Conner, Nelson, Buckwalter, & Erickson 2014). In addition, food product manufacturers are subject to constant pressure from consumers. The prevailing consumerism mainly in the rich countries of Western Europe, North America and some Asian countries, as well as in Poland, forces food producers to increase the supply of food products to these markets, which contributes to an even greater exploitation of the Earth's natural resources and degradation of the natural environment (Pereira & Chatzidakis 2012).

3. Research methods

The research conducted among staff employed in food industry enterprises concerned the attitudes of managers and non-managerial staff in relation to sustainable development. The research used the CATI (Computer Assisted Telephone Interview) interview method. This type of method allows conducting large-scale tests in a short time and relatively low costs. In addition to the CATI method, the study also used the CAWI (Computer Assisted Web Interview) method, in which the respondent was asked to complete the research questionnaire in an electronic form in the web application. The CAWI method, as in the case of the previous method, also allows tests to be carried out on very large samples, in a short time and with low testing costs.

In order to increase the credibility of the obtained research results, the author of this study also decided to use an additional, third research method, which was a direct interview. The advantage of the interview method is its high reliability, guaranteed by the ability to ask questions directly related to the phenomena studied. The research carried out by means of the interview method consisted of asking unified and the same worded questions and circling the answers in the same order in which the questions were asked. The advantage of this research method was the direct contact with the respondents, which enabled them to deepen specific thematic issues, and also gave the respondent the opportunity to develop and justify statements. The interview was conducted in places where the surveyed food industry enterprises have their headquarters in the Silesian, Masovian and Lesser Poland voivodeships. The respondents were employed in the surveyed enterprises in managerial and non-managerial positions. The general purpose of the methods used was to learn the facts and capture as much detail as possible in relation to the questions raised.

In the case of a large population, it is often necessary to conduct representative research that focuses on some part of the population. Conducting representative research requires specifying the method of selecting the research sample. One way is to define the sample according to *any rules, adopted according to the beliefs of the researcher*, the other way is to select the sample based on *the probability theory*. The first approach distinguishes a deliberate sample selection and a quantitative selection, while in the case of sample selection based on the probability calculus, random, stratified, proportional and multi-layered sample selection is distinguished (Sztumski 2005).

In the conducted research, stratified sampling was used assuming the error level d = 0.05 for the sample size of n = 74 enterprises. The stratified selection consists in the division of the studied population into subsets that can be distinguished within it, while ensuring that no element of the population is included in more than one subset at the same time. The distinguished subsets are treated as layers, each of which is separately selected from a random sample. The sample size that is selected from each layer may be equal to or proportional to its size (Sztumski 2005, Frankfort-Nachmias, & Nachmias 2001, Stachak 2006). 74 employees employed in managerial and non-managerial positions in food enterprises in Poland took part in the study. The characteristics of the group of respondents is presented in Figure 1.

Fig. 1. Characteristic of the group of respondents; a) job seniority, b) position, c) number of employees

4. Results and discussion

The aim of the research is to analyse the attitudes of management staff employed in Polish food industry enterprises towards the concept of sustainable development. The introduction and management of production activities that respect the principles of sustainable development depends to a large extent on the attitude and behaviour of management staff and lower-level employees. The results of statistical tests regarding the examined staff are presented in Tables 1-3.

Table 1. Results of Kruskal-Wallis test (grouping variable: seniority)

	Statistic Chi-square	Number of freedom degrees df	*p* – Asymptotic significance
Employee sensitivity to natural environment and social problems	1.571	2	0.456
Employees professional experience in the environmental and pro-social areas	2.109	2	0.348
Knowledge of the concept of sustainable development	1.121	2	0.571
The need to acquire more information about the sustainable development	2.075	2	0.354

Table2. Results of Mann-Whitney U test (grouping variable: position taken)

	Mann-Whitney U	Z	Asymptotic significance (two sided)
Employee sensitivity to natural environment and social problems	337.000	-3.191	0.001
Employees professional experience in the environmental and pro-social areas	418.500	-2.163	0.031
Knowledge of the concept of sustainable development	489.500	-1.319	0.187
The need to acquire more information about the sustainable development	305.500	-3.615	0.000

Table 3. Results of the Kruskal-Wallis test for the assessment of the socio-ecological sensitivity of employees (grouping variable: size of the enterprise measured by the number of employees)

	Statistics Chi-square	Number of freedom degrees df	Asymptotic significance
Employee sensitivity to natural environment and social problems	11.842	2	0.003
Employees professional experience in the environmental and pro-social areas	17.065	2	0.000
Knowledge of the concept of sustainable development	12.397	2	0.002
The need to acquire more information about the sustainable development	8.898	2	0.012

The determination of the measurement scale was of significant importance in the research process. The research used a seven-point version of the Likert scale to increase the accuracy of the measurement. Referring to the obtained research results, it can be pointed out that the staff employed in food industry enterprises are sensitive to environmental and social problems and know the concept of sustainable development. In addition, it has been shown that the knowledge, experience and socio-ecological sensitivity of employees do not depend on seniority (Table 1), but depend on the position held (Table 2, 3). As a result of the analysis it can be concluded that:

a) higher level employees are more sensitive to environmental and social problems than employees in lower positions,
b) management staff have professional experience in the environmental and pro-social area,
c) employees in managerial positions show willingness and need to obtain information on sustainable development than lower-level employees.

In addition, it has been shown that the socio-ecological sensitivity of employees, professional experience, staff knowledge of sustainable development and the willingness to obtain more information about the nature and importance of sustainable development depend on the size of the enterprise (Tables 4, 5).

Table 4. Results of Games-Howell comparing of means (post hoc analysis) (grouping variable: size of enterprise)

Dependent variable	(I) employment size	(J) employment size	Means difference (I-J)	Significance
Employee sensitivity to natural environment and social problems	1	2	-0.976	0.064
		3	-1.567*	0.003
	2	1	0.976	0.064
		3	-0.590	0.077
	3	1	1.567*	0.003
		2	0.590	0.077
Employees professional experience in the environmental and pro-social areas	1	2	-0.917*	0.004
		3	-2.217*	0.000
	2	1	0.917*	0.004
		3	-1.300*	0.011
	3	1	2.217*	0.000
		2	1.300*	0.011
Knowledge of the concept of sustainable development	1	2	-1.631*	0.006
		3	-2.183*	0.001
	2	1	1.631*	0.006
		3	-0.552	0.298
	3	1	2.183*	0.001
		2	0.552	0.298
The need to acquire more information about the sustainable development	1	2	-0.286	0.683
		3	-0.917*	0.030
	2	1	0.286	0.683
		3	-0.631*	0.034
	3	1	0.917*	0.030
		2	0.631*	0.034

Table 5. Results of Games-Howell test – size of enterprise

Dependent variable	(I) size of enterprise	(J) size of enterprise	Means difference (I-J)	Standard error	Signifi-cance
The company's staff show indifference to social and environmental problems	1	2	1.131*	0.312	0.006
		3	1.450*	0.302	0.001
	2	1	-1.131*	0.312	0.006
		3	0.319	0.183	0.200
	3	1	-1.450*	0.302	0.001
		2	-0.319	0.183	0.200
Y – cumulative average enterprise rating in applying the concept of sustainable development	1	2	-0.1153075*	0.0298370	0.002
		3	-0.2006693*	0.0308478	0.000
	2	1	0.1153075*	0.0298370	0.002
		3	-0.0853618*	0.0243282	0.003
	3	1	0.2006693*	0.0308478	0.000
		2	0.0853618*	0.0243282	0.003

*The difference of means is significant at the level of 0.05

Considering the results of statistical tests included in Tables 4 and 5, the following conclusions can be made:

a) employees of small enterprises (less than 50 employees) are less sensitive to environmental and social problems compared to employees employed in large enterprises (more than 249 employees),
b) the larger the company, the greater professional experience of employees in the environmental and pro-social area,
c) employees employed in small enterprises are less familiar with the concept of sustainable development than employees of medium and large enterprises,
d) employees of small and medium-sized enterprises show a lower need to obtain information on sustainable development than employees of large organizations.

Additionally, it has been shown (Table 5) that the larger the enterprise, the higher is the rate of application of the concept of sustainable development in economic activity. This is probably due to the fact that larger food companies with significant financial resources can be more involved in sustainable business activities. Therefore, it can be concluded that employees of small enterprises (less than 50 employees) exhibit lower socio-ecological sensitivity, small professional experience in the social and pro-ecological area, and less knowledge about this concept than employees of medium and large enterprises.

5. Summary

The article attempts to determine the attitudes of personnel employed in Polish food enterprises towards the concept of sustainable development. To this end, issues related to employee sensitivity to environmental and social problems, professional experience of staff acquired at work in the environmental and social area, level of knowledge of the concept of sustainable development among employees and expression of the will to obtain more information on sustainable development were considered.

Results of the conducted research indicate that the surveyed personnel employed in food industry enterprises is sensitive to environmental and social problems. An affirmative answer was indicated by as many as 85.1% of the surveyed employees of the organization. 12.2% of the respondents were insensitive to social and environmental issues. In turn, 2.7% did not take a clear position on this issue.

The research questionnaire also included a question about professional experience in the pro-environmental and pro-social area of the surveyed personnel. The obtained responses prove that the employees participating in the survey do not have any professional experience in this area. A total of 70.2% of employees do not have experience. On the other hand, 25.7% indicated professional experience gained in the previous years in the pro-social and pro-environmental area. The remaining respondents, i.e. 4.1%, showed an ambiguous attitude to these issues.

In implementing the concept of sustainable development, the knowledge of the management and non-management staff of sustainable development is essential. The obtained research results prove that a total of 63.5% of respondents declare knowledge of the concept of sustainable development, while 33.8% of respondents do not know this idea. The remaining respondents, constituting 2.7%, were not able to give a clear answer.

The analysis of the attitudes of the staff employed in the confectionery industry enterprises was complemented by the question of employees' efforts to obtain more information on sustainable development. The results of the research in this area may be optimistic, as many as 91.9% of respondents declare their will to obtain information on sustainable development. 5.4% of respondents do not demonstrate such a will, while 2.7% have no opinion.

The reason for the subject of the study is the rapid degradation of the natural environment caused by the economic activity of industrial enterprises, including from the food sector. Negative effects of business operations of enterprises contribute not only to the degradation of the ecological environment, but also to the emergence of social problems (Zaremba-Warnke 2013). Interference with the planet's ecosystem through uncontrolled and excessive sourcing of raw materials and ingredients for the production of foodstuffs, emission of harmful gases and dusts, exploitation of goods in the form of fuels, gases, energy and water needed to ensure production processes, and excessive consumption of food products accompanied by food waste, contribute to irreversible changes in the natural environment. A chance to stop negative trends is the change of consciousness (Adamek & Ziernicka-Wojtaszek 2018) among those responsible for production, organisational and sales processes in manufacturing enterprises, including food industry. The introduction of positive changes in the area of business activity depends mainly on high-level managers who set the course and development of the enterprises in which they are employed.

Theoretical considerations, conclusions and analysis of research results included in the study do not fully solve the subject matter. Therefore, an open issue remains the search for new and creative solutions aimed at reconciling the economic development of food industry enterprises as well as other economic entities with ecological and social values.

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Abstract

The essence of the study is the analysis of managers' attitudes towards the concept of sustainable development carried out on the example of food industry enterprises. The first part of the article contains the purpose of the study and draws attention to the progressive degradation of the natural environment, in which the food industry enterprises also participate. The rest of the article presents the state of the literature on sustainable development issues. The empirical part of the study presents the research methods that have been used in the research, the characteristics of the research sample and the results of own research. Based on the results obtained, conclusions were formulated that were presented in the final part of the study. The article ends with a summary.

Keywords:
manager, sustainable development, environmental degradation, food enterprises

Postawy menedżerów wobec koncepcji zrównoważonego rozwoju w polskich przedsiębiorstwach przemysłu spożywczego

Streszczenie

Istotą opracowania jest analiza postaw menedżerów wobec koncepcji zrównoważonego rozwoju przeprowadzona na przykładzie przedsiębiorstwach przemysłu spożywczego. We wstępnie artykułu zawarto cel opracowania oraz zwrócono uwagę na postępującą degradację środowiska naturalnego, w której udział mają także przedsiębiorstwa przemysłu spożywczego. W dalszej części artykułu zaprezentowano stan literatury dotyczącej zagadnień zrównoważonego rozwoju. Empiryczna części opracowania przedstawia metody badawcze, jakie zostały wykorzystanie w przeprowadzonych badaniach, charakterystykę próby badawczej oraz wyniki badań własnych. Na podstawie osiągniętych wyników sformułowano wnioski, które zostały zaprezentowane w końcowej części opracowania. Artykuł kończy podsumowanie.

Słowa kluczowe:
menadżer, zrównoważony rozwój, degradacja środowiska, przedsiębiorstwa spożywcze

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Control of Hydrogen Sulfide Concentrations in Pressure Sewers in the System of Emission-Free Sewage Transport

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1. Introduction

Organic substances in raw sewage in sewage systems are the primary source of hydrogen sulfide, characterized by the highest odour nuisance and dominance. It is a product of anaerobic biological wastewater transformation and appears along with ammonia or sulfur organic compounds, such as thiophene, dimethyl sulphide, dimethyl disulfide or mercaptans. Hydrogen sulfide is a potential threat to human health and life, and also causes problems during the operation of sewage systems and equipment because it causes corrosion of concrete and other materials used in sewage transport systems (Dębowski et al. 2008, Podraza 2014, Pochwat et al. 2019, Smyk et al. 2019).

Hydrogen sulfide is readily absorbed through the lungs, attacking the central nervous system and lungs. The smell of hydrogen sulfide becomes noticeable at low concentrations (0.0005 ppm). But 2-15 minutes of exposure to 100 ppm causes a loss of smell. Therefore, high concentration (> 500 ppm), no longer noticeable by humans, can cause unconsciousness and fatal respiratory paralysis. Hydrogen sulfide concentrations in the range 50-100 ppm cause such ailments as conjunctivitis, nose and throat irritation, and severe lung complications. (Schneider et al. 1998, Wasch et al. 1989, Malone Rubright et al. 2017).

Hydrogen sulfide is most often released from an expansion well or pumping station in the pressure sewage system. As a gas denser than air, it stays in the pipes until pumping sewage stage, which usually takes place cyclically when a certain level in the well is reached. The nuisance for sewerage system workers and, above all, the surrounding inhabitants induces more and more operators to search for efficient solutions for hydrogen sulfide emission control.

Currently, two main lines of action are used: prevention and elimination. The first one uses the chemical methods (e.g., magnesium peroxide (MgO_2) and calcium oxide (CaO)) and physical processes (aeration or oxidation) to maintain oxygen conditions in the sewage system. Operators may also apply methods that prevent the development and activity of sulfide-reducing bacteria (cleaning pipelines from sludge, increasing sewage pH, or controversial use of bactericides). The elimination of odours includes physicochemical methods, such as adsorption on activated carbon or chemical precipitation and oxidation with nitrate salts ($NaNO_3$, $Ca(NO_3)_2$), strong oxidants (H_2O_2; Cl_2; NaClO; $KMnO_4$; $NaMnO_4$) or iron compounds ($FeCl_3$, $FeCl_2$; $Fe(NO_3)_3$; $Fe_2(SO_4)_3$). Biological methods (biofilters or bio scrubbers) can also be applied, depending on hydrogen sulfide concentration (Brandt et al. 2017, Talaiekhozani et al. 2016, Piekarski & Dąbrowski 2009). The essential condition for the application of a given method is not only its efficiency but also the anticipated secondary effects, such as the impact on subsequent wastewater treatment processes.

The introduction of new methods solving above mentioned problems requires verification in real conditions, which is often not an easy task to do. Appropriate selection of an object, consent of an operator, adjustment to measurements, and unexpected circumstances that do not occur in stable conditions of laboratory tests constitute a difficulty, but also the value of the obtained results. This paper presents a part of field research of new technology for aeration and flushing of the pressure pipelines with compressed air called Emission-free Sewage Transport EST (BST in Polish), which regards the scope of control of hydrogen sulfide emission in the pressure sewage system.

2. Materials and methods

2.1. Objects under consideration

Two sections of different pressure sewage systems collecting wastewater from independent catchments were selected to verify the effectiveness of the EST system under real conditions. Both objects differed in volume flow, sewage characteristics, and pipeline diameter. In both cases, the tests were carried out on the sections *Pump station – Expansion well* of similar length. The essential features of both objects are given in Table 1.

Object-1 was a fragment of the system servicing a rural locality with a low inflow of sewage (Giezkowo, West Pomeranian Voivodeship, Poland). Measurements of wastewater inflow to the pumping station showed that they were not deep decay and the average redox potential was 35 mV (from -106 mV to 195 mV); it was positive in most of the measured samples. The average retention time of sewage in the tested pipeline section was 14.4 hours.

Table 1. Essential features of examined sections of delivery pipelines

Selected parameters	Unit	Object-1	Object-2
Length of the section: *Pump station – Expansion well*	m	3925	3406
Inner diameter of pipeline	mm	79.2	147.6
Sewage inflow to the *Pump station*, $Q_{śrd}$	m^3/d	32.1	745.5

Object-2 was a part of a branched pressure sewer system servicing the big catchment area (Konikowo, West Pomeranian Voivodeship, Poland). Object-2 has a high flow and short residence time of sewage in the delivery pipeline (2.1 h on the average). Wastewater inflowing to the pumping station, however, had negative redox potential (from -185 mV to -360 mV), causing a high odour nuisance.

The course of tested pipelines varies in height between individual wells. Object-1 has eight wells on the tested section, while Object-2 has 12. The tests were carried out in the spring and summer, at the air temperature in the measurement well of 15-21°C.

2.2. Emission-free Sewage Transport (EST)

EST technology has been developed and tested in a wide range, on a laboratory scale, by the Polish company EkoWodrol. It is a system for aeration and flushing of the delivery pipeline using compressed air. The system is based on an innovative work algorithm developed in numerous simulations. The algorithm models the flow and aeration of sewage in the pipeline and optimizes the operation of the pumping station. The device which contains, among others, a properly selected compressor is housed in an individual container body, which is located close to the pumping station.

During tests, the air was introduced into pipelines directly behind the pumping station of both objects, in a point and a time manner. The operating parameters of the EST system are given in Table 2. During the purge of the delivery pipeline, the pumping station is stopped, existing vent valves were closed, which is also a characteristic feature of this technology.

Table 2. Input data for field tests

Selected parameters	Unit	Object-1	Object-2
The air pumping time	min	60	30-40
The volume of introduced air	m^3	97	91-121
Purge frequency	d^{-1}	1-2	1-2

2.3. Measurements of hydrogen sulfide concentration

The concentration of hydrogen sulfide was measured in the expansion well of a selected section of the pressure sewage system, both during standard system operation (as a reference level) and the EST system operation. The measurements were carried out automatically using a *H_2S BE* sensor (with a basic range of 0-2000 ppm and a peak value of 3900 ppm) and a *BLE Gateway 300640* sensor. Results were sent online and archived on the internet platform with a frequency of 1 min.

3. Results and discussion

3.1. The level of hydrogen sulfide concentration before application of the EST system

Analysis of the variability of hydrogen sulfide concentration in the expansion well of both objects was carried out at different periods. The obtained data shows a significant variation in the value of the measured parameter, from close to one up to 700 ppm. In the case of Object-1, despite the inflow of fresh sewage to the pumping station, low flows and long retention time promoted anaerobic transformations in wastewater, as well as the creation of a biological film and sludge, causing conditions for rapid deoxidation of flowing sewage. The effect was a significant production of hydrogen sulfide (Fig. 1) with significantly higher concentrations than those measured in Object-2. The wastewater inflowing to the pumping station at Object-2 was characterized by a high degree of decomposition and thus lower gas-generating potential. Analysis of measurements showed, in both cases, the occurrence of sudden increases in the concentration of hydrogen sulfide in the expansion wells, mainly during the pumping of wastewater.

Figure 2 presents an example of the daily distribution of hydrogen sulfide concentration during several selected cycles of pumping station operation. Hydrogen sulfide accumulates in the delivery pipeline between each subsequent pumping of wastewater. During the pumping of sewage, it is transported to the expansion well, where it may be released to the atmosphere. The dynamic increase in gas concentration does not always end directly after the stopping of sewage pumps. It is the resultant amount of hydrogen sulfide in the pipeline and the time of pump operation. In some cycles, a slight decrease in gas concentration occurs during the work of the pumping station. Therefore, the analyzes focused mainly on the results of hydrogen sulfide measurements obtained only during the wastewater pumping cycle.

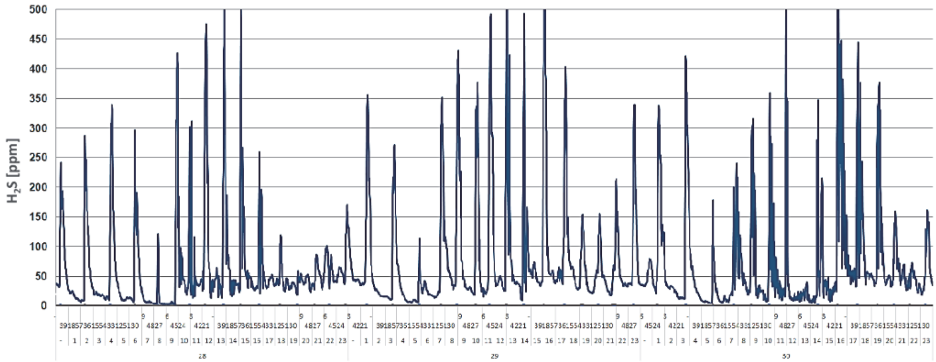

Fig. 1. Daily distribution of hydrogen sulfide concentration in the expansion well for an exemplary period of operation of pressure pipeline of Object-1 without EST purge (28-30 July 2019)

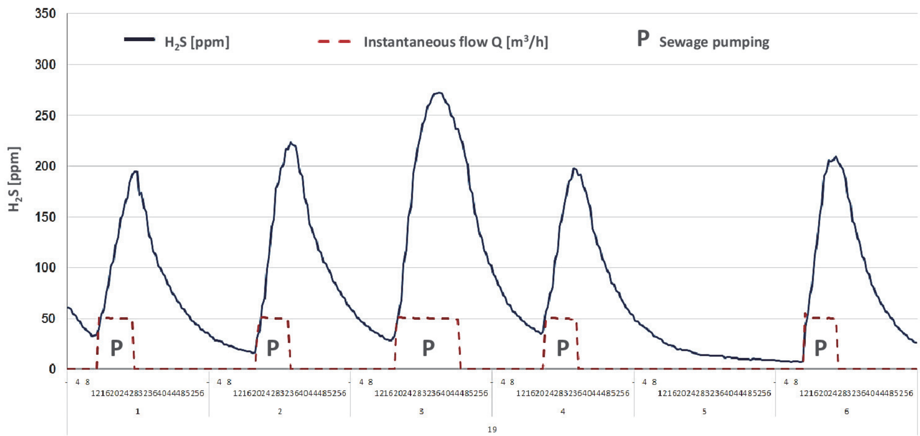

Fig. 2. Hydrogen sulfide released in an expansion well during sewage pumping (5 pumping station cycles, 19.08.2019) at Object -2 before application of EST

The average value of hydrogen sulfide concentration released in the expansion well at Object-1 was 310 ppm (ranging from 58 to 691 ppm), while at Object-2 it was 163 ppm (range from 44 to 338 ppm). Table 3 provides an analysis of the frequency of occurrence of specific H_2S concentration ranges for both objects and only during the sewage pumping. This analysis includes values of hydrogen sulfide concentration as the highest value of measurements taken within the time range of the sewage pumping cycle and a few minutes after its completion.

Since the value of hydrogen sulfide concentration alone does not fully reflect the actual nuisance of the objects, a simplifying assumption was made; all hydrogen sulfide is pushed out of the pipeline up to the maximum concentration during a given pumping. Then it is released to the atmosphere.

Table 3. Analysis of the frequency of H_2S concentration in the expansion well only during sewage pumping (Object-1 – 48 pump cycles, Object-2 – 54 cycles)

Concentration range, ppm	% share	
	Object-1	Object-2
0-50	0.00	3.70
50-100	6.25	24.07
100-200	22.92	35.19
200-300	16.66	31.48
300-400	25.00	5.56
400-500	16.67	
500-700	12.50	

This way, it is possible to determine the instantaneous hydrogen sulfide load for a given pumping cycle, calculated multiplying maximum gas concentration, and the amount of sewage pumped. The results of such analysis are presented in Table 4.

Table 4. Results of hydrogen sulfide measurements from the period including only pump cycles – EST system not applied (reference)

Parameters	Object-1			Object-2		
	min	average	max	min	average	max
H_2S [ppm]	58	310	691	44	163	338
Sewage volume in the cycle [m^3]	0.241	1.772	2.053	4.0	19.0	67.0
H_2S, [mg/l]*)	82	439	976	63	230	479
H_2S load in the cycle [mgH_2S/pump cycle]	145	758	1 956	1 153	3 914	12 317

*) calculations for 20.6°C according to formula: concentration [mg H_2S/l] = concentration of H_2S [ppm] 414.96/273+temp. °C

The average value of the instantaneous hydrogen sulfide load for Object-1 was 758 mg H_2S/pump cycle, while for Object-2, it was 3 914 mg H_2S per cycle. The values indicate a much more significant nuisance of the Object-2. It generates much more significant hydrogen sulfide load during the pump cycle (more sewage, longer pump operation time, and larger pipeline diameter), despite the lower concentrations of hydrogen sulfide released in the expansion well. At the same time, the pump cycle frequency at the Object-2 was about 30 starts daily, increasing the effect of the nuisance. At the Object-1, the pump cycle frequency was two times lower (15 cycles/day).

3.2. Hydrogen sulfide concentration after application of the EST system

Application of EST system that purges the delivery pipeline of Object-1 with compressed air once a day caused significant change of hydrogen sulfide concentration in the expansion well. 89% from 78 measurements taken during pump cycles were below 25 ppm. For two purges per day (morning and evening), 93% of measurements (from 57) were below 25 ppm. The remaining 7% of the results were within the range of 25-50 ppm. High concentrations of hydrogen sulfide were observed only during the purge when it was removed from the pipeline to the atmosphere, i.e., 1-2 times a day (Fig. 3). Without the EST system, the number of such outbursts per day was higher (over a dozen), along with each pumping cycle. Also, an increase in the number of purges and the improvement of conditions in the sewage system may cause a gradual decrease in the amount of hydrogen sulfide released.

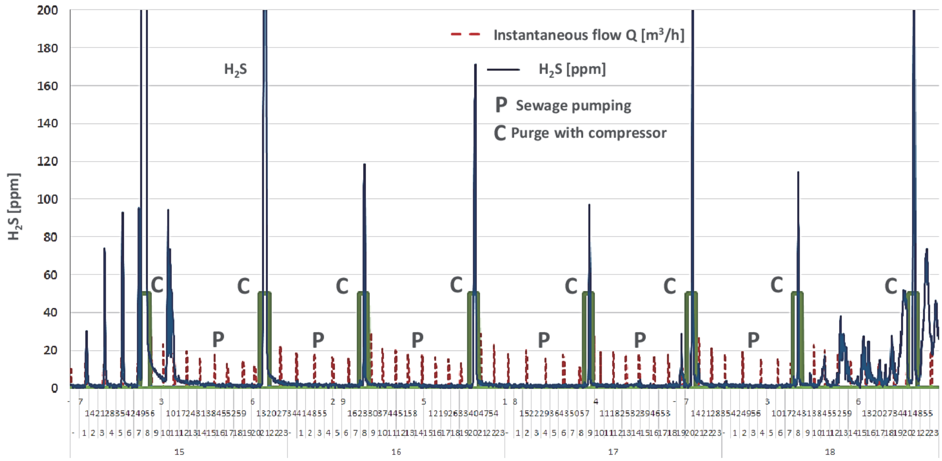

Fig. 3. Daily distribution of hydrogen sulfide concentration for an exemplary period of EST application (15-18.07.2019) at Object-1 (two purges per day)

During tests, sporadic situations (Fig. 3, day 18) of a slight increase in the concentration of hydrogen sulfide between purges also occurred. It was probably caused by an inflow of hydrogen sulfide to the expansion well from a further section of the sewage system, due to incomplete filling of the pipeline with sewage. This example shows that in the real conditions of pipeline operation, various difficulties are resulting from the specificity of a given sewage system. Therefore, it is essential to optimize the work of the EST system individually, flexibly adapting it to the existing, but also changing conditions.

A list of average values obtained from the analysis of hydrogen sulfide concentration released during the pump cycle measurements is given in Table 5. Application of EST system caused the decrease in the average hydrogen sulfide concentration measured during the pump cycle from 310 to 13.5 ppm, and the instantaneous gas load released in the expansion well during sewage pumping was reduced by 95.4% at one purge per day. An increase in the number of purges in the delivery pipeline decreased concentration of H_2S to 6.1 ppm and increased to 98% reduction of the hydrogen sulfide load.

Table 5. Analysis of the results of hydrogen sulfide measurements for a selected test period with and without the EST system (five consecutive days with one purge per day and four days with two purges per day) obtained during sewage pumping only at Object-1 (about 15 pump cycles per day)

<table>
<tr><th colspan="2" rowspan="2">Parameter</th><th rowspan="2">Unit</th><th colspan="3">Number of purges per day, d^{-1}</th></tr>
<tr><th>0</th><th>1</th><th>2</th></tr>
<tr><td colspan="2">Share of H_2S concentration within the range of 0-50 ppm</td><td>%</td><td>0.0</td><td>92.3</td><td>100</td></tr>
<tr><td colspan="2">Average H_2S concentration</td><td>ppm</td><td>310</td><td>13.5</td><td>6.1</td></tr>
<tr><td>Instantaneous load of H_2S in expansion well during the pump cycle</td><td>min-max
average</td><td>mg H_2S/pump cycle</td><td>145-1956
758</td><td>1-404
35</td><td>2-100
15</td></tr>
</table>

The use of the EST system in Object-2 required more optimization of the aeration frequency to the existing situation in the sewage system than in Object-1. The measurement period starts at the end of the purge. The measurement period ends when the purge effect fades (H_2S concentration increases above 50 ppm). The general principle was adopted – the limit concentration of the next purge is 50 ppm. Data collected during different measurement periods (2,192 measurements from 4 days of tests) show that after application of purge, 76.5% of the results of hydrogen sulfide concentration in the expansion well during sewage pumping are within the range of 0-10 ppm.

Before the application of EST, more than 96% of measurements of H_2S concentration during the pump cycle exceeded 50 ppm, with the average value of 163 ppm. Purges with air decreased an average H_2S concentration to 11.6 ppm (Table 6).

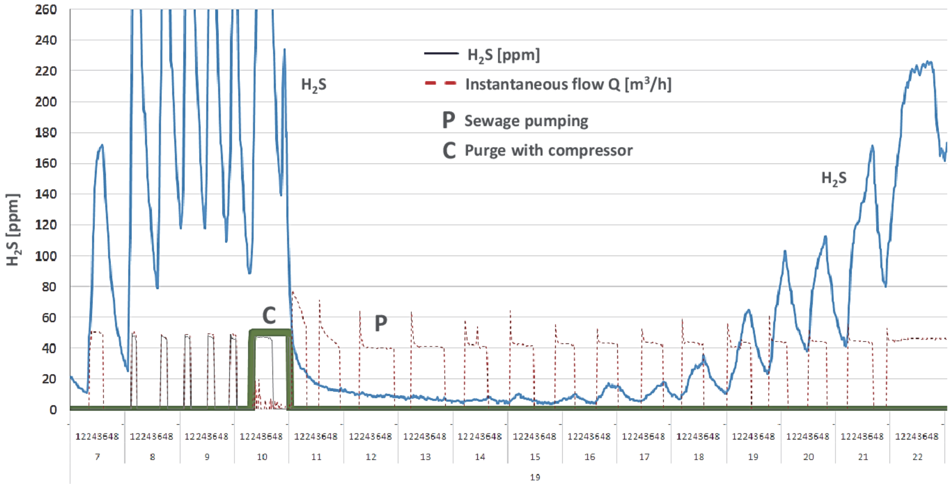

Fig. 4. Changes in hydrogen sulfide concentration for an example purge in the EST system (19.08.2019) at Object-2

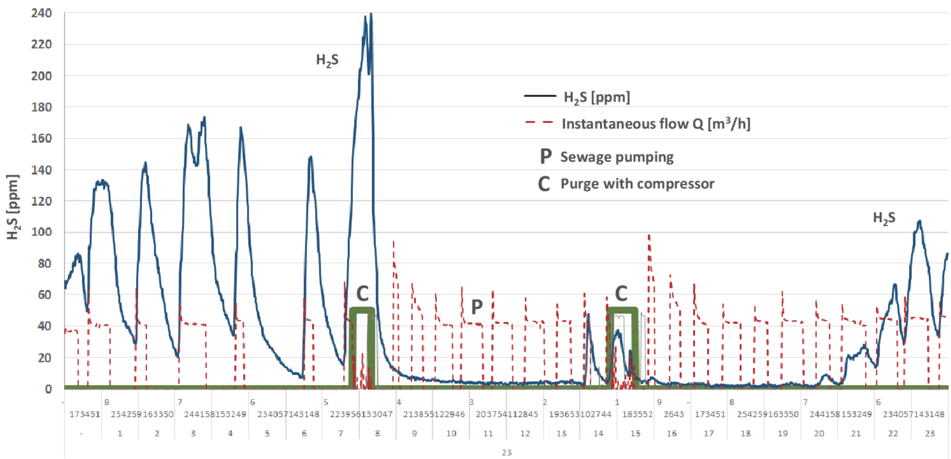

Fig. 5. Daily changes in hydrogen sulfide concentration for two exemplary purges in the EST system during the day (23.08.2019) at Object-2

Table 6. Analysis of the results of hydrogen sulfide measurements for a selected test period with and without the EST system (four consecutive days with 1-2 purges per day) obtained during sewage pumping only at Object-2 (about 30 pump cycles per day)

Parametr		Unit	Number of purges per day, d^{-1}	
			0	1-2
Share of H_2S concentration within the range of 0-50 ppm		%	3.7	100
Average H_2S concentration		ppm	163.0	11.6
Instantaneous load of H_2S in expansion well during the pump cycle	min-max average	mg H_2S/pump cycle	1 153-12 317 3 914	68-1 302 322

Studies have shown that the purge carried out at Object-2 was sufficient to maintain the concentration of hydrogen sulfide in the expansion well below 50 ppm for 8-10 pump cycles (i.e., from 8 to 12 hours). It was noted that the increase in hydrogen sulfide concentration over 50 ppm occurred only when the analyzed section of the pipeline was filled with sewage 2.5-3 times. At that moment, the next purge is required. It is visible on the charts of H_2S concentration courses in Fig. 4-5. The average hydrogen sulfide load in the expansion well released during sewage pumping decreased by 92% (Table 6).

4. Summary and conclusions

Field tests of the emission-free sewage transport system presented in this paper, were an essential supplement to previously performed a wide range of laboratory tests. Results obtained in the real conditions showed the possibility of effective control of the generation and emission of hydrogen sulfide in a pressure sewage system. So the EST system is a good alternative to the available methods of reduction of odor nuisance of a sewage system. The presented results, obtained at two different objects, allow us to draw the following conclusions:

- The highest concentration of hydrogen sulfide in the expansion well at both objects occurred abruptly during the cyclic operation of the pumping station as a result of pushing gas by pumped sewage. The range of H_2S concentration was from 44 to 691 ppm.
- The use of aeration and flushing of the pipeline in the EST system decreased hydrogen sulfide concentration in the expansion well below 50 ppm and maintained that value during subsequent wastewater pumping cycles.

- Purges of pipelines by the EST system in a cycle of one to two per day caused the decrease of instantaneous hydrogen sulfide loads released in the expansion well by 92-98%.
- During the operation of both objects without EST system, short-term increases in the concentration of hydrogen sulfide occurred, depending on the number of pumping cycles, from a dozen to nearly 30 times a day. When the EST system was applied, short-term increases in H_2S occurred only during the purge with air.
- The cyclical purge in the EST system allows to keep a delivery pipeline free of deposit, which contributes to the generation of hydrogen sulfide. EST purges also create temporary oxygen conditions as a result of the gradual washing of aeration zones formed in the upper parts of the pipeline. Both actions lead to a decrease in the frequency of EST purges in the long run.
- The EST system ensures high efficiency of reduction of hydrogen sulfide release in the expansion well and the lack of side effects. Thus no chemical compounds have to be dosed in the situation of a significant nuisance of odors generated by the sewage system.

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Abstract

The EST system – emission-free sewage transport is one of many methods used to counteract and limit the formation of hydrogen sulfide in the sewage system. EST method is the environment and human friendly, and effective at the same time. This solution applies aeration and flushing of pressure pipelines using compressed air with closed vent valves. The paper presents the results of field tests of the EST system, which also verified previous laboratory tests carried out in a broader range.

The tests were carried out on two different delivery pipelines (Object-1, Object-2), consisting of several kilometers long sections *Pump Station – Expansion well* with hydrogen sulfide concentration measurement. The results show that the EST system is an effective solution for controlling hydrogen sulfide in a pressure sewage system. The application of the EST system caused an immediate decrease in H_2S concentration under 50 ppm. The measurements were taken in the expansion well, where short-term outbursts of large loads of hydrogen sulfide were observed during sewage pumping. Purges carried out 1-2 times a day, caused a decrease in instantaneous gas load (from the average level of 758 mg H_2S/pump cycle at Object-1 to 15 mg H_2S/cycle and from 3 914 to 322 mg H_2S/cycle at Object-2).

Results of field studies have also shown that individual optimization of the EST system operation for a selected section of the pressure sewage system (length of the aeration cycle and its frequency during the day), may control the concentration of H_2S. The EST system, reducing the concentration of H_2S by over 90%, ensures the safety of sewage system operation and decreases its impact on the surrounding environment.

Keywords:
pressure sewage systems, pipeline aeration, sulfate corrosion, hydrogen sulfide, elimination of odours, EST system, odour emission

Kontrola stężenia siarkowodoru w kanalizacji tłocznej w systemie bezemisyjnego transportu ścieków

Streszczenie

Wśród wielu stosowanych metod przeciwdziałania i ograniczenia powstawania siarkowodoru, jedną z bardziej przyjaznych zarówno dla środowiska, jak i człowieka, a jednocześnie skuteczną jest system BTS – bezemisyjnego transportu ścieków. Rozwiązanie to bazuje na napowietrzaniu oraz płukaniu rurociągów tłocznych sprężonym powietrzem przy zamkniętych zaworach odpowietrzających. W niniejszym artykule przedstawiono wyniki testów terenowych systemu BTS, które były jednocześnie weryfikacją przeprowadzonych wcześniej w szerszym zakresie badań laboratoryjnych. Badania przeprowadzano na dwóch różnych rurociągach tłocznych (Obiekt-1, Obiekt-2), obejmujących kilkukilometrowe odcinki *Pompownia – Studnia rozprężna* z pomiarem stężenia siarkowodoru. Uzyskane wyniki wykazały, że system BTS jest skutecznym rozwiązaniem kontroli siarkowodoru w kanalizacji ciśnieniowej. Bezpośrednio po jego zastosowaniu stężenie H_2S obniżało się do wartości <50 ppm. Pomiary wykonywane były w studni rozprężnej, w której to obserwowano chwilowe wyrzuty dużych ładunków siarkowodoru podczas pompowania ścieków. Przeprowadzone przedmuchy płuczące rurociągu w cyklu 1-2 razy na dobę pozwoliły na obniżenie chwilowego ładunku gazu z poziomu średniego 758 mg H_2S/cykl pompowy dla Obiektu-1 do 15 mg H_2S/cykl oraz z 3914 do 322 mg H_2S/cykl dla Obiektu-2. Badania terenowe wykazały, że w oparciu o indywidualną optymalizację pracy systemu BTS dla wybranego odcinka sieci kanalizacji tłocznej, w zakresie długości cyklu napowietrzania oraz jego częstotliwości w ciągu doby można uzyskać kontrolę stężenia siarkowodoru zapewniając bezpieczeństwo w zakresie eksploatacji kanalizacji oraz oddziaływania na otaczające środowisko, zmniejszając stężenie gazu o ponad 90%.

Słowa kluczowe:
kanalizacja tłoczna, napowietrzanie, korozja siarczanowa, siarkowodór, system BTS, usuwanie odorów, emisja gazów

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Geographic Information System as a Tool to Support Environmental Monitoring and Management – Case Study of Bottom Sediments

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1. Introduction

Commonly observed, dynamic socio-economic development has a significant influence on the state of the natural environment. Human activity often has a negative impact on the environment and its components, both on a global and local scale. From the mid of the 20th century, human, who is a part of the natural environment, has increasingly began to analyse the range of problems resulting from water, soil and atmospheric air pollution, as well as the exploitation of natural resources. The consequences of these issues have been associated with health effects that can be observed with continuing, unsustainable economic growth (Gajos & Siekierka 2011). As a consequence, in 1987 the definition of sustainable development appeared in the report *Our Common Future* by the United Nations World Com-mission on Environment and Development, i.e. *which will ensure the fair satisfaction of the needs of modern society without compromising the ability to meet the needs of future generations* in the economic, ecological and social sphere (WCED 1987). The latest document on a sustainable development plan for the world is the 2030 Agenda signed at the 2015 UN Summit in New York. The agenda defines 17 goals, which assume, among others: protection of the natural environment and its resources (United Nations 2015). In accordance with the principles of sustainable development, the interaction between economic, social and environmental aspects should be non-invasive and harmonious in relation to other spheres. Unfortunately, the dynamic progress of civilization based on the continuous increase in the consumption of goods and services, the development of the automotive industry, the production of mass disposable products and the accumulation of waste often takes place without respecting the assets and resources of the natural environment (Rozpondek & Rozpondek 2017).

Currently, increasing environmental awareness of the society (Kłos 2015) has a significant impact on the development of research and investigations into new methods to solve problems related to environmental management. An important tool, which enables the collection, analysis and visualisation of environmental data, as well as its processes, is the Geographic Information System (GIS). This technology is applicable in various fields: administration, transport, security, natural environment, education, business, infrastructure and telecommunications, as well as in tourism and recreation. An example of utilising GIS in the problems of the natural environment is supporting the analyses carried out during the assessment of ecological vulnerability of particular areas (He et al. 2018), determining the type of land management, e.g. relating to the selection of the location for a landfill, taking into account its potential impact on the environmental components (Bahrani et al. 2016), assessing the suitability of an area for the development of renewable energy sources (Noorollahi et al. 2016) or modelling various types of threats affecting flora and fauna (Zeilhofer et al. 2011). The use of GIS supports environmental management by the interpretation of multifaceted relationships, modelling and forecasting changes in the natural environment and integrating various types of data. GIS helps to monitor the environment, including noise (Alam et al. 2020), air pollution (Alsahli & Al-Harbi 2017) and water (Mira et al. 2017) or the management of protected areas (Vaissi & Sharifi 2019). The main argument for the use of geostatistical methods in the analysis of the natural environment is the fact that they allow for the reduction in the costs of research, which are usually very high (Zawadzki 2011, Urbański 2012). Owing to the wide rage of possibilities enabling the combination of engineering and technical solutions with scientific knowledge, GIS technology is also used in evaluating the problematic aspects of bottom sediments monitoring.

Bottom sediments, due to their structure, which affects the increased accumulation of pollutants entering stagnant and running waters, are a valuable indicator of pollution monitoring (Förstner & Salomons 2010, Kennish 2017). It is considered that studies on the chemical composition of bottom sediments are often a better indicator of environmental pollution than the studies on the composition of water, which is more susceptible to time changes (Szarek-Gwiazda 2013, Szydłowski et al., 2017). As a result of human activity or natural processes, an imbalance between the water column and sediments is commonly observed. The aforementioned imbalance may lead to the activation of harmful substances accumulated in the sediments and cause secondary pollution of the reservoir water. As a consequence of this process, blockades in the use of water in the industry, municipal economy or agriculture may occur. Research on the bottom sediments and a detailed analysis of the obtained results allow identification of harmful human activities undertaken in the analysed region (Baran & Tarnowski 2013, Wojciechowska et al. 2017). These studies are extremely important as bottom sediments perform a number of roles in the natural environment, which include ecological, geochemical as well as economical functions (Szalińska 2011, Baran et al. 2016).

Accurate assessment of the state of bottom sediments, obtained from several dozen measuring stations, requires considerable labour and financial resources. The aim of the conducted studies was made to develop a bottom sediment monitoring network for selected water reservoirs of the Śląskie voivodeship (Ostrowy, Poraj and Dzierżno Duże reservoirs) using the GIS. It was assumed that the performed activities should allow achievement of the best ratio of the quantity and quality of the acquired data on the status of bottom sediments, while reducing the number of measuring stations.

2. Study area and methodology

The Silesian Voivodeship, located in the southern part of Poland, is characterized by the presence of many anthropogenic water reservoirs in its territory. The small share of natural lake basins results mainly from the ancient glacial nature of the terrain and the broadly understood anthropogenization of areas. The characteristic types of artificial water reservoirs in the Silesian Voivodeship include, among others dam reservoirs and reservoirs created as a result of land subsidence. The water reservoirs of the Silesian Voivodeship are commonly regarded as multifunctional objects (Rzętała 2008).

Due to its size, the industry of the Silesian Voivodeship has a significant impact on the level of contamination of surface water resources, and thus on the quality of bottom sediments. Bottom sediments are sensitive indicators of pollution monitoring because they can act as an absorber and carrier for substances polluting the aquatic environment (Kazimierowicz & Kazimierowicz 2014). Additionally, it should be noted that only some of the anthropogenic water reservoirs located in the Silesian Voivodeship are included in the research under the State Environmental Monitoring. Objects with an area greater than 250 ha belong to this group. There is a high need to include small tanks in monitoring studies. This is due to the fact that, like large water reservoirs, they are characterized by a significant degree of bottom sediment contamination. Therefore, the research covered three water reservoirs: Ostrowy, Poraj and Dzierżno Duże (Fig. 1, Table 1). Field work related to the collection of bottom sediment samples was carried out at the turn of July and August 2016.

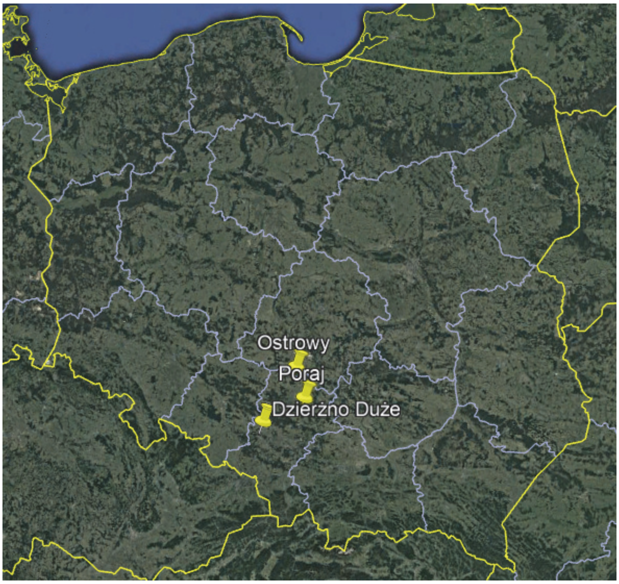

Fig. 1. The location of the Ostrowy, Poraj and Dzierżno Duże water reservoirs against the background of the map of Poland

Table 1. Features of the Ostrowy, Poraj and Dzierżno Duży water reservoirs

Feature	Reservoir		
	Ostrowy	Poraj	Dzierżno Duże
Longitude	19°01′42″E	19°14′02″E	18°33′32″E
Latitude	50°59′28″N	50°38′58″N	50°22′08″N
Year of putting into use	2003	1978	1964
Main river	Biała Oksza	Warta	Kłodnica
Area [ha]	39	550	615
Maximum depth [m]	5.3	7.4	16.5
Number of measuring points	31	46	52

To develop the grid for placing the sampling points, ArcGIS 10.2.2 software and an orthophotomap available as part of the WMS service by the Geoportal were utilised. Before starting the collection of research material, a field interview was conducted to check the availability of selected objects and confirm the possibility of collecting samples of bottom sediments. Due to the elongated shape of the Ostrowy water reservoir, the bottom sediment sampling grid was planned on the basis of cross-sections. Additional samples were also collected in the vicinity of the dam, in the bay and at the inlet and outlet of the reservoir. In total, material was collected for the analyses from 31 out of 32 planned measurement points from the depth of 0.3 to 5.3 m. The collection of sample number 31 was not possible due to the inaccessibility of the area due to abundant water vegetation (Fig. 2a). In the remaining objects, the measurement network was developed on the basis of a square grid. In the case of the Poraj reservoir, the mesh side was approximately 300 m, and in the Dzierżno Duże reservoir – approximately 350 m. Due to the inaccessibility of the area, the location of the previously planned points was slightly changed. From the Poraj reservoir, samples of bottom sediments were collected at 46 designated measurement points from the depth of 0.4 m to 7.4 m (Fig. 2b). In the case of the Dzierżno Duże reservoir, material was collected at 52 out of 56 planned points from a depth of 0.3 m to 16.5 m below the water table. The uptake at points 19, 36, 55 and 57 was prevented due to non-blistering ground conditions (too shallow bottom, lush water vegetation) (Fig. 2c).

Samples of bottom sediments were collected using KC Denmark's specialist Van Veen bottom sediment catcher lowered on a rope. A bottom sediment catcher with a hoist and a vessel were part of the measuring station, thanks to which samples of bottom sediments were obtained. Three samples were taken from each selected point, which only after mixing constituted a representative sample. The collected bottom sediment samples were dried in air-dry conditions, and then pre-sieved through a 2 mm sieve. They were subsequently dried in an oven at 105°C to constant weight and milled in a vibratory mill to sludge fractions with particle diameters of <0.2 mm. Three samples were prepared for each measurement point. The total content of heavy metals (Cd, Cr, Cu, Ni, Pb, Zn) in bottom sediments was determined using the ICP-OES IRIS Thermo plasma spectrophotometer. Royal water was used for the extraction, in accordance with standard 11466:2002 (a mixture of concentrated hydrochloric acid and nitric acid in a 3:1 volume ratio). Mineralisation was carried out at 180°C, over 30 minutes, using a Berghof high pressure microwave mineraliser (Rozpondek & Rozpondek 2017, Rozpondek et al. 2017, Rozpondek & Rozpondek 2018).

Currently, no strictly defined classification of the bottom sediments exists in the Polish legislation in relation to the heavy metal content specified therein. Until 2012, the legal regulation of the aforementioned field had been the Regulation of the Minister of the Environment from the 16th of April 2002 concerning the types and concentrations of substances that cause contamination of the spoil. Since 2013, as a part of the State Environmental Monitoring, the assessment of the quality of bottom sediments in the context of their heavy metal pollution has been based on geochemical methods (Bojakowska 2001). This classification is based on the comparison of the content of the polluting components in the sludge with those found in natural conditions or slightly contaminated sediments. The concept, which explains the natural content of an element in the environment is the geochemical background. This term defines the amount of metal originating from biochemical, geological and other natural processes. In the case of water and bottom sediments, the processes responsible for the concentration of the element as geochemical background values include natural atmospheric deposition, uncontaminated erosion of the river bank or the inflow of natural organic materials.

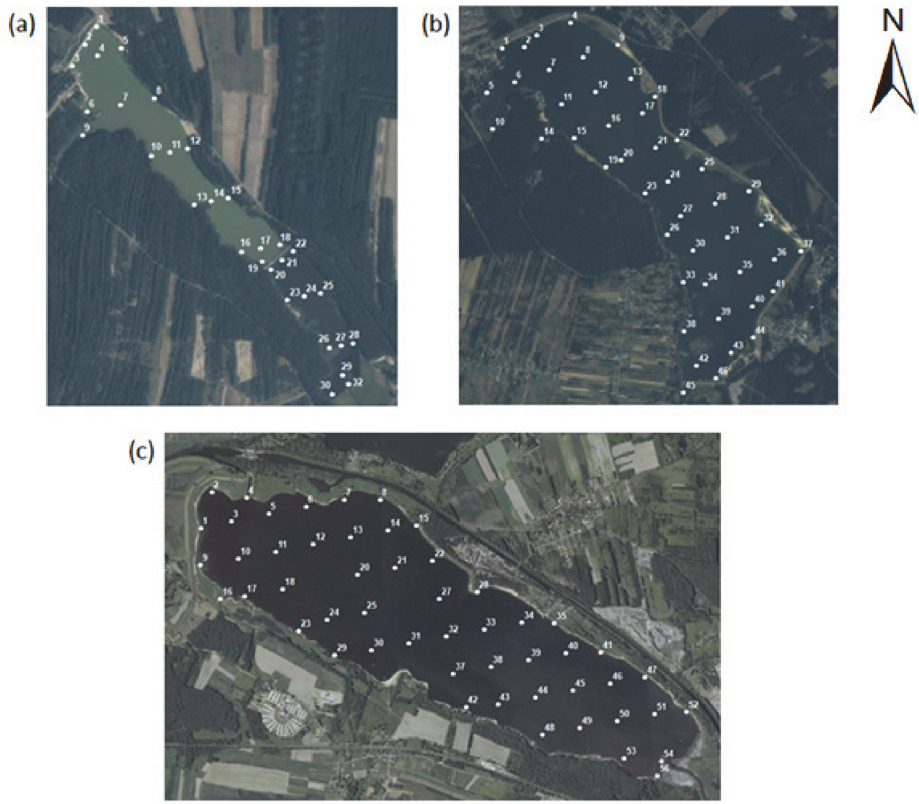

Fig. 2. Research objects with the measurement networks (a) Ostrowy, (b) Poraj and (c) Dzierżno Duże

Table 2. Qualitative classification of bottom sediments according to geochemical classification (mg/kg) (Bojakowska 2001)

Elements	Geochemical background	I class	II class	III class	IV class
Cd	<0.5	<1	3.5	6	>6
Cr	5	<20	<100	<500	>500
Cu	6	<40	100	200	>200
Ni	5	<16	40	50	>50
Pb	10	<30	100	200	>200
Zn	48	<200	500	1000	>1000

The geochemical classification of bottom sediments distinguishes pollution classes (Table 2, Table 3). When determining marginal values, it is assumed that values greater than the sum of the mean content of an element and two standard deviations determined for the analysed data set are considered as unnatural content of the element in the natural environment. The sediment is classified as contaminated when values higher than the permissible content even for one element are observed.

Table 3. Class of geochemical classification of bottom sediments with their characteristic features

Class	Degree of sediment pollution	The concentration of metals in relation to the geochemical background
I	slightly polluted	from 2 to 10 times higher
II	moderately polluted	from 10 to 20 times higher
III	polluted	from 20 to 100 times higher
IV	heavily polluted	> 100 times higher

Taking into account the results of the research on the total content of heavy metals and their geochemical classification, bottom sediment monitoring networks of the Ostrowy (Rozpondek & Rozpondek 2017), Poraj (Rozpondek et al. 2017) and Dzierżno Duże reservoirs (Rozpondek & Rozpondek 2018) were planned. Based on the obtained spatial distributions, the location of points was selected, which should be considered in further studies – the inlet and outlet zones of the reservoir, as well as locations indicating achievement of limit values between individual geochemical classes. In the search for the optimal solution, it was assumed that the network enabling collection of reliable results on the sludge quality, while minimising financial outlays, should not exceed 25% of measurement points from the base year. In order to define the quality and accuracy of the planned network, a visual assessment of the obtained spatial distributions was used. A comparison of the classification of measurement stations with respect to the quality assessment of the geochemical criterion in relation to the selected heavy metal real data, as well as the values obtained on the basis of the simulation was made. Interpolation of spatial data of the planned bottom sediment monitoring network was performed using the weighted reverse distance method.

3. Results and discussion

For the Ostrowy reservoir, based on the assumption that the bottom sediment monitoring network should consist of 25% of baseline measurement points, no satisfactory results were obtained. Due to the elongated shape of the facility and the layout of the basic measurement network based on cross sections, the utilised interpolation algorithm did not reflect the actual state associated with the content of heavy metals in bottom sediments. On this basis, it was decided to increase the number of points making up the monitoring network from 8 to 10 positions, which constituted 32% of the samples of the basic measurement network. To a large extent, bottom sediments of the analysed facility showed no (Cd), weak (Cu) or medium pollution (Pb, Zn) caused by the presence of the selected heavy metals, which is associated with the obtained comparative analysis results. The significant level of contamination resulting from the chromium and nickel content caused that the range of the classification changes varied from 0 to 5 test stands (Fig. 3).

The results indicating the high quality of the conducted simulation were obtained in the scope of estimating the content of copper, zinc and lead in the bottom sediments of the Ostrowy reservoir. Discrepancies were found in the classification of simulation results in relation to the actual test results for the nickel and chromium content. In the case of these elements, the size of the class indicating no pollution was underestimated, whereas the class informing about contaminated (Cr) and highly contaminated sediments (Ni) was overestimated. Visual assessment of the obtained spatial distributions (Fig. 4) indicates high quality of the planned measurement network.

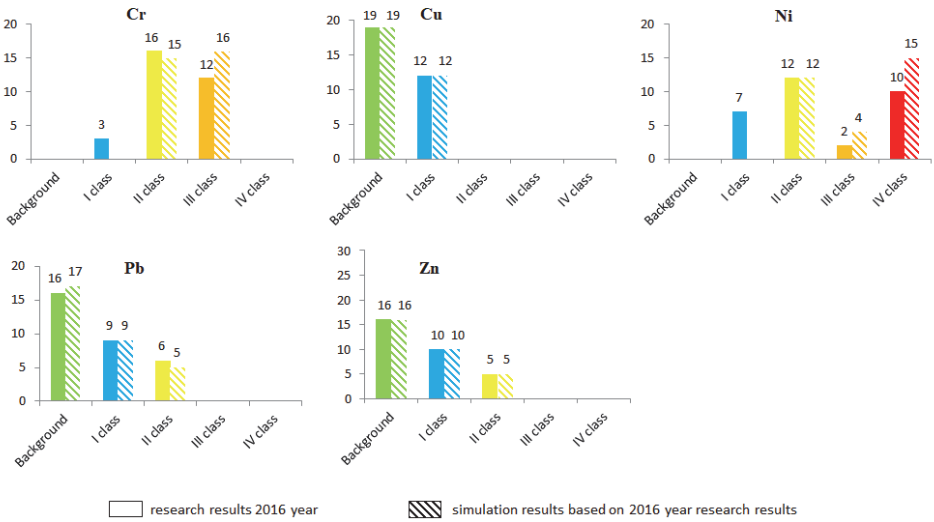

Fig. 3. Comparison of the classification of the total heavy metal content in the bottom sediments of the Ostrowy reservoir on the basis of the test results and the simulation results (vertical axis – number of measuring stations, horizontal axis – final assessment according to the geochemical classification)

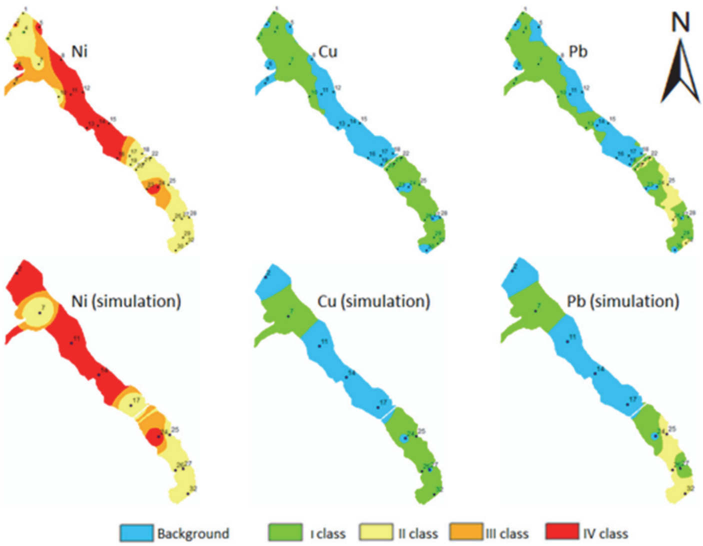

Fig. 4. The spatial distributions of the contents of selected heavy metals in the bottom sediments of the Ostrowy reservoir were obtained on the basis of the real data and simulation results

Based on the classification of the measuring positions of the Poraj reservoir in relation to the quality assessment of the geochemical criterion, significant changes were found in the classification of the individual measuring points. The range of the changes relating to the increase or decrease in the size of a given class was between 0 to 19 test stands (Fig. 5).

The simulation of the measuring network of the Poraj reservoir was based on 28% of the base points (13 stands). Utilising a smaller number of test stands did not allow for collection of satisfactory results. It was found that the results of the simulation lead to an underestimation of the value for selected heavy metals, particularly in the case of the geochemical background (Cu, Ni, Pb) and first class (Cd, Cr, Zn), while the overestimation of values was obtained for first (Cu, Ni), second (Cd, Cr, Pb) and third class (Zn) of geochemical criteria (Fig. 5).

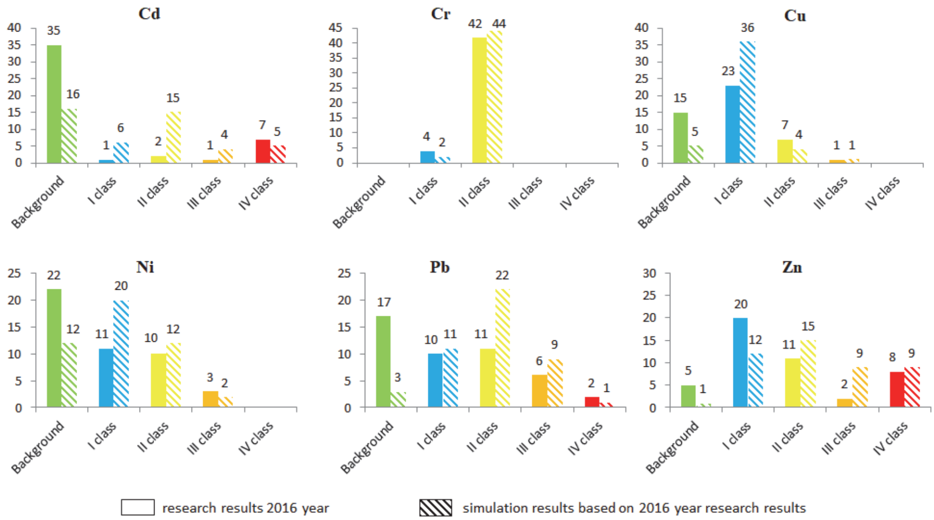

Fig. 5. Comparison of the classification of the total heavy metal content in the bottom sediments of the Poraj reservoir on the basis of the test results and the simulation results

Bottom sediments of the Poraj reservoir were characterised by point increase in heavy metal content, which affected their values obtained in the process of data estimation. However, visual assessment of the spatial distributions (Fig. 6), which were obtained on the basis of 13 test stands, allows the selection of areas that should be included in systematic research.

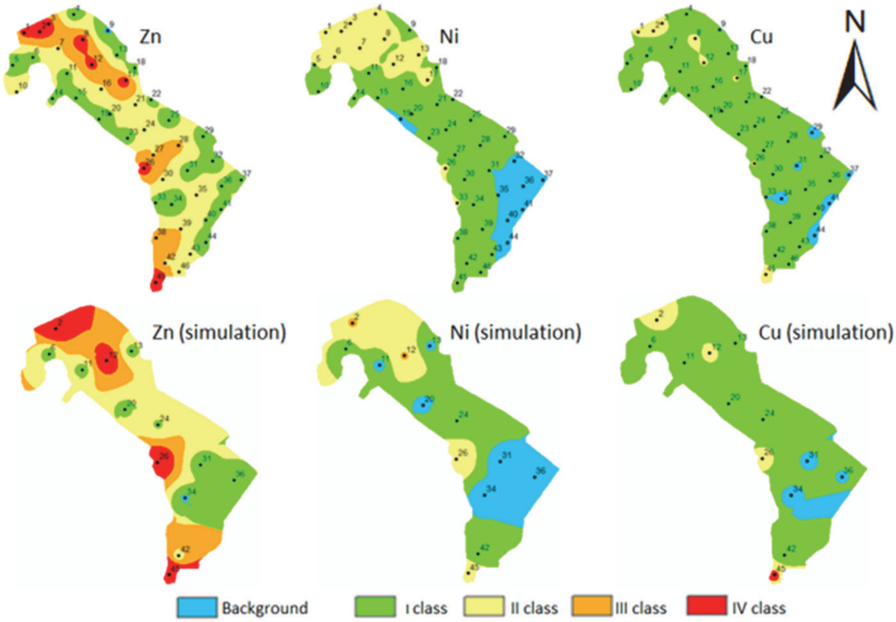

Fig. 6. The spatial distributions of the contents of selected heavy metals in the bottom sediments of the Poraj reservoir were obtained on the basis of the real data and simulation results

The bottom sediment monitoring network in the case of the Dzierżno Duże reservoir was constructed on the basis of 25% of base points, i.e. a network consisting of 13 test stands. Based on the real test results and the simulation outcomes, it was found that changes in the classification of the individual measuring positions are in the range of 0 to 16 (Fig. 7).

Based on the obtained outcomes, it was found that the results of the simulation lead to an underestimation of the values for individual elements, mainly for the geochemical background (Cd, Cu, Ni, Pb) and first class (Cr, Ni, Zn), while the value was primarily increased for the second class of the geochemical criteria (Cr, Cu, Ni, Pb, Zn) (Fig. 7). The largest discrepancies in the classification of the simulation results in relation to the real test results were found for the chromium and nickel content, and the smallest for the level of cadmium, copper and zinc content. Based on visual assessment of the spatial distributions of the heavy metal content obtained on the basis of the simulation (Fig. 8), it was determined that they enable planning of high-quality research, while minimising the financial outlays allocated to it.

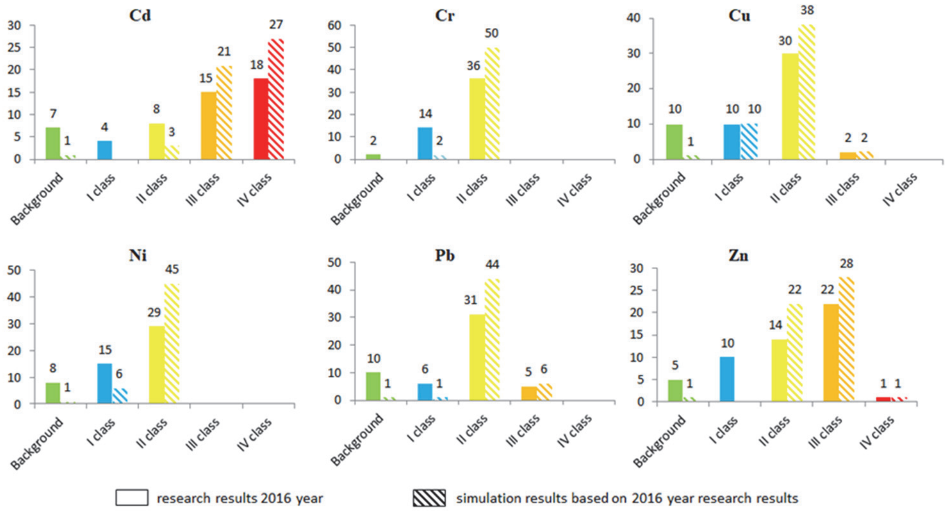

Fig. 7. Comparison of the classification of the total heavy metal content in the bottom sediments of the Dzierżno Duże reservoir on the basis of the test results and the simulation results

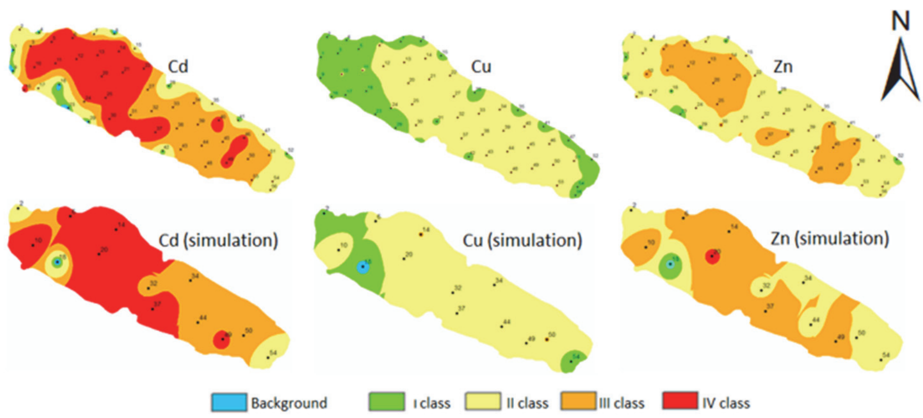

Fig. 8. The spatial distributions of the contents of selected heavy metals in the bottom sediments of the Poraj reservoir were obtained on the basis of the real data and simulation results

The overestimation of the simulation results is conditioned by the specificity of the interpolation method used, the algorithm of which assigns the value to a point in space based on the result of the estimation of the values from the test stands from the previously chosen neighbourhood. The methodology for selecting points composing the bottom sediment monitoring network, included test stands in the inlet and outlet areas of the reservoirs and in the areas characterised by limit values between particular geochemical classes. Therefore, obtaining overestimated values, particularly for sediments characterised by high levels of pollution, was an unavoidable stage of the study. A significant increase in the number of points making up the measurement network would allow for achieving higher quality results. However, this option was rejected due to the fact that it contradicts the adopted assumptions concerning minimising the financial outlays allocated to the research. Visual assessment of the spatial distribution of the content of selected heavy metals in the bottom sediments of the analysed facilities enabled the selection of areas that should be covered by systematic research. This indicates an important role of the employed criterion in assessing the quality of the planned monitoring network of the bottom sediments of the Ostrowy, Poraj and Dzierżno Duże reservoirs (Rozpondek 2019).

The latest literature reports on the content of heavy metals in other Polish water reservoirs, including geochemical classification, are shown below (Table 4).

The geochemical class of the bottom sediments of selected water reservoirs was determined based on the maximum value of the total content of a given element. The geochemical monitoring network, which operates under the State Monitoring subsystem, i.e. Inland surface water quality monitoring, consists of river sediments and sediments of selected lakes and water reservoirs. As a part of this project, bottom sediments of artificial water reservoirs include the facilities of large volumes or these utilised for water supply purposes. The presented data (Table 2), as well as our own research, show that bottom sediments of water reservoirs, regardless of the size, are characterised by high levels of pollution caused by heavy metal content.

Table 4. Content of heavy metals in bottom sediments (mg/kg)

Reservoir		Cd	Cr	Cu	Ni	Pb	Zn	Area [ha]
Łoje (Cymes et al. 2017)	Min. – Max	0.1-0.8	3.4-33.0	1.2-19.0	2.1-22.7	6.3- 41.0	6.5-88.0	5
	Avg.	0.4	11.9	7.6	9.6	20.4	41.4	
Września (Sojka et al. 2019)	Min. – Max.	0.2-0.7	4.0-6.1	3.7-18.7	2.5-9.8	7.0-32.8	27.8-1990.4	33
	Avg.	0.4	6.1	9.4	5.5	15.2	678.4	
Środa (Sojka et al. 2019)	Min. – Max.	0.1-0.3	1.7-9.3	1.4-8.7	1.0-6.0	2.8-13.0	50.8-1131.7	39
	Avg.	0.2	4.8	4.6	3.5	7.4	357.5	
Ostrowy (Roz-pondek & Roz-pondek 2017)	Min. – Max.	–	10.4-283.7	0.8-31.9	7.9-128	<* -57.7	7.0-441.6	39
	Avg.	–	93.5	9.0	41.8	15.9	96.9	
Pakosław (Sojka et al. 2019)	Min. – Max.	<*-0.1	0.7-4.7	0.3-4.7	0.4-4.8	0.9-5.3	8.2-510.7	54
	Avg.	0.1	2.0	2.0	2.0	2.6	221.7	
Besko (Piwińska et a. 2018)	Min. – Max	0.4-1.3	38.4-46.3	2.5-31.8	29.2-35.3	–	75.8-81.9	130
	Avg.	0.7	42.3	26.7	31.5	–	79.0	

Background I class II class III class IV class

* value below detection threshold

Table 5. cont.

Reservoir		Cd	Cr	Cu	Ni	Pb	Zn	Area [ha]
Rzeszów (Bartoszek et al.2015)	Min. – Max	2.1-3.1	46.9-67.7	24.4-38.6	28.5-42.9	37.8-63.9	79.6-133.6	203
	Avg.	2.5	56.3	32.7	35.6	53.5	103.9	
Brody Iłżeckie (Smal et al. 2015)	Min. – Max.	0.3-6.4	<*-106.0	1.3-47.7	<*-55.4	36.3-116.0	21.4-826.0	204
	Avg.	2.5	41.4	16.6	14.3	69.2	354.0	
Chańcza (Baran et al. 2011)	Min. – Max.	<*-0.9	5.3-30.2	6.5-89.6	5.1-30.2	13.9043.2	61.6-212.0	340
	Avg.	0.5	18.4	40.7	18.4	23.8	112.1	
Poraj (Rozpondek et al. 2017)	Min. – Max.	<*-9.1	16.7-74.9	3.0-105.0	<*-45.1	2.4-253.3	19.6-3058.4	550
	Avg.	1.3	31.9	17.2	11.6	50.6	461.4	
Rybnik (Baran et al. 2016)	Min. – Max.	0.1-15.7	2.9-132.7	33.5-1506.0	3.3-68.8	35.7-136.8	79.7-1796.0	555
	Avg.	3.7	32.2	258.3	20.4	67.6	439.4	
Dzierżno Duże (Rozpondek & Rozpondek 2018)	Min. – Max.	0.2-22.7	2.3-88.2	0.4-100.9	<*-36.5	0.9-134.4	13.3-1056.3	615
	Avg.	5.1	36.3	40.1	16.2	56.6	410.0	

Background I class II class III class IV class

* value below detection threshold

Planning of the bottom sediment monitoring network is particularly important for facilities with a small area (less than 250 ha), which are not covered by the State Environmental Monitoring research. Due to their functions, as well as the rapid rate of silting and the necessity for periodic removal of the silt, systematic and detailed monitoring of the properties of bottom sediments of small water reservoirs, plays an important role. Moreover, a deliberately planned collection of bottom sediment samples is also justified for large water reservoirs. According to the data of the State Environmental Monitoring between 2010 and 2015, bottom sediments of 58 dam reservoirs were tested at 74 test stands (GIOŚ 2017). This indicates that there was an average of 1.3 test stands per water reservoir. The use of this number of points allows for reduction in the amount of labour and financial resources; however, it is not the basis for a precise analysis of the condition of the bottom sediments in the examined facility. The research conducted in the current study indicates that the pollution of the bottom sediments is often characterised by point or area character. Therefore, the exact designation of the quality of the matter residing at the bottom of artificial water reservoirs is associated with the collection of a significant amount of bottom sediment samples (Rozpondek 2019). The proposed solution of developing a network of bottom sediment monitoring points is an example of precise activity supporting environmental management in accordance with the principles of sustainable development.

4. Summary

In recent years, there has been a continuous interest in the issues related to the natural environment, including in particular issues related to determining the level of its pollution, as well as defining innovative solutions aimed at monitoring its condition and preventing degradation, as well as managing its elements. One of the tools enabling such activities is the GIS, which is an important diagnostic tool for the state of the environment, as well as facilitates inference about the mechanisms and processes occurring in it in the environment. Based on the research, the following conclusions were conducted:

- The material collected at the bottom of the Ostrowy, Poraj and Dzierżno Duże reservoirs is characterized by a high concentration of heavy metals, which proves a significant level of contamination. For this reason, it is recommended that local authorities take into account the determination of sources of pollution in their policies and take decisions related to measures to prevent their formation, as well as monitor the condition of bottom sediments.
- Spatial distributions of the concentration level of heavy metals in bottom sediments of selected water reservoirs can be used to restore the condition of water ecosystems to the proper condition. On the basis of the adopted criteria within the Ostrowy, Poraj and Dzierżno Duże reservoirs, areas showing a

different level of pollution were identified. In the case of planning the reclamation of water reservoirs, this knowledge will make it possible to narrow the reclamation activities to particularly degraded zones. In this way, human interference in the natural environment will be limited. Zones within the reservoir with no bottom sediment contamination will remain intact. These actions are an example of the fulfillment of the environmental protection assumptions contained in the Polish Environmental Protection Law, and therefore should be taken into account by local authorities when managing the analyzed water reservoirs.

- Visualisation of laboratory test results using the GIS provides a clear message about the quality of the bottom sediments. Making these types of studies available to the public administration bodies, as well as the public will increase their environmental awareness.
- Based on the comparison of the classification of test stands in relation to the quality assessment of the geochemical criterion of real data (2016), as well as the values obtained on the basis of the simulation, it was determined that the most satisfactory results were obtained for the bottom sediments of the Ostrowy reservoir. The significant level of contamination resulting from the chromium and nickel content caused that the range of classification changes varied from 0 to 5 test stands. In the case of other water reservoirs, a higher scope of changes was found in the adopted comparative analysis (Poraj 0-19 stands, Dzierżno Duże 0-16 stands). This phenomenon is associated with a significant range of the base data resulting from high pollution of the bottom sediments with individual heavy metals (Poraj – Cd, Pb, Zn, Dzierżno Duże – Cd, Zn).
- Considering the conducted research, it was found that the sustainable management of the environment by determining the bottom sediment monitoring network of the Ostrowy, Poraj and Dzierżno Duże reservoirs should be based on an individual research approach for each of the facilities. This necessity results from the differential level of heavy metal content in the analysed material.
- The development of a bottom sediment monitoring network is an innovative solution based on the assumption that data on the quality of bottom sediments is collected in a financially justified manner.
- Although the study uses the geochemical classification of the quality of bottom sediments used in Poland, the proposed methodology for the bottom sediment monitoring network is so universal that it can be successfully used internationally by countries using a different type of bottom sediment quality classification of water reservoirs.

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Abstract

The aim of the conducted studies was made to develop a bottom sediment monitoring network for selected water reservoirs of the Silesian voivodeship (Ostrowy, Poraj and Dzierżno Duże reservoirs). Based on the obtained spatial distributions, the location of points was selected, which should be considered in further studies. In the search for the solution, it was assumed that the network enabling collection of reliable results on the sludge quality, while minimising financial outlays, should not exceed 25% of measurement points from the base year. In order to define the quality and accuracy of the planned network, a visual assessment of the obtained spatial distributions was used. A comparison of the classification of measurement stations with respect to the quality assessment of the geochemical criterion in relation to the selected heavy metal real data, as well as the values obtained on the basis of the simulation was made. Comparative analysis showed a high range of changes in the classification of measuring positions (Ostrowy 0-5 positions, Poraj 0-19 positions, Dzierżno Duże 0-16 positions). This fact is associated with a significant range of base data resulting from high pollution of bottom sediments with individual heavy metals (Ostrowy – Cr, Ni, Poraj – Cd, Pb, Zn, Dzierżno Duży – Cd, Zn). Considering the conducted research, it was found that the sustainable management of the environment by determining the bottom sediment monitoring network of the Ostrowy, Poraj and Dzierżno Duże reservoirs should be based on an individual research approach for each of the facilities. The research allowed to state that GIS has a significant impact on decision-making in the field of environmental management.

Keywords:
geochemical classification, heavy metals, decision making

System Informacji Geograficznej, jako narzędzie wspomagające monitoring i zarządzanie środowiskiem – przykład osadów dennych

Streszczenie

Celem przeprowadzonych badań była próba opracowania sieci monitoringu osadów dennych wybranych zbiorników wodnych województwa śląskiego (zbiornik Ostrowy, Poraj i Dzierżno Duże). Na podstawie uzyskanych rozkładów przestrzennych całkowitej zawartości metali ciężkich i ich geochemicznej klasyfikacji wytypowano lokalizację punktów, które powinny zostać uwzględniane w dalszych badaniach. W poszukiwaniu rozwiązania założono, że sieć pozwalająca na uzyskanie wiarygodnych wyników jakości osadów, przy jednoczesnej minimalizacji nakładów finansowych, nie powinna przekraczać 25% punktów pomiarowych pochodzących z roku bazowego. W celu zdefiniowania jakości i poprawności zaplanowanej sieci posłużono się wizualną oceną uzyskanych rozkładów przestrzennych. Dokonano również porównania klasyfikacji stanowisk pomiarowych względem oceny jakości kryterium geochemicznego w odniesieniu do wybranego metalu ciężkiego danych rzeczywistych, jak i wartości uzyskanych na podstawie przeprowadzonej symulacji. Analiza porównawcza wykazała wysoki zakres zmian klasyfikacji stanowisk pomiarowych (Ostrowy 0-5 stanowisk, Poraj 0-19 stanowisk, Dzierżno Duże 0-16 stanowisk). Zjawisko to związane jest ze znaczną rozpiętością wartości danych bazowych wynikającą z wysokiego zanieczyszczenia osadów dennych poszczególnymi metalami ciężkimi (Ostrowy – Cr, Ni, Poraj – Cd, Pb, Zn, Dzierżno Duże – Cd, Zn). Na podstawie przeprowadzonych badań stwierdzono, że zrównoważone zarządzanie środowiskiem poprzez wyznaczanie sieci monitoringu osadów dennych zbiornika Ostrowy, Poraj i Dzierżno Duże powinno odbywać się w oparciu o indywidualne podejście badawcze w odniesieniu do każdego z obiektów. Przeprowadzone badania pozwoliły na stwierdzenie, że GIS ma istotny wpływ na podejmowania decyzji w zakresie zarządzania środowiskiem naturalnym.

Słowa kluczowe:
klasyfikacja geochemiczna, metale ciężkie, podejmowanie decyzji

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Integrated Environmental Quality Management as a Function of the Adopted Concept of Development

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1. Introduction

Environmental quality management is a complex category: management + environmental quality. Quality is a set of positive and negative attributes, which characterize the environment. By using the environment, man can change it to a certain extent, and by managing its quality, he can regenerate this quality. The question is how to manage quality to ensure positive effects from human and environmental points of view. Environmental quality management is a component of every concept of development. Depending on the adopted concept of development, its priorities (goals) and implementation tools can be and are highly diverse, and even opposing or separate. Such separation is determined by the separation of the concepts of development.

Two subsets of the concept of development can be distinguished:

1. based on sustainability processes (subset 1),
2. based on unsustainability processes (cf. point 1 in the text, and in a broad scope, in the work Piontek & Piontek, 2016, p. 39 et seq.; subset 2).

At this stage, in environmental quality management such priorities (goals) are adopted that are appropriate for concepts based on sustainability, and management tools (institutional solutions) appropriate for concepts based on unsustainability processes are used to implement them. It is an attempt to integrate (eliminate) separation resulting from the separation of the alternative concepts of development. This is confirmed by the analysis of the Declaration of the United Nations Conferences in Monterrey (2002) and Johannesburg (Piontek 2002, Piontek 2017, pp. 192-198).

Initiatives taken in environmental quality management in Poland also justify the need to discuss environmental quality management in terms of the promoted and functioning concepts of development.

The purpose of the paper is:

- to analyze and assess assumptions that determine the functioning of the category of environmental quality management,
- to present criteria and assumptions for integrated environmental quality management.

A research hypothesis is as follows: Effectiveness and efficiency in environmental quality management:

- is determined by the separation of the concepts of development,
- integrated environmental quality management requires:
  - acknowledging that environmental quality is part of the category of the quality of life,
  - limiting the functioning of the deregulation paradigm,
  - limiting the functioning of the free market paradigm,
  - applying the right institutional solutions and decision-making will.

The following methods were used in the discussion:

- descriptive and critical analysis,
- a deduction method,
- a coherence method.

The purpose and hypothesis determine the structure of the paper:

1) The alternative concepts of development and their assumptions for environmental quality management,
2) Environmental quality management in relation to the integration and separation of the alternative concepts of development,
3) Assumptions for environmental quality management and their effects in real terms,
4) Criteria for the integrated implementation of the concept of development and management for improving environmental quality in real terms.

In the available literature, the issue (a formal object) has not been raised. Partial studies address the issue in terms of effects (an end-of-pipe effect – an environmental protection concept). In addition to the scientific literature, journalistic publications have been indicated. They shape the virtual and real environment (paradigms and institutional solutions, decision-making will, environmental quality management and effects in real terms).

2. The alternative concepts of development and their assumptions for environmental quality management

In synthetic terms, the attributes that diversify the highlighted concepts of development are as follows:

- The basis for the concept based on sustainability (subset 1) is the rules of universal procedures, inscribed in the nature of human capital and to a certain extent, they determine its functioning, and the basis for concepts based on unsustainability (2) – institutionally formulated paradigms, which are relative,
- An attitude to different types of capital: taking into account three basic types of capital: economic, human and natural, with the primacy of human capital (1), and in the subset (2) – focusing on one superior, for example economic capital; other types of capital are only production factors,
- The growth process is treated as a component of development, like the management of natural capital in the subset (1); in (2), growth is an independent category, the result of which may be development, but there may also be inequalities in social and natural spheres,
- Shaping relationality (the structural order) is different: in subset (1) – one type of capital cannot develop or increase at the expense of others (cf. the principle of sustainable development, Article 5 of the Constitution of the Republic of Poland), and in the subset (2) – it is possible (free market).

Differentiation is manifested in relation to environmental quality management: in the subset (1), the ability of the environment to renew its quality should be preserved and used; in the subset (2), environmental quality management should be subordinated to the requirements of the free market and the use of institutional, technological and technological solutions

Sustainable development is a component of the first subset (1), whereas the process of globalization is a component of subset (2) (cf. Piontek & Piontek 2016, p. 37 et seq., Piontek & Piontek 2017, p. 35 et seq.).

The two concepts distinguished for the purposes of analysis are explained by numerous definitions (Piontek 2002, pp. 16-26, Piontek & Piontek 2016, p. 48).

The author's definition of sustainable development is as follows: *it is the process of transformation, changes, transition to states or more perfect forms, subordinated to human capital* (which serves man) *and satisfying the criteria articulated by the rules of universal procedures* (norms of the Constitution of the World, Piontek & Piontek 2019). They are part of the achievements of civilization, and to a certain extent, they are articulated by national constitutions.

Environmental quality management as a component of the quality of life is a component of the concept of sustainable development.

The definition which shows the essence of the process of globalization is *the river of free capital* (loans; Martin Schumann 1999, p. 38-41). This definition is specified by S. Solomon: *a stream of stateless (private) money* (Solomon 2000, p. 16). Annexes to the loans are adjustment programs: they shape the economic structure of the borrower, and sometimes the request for specific changes in environmental quality management is used to make changes in the economic and social structures of borrowers. To a certain extent, an example can be the demand to ensure sales (demand) for gas or other energy in significant quantities. This statement does not exclude gas import practice, etc.

Such programs, annexes, are subject to financial engineering. Their compliance with the constitution of a given country is not examined. However, it can be important for ensuring the sovereignty of the country's economy in the long term.

The comparison of both concepts requires a reference to the foundation of the functioning of the world. It is *the principle of diversity* (dualism, pluralism), which accepts *the substance diversity of beings*. It is confirmed by the achievements of civilization: the Bible (Gen. 11.1-9), Koran (5/48), research in the world of nature (identified biodiversity), and research in the field of medicine (J. Eccles – Nobel 1963).

According to *the principle of diversity*, the concept of sustainable development promotes the primacy of human capital at the expense of other types of capital. It is a concept "inscribed" in the nature of the World and defining its functioning, in accordance with *the principle of diversity.*

The principle of homogeneity (materialistic and spiritualistic monism) is a denial of *the principle of diversity* (antithesis). This principle is not "inscribed" in the nature of the functioning of entities. Both materialistic and spiritualistic monism is a purely institutional "product" (an intellectual being). The concept of development, which is a process of globalization (based on the principle of homogeneity -economic monism), is also exclusively an institutional "product".

The different nature of these concepts – natural in the subset (1) and institutional in the subset (2) – determines that environmental quality management in the process of globalization process can be (and is) subordinated to economic monism and other institutionally formulated paradigms, in particular:

- a deregulation paradigm,
- a free market paradigm,
- it is possible to change the subject scope of the category of environmental quality management (natural and virtual environments),
- search for product excellence in technology – based environmental management,
- industrial efficiency in agriculture,
- diversified treatment of environmental components such as land, air, and noise,
- the primacy of environmental quality over the quality of life.

The paradigms determine the separation of assumptions in environmental quality management. It is necessary to make attempts to integrate these separations, which is generated by the different nature of both concepts, to effectively and efficiently manage environmental quality.

3. Environmental quality management in relation to the integration and separation of the alternative concepts of development

The purpose of point 2 is to indicate the theoretical foundations for the diversification of the concepts and methods of environmental quality management in the implementation of the process of globalization and sustainable development in practice.

The need for such reflection is justified by the following:

- A discipline of management emerged from the field of science: economics,
- In the early periods, economics was based on the laws of physics ("hard" laws), and at the same time referred to natural law (a component of the rules of universal procedures) (Smith 1989, Blaug 2000, p. 78). Economics had a normative (evaluative) character,
- Economics became a discipline in the current classification of science. It also gradually lost its normative character and became positive economics describing economic phenomena,
- The modern classifications of science do not include logic, epistemology and the methodology of science, either and philosophy (history of philosophy) is classified as a positive science. Management as a discipline has no relation to the theoretical foundations in economics or philosophy. Environmental quality management requires the identification of theoretical assumptions,
- The accepted classification of management types distinguishes several subsets:
  - In terms of functions performed:
    - ✓ management understood broadly (*sensu largo*): management, administration and public management include the functions of planning, organizing, motivating and controlling,
    - ✓ systemic management – processes occurring in systems (companies) and in the relationship to the environment, which ensure the efficient functioning of systems (processes),
  - as a set of procedures:
    - ➢ it can be a component of institutional solutions (building an organization and defining procedures or regulations for its functioning),
    - ➢ it can be classified as technology (technologies are procedures; Ritzer 1999, pp. 174-178),

– As a concept for the strategy of the organization (enterprises):
  - Benchmarking – equalling the highest achievers in a given, also environmental field, (Zimniewicz 1999, p. 36),
  - Outsorcing – a new look at the functioning of supply; it also includes service activities (also outsourcing of harmful production to other companies and countries (Zimniewicz 1999, p. 48).

The types (concepts and methods) of management do not exhaust the components of the distinguished subsets. Marketing is also a subset of management. In its extreme form, it may involve managing people's consciousness and stimulating their ecological and anti-ecological choices.

For example, the distinguished types (concepts and methods) of management can be used in environmental quality management: in the process of globalization and sustainable development. The problem, however, is that they were built on the basis of broadly understood economic capital and the free market paradigm. They include other types of capital (human and natural), but define their functioning within the free market. The result may be the primacy of the quality of the environment in relation to the quality of life.

The distinguished types (concepts and methods) of management are primarily focused on increasing economic capital: maximizing profit, reducing costs, searching for new markets, and improving operational efficiency.

Their use in environmental quality management may be justified, but requires:

- limiting the separation of the concepts of development (the process of globalization and sustainable development; see point 1),
- determining the acceptable range of their application. Institutional and technological solutions cannot exclude the natural ability of the environment to renew its quality (and generate unnecessary costs),
- identifying assumptions that are important for environmental quality management, institutionally (intellectually) formulated based on the paradigm of the primacy of the process of globalization over sustainable development. The adopted and unverified assumptions subordinate natural capital to economic capital in environmental quality management.

4. Assumptions for environmental quality management and their effects in real terms

The implementation of the process of globalization and sustainable development as separate concepts (cf. point 1) in practice requires different (separate) assumptions for management in general, including environmental quality management. The question is: What enables broadly understood freedom in the formulation of assumptions and in the choice of concepts and methods of environmental quality management?

In our opinion, it is necessary to pay attention to the civilization code, which is the principle of contradiction:

$$\text{YES} \neq \text{NO}$$

It determines the foundations of civilization: truth ≠ false; good ≠ evil; and beauty subordinated to human tastes should serve truth and goodness.

The Group of Lisbon mentions *deregulation* as one of the principles of the process of globalization (G.L. 1996, pp. 65-67). This paradigm consists of breaking the civilization code. In the language of logic, it is written as follows:

$$\text{YES} = \text{NO} = \text{CAN BE}$$

The broken civilization code is the theoretical foundation for accepting other institutionally (intellectually) formulated assumptions. It is not limited to the process of globalization, but it covers civilization. In environmental quality management, it allows for the limitation of procedures for evaluating and integrating the formulation of priorities regarding environmental quality.

The following are the examples of the effects of separation in environmental quality management:

- In the field of changing the subject scope of the human life environment:
  - Postulating the improvement of the natural environment (or its component) while neglecting undertakings aimed to protect the virtual environment
  - Using the virtual environment to shape and motivate human choices in order to limit public activities to comply with Art. 74 and 76 of the Constitution of the Republic of Poland (health, healthy food production, improving the quality of life) while ensuring the defense of the interests of specific economic endogenous and exogenous institutions,
  - Promoting the priority of animal protection while not mentioning their death to maximize the supply of meat production. The scale of this phenomenon is illustrated by Ph. Lemberg in the book entitled *Dead Zone Where the Wild Thing Were*: [...] every year the amount of meat corresponding to the weight of twelve billion farm animals is disposed of [...] (quoted after Hołownia 2018, p. 29). In whose interest?
  - In the field of diversified treatment of the natural environment:
    - ➢ Justified motivation to protect the quality of air, while not taking action on noise protection and postulating dynamic space development (cf. Seym draft acts; Piontek 2013a, pp. 7-26; Piontek 2013b, p. 63 et seq.),

   - Practice regarding consent to the import of waste, which is related to its retention, storage, contamination of land, as well as its fires and the degradation of air quality,
- Differences related to subordinating the quality of life to the requirements (paradigm) of the free market:
   - Food products and their relation to health prevention, higher prices of so-called organic products (cf. Article 68 (1) of the Constitution of the Republic of Poland),
   - Medicine and pharmacy on the free market (shortened trial period, replacement products). This is justified by the paradigm: *wealth is not gained today by improving what is known (...) but by introducing product and marketing innovations* (statement by K. Kelly, quoted by Sobczak 2019). Hence, many products are tested by the patient.

The examples of separation in environmental quality management are available in the media and generally well-known. They do not require additional confirmatory research.

5. Criteria for the integrated implementation of the concept of development and management for improving environmental quality in real terms

An attempt is being made to formulate criteria for alternative concepts and management:

- On the side of unsustainability-based concepts (including the process of globalization):
   - Recognizing environmental quality as a component of the quality of life,
   - Accepting the verifying functions of the rules of universal procedures (including the principle of contradiction YES ≠ NO) in creating institutional (organizations, procedures) and technological solutions for environmental quality management. The specific rules of universal procedures are articulated by national constitutions, including the Constitution of the Republic of Poland,
   - Control of technologies is demanded by many authors, for example A. Toffler in his book “Future Shock” (Toffler 1970). An example of a technology that subordinates human dignity to environmental quality management is the technology developed by the Swedish scientist S. Wugh-Masakk. (Walat 2002, Polityka No. 28) and technology offered by Life Gem (Domańska 2002, Wprost),

  - Limiting the functioning of the deregulation paradigm (breaking the civilization code), enabling, to a large extent, the replacement of the rules of universal procedures with unverified institutional and technological solutions,
  - In environmental quality management, promoting such types of management that are open to the rules of universal procedures and the criterion of improving the quality of life and the environmental quality,
  - Limiting the functioning of the free market paradigm and observing the structural order in the market – environment relationship (also the technologies – environment relationship),
- On the side of the concepts of development based on sustainability processes:
  - The use of such solutions from the process of globalization in environmental quality management that are "open" to the verifying function of the rules of universal procedures (also those included in the Constitution of the Republic of Poland),
  - The use of such technical-technological and institutional solutions (organizations, projects developed under unsustainability-based concepts, law) that contribute to improving the quality of life and environmental quality.
- On the side of management:
  - Knowledge of the achievements of concepts based on sustainability processes,
  - Knowledge of the achievements of concepts based on unsustainability processes,
  - Knowledge of the rules of universal procedures (including rules articulated by the Constitution of the Republic of Poland),
  - An ability to evaluate and the decision-making will.

6. Conclusion

The reflections presented in the paper allow for the formulation of a conclusion in synthetic terms: Integrated environmental quality management requires:

- The verification of institutional solutions functioning between the alternative concepts of development and between the concepts of management (a necessary condition),
- The decision-making will which accepts the verification, its assumptions and criteria (verification criteria have been presented in the text) – a sufficient condition,
- Limitations of the *consent* paradigm, based on the deregulation paradigm (breaking the civilization code) – a necessary and sufficient condition

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Abstract

The purpose of the paper is:

- to analyze and assess assumptions that determine the functioning of the category of environmental quality management,
- to present criteria and assumptions for integrated environmental quality management.

Hypothesis: Integrated environmental quality management requires:

- a necessary condition – the verification of institutional solutions functioning between the alternative concepts of development and between the concepts of management,
- a sufficient condition – the decision-making will which accepts the verification, its assumptions and criteria presented in the text.

A final conclusion: Limitations of the *consent* paradigm, based on the paradigm of deregulation (breaking the civilization code)

Keywords:
alternative concepts of development, environmental quality management, civilization code, deregulation paradigm

Zintegrowane zarządzanie jakością środowiska – funkcją przyjętej koncepcji rozwoju

Streszczenie

Cel artykułu:

- Analiza i ocena założeń decydujących o funkcjonowaniu kategorii zarządzanie jakością środowiska,
- Wskazanie kryteriów i założeń zintegrowanego zarządzania.

Hipoteza: Zintegrowane zarządzanie jakością środowiska wymaga:

- warunek konieczny: Weryfikacja rozwiązań instytucjonalnych i techniczno-technologicznych funkcjonujących między koncepcjami rozwoju i między koncepcjami a zarządzaniem,
- warunek dostateczny: wola decyzyjna akceptująca weryfikację i jej założenia i kryteria, wskazane w tekście.

Wniosek końcowy: Ograniczenie paradygmatu *przyzwolenie*, opartego na paradygmacie *deregulacja* (łamanie kodu cywilizacji).

Słowa kluczowe:
alternatywne koncepcje rozwoju, zarządzanie jakością środowiska, kod cywilizacji, paradygmat deregulacji

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Laboratory Research on the Possibility of Producing Fuels from Municipal Sewage Sludge, Rubber Waste and Biomass

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1. Introduction

The intensive development of sewerage systems results in a rapid increase in the construction of municipal sewage treatment plants. Consequently, with the construction of new sewage treatment plants and the modernization and extension of existing ones, an upward trend can be expected in the generation of municipal sewage sludge that needs to be managed (Ministerstwo Środowiska 2018). According to the National Waste Management Plan (KPGO 2015), it is estimated that every year the amount of municipal sewage sludge per dry mass will increase by about 2.5%. In Poland, the management of municipal sewage sludge has been conducted for many years through:

- agricultural use (provided the sanitary conditions are met) (Siuta 2015),
- reclamation of industrial areas and waste landfills;
- development of sewage treatment plant areas and storage of sludge in these areas,
- production of compost,
- landfilling at municipal waste landfills,
- thermal transformation (Zabielska-Adamska 2015).

According to the Ministry of the Environment, the strategy for managing municipal sewage sludge for the years 2019-2022 provides for the management of municipal sewage sludge through:

- the use of municipal sewage sludge on the earth's surface,
- composting,
- the use in biogas plants,
- thermal transformation (Ministerstwo Środowiska 2018).

As can be seen from the strategy for managing municipal sewage sludge, it is impossible to store municipal sewage sludge in municipal landfills. This results from the Ordinance of the Minister of Economy (RMG 2015) of 16 July 2015 on the acceptance of waste for landfill (Journal of Laws 2015, item 1277), which prohibits the storage of untreated sewage sludge in municipal waste landfills. Currently, the municipal sewage sludge is commonly used in agriculture and nature (Obarska-Pempkowiak et al. 2015) due to the high content of organic matter and nutrients for plants such as nitrogen, phosphorus, and microelements (Ministerstwo Środowiska 2018). This form of municipal sewage sludge management can be applied if fertilisation with municipal sewage sludge does not pose a threat to the environment. According to the data of the National Waste Management Plan, the share of municipal sewage sludge management through its thermal transformation is expected to increase in the coming years (KPGO 2015). Currently, thermal processing of municipal sewage sludge represents the most prospective technology due to the search for alternative sources of energy such as municipal sewage sludge (Czechowska-Kosacka et al. 2015).

The use of thermal methods (incineration, co-incineration) to manage sewage sludge usually requires initial drying. Sewage sludge drying is performed in sludge dryers, including mechanical and solar dryers. The effective drying process in natural conditions requires large areas, whereas negative temperatures in winter can cause freezing of sewage sludge. Mechanical drying is expensive due to large amounts of energy required for the process. Processes of sewage sludge drying have an impact on the environment as they lead to the formation of odours and pose the risk of dust explosion and spontaneous combustion (Bień et al. 2016).

In recent years, there has been a dynamic development of the automotive industry in the world, which results in an increasing amount of used rubber waste (Duda 2017). The mass percentage of rubber elements with tyres in the structure of a passenger car is approximately 5-7% of the vehicle mass (Abramek & Uzdowski 2011). Used tires from the disassembly of end-of-life vehicles (ELVs) represent the largest source of rubber waste while the remaining part consists of all kinds of gaskets, seals, belts and rubber elements used to absorb energy (Rećko 2012). Currently, the global production of car tyres and rubber is more than 15 billion Mg (Sulman et al. 2016). It is estimated that around 13 to 17 million Mg of tire waste is generated every year (Czajczyńska et al. 2017). According to world data (Ambrosiewicz-Walacik & Danielewicz 2015), the global stocks of used tyres amount to approx. 29 million Mg. The report published by the International Organization of Motor Vehicle Manufacturers (Raport 2017) states that ca. 190,000 Mg of rubber waste in Poland is produced every year, including ca. 150,000 Mg of worn tyres. Used tyres, due to their quantity, composition and structure, are a noxious waste, while their material recycling is much more difficult and expensive than in the case of steel and glass (Rećko 2012). In Poland, environmental law prohibits the storage of used tyres in whole or in part (Ustawa o odpadach 2012). An alternative to managing used tyres is to use them as alternative fuels for energy generation in the cement industry due to their high calorific value.

The production of walnuts and hazelnuts is constantly increasing due to the growing demand in the food market. The increase in the production and consequently the consumption of these nuts results in increasing volumes of production waste in the form of shells. As waste from the food industry, walnut and hazelnut shells are classified as biomass, which, due to its low water and ash content, is a good waste material for fuel production (Bryś et al. 2017)

In Poland, the cement industry is a leading sector in European countries in terms of replacing hard coal with alternative (refuse-derived) fuels. According to the Association of Cement Producers (SPC 2020), the current rate of coal replacement by alternative fuels in the cement industry in Poland is ca. 70% and some plants are even approaching the level of 85-90%, which puts Poland in the group of countries such as Austria and Germany. The average for the entire European Union is 44% (SPC 2020). The cement industry uses mainly RDF fuel based on municipal waste, while the remaining alternative fuels used in cement plants include used tyres, rubber waste, waste from mineral processing, sewage sludge, and waste from power plants (Nowak & Szul 2016).

The possibility of using a mixture of sewage sludge with beech sawdust and sewage sludge with lignite was presented in the paper (Constantinescu et al. 2018), which describes the use of sewage sludge and biomass as an alternative fuel.

Other authors (Chalamoński & Syczak 2017) report the possibility of using a mixture of sewage sludge with the waste of wood, rapeseed and rye straw, pine bark and coal in various mass proportions as an alternative fuel.

It was also demonstrated (Dąbrowski & Dąbrowski 2016) that it is possible to co-fire sewage sludge as a mixture with rubber waste at specific mass ratios.

This study presents the results of laboratory tests of production of a secondary fuel from municipal sewage sludge, rubber waste from ELVs, and hazelnut and walnut shell waste at different mass ratios. These fuels were subjected to proximate and ultimate analysis in order to determine the basic qualitative properties determining their energy use in the cement industry.

2. Materials used in the study

Municipal sewage sludge, rubber waste and hazelnut and walnut shell waste were analysed in the study.

Municipal sewage sludge was collected from the Warta sewage treatment plant in Częstochowa, Poland, after dewatering on mechanical presses at various points. The sewage sludge is shown in Figure 1.

Fig. 1. Sewage sludge

Rubber waste came from end-of-life vehicles (ELVs) at a car tyre disassembly station. The used car tyres are a multi-material waste, therefore only the elements constituting the rubber layer were separated. Rubber waste is shown in Figure 2.

Fig. 2. Rubber waste

Hazelnut shell and walnut shell waste came from the segregation of own municipal waste. Hazelnut and walnut shell waste is shown in Figure 3.

Fig. 3. Hazelnut shell waste (a) and walnut shell waste (b)

3. Methodology

The research consisted in the determination of basic fuel parameters for municipal sewage sludge, rubber waste and hazelnut and walnut shell waste in terms of energy use in the cement industry. The tests were performed in accordance with the following standards:

- water content was determined using the dryer method: Part 3: water content in the general analytical sample according to PN-EN 15414-3:2011
- volatile matter content was evaluated according to PN-EN 15402:2011
- ash content was determined according to PN-EN-15403: 2011
- carbon and hydrogen contents were determined using the LECOTru Spec CHN/S automated analyser according to ISO 29541:2010
- sulphur content was determined using a LECOTru Spec CHN/S automatic analyser according to ISO 19579:2006
- chlorine content was evaluated according to PN-ISO 587:2000
- combustion heat was evaluated according to ISO 1928:2009.

4. Results

The initial stage of the research included the proximate (as received state) and ultimate (analytical state) analysis of materials used for testing, consisting in determining the parameters characterizing secondary fuels.

Table 1 presents the results of the proximate and ultimate analysis of municipal sewage sludge.

The sludge studied was characterized by a high water content of 80%. Such a hydration of sewage sludge has a negative effect on the efficiency of the combustion process, as it significantly reduces energy value. The volatile matter content of the tested sewage sludge was 59.75%, whereas ash content was 33.54%.

Table 1. Proximate and ultimate analysis of sewage sludge

Parameter	Unit	Sewage sludge from the Warta sewage treatment plant in Częstochowa, Poland
Water content W	%	80.22
Volatile matter content V	%	59.75
Ash content A	%	33.54
Carbon content C	%	30.50
Hydrogen content H	%	3.60
Sulphur content S	%	1.36
Chlorine content Cl	%	0.08
Calorific value Q_i	MJ/kg	0.89

Table 2 presents the results of the proximate and ultimate analysis of rubber waste.

Table 2. Proximate and ultimate analysis of rubber waste

Parameter	Unit	Rubber waste
Water content W	%	0.80
Volatile matter content V	%	70.61
Ash content A	%	22.80
Carbon content C	%	54.01
Hydrogen content H	%	4.73
Sulphur content S	%	1.49
Chlorine content Cl	%	0.21
Calorific value Q_i	MJ/kg	29.48

Rubber waste was characterized by a high calorific value of 29.48 MJ/kg, low water content of 0.80% and sulphur content of 1.49%.

The proximate and ultimate analysis of hazelnut and walnut shell waste is presented in Table 3.

Table 3. Proximate and ultimate analysis of hazelnut shell waste and walnut shell waste

Parameter	Unit	Hazelnut shells	Walnut shells
Water content W	%	8.26	7.86
Volatile matter content V	%	89.01	92.28
Ash content A	%	2.20	0.80
Carbon content C	%	45.55	44.08
Hydrogen content H	%	6.04	6.25
Sulphur content S	%	0.02	0.00
Chlorine content Cl	%	0.12	0.15
Calorific value Q_i	MJ/kg	17.58	17.59

Both hazelnut and walnut shells had low water content, which was on average 8%, ash content was on average 2.2% in hazelnut shells and 0.8% in walnut shells, volatile matter content was 90%, and the comparable calorific value was 17.6 MJ/kg.

Based on the examinations of the waste materials, an appropriate composition of fuel blends was prepared. Choosing the right proportions in the blend allows for obtaining a fuel with appropriate parameters. The composition of fuel blends is presented in Tables 4 and 5.

Table 4. Percentage of components in the OL fuel blend

Examina-tion	Percentage of OL components		
	Sewage sludge [%]	Rubber waste [%]	Hazelnut shells [%]
I	50	25	25
II	40	20	40
III	30	30	40
IV	25	25	50

Table 5. Percentage of components in the OW fuel blend

Examination	Percentage of OW components		
	Sewage sludge [%]	Rubber waste [%]	Hazelnut shells [%]
I	50	25	25
II	40	20	40
III	30	30	40
IV	25	25	50

The preparation of the composition of mixtures consisted in thorough mixing of waste materials in variable proportions of municipal sewage sludge, rubber waste and hazelnut and walnut shells. Before mixing, rubber waste was fragmented to the size of rubber dust with size of 0-1 mm, as shown in Figure 4.

Fig. 4. Fragmented rubber waste

Similar to rubber waste, hazelnut and walnut shells were crushed on a jaw crusher and then ground in a laboratory vibration grinder to dust, as shown in Figure 5.

Fig. 5. Crashed and ground hazelnut shell waste (a) and walnut shell waste (b)

Compositions of blends presented in Tables 4 and 5 are marked as OL and OW fuels. These fuels differed in the percentage of individual components and the type of nutshells used in the study. The prepared waste mixtures were granulated in a granulator. The granulator was equipped with a conical tank to which the prepared fuel blend was supplied. The amount of the blend supplied to the granulation chamber could be adjusted by a feeder equipped with a flow rate scale. From the tank, the blend was supplied to the granulating chamber, where a pair of cylindrical rollers pressed the material into the cylindrical holes of the flat matrix. The fuel obtained in the form of granules with a diameter of 6 mm is shown in Figure 6.

Fig. 6. OL and OW fuels in the form of granulates

The next stage of the research was to determine the basic parameters of fuels as-received state such as water content, volatile matter content, ash content, carbon content, hydrogen content, sulphur content, and calorific value. The results of tests I, II, III, IV are presented in Tables 6, 7, 8 and 9.

Table 6. Fuel parameters obtained in test I

Parameter	Unit	Fuel OL	Fuel OW
Water content W	%	39.94	39.01
Volatile matter content V	%	72.33	75.52
Ash content A	%	15.90	15.70
Carbon content C	%	31.43	30.61
Hydrogen content H	%	7.27	7.33
Sulphur content S	%	0.63	0.60
Calorific value Qi	MJ/kg	13.21	13.43

Table 7. Fuel parameters obtained in test II

Parameter	Unit	Fuel OL	Fuel OW
Water content W	%	30.44	30.82
Volatile matter content V	%	73.09	75.43
Ash content A	%	17.70	18.00
Carbon content C	%	36.98	36.01
Hydrogen content H	%	6.81	6.89
Sulphur content S	%	0.54	0.51
Calorific value Qi	MJ/kg	16.23	16.52

Table 8. Fuel parameters obtained in test III

Parameter	Unit	Fuel OL	Fuel OW
Water content W	%	23.28	22.58
Volatile matter content V	%	72.38	77.93
Ash content A	%	15.20	14.70
Carbon content C	%	41.74	39.99
Hydrogen content H	%	6.61	6.69
Sulphur content S	%	0.47	0.45
Calorific value Qi	MJ/kg	19.19	19.36

Table 9. Fuel parameters obtained in test IV

Parameter	Unit	Fuel OL	Fuel OW
Water content W	%	18.66	17.93
Volatile matter content V	%	72.20	76.25
Ash content A	%	16.80	16.30
Carbon content C	%	47.24	46.03
Hydrogen content H	%	6.69	6.71
Sulphur content S	%	0.39	0.36
Calorific value Qi	MJ/kg	21.44	21.51

Tables 6 to 9 present the results of tests of basic parameters of OL and OW fuels obtained in tests I to IV. In the case of OL and OW fuels, the results obtained in the test I did not indicate the possibility of obtaining a fuel with good parameters. Both the obtained calorific value of 13 MJ/kg, water content of above 39% and the sulphur content of 0.6% differed from the requirements for alternative fuels. Since 2017, the requirements for alternative fuels used in the cement industry have been as follows:

- water content ≤ 20%,
- ash content < 20%,
- sulphur content < 0.5%,
- chlorine content ≤ 0.8%,
- calorific value ≥ 21 MJ/kg (Hryb et al. 2017).

Subsequent tests allowed to obtain fuel with parameters meeting the requirements for alternative fuels intended for co-firing in cement furnaces. Test IV (Table 9) presents the results which clearly indicate that the obtained calorific value of OL and OW fuels at the level of ~21.5 MJ/kg, water content of ~18%, ash content of ~16% and sulphur content of 0.36-0.39% meet the requirements for alternative fuels.

5. Conclusions

The mixtures in the form of municipal sewage sludge, rubber waste and hazelnut and walnut shell waste examined in terms of fuel parameters are assessed as OL and OW fuels meeting the requirements set by cement plants for alternative fuels used in the co-firing process.

The results obtained in the study lead to the following conclusions:

- the fuels produced had water content of 17.9-18.6%,
- the ash content in fuels ranged from 16.30% to 16.80%,
- the sulphur content in the fuels tested did not exceed the value of 0.5% required by the cement plants,
- OL and OW fuels had a calorific value that exceeded the required 21 MJ/kg,
- the fuels obtained from municipal sewage sludge did not require an energy-intensive drying process.

The developed method of fuel production based on municipal sewage sludge meets the criteria for using the co-firing process in the cement industry. An additional advantage of this method is that it does not require the process of pre-drying of the municipal sewage sludge.

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Abstract

The paper presents the results of laboratory tests aimed to analyse the opportunities for fuel production based on municipal sewage sludge, rubber waste from end-of-life vehicles (ELVs) and hazelnut and walnut shells in terms of their thermal transformation in the process of co-firing in the cement industry. The parameters of solid fuels used in the cement industry were determined for the fuels obtained in the study. The following parameters were determined in fuels: water content, ash content, sulphur content, and calorific value.

The fuel composition and process of fuel preparation were designed so as not to use the energy-intensive process of pre-drying of municipal sewage sludge. However, it should be emphasized that the maximum percentage of municipal sewage sludge in fuel should not exceed 25% in order to maintain the parameters required by the cement industry. The analysis of the obtained parameters of OL and OW fuels demonstrated that the fuels obtained in the study meet the requirements for fuels used in the cement industry.

Keywords:
sewage sludge, rubber waste, hazelnut and walnut shell waste, alternative fuels

Badania laboratoryjne nad możliwością wytwarzania paliw z komunalnych osadów ściekowych, odpadów gumowych i biomasy

Streszczenie

W publikacji przedstawiono wyniki badań laboratoryjnych nad możliwością wytwarzania paliw na bazie komunalnych osadów ściekowych, odpadów gumowych pochodzących z pojazdów wycofanych z eksploatacji (PWE) i łupin orzechów laskowych oraz włoskich pod kątem ich termicznego przekształcania w procesie współspalania w przemyśle cementowym. Dla otrzymanych paliw wykonano oznaczenia parametrów charakteryzujących paliwa stałe stosowane w przemyśle cementowym. W paliwach oznaczono takie parametry jak: zawartość wilgoci, zawartość popiołu, zawartość siarki oraz wartość opałową.

Skład i proces przygotowania paliw został tak opracowany, aby nie stosować energochłonnego procesu podsuszania komunalnych osadów ściekowych. Należy jednak podkreślić, że maksymalny udział komunalnych osadów ściekowych w paliwie nie powinien przekraczać 25%, aby zostały zachowane parametry wymagane przez przemysł cementowy. Analiza otrzymanych wyników parametrów paliw OL i OW pozwalają zatem stwierdzić, że otrzymane paliwa spełniają wymagania stawiane paliwom stosowanym w przemyśle cementowym.

Słowa kluczowe:
osady ściekowe, odpady gumowe, odpady łupin orzechów laskowych i włoskich,
paliwa alternatywne

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Impact of Fine Fractions of Recycled Aggregate on Selected Properties of Cement Mortars

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1. Introduction

One of the most serious problems of the steadily developing economies is the high amount of waste from the construction sector, which in 2016 was equal to 36.4% of the total quantity of waste generated in UE countries (Eurostat 2016). Directive on Waste (Directive 2008/98/WE), points to the requirement of waste prevention but when this is not possible requires the creation of conditions necessary to implement the recycling policy focused on selective collection and then the recycling process itself. If it is not possible to recover the material for its reusing (when it is harmful to human health and life – e.g. reusing asbestos), then a safe disposal procedure or other methods of recovery (e.g. energy recovery) should be applied. Recycled aggregate, especially recycled concrete aggregate (RCA), is increasingly used in the production of concrete and mortar. Numerous authors point out the potential benefits and disadvantages of its usefulness (e.g. Poon et al. 2002, Eguchi 2007, Evangelista 2007, Etxeberria 2007).

The basic characteristics of RCA refers to the size of its fraction. Coarse recycled aggregate (fractions above 4 mm) is more willingly used in cement composites, and the main benefit of its use is the protection of raw material resources and even CO_2 absorption during carbonation process, which can be intensified after crushing of waste concrete (Zając & Gołębiowska 2012, Mądrawski et al. 2013, Grabiec et al. 2015). Unfortunately, a serious disadvantage of coarse aggregates is the fact that after crushing process irregular and elongated grains, polluted with dust from smaller fractions, are obtained. Such grains deteriorate the rheological properties of concrete mix. Also, the presence of old cement slurry results in increased porosity of aggregate, lower density, and increased water absorption.

Despite the fact that coarser fractions are more commonly used, some mortar properties can be improved by adding fine aggregates. Silva et al. (2009), present the effect of 5% and 10% participation (by volume) of brick dust addition with 0-0.15 mm grain size on the properties of cement mortar. It was found that the addition of brick dust improves not only the compressive strength but also the flexural strength of the cement mortar. The results obtained for mortars with brick dust were compared with the results for cement mortars in which limestone, red gravel and mica-slate as well as granulite were used (Angelim et al. 2003 cited by Silva et al. 2009). It was found that only ceramic dust contributes to the increase in compressive and flexural strength, whereas for mortars with the addition of gravel powder, shale dust and granite powder (in the amount of 10% by volume) the decrease in strength should be taken into account. Silva et al. (2009) indicated an almost linear function of water absorption coefficient decrease (during capillary absorption) with an increase in the amount of red brick powder. For samples with addition of 10% of brick powder the decrease of water vapour permeability and water permeability was also obtained. Of course, lower water vapour permeability in case of mortars is not always a positive feature (when it makes it difficult to remove moisture from a building barrier, e.g. plaster), but low values obtained in water penetration test is a most desirable property, especially for structures such as swimming pools, tanks.

Zhao et al. (2015) focused on the use of recycled concrete sand (RCS) with a grain size lower than 5 mm for mortar, which they divided into four fractions. The percentages of RCS were selected in such a way that the resulting recycled grading curve coincides with the grading curve of the natural sand. The volume of RCS replaced natural sand partially or completely. Three groups of series were prepared in order to: (I) verify the difference between the properties of mortar with pre-soaked aggregate (by adding water to the aggregate itself before mixing the other ingredients) and dry aggregate without soaking, with three different water and cement coefficients (0.5; 0.55 and 0.6), (II) determinate the effect of the RCS participation on the mechanical properties of mortar at a constant w/c = 0.5. (III) formulate the effect of each fraction of recycled sand on the mortar properties at two w/c levels (w/c = 0.5 and w/c = 0.6). In the third group all aggregate fractions were previously pre-soaked in water for 24 hours. Compressive strength for mortars with dry RCS was higher than for mortars with water-saturated RCS and this was valid for all investigated w/c coefficients. However, the thickness of the Interfacial Transition Zone of aggregate for pre-saturated RCS was higher than for aggregate in dry state. As the amount of RCS in the mortar increased, the compressive strength decreased and the relationship was quasi linear. The most unfavorable influence on mortar properties had the smallest fraction of aggregate (0-0.063 mm), which is a result of higher content of paste, connected with higher water absorption and lower mechanical parameters.

The degree of mortar fluidity – as a criterion for the quality evaluation of mortars containing fine RCA – was proposed by Kumar (2019). Three fixed values of the flow were proposed: 110±2.5 mm, 135±2.5 mm and 160±2.5 mm. It turned out that in order to obtain the same flow in the samples, the water content must be higher for the pre-soaked aggregate than in the control samples. Moreover, the setting time of the pre-soaked mortar was shorter than the setting time of the reference mortar. In addition, the values of the strength parameters of the RCA samples are worse for the higher participation of recycled aggregate. Moreover, more recycled fine aggregate leads to lower content of chemically bound water, higher porosity in the mortar, and consequently higher water absorption and sorption (compared to the control mortar).

The pressaturation technique was also used by Katzer & Domski (2013). This procedure proved to be useful and increased the workability and required consistency of mixtures with ceramic waste. The second benefit was an increase in compressive strength compared to ceramic waste itself.

In the studies presented by Corinaldesi & Moriconi (2009) three types of fine aggregate were used: brick, RCA and mixed aggregate. The highest values of compressive strength were recorded in series with natural aggregate (reference series). Significantly worse results (but close to each other) of compressive strength were obtained for mortar samples made of RCA, brick and mixed aggregate. In the case of flexural strength tests (after 28 days of hardening) the situation was slightly better - the highest values were found for mortars with RCA, then for mortars with natural sand. The lowest values of flexural strength were recorded for mortar with mixed aggregate and slightly higher values for mortar with brick sand.

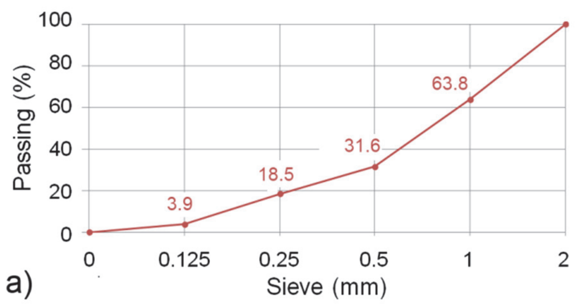
Dobiszewska (2016) also obtained results confirming the positive influence of fine aggregate (in case of waste basalt powder) on the mortar and concrete strength. The highest increase in compressive strength was observed when 30% of natural sand was replaced (by mass) by waste aggregate. It reached even 40% after 28 days and 60% after 56 days. The remaining series of mortars, in which sand mass was replaced by basalt powder (10% and 20%), were also characterized by higher values of compressive strength than the control sample. The explanation for the increased strength is the fact that basalt powder has a smaller particle size than natural sand grains, so it tightens the structure of the cement matrix, reducing the total volume of pores in the mortar, pore diameter and porosity of the structure. The effect of filler on mortars was also confirmed by lower water absorption in each series with the addition of basalt powder compared to the results of the reference series.

The research conducted by Domski & Głodkowska (2017) have also confirmed that the properties of cement composites containing waste sand as a fine aggregate meet the requirements for building materials and can be used on a larger scale. This can solve problems related to the depletion of natural resources and reduction of material waste.

2. Material and methods

Two types of cement were used in the research: CEM I 42,5 N and CEM III/A 42,5 N LH/HSR/NA. The proportions of ingredients were as for standard mortars (EN 197), i.e. 450 g of cement, 225 g of water and 1350 g of aggregate (gradation presented in Fig. 1a), modifying only the proportions of natural and RCA within a given fraction (Table 1). 5-level Central Composite Design (CCD) for 3 independent factors was implemented, i.e. the volume participation of recycled grains in the total volume of aggregates in each of the three groups of fractions: 0/0.25 (designed as *f*), 0.25/1 (*m*) and 1/2 mm (*c*). Each factor was present in a given group at levels based on rotatability of CCD: 0% (level -α), 17 (level "-1"), 42 (central level), 67 (level "+1") and 84% (level +α), which corresponded to the share of natural aggregates: 100, 83, 58, 33 and 16% respectively. Three repetition of central series (no. 5, 10 and 17 – series with RCAs amount equal to 42% in each group of fraction) was applied (which is a basic rule of CCD). Fig. 1b presents an example of 2-dimensional CCD. Statistical analysis was performed using Statistica Software, licence no.: JPZ612B037802AR-P.

After mixing the all components, flow diameter (measured on the flow table after 30 compactions) was investigated. Then the mixes were placed and compacted in moulds (triple 4x4x16 mm). After 28 days compressive strength was measured (Fig. 2) using 6 samples per each series (with testing area of 40x40 mm), followed by a water absorption test (three 40x40x40 mm samples).



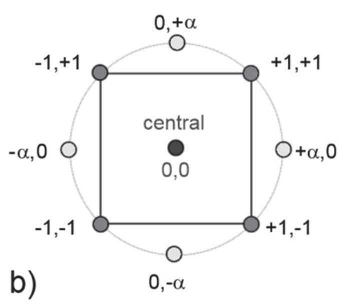


Fig. 1. Composition of natural aggregate (a) and the scheme of CCD approach (b)

Table 1. Mixture composition with weights of individual fractions

Series	RCA total	f – 0/0.25 mm			m – 0.25/1 mm			c – 1/2 mm		
		Nat	Rec		Nat	Rec		Nat	Rec	
	(%)	(g)	(g)	(%)	(g)	(g)	(%)	(g)	(g)	(%)
1	17.0	208.3	37.7	17	507.2	91.8	17	405.6	73.4	17
2	57.7	208.3	37.7	17	201.7	361.5	67	161.3	289.1	67
3	44.3	82.8	148.4	67	507.2	91.8	17	161.3	289.1	67
4	48.9	82.8	148.4	67	201.7	361.5	67	405.6	73.4	17
C-5*	42.0	145.5	93	42	354.4	226.6	42	283.4	181.2	42
6	35.1	208.3	37.7	17	507.2	91.8	17	161.3	289.1	67
7	39.6	208.3	37.7	17	201.7	361.5	67	405.6	73.4	17
8	26.3	82.8	148.4	67	507.2	91.8	17	405.6	73.4	17
9	67.0	82.8	148.4	67	201.7	361.5	67	161.3	289.1	67
C-10*	42.0	145.5	93	42	354.4	226.6	42	283.4	181.2	42
11	34.2	251	0	0	354.4	226.6	42	283.4	181.2	42
12	49.8	40.1	186.2	84	354.4	226.6	42	283.4	181.2	42
13	23.0	145.5	93	42	611	0	0	283.4	181.2	42
14	61.0	145.5	93	42	97.8	453.2	84	283.4	181.2	42
15	26.8	145.5	93	42	354.4	226.6	42	488.7	0	0
16	57.2	145.5	93	42	354.4	226.6	42	78.2	362.5	84
C-17*	42.0	145.5	93	42	354.4	226.6	42	283.4	181.2	42

* 3 identical series with amount of each RCA fraction equals to central (C) level of 42% (according to 5-level CCD for 3-factors at least three C series are needed)

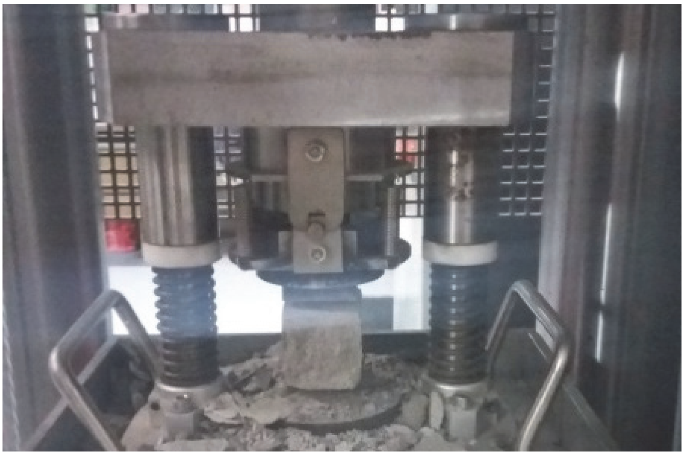


Fig. 2. Compressive strength test

3. Results

The results of flow diameter (which is a measure of the degree of consistency) and water absorption of mortars are presented in Table 2.

Table 2. Results of average flow and water absorption of mortars

Series	RCA total	Participation of *f-m-c*	Flow diameter (mm)		Water absorption (%)	
	(%)	(%)*	CEM I	CEM III	CEM I	CEM III
1	17.0	17-17-17	235	235	**9.4± 0.1**	**9.2**±0.7
2	57.7	17-67-67	175	150	10.5±0.1	12.6±0.6
3	44.3	67-17-67	175	175	10.1± 0.1	12.5±0.4
4	48.9	67-67-17	135	170	10.9±0.3	11.6±0.7
5-C	42.0	42-42-42	210	210	10.2±0.1	12.6±0.3
6	35.1	17-17-67	255	200	9.9±0.2	10.6±0.2
7	39.6	17-67-17	230	180	10.0±0.1	11.4±0.2
8	26.3	67-17-17	245	205	9.7±0.1	10.8±0.3
9	67.0	67-67-67	**110***	**130***	**11.3± 0.1**	**13.3**±0.9
10-C	42.0	42-42-42	200	200	9.5± 0.2	12.3±0.2
11	34.2	0-42-42	**270***	**240***	9.5±0.1	11.3±0.8
12	49.8	84-42-42	190	150	10.9± 0.1	10.9±0.5
13	23.0	42-0-42	260	215	**9.4**±0.1	9.8±1.0
14	61.0	42-84-42	140	**130***	10.7± 0.1	11.6±0.6
15	26.8	42-42-0	255	215	9.7±0.1	12.4±0.1
16	57.2	42-42-84	165	180	10.5±0.3	12.3±0.6
17-C	42.0	42-42-42	220	170	10.2±0.2	12.0±0.6

* Participation of RCA in each of aggregate group (not in the total amount of RCA)
** The lowest and highest values obtained for a given cement were marked

3-factor square regression model (taking into account all three independent factors, i.e. content of *f*, *m* and *c* fraction groups) was estimated for compressive strength of mortars. Statistical analysis showed the lack of relevance of some parameters of the model. Ultimately, the regression equations took the following forms (for CEM I and CEM III respectively):

- *compr_str* = $53{,}232 + 4{,}452\ f - 3{,}670\ f^2 - 1{,}663\ m - 2{,}558\ c - 3{,}175\ c^2 - 7{,}002\ fm - 3{,}323\ fc - 4{,}391\ mc$,
- *compr_str* = $51{,}918 - 1{,}803\ f - 1{,}971\ m - 4{,}021\ c - 6{,}780\ c^2 - 3{,}532\ fc$.

Values of R^2 are not high (0.667 and 0.637 respectively), however, they are similar for both cements. It should be pointed out that the value of R^2 should be interpreted each time in the context of the research area (a characteristic feature of RCA is the randomness of properties within each grain).

Figures 3-5 show the visual presentation of the compressive strength tests, but each figure shows the response area for 2 of 3 fraction group pairs: f (0/0.25 mm), m (0.25/1 mm) and c (1/2 mm). Each time the level of RCA amount for the third group is constant and is equal 42% (value of central level in 5-level CCD). The flow results as the function of total RCA content are presented in Fig. 6.

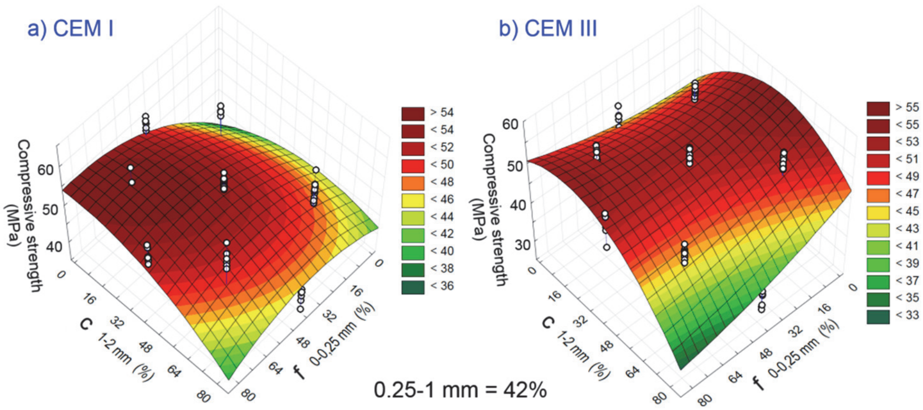


Fig. 3. Compressive strength results (relation of f and c RCA fractions; quantity of m is equal to 42%)

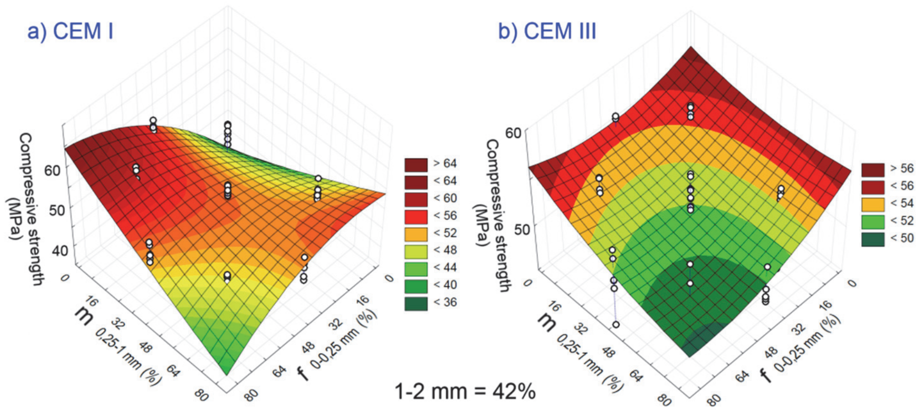


Fig. 4. Compressive strength results (relation of *f* and *m* RCA fractions; quantity of *c* is equal to 42%).

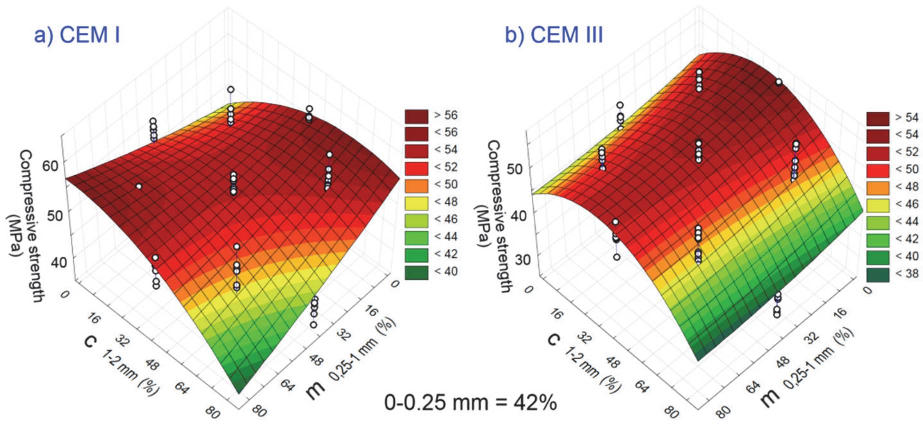


Fig. 5. Compressive strength results (relation of *m* and *c* RCA fractions; quantity of *f* is equal to 42%)

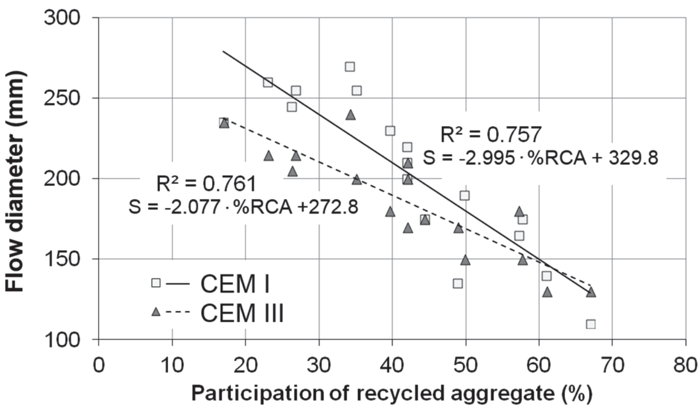


Fig. 6. Relation of flow results of mortars as the function of total mass content of RCA

4. Discussion

The results of the flow diameter (Table 2) show that the flowability is strongly influenced by the total amount of recycled aggregate. A significant linear correlation can be observed (Fig. 4) both for mortars with CEM I cement (R^2 = 0.757) and with CEM III (R^2 = 0.761). With the increase in the total amount of recycled aggregate, the flow of the mix decreases (worse workability is achieved). This is logical because recycled aggregate is more water-absorbable than natural aggregate.

Analysing the results of the water absorption tests (Table 2), it can be observed that the maximum values were obtained for the series with the highest participation of recycled aggregate (67%). It amounted to respectively: 13.3% for CEM III cement and 11.3% for CEM I. The effect on mortar absorbability, which Dobiszewska (2016) achieved in her studies for basalt powder, is not confirmed. The lowest water absorption values were obtained for mortars with the total amount of recycled aggregates equal to 17% – it reached 9.4% and 9.2%, for CEM I and CEM III respectively.

The results of the compressive strength tests presented in Fig. 3a (for mortars made of CEM I cement and containing a constant 42% participation of *m* RCA fraction in the mixture) showed that the highest values were obtained with a high amount of the smallest *f* RCA fraction and a minimum amount of 1/2 mm grains. With an increase in the proportion of the latter and a decrease in the weight of fine aggregate, the strength also decreased. This can be explained by four different effects. Firstly: when the amount of *f* is higher, there is (locally) a higher water uptake from the paste than in the case of *c* fraction (due to large specific surface area of *f* and resulted water content). The reduction of the mortar's w/c ratio results in reinforcement in terms of strength parameters. Secondly: fine recycled aggregate also has a certain amount of unreacted cement from the old matrix. When it comes into contact with water again, additional hydration may occur (in addition to the hydration of cement added as a component of the mortar), which also can improve strength. Thirdly, in the case of a large amount of fine grains and a small amount of *c* fraction, the role of stress transfer to the compression of natural aggregate (1/2 mm) increases. Fourthly: there is an effect of sealing the cement matrix and reducing the total volume of mortar pores, porosity and pore dimensions in the structure, in accordance with Dobiszewska (2016).

In the case of interaction of the *f* (0/0.25 mm) and *m* (0.25/1 mm) fractions of RCA, the higher participation of both fractions in the mortar resulted in a deterioration of compressive strength, regardless of the cement used (Figures 4a, 4b). The same happened in the case of *c* fraction and *m* fraction (Figures 5a, 5b). The higher the amount of these fractions in the composition, the lower the strength values, while using CEM I the highest strength was recorded with a low participation of RCA in the 1/2 mm fraction (up to 17%) and at the same time a very high participation in the *m* fraction (about 67-84%) and the reverse ratio of these fractions (Fig. 5a). In the case of CEM III, the dominant influence on the compressive strength was exerted by the RCA of the 1/2 mm fraction, while the strength did not depend so much on the amount of the RCA 0.25/1 mm fraction (Fig. 5b).

It can be stated that the studies of the impact of fine (up to 2 mm) RCA confirmed the studies of Kumar (2019) and Zhao et al. (2015), because the strength values are lower when the higher is the participation of RCA in the mortar. However, the effect of each grain fraction group is different and within certain limits of the volumetric participation use of fine RCA does not necessarily mean that the mortar's properties must be significantly affected.

5. Summary

Presented results confirmed the significant influence of fine RCA on the compressive strength and flow of cement mortars. However, its influence was not shown in the water absorption test (differences were not noticed). It depended mainly on the amount of RCA and not on the grain size, which was found in the occurrence of correlation between the total amount fine aggregate and the mortar flowability. Other conclusions can be drawn in case of compressive strength results – it is not possible to determine the positive effect of fine RCA on strength, as Dobiszewska (2016) and Salvini et al. (2009) stated. It is also not only a negative influence, as Corinaldesi and Moriconi (2009) claim. It seems that a very important factor is the selection of appropriate proportions of the fine RCA fractions in order to achieve the desired effects of i mortar strength. It can also be suggested that the right approach is not to use more than 30% RCA, which is often reported in the relevant literature sources.

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Abstract

The paper presents the influence of fine recycled concrete aggregate (RCA) on selected physical and mechanical parameters of cement mortar. RCA was divided into three groups: fine (0/0.25 mm), medium (0.25/1 mm) and the thickest fraction 1/2 mm. The investigations confirmed a significant correlation between the total amount of RCA and the obtained flow for the mixtures and compressive strength. Results showed that the fine RCA should be separated into subgroups as not only total RCA amount but quantity of RCA in each subfraction can have varying influence on mortar properties.

Keywords:
fine fractions, recycled concrete aggregate, cement mortar

Wpływ drobnych frakcji kruszywa z recyklingu na wybrane właściwości zapraw cementowych

Streszczenie

W artykule przedstawiono wpływ drobnego kruszywa recyklingowego (ang. RCA) na wybrane parametry fizyczne i mechaniczne zapraw cementowych. Kruszywo podzielono na trzy podgrupy frakcyjne: drobne (*f*: 0/0,25 mm), średnie (*m*: 0.25/1 mm) oraz najgrubszą frakcję *c*: 1/2 mm. Badania potwierdziły istotne powiązanie pomiędzy sumaryczną ilością RCA a uzyskiwanym rozpływem mieszanek i wytrzymałością na ściskanie. Uzyskane rezultaty wskazały również na to, iż w obrębie RCA warto wydzielić podgrupy frakcji, gdyż nie tylko sumaryczna ilość, ale również udział RCA w danej podgrupie może mieć znaczący wpływ na właściwości zapraw.

Słowa kluczowe:
drobne frakcje, kruszywo recyklingowe z betonu, zaprawa cementowa

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Analysis of the Problem of Natural Gas Waterlogging

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1. Introduction

The historical orientation of the fuel balance of Poland towards solid fuel causes huge technical, economic and ecological problems for the country, also on an international scale. The Polish government has announced a broad programme of ensuring of energy security of the country by diversification of the natural gas supply from various sources and directions thanks to the effective use of the LNG terminal on the Polish coast and creation of new cross-border connections (Project 2019). It anticipates development of the gas supply industry in the coming years and at an unprecedented pace (Polska Spółka 2016).

Therefore, technologically advanced, effective and environmentally friendly conversion of the domestic heat power engineering and municipal economy into gas fuel becomes a call for the Polish gas industry. It is these devices that constitute the most numerous and very dispersed group of thermal technology devices. Currently, they are characterised by low efficiency and significant impact on environmental pollution in the places where people live and work. The exhaust fumes from these devices are discharged into the atmosphere through low chimneys or just above the roof of buildings. The issue of the global warming and the obligations of Poland to reduce greenhouse gas emissions are also significant. Combustion of natural gas ensures CO_2 emissions that are almost twice lower compared to hard coal (the maximum content of carbon dioxide in natural gas flue gas is 11.8% by volume in comparison with 21% by volume for coal).

In the conditions of the anticipated development of the domestic gas industry, the key issue is to increase the capacity of the Polish natural gas transmission network and to ensure reliability of the gas supply process as well as its appropriate quality (Polish Standard 2011-2). One of the acute problems from this point of view is the moisture content of the gas fuel (Szkarowski et al. 2013).

This problem is further intensified by the increasing scale of the use of the liquefied natural gas being technologically associated with the cryogenic processes.

2. Analysis of the principles for gas supply in terms of moisture content

It is not widely known that water may appear in the gas pipelines that distribute the natural gas directly to the consumers. On the other hand, the specialists in the field of operation of the gas networks deal with this phenomenon on a daily basis. Where does this water come from? Certainly not through the leakage places arising on the network due to mechanical damage or corrosion, as the gas pipeline is always under positive pressure.

The natural gas extracted from the ground is usually contaminated with solid fractions and loaded with moisture as well as has caustic properties. The previously dried gas taken from the underground gas storage facilities is also saturated with water. The presence of water in the natural gas is undesirable because it intensifies corrosion of pipes and equipment, especially in the presence of H_2S and CO_2, while in winter it forms ice plugs. It may also contribute to formation of the hydrates that block the flow of the gas, especially in case of liquid hydrocarbon recovery processes, such as freezing or cryogenic processes (Grynia & Carroll 2013).

Moisture removal is the key stage in the pre-treatment of the natural gas directly at the point of its extraction and further processing before sale. Over the time, a stereotype that 'dry gas' should be delivered to the consumers has developed. In the aforementioned PN-C-04753 standard, humidity of the gas is not even mentioned among the 'values relevant for the assessment of gas quality'. This stereotype resulted in the fact that the dehydrators installed previously at each connection and even under the gas installation risers disappeared from the designing practice.

In fact, the **dried** natural gas cannot be 'dry', i.e. completely devoid of moisture. Even the already criticised standard, not setting any requirements in the field of the moisture content in the gas, paradoxically speaks about the processes that 'may cause formation of water condensates'. The resulting contradiction is also based on the measurement technology. Using the chromatographic analysis methods to determine the gas fuel composition, the sample is first subjected to drying. Therefore, the analysis shows not moist ('real' or 'working'), but so-called 'dry' gas composition, without the moisture content.

The gas suppliers are aware of the contradiction described above. To ensure adequate gas properties, the transmission network operators provide declarations regarding the properties of the transmitted fuel on their official sites. They include *inter alia* the permissible moisture content in the form of the maximum dew point temperature t_r, separately for summer and winter. The safety of the gas in transport and further use depends on it directly and its efficiency is important from the point of view of fulfilment of the contractual tax obligations (Kollas & Parker 2015).

The tr value in the certificates analysed in the work (Szkarowski et al. 2013) ranged from +4°C to -6°C. In general, these values are very close to the requirements for the gas quality in the transmission networks (Polish Standard 2011-1) (-5°C in winter and up to +3.7°C in summer). However, tests of the gas samples taken from the network showed that the dew point temperature could reach even +20°C. This means that in the winter season gas saturation with water vapour with its subsequent condensation is inevitable. It may be therefore concluded that determination of the t_r value, which may possibly be higher than the gas distribution temperature, in the certificate indicates a high probability of condensation forming in the gas pipelines.

The dew point means that water in the gas composition is in a saturated state, i.e. the partial pressure of the water vapour p_p is equal to the water saturation pressure p_p^n at a given temperature. For example, at 0°C $p_p = p_p^n = 611$ Pa (Recknagel et al. 1994). The thermodynamic calculations show that under normal conditions (0°C and 101325 Pa) the absolute humidity of the gas in the saturated state (water vapour content in 1 m^3 of the moist gas) is 4.88 g/m^3 and the molar share of the water vapour corresponding to the dew point is 0.0061 (0.61% by volume).

The financial conclusions are quite obvious. If gas humidity only oscillates on the edge of the dew point, an example boiler room that needs 1 million m^3 of the gas annually 'consumes' over 6000 m^3 of the water vapour in its composition. The meter indicates this volume as the gas and the user pays for it. In addition, 1% of the water vapour by volume reduces the calorific value of E-group high-methane gas by approx. 0.37 MJ/m^3, which is more than 1% (Szkarowski et al. 2013). The efficiency of the gas devices is proportionally reduced.

However, the hazards arising during the operation of the gas networks in case of presence of the condensed water in the gas pipelines are much more important. That is why it is so important to analyse each failure and the resulting conclusions thoroughly – in terms of the causes of the abnormal states and disturbance of the stability of the supervised systems as well as of the ways to prevent such events in the future. The authors have attempted to conduct such analysis on the basis of the gathered data on gas network failures and their own measurements.

Table 1. Natural gas humidity measurement and recalculation results

Date of measure-ment	Dew point temp., °C	Gas humidity, g/m^3	Recalculation into medium-pressure conditions			Recalculation into high-pressure conditions		
			Pressure, MPa	Dew point temp., ºC	Gas humidity, g/m^3	Pressure, MPa	Dew point temp., ºC	Gas humidity, g/m^3
25.06.19	-29.4	0.322	0.298	-16.1	4.36	4.2	16.4	46.42
06.06.19	-22.1	0.66	0.292	-7.7	13.84	2.5	19.1	88.83
20.06.19	-25.5	0.461	0.297	-11.9	9.92	4.23	22	83.53
21.05.19	-27.5	0.385	0.293	-14.4	9.75	4.22	18.7	104.33
22.05.19	-27.7	0.366	0.293	-15.2	12.56	4.19	17.5	133.38
13.06.19	-25.8	0.362	0.296	-14.8	6.9	4.2	17.9	72.94
21.06.19	-27.9	0.362	0.298	-14.9	8.25	4.21	17.7	86.76
23.06.19	-28.1	0.351	0.294	-15.7	10.62	4.15	16.8	112.05
21.06.19	-28.2	0.35	0.298	-15.4	6.61	4.3	17.7	72.2
01.07.19	-28.3	0.35	0.297	-15.4	6.98	4.1	16.9	72.91
01.09.19	-28.3	0.344	0.296	-15.4	4.89	4.02	16.7	50.13
26.06.19	-28.5	0.34	0.297	-15.5	4.59	4.13	16.9	48.19
24.06.19	-28.7	0.331	0.299	-16	6.84	4.31	16.8	74.61
24.05.19	-28.8	0.329	0.294	-16.3	7.12	4.22	16.3	76.95
06.08.19	-28.9	0.327	0.297	-16.2	6.17	4.02	15.6	63.07
27.06.19	-28.9	0.325	0.298	-16.3	7.31	4.02	15.3	74.56
02.07.19	-29.2	0.316	0.298	-16.8	8.24	4.29	15.8	89.68
21.08.19	-29.4	0.305	0.3	-17	6.51	4.25	15.3	69.78
22.06.19	-29.9	0.293	0.299	-17.6	6.61	4.09	14	68.39
16.06.19	-30	0.289	0.298	-17.8	6.9	4.21	14.2	73.63

Measurement conditions: $\boldsymbol{t}$ = 22ºC, $\boldsymbol{p}$ = 1.13 kPa ($\boldsymbol{p_{abs.}}$ = 0.102625 MPa)

3. Analysis of failure causes connected with natural gas waterlogging

The analysed failures have different scale, reach and publicity in the media. The most well-known failures include the one of the Russian gas transit system (supplier – Russian State Concern Gazprom), when the Polish customer (Operator Gazociągów Przesyłowych GAZ-SYSTEM S.A.) announced suspension of all gas supplies from the Yamal gas pipeline on 22 June 2017. This was done due to the failure of the Russian gas drying instance in fear of the safety of the Polish gas pipelines. In this information, it was stated that Poland did not have its own installation for drying of such gas flows and that the closest one was in Germany.

Despite the international scale of the failure and huge quantities of the raw material, it did not affect the gas supplies for the consumers. The gas tanks performed their task and already on 23 June 2017 at 6:00 a.m., due to improvement of the quality parameters of the natural gas, GAZ-SYSTEM resumed reception of the fuel to the national transmission system at the Interconnection Point. Therefore, it can be considered an accidental phenomenon, as in general, the gas drying installations at Gazprom operate in a faultless way. The most commonly used solutions are glycol installations and the supply system is stabilised in such a way that it provides the opportunity to choose the optimal time of contact of the gas with the glycols. Even the effective trade agreements ensure such stabilisation of supplies, as in case of lower consumption, the generated surplus of the transit gas is injected into the underground warehouses all over Europe.

The gas drying cycles operate in a much worse way in the regional gas distribution systems based mainly on the local wells with the nitrogen-rich gas mines. These systems are characterised by large fluctuations of the flows during the transitional periods (spring and autumn), in case of sudden changes of the weather and even during the day. Then, the drying processes encounter a big problem due to lack of the possibility to stabilise the gas-glycol contact time. This situation occurs in all distribution networks in Poland supplying the Lw and Ls subgroup natural gas to the customers.

The entire coastal zone in the central part of western Pomerania, including Kołobrzeg, is supplied with the natural gas from the Ls subgroup. In the distribution systems, there are still some engineering interventions aimed at ensuring of high quality of the gas supply as well as of widely-understood security. Such events are both planned and unexpected, classified as failures. They are thoroughly analysed in terms of potential threats and undesirable effects. A number of instructions, guidelines and regulations, which together form a specific technological regime in the field of designing, construction and operation of each distribution network, are created.

Many typical failures are currently very well analysed and described in the field of the actions to be taken. Even the failures that are very well known to the public are often typical and the extent of their consequences determines their publicity. Another type of the events includes the ones which surprise the specialists, since they do not have well-developed and proven methods of action.

One of such unexplained failures on the low-pressure gas network was the sudden suspension of the natural gas supply to the Spa District in Kołobrzeg in February 2016. Kołobrzeg has a specific layout. The Spa District, situated along the coastline, is practically 'cut off' from the rest of the city by railway tracks. This results in difficult access to it in terms of the road, municipal as well as gas infrastructure. Development of the heating technology based on the natural gas has quickly forced an increase of the gas supply to this district.

At that time, at the end of the 1980s, the technology of construction of the polyethylene pipe networks was not used in Poland yet and the gas was supplied to the customers only by low-pressure networks (1.3-1.6 kPa). It was a natural solution to replace the supply gas pipeline with 100-150 mm diameter with a new one with 300 mm diameter. For many subsequent years, the gas was supplied to the district in a stable manner and the occurring slight pressure drops were explained by the continuous increase of the demand resulting from expansion of the existing facilities and construction of the new ones. Over the time, more and more pressure problems began to appear, especially in winter during the holidays. On 2 February 2016, the employees of the Gasworks in Kołobrzeg recorded numerous reports on lack of gas pressure.

Pressure measurements at the sampling points showed unacceptable values in the range of 0.65-0.82 kPa. At that time, the reduction stations supplied the gas at the right pressure with a large capacity reserve. This indicated that the main gas pipeline was no longer permeable. The network layout and the foundation ordinates, the pressure measurements, the lay as well as the type of land development and utilities were analysed. As a result of this analysis, the characteristic points on the gas network where the control excavations had to be made were selected. Measurements were made with the use of a double bag-positioning device. In this way, the search site narrowed to a section of about 15.0 m at the lowest point of the terrain.

After cutting of the pipe, water escaped from it instead of the gas and a pump was installed instead of the bag-positioning device. In total, about 500 litres of water were pumped out, which meant geometrically that a section of the gas pipeline of the length of almost 7.50 m was completely flooded with water. The sections flooded with water were also found in other areas of the network system (Fig. 1).

The analysis of the causes of the incident from the side of the gas plant was conducted only in one direction - the search for a potential place of leakage which would allow for penetration of such quantity of water into the gas pipeline from the outside. Such a place was not found until these gas pipelines were replaced with new polyethylene ones. Therefore, the thesis that water got into the gas pipeline through the places of leakage has never been proved unambiguously.

Fig. 1. Cutting of the DN300 gas pipeline at Myśliwska in Kołobrzeg

We may also refer here to the case of the famous accident that took place in Zielona Góra on 30 November 2010. Then, as a result of a failure of the gas reduction system, the medium-pressure gas penetrated into the low-pressure housing estate gas network at three housing estates, causing an explosion of flats and fires (Shkarovskiy & Kotuła 2018). The analysis conducted by the public prosecutor's office proved that one of the main factors of the failure was undoubtedly water which froze in the devices and pipes of the gas station regulation and safety systems. However, the experts decided *a priori* that it was water from precipitation. No observations and studies in this direction were undertaken. Again, the prevailing stereotype that the natural gas is a dry gas, as highlighted in this article, worked.

4. Experiment conditions and experimental studies results

All analyses and research in the field of natural gas humidity have always concerned the area of mines, high-pressure transit gas pipelines and – to lesser extent – medium-pressure gas networks. The current water protection system ends with dehydrators installed as a standard on the inlet systems of the medium-pressure gas stations. There is no data on the study of this phenomenon at the side of the low-pressure network, i.e. directly in front of the consumer. As it has already been said, there are currently no provisions requiring the use of the dehydrators in the low-pressure systems as well.

The author's analysis of a number of failures has showed that the low-pressure systems may contain water, the presence of which cannot be explained by leakages or penetration of precipitation into the network. Therefore, it has been decided to carry out an analysis of the water content in the low-pressure natural gas that is supplied directly to the customers. The local gas network system in the Kołobrzeg zone distributing the medium-pressure Ls subgroup gas with subsequent reduction to 1.3 kP pressure was selected for the study. The point, at which the sampling was carried out, was at a household customer supplied **directly** from the medium-pressure gas network. The low pressure is obtained thanks to a household gas regulator, which only has a standard inbuilt tissue filter. Such conditions of the experiment allowed for examination of the moisture content after leaving of the high-pressure station and before passing through the dehydrators at II° gas stations.

Fig. 2. XENTAUR moisture meter, HPDM type

The measurements were carried out with the use of XENTAUR portable dew point analyser, HPDM type (Fig. 2). It is a microprocessor-controlled, battery-powered moisture meter, equipped with a dry chamber for storage of the sensor. This allows for obtaining of a reliable result after moving of the sensor to the measuring cuvette, ensuring the maximum possible tightness and the lowest possible gas exchange between two chambers during the sensor movement.

The thermodynamic calculations allow for calculation of the experimentally obtained dew point temperature value based on the known conditions in the higher-pressure gas pipelines. The generally accepted principles of such recalculation are based on the Goff-Gratch formula or on a similar method of the World Meteorological Organization. In the work, the JSC 'Ecological Sensors and Systems' humidity calculation software (Humidity units 2019), which allows for comparison of the results according to both methods and for changing of the type of the analysed gas, has been used. Both the measured values and the ones obtained as a result of such calculations are presented in Table 1.

The table data shows that the gas with a very low dew point temperature is formally transported through the low-pressure network. On the other hand, the recalculations into the medium- and high-pressure conditions show that the same water vapour content before pressure reduction does not exclude the possibility of water condensation in the domestic climate conditions. The performed analysis of the reports on the supervision over the dehydrators located on the high-pressure network in the Gas Plant in Koszalin, conducted in the period from January 2016 to December 2019, showed that water was pumped out from the dehydrators in the quantity of about 3,700 litres. The maximum quantity of water utilised from one dehydrator was 375 l.

The failures analysed above show that in the conditions of higher pressures and high gas velocities, penetration of liquid water through the dehydrators and then through the reduction station equipment into the low-pressure network cannot be excluded.

5. Summary

In the recent years, along with development of the polyethylene pipe technology, a growing tendency to move away from the old principles for designing and construction of the gas networks, proved over the years, has been observed. The declines of the laid gas pipelines are only forced naturally by the fall of the terrain and upon the repairs and replacements of the steel network with the PE one, the old dehydrators are massively removed at the lowest points of the network. In most cases, this does not cause problems in the further operation, even if in such a system a part of the network is already made of polyethylene pipes and a part is still made of steel. But usually these are the systems supplied by the E subgroup gas, where the main supplier seeks the permissible moisture content in the gas. It is bound by the supply agreement specifying the maximum dew point temperature value.

The situation is different in the systems supplied by the Lw or Ls sub-group gas from the local mines. The changing designing trends result in the fact that the dehydrators are less and less installed on the networks. The suddenly appearing water, causing failures, surprises the employees of the gas plants, who are unable to explain the reasons for this phenomenon.

This is what happened in the case of the analysed failure in Kołobrzeg. At that time, the use of the dehydrators during construction of passages under the tracks was definitely required due to greater deepening with creation of a natural trap. However, this requirement was omitted during network modernisation.

Appropriate conclusions were drawn only after the failure. Fig. 3 shows the dehydration system prepared for installation during replacement of three sections of the gas pipelines running under the tracks with a new PE gas pipeline with the main diameter DN 355 mm upon the request of the network operator in Kołobrzeg.

Fig. 3. Polyethylene dehydrator with diameter DN 355 (without inspection pipe)

6. Conclusions

1. The research results presented in the article prove that water condensation in the higher-pressure networks, having the consequence of penetration through the I° and II° reduction stations, may be the source of significant quantities of water in the low-pressure networks. No studies have proved or excluded the possibility of water entering directly the low-pressure gas pipelines through leakage places.
2. The analysed failures prove that regardless of the source of water, it is unjustified to dispose of the dehydrators, especially in a mixed gas network made of polyethylene and steel pipes distributing the gas from the local wells of the Ls and Lw subgroups.
3. The target action would be to introduce appropriate changes to the 'Rules for designing n of low- and medium-pressure steel gas pipelines and polyethylene gas pipelines' and the Regulation of the Minister of Economy of 26 April 2013 'On technical conditions to be met by gas networks and their location' in terms of introduction of the legal conditions relating to the possibility or necessity to use the dehydrators in the specific cases.

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Abstract

The domestic gas industry has been set an ambitious goal in the form of a state programme for extensive gasification of Polish cities and towns. This provides for transition of the municipal thermal energy and of the municipal economy to natural gas. Ensuring of reliable and safe transport of the gaseous fuel is also a part of this programme.

The article discusses the problems of transporting of the nitrogen-rich natural gas from the local mines, related to water of unknown origin appearing in it. The events that can confirm that there is a possibility of moisture condensation from the gas and its migration deep into the distribution network have been analysed.

The actual level of moisture in the natural gas, which is already directly supplied to the consumers, has been experimentally tested.

It has been proved by the computer calculations that in the conditions of high pressure in the network, there is a possibility of such condensation, depending on the external atmospheric conditions and physicochemical parameters of the gas.

It has been proposed to change the existing designing & construction legal provisions in order to protect the gas networks against water accumulating in them in a better way.

Keywords:
natural gas, water condensation, gas transport, high pressure, gas moisture

Analiza problemu zawodnienia gazu ziemnego

Streszczenie

Gazownictwu krajowemu postawiono ambitny cel w postaci państwowego programu szerokiej gazyfikacji polskich miast i miejscowości. Przewiduje to przestawienie miejskiej energetyki cieplnej i gospodarki komunalnej na gaz ziemny. Nieodzowną częścią tego programu jest także zapewnienie niezawodnego i bezpiecznego transportu paliwa gazowego.

W artykule rozpatrzono problemy transportu gazu ziemnego zaazotowanego, pochodzącego z kopalni lokalnych, związane z pojawiającą się w nim wodą niewiadomego pochodzenia. Przeanalizowane zostały zdarzenia, które mogą potwierdzić, iż istnieje możliwości wykraplania się wilgoci z gazu i jej migracji w głąb sieci dystrybucyjnej.

Doświadczalnie zbadano faktyczny poziom zawilgocenia w gazie ziemnym, który jest już bezpośrednio dostarczany konsumentom.

Udowodniono poprzez komputerowe obliczenia, że w warunkach wysokiego ciśnienia w sieci istnieje możliwość takiego wykraplania, w zależności od zewnętrznych warunków atmosferycznych i fizykochemicznych parametrów gazu.

Zaproponowano zmianę obowiązujących przepisów projektowo-wykonawczych, w celu lepszego zabezpieczenia sieci gazowych przed gromadzącą się w nich wodą.

Słowa kluczowe:
gaz ziemny, wykraplanie wody, transport gazu, wysokie ciśnienie, zawilgocenie gazu

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Application of Biophilic Installations for Indoor Air Quality Improvement

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1. Introduction

The progress of civilization forced a change in the human behavior and activity, which translated into the increased period of time spent indoors during the day by the inhabitants of developed countries. The available scientific data indicate that people stay in the space of the indoor environment for 85-90% of the day, or 19-21 hours. This time is devoted to studying, professional, social and home responsibilities, entertainment, exercise and rest (Godish 2001). Due to the progressive degradation of the natural environment, including air pollution in large urban centers, many residents intentionally avoid staying outdoors for extended periods of time. It is therefore obvious that people expect to have a safe indoor environment around them, as well as comfortable conditions for learning and working. Unfortunately, this comfort is often understood by designers, builders and architects as ensuring the proper indoor temperature and limiting the escape of heat. Ensuring proper air quality is hardly remembered.

The results of numerous international studies indicate a strong influence of the indoor air quality on health, well-being as well as the work efficiency and academic achievements (van den Bogerd et al. 2020, Luengas et al. 2015, Midouhas et al. 2018, Mujan et. al 2019). Poor air quality is responsible for numerous diseases of the upper and lower respiratory tract, headaches, rhinitis, allergies and skin changes. Prolonged exposure to airborne carcinogens may result in increased cancer incidence (passive smoking) (Stamatelopoulou et al. 2019). The most well-known phenomenon associated with improper air quality is the so-called sick building syndrome. Importantly, after leaving the sick building, the discomfort disappears (Pluschke & Schleibinger 2018). Therefore, it is reasonable to search for the techniques that ensure the removal of pollutants from indoor air and at the same time allow obtaining acceptable quality with least financial outlay. Such solutions include, among others biophilic installations (green walls) (Söderlund & Newman 2015).

Biophilia is the innate desire for humans to be in touch with nature through surroundings. This is represented in the built environment through the use of natural finishes, indoor plants and references to nature or its symmetry; all of which create a closer interaction with nature (Alhorr et al. 2016) Nowadays, in the modern workplaces, office, hospitals and commercial buildings, biophilia is becoming an important consideration for any interior design focused on the well-being of staff (Reeve et al. 2017). More and more attention is also paid to the aspect of using biophilic installations to purify indoor air. Although this movement has become a standard in many places around the world, it is yet to reach similar popularity in Poland.

The objective of this paper is to show the possibilities and limitations in using green wall structures to improve the indoor air quality.

2. Indoor air quality

The levels of indoor air pollutants are often a few times higher and much more concentrated than outdoors (Fleck et al. 2020). This is the result of outdoor air pollution and tightness of currently constructed buildings due to their energy saving requirements (Massey et al. 2016). The contaminants present in the indoor air can originate from the stream of infiltrating outdoor air, i.e.: polycyclic aromatic hydrocarbons (PAHs) and heavy metals sorbed on particulate matter (PM) and tropospheric ozone (O_3). Indoor pollutants can also come from typically endogenous sources as emissions of volatile organic compounds (VOCs) from interior furnishings – textiles, appliances, building materials, furniture; cleaning products (Dudzińska et al. 2010), and in the case of nitrogen oxides (NO_x) – from cooking. In turn, the main source of biological bioaerosol and carbon dioxide are the users themselves (Hospodosky et al. 2012). Additionally, the indoor air quality is affected by smoking in rooms, the use of household chemicals and the cleanliness of the ventilation system (Dela Cruz et al. 2014). Some chemical compounds present in the indoor environment in a gas phase (terpenes) or combined with dust particles (polybrominated diphenyl ethers) are susceptible to undergoing chemical transformations under the influence of light or oxidants. The products of these reactions show higher toxicity than the parent compounds (Staszowska 2017, Wolkoff 2020). Although not normally regarded as toxic, at elevated (>1000 ppm) concentrations CO_2 can cause adverse health effects relating to the mucous membranes (dry eyes, sore throat, sneezing) and the lower respiratory tract (tight chest, short breath, cough). An increase in the CO_2 concentration above the recommended values is manifested by drowsiness and fatigue of users (Godish 2001).

In most modern buildings, the air quality is unsatisfactory and needs improvement. It can be obtained by implementing the following solutions. Firstly, low emission building materials should be used in construction and furnishing. The second recommended action is to increase the air exchange rate to refresh the indoor air and dilute contaminants. The costs of such action are problematic, as maintaining mechanical ventilation or air conditioning systems requires significant financial outlays. The last tool to improve the indoor air quality is to use the purification techniques (Guieysse et al. 2008). They focus on removing contaminants from the air, or masking their presence or mitigating its effects. The indoor air can be purified using conventional techniques (filtration, sorption on activated carbon, ionization) as well as unconventional solutions, which include photocatalysis and phytoremediation (Luengas et al. 2015).

3. Application of plants for indoor air purification

Greenery can affect various aspects of life, some can relieve and reduce stress, while others stimulate cognitive functions, creativity and commitment (Alcock et al. 2014, Chen et al. 2020, Yin et al. 2018). The universal intention of biophilic design is healing, both for people and the surrounding space. Moreover, the studies conducted over the last few decades have demonstrated that potted plants can reduce the concentrations of most types of indoor air pollutants (Table 1) (Darlington et al. 2010, Kim et al. 2018).

Plants are capable of depositing and assimilating a wide group of gaseous pollutants and dusts present in the air. Due to the subject of this study, only those pollutants that have the greatest impact on the indoor air quality will be discussed. Ornamental plants, owing to the secreted phytoncides, are able to inhibit the growth of harmful microorganisms in their environment (Pettit et al. 2018). They can also purify the air, because they show high tolerance to a wide range of inorganic and organic pollutants. This is confirmed by the results of the studies conducted under model laboratory test-chamber conditions since the beginning of the 1980s (Irga et al. 2018). However, the mechanism of phytoremediation of indoor air pollutants has still not been fully explained. It is believed that both the aboveground parts (leaves, stems) and the root zone of decorative plants have the ability to remove various groups of chemical substances and the effectiveness of this process depends on the species of the plant, lighting conditions, ambient temperature, type and humidity of the growing medium, as well as lipophilicity of the removed impurity (Darlington et al. 2010, Dela Cruz et al. 2014). Initially, ornamental house plants were tested. Currently, the subject of research are mainly modular biophilic installations called *green walls*, which form both vascular plant species, as well as bryophytes, mosses, liverworts and gills (Irga et al. 2018).

Table 1. Recommended indoor air purifying ornamental potted plants

Plant name	Botanical name	Pollutants removed
Devil's ivy	*Epipremnum aureum*	xylene, benzene, formaldehyde, trichloroethylene
Dwarf date palm	*Phoenix roebelenii*	formaldehyd, xylene
Peace lilies	*Spathiphyllum spp.*	benzene, carbon monoxide, formaldehyde, trichloroethylene, xylene, acetone
Heartleaf philodendron	*Philodendron scandes*	formaldehyde
Spider plant	*Chlorophytum comosum*	formaldehyde, xylene
Florist's daisy	*Chrysanthemum morifolium*	ammonia, benzene, formaldehyde, xylene
Rubber plant	*Ficus elastic*	xylene, benzene, formaldehyde, trichloroethylene
Boston fern	*Nephrolepis exaltata*	formaldehyde and xylene
Areca palm	*Chrysalidocarpus lutescens*	benzene, carbon monoxide, formaldehyde, trichloroethylene, xylene
Pineapple plant	*Ananas comosus*	CO_2
Dracaena fragrans	*Dracaena deremensis*	xylene, trichloroethylene, formaldehyde
Snake plant/ Mother-in-law's tongue	*Sansevieria trifasciata*	formaldehyde, trichloroethylene, benzene, xylene
Aloe vera	*Aloe vera*	formaldehyde
English ivy	*Hedera helix*	formaldehyde, benzene
Flamingo lily/Fleur	*Anthurium andraeanum*	formaldehyde, ammonia, xylene, toluene
Lady palm	*Rhapis excelsa*	formaldehyde, ammonia, xylene
Bamboo palm	*Chamaedorea seifrizii*	formaldehyde, trichloroethylene, benzene

Toxic volatile organic compounds, e.g. formaldehyde, benzene, toluene, and xylenes, after penetration through stomata can be accumulated in tissues in an unchanged form, metabolized and incorporated into cellular structures or undergo biotransformation with the participation of microorganisms inhabiting the phyllosphere and rhizosphere. The absorption of VOCs by substrate particles has also been reported. In most cases of the tested ornamental plant species, the effectiveness of VOCs air purification increased along with the concentration of pollutants in the air and was best carried out under the daytime conditions. Even a long-term exposure of plants to high VOC concentrations did not inhibit their growth (Dela Cruz et sl. 2014, Fujii et al. 2005, Kim et al. 2018, Soreanu et al. 2013).

Ozone, which can come from infiltration as well as in situ, is removed mainly through stomata. The speed of the process depends on the plant species

(Abbass et al. 2017). In the case of particulate matter, the effectiveness of their removal by plants is proportional to the mixing of the aerodynamic diameter of dusts and constitutes a passive process. The mechanism itself has not been fully understood. The key role is played by waxes, which cover the leaf blades. In addition to dry PM deposition on the leaf surface, the reactions between dust components, e.g. hydrophobic PAHs, electrostatic interactions of adsorbed heavy metals and waxes cannot be excluded. It is also possible to use the PM components for plant metabolism (Gawrońska & Bakera 2015, Peng et al. 2020, Petitt et al. 2017).

The issue of the effectiveness of plants in removing the excess carbon dioxide from indoor air is still debatable. Some researchers claim that the CO_2 assimilation is rather small (Gubb et al. 2018), while others, on the contrary, believe that they reduce the ventilation costs (Tudiwer & Korjenic 2017). Torpy et al. (2014) indicates that the rate of CO_2 removal from the air by the tested plants depends on the species and lighting conditions (intensity and time).

The presence of indoor plants has a positive effect on the regulation of relative humidity (RH), which is particularly beneficial during the heating period. At the same time, the growth of RH by plants does not generate the conditions for the development of mold fungi, even in very airtight rooms (Tudiwer & Korjenic 2017, Irga et al. 2017, Fleck et al. 2020).

What is known for sure is that the potted plants alone are unable to remove enough pollutants to improve the indoor air quality in commercial buildings. Studies have now moved onto green walls (living walls, indoor vertical gardens) which boast a higher density of plants and increased the purifying properties (Fig. 1 and Fig. 2).

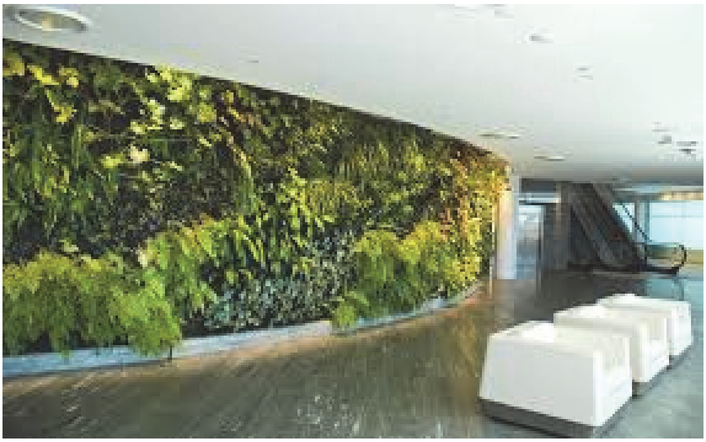

Fig. 1. Living wall in building lobby (www.asiagreenbuildings.com)

In terms of construction, three types of biophilic installations can be distinguished. The first one is usually a group of several or a dozen popular potted plants, the arrangement of which in the room is free and is mainly due to the aesthetic reasons. The second and third types are called passive and active vertical green walls. Their construction is almost identical to that of external green wall systems found on facades and balconies of buildings. They are modular systems (trays, vessels, planter tiles and flexible bags) filled with plants of various species or being a monoculture. The main difference between passive and active green walls is the way how air is circulated within the structure itself. Active indoor green installations represent the technical advancement that enhances the air purifying services further by actively forcing air through a bio-wall filter with the use of air fans (Gunawardena & Steemers 2019).

Indoor living green walls include a vertically applied growth medium such as soil, substitute substrate, or hydroculture felt; as well as an integrated hydration and fertigation delivery system. Indoor green walls are often constructed of modular panels that hold a growing medium and can be categorized according to the type of growth media used: mat media, and structural media. The mat type systems tend to be either coir fiber or felt mats. The mat media are quite thin, even in multiple layers, and as such cannot support extensive root systems of mature plants for more than three to five years before the roots overtake the mat and water is not able to adequately wick through the mats. The method of repairing these systems is to replace large sections of the system at a time by cutting the mat out of the wall and replacing it with a new one. This process compromises the root structures of the neighboring plants on the wall and often kills many surrounding plants in the reparation process (Clapp & Klotz 2018, Moya et al. 2019).

The most popular are semi-open cell polyurethane sheet media utilizing an egg crate pattern, which have been successfully used for vertical walls in recent years (Fig. 2).

Fig. 2. Installation of green wall (www.gardenspot.pl)

The water holding capacity of these engineered polyurethanes vastly exceeds that of coir and felt based systems. Polyurethanes do not biodegrade, and hence stay viable as an active substrate for 20+ years. The vertical wall systems utilizing polyurethane sheeting typically employ a sandwich construction where a water proof membrane is applied to the back, the polyurethane sheeting (typically two sheets with irrigation lines in between) is laid and then a mesh or anchor braces/bars secure the assembly to the wall. Pockets are cut into the face of the first urethane sheet into which plants are inserted. Soil is typically removed from the roots of any plants prior to insertion into the urethane mattress substrate. A flaked or chopped noodle version of the same polyurethane material can also be added to the existing structural media mixes to boost water retention (Riley 2017).

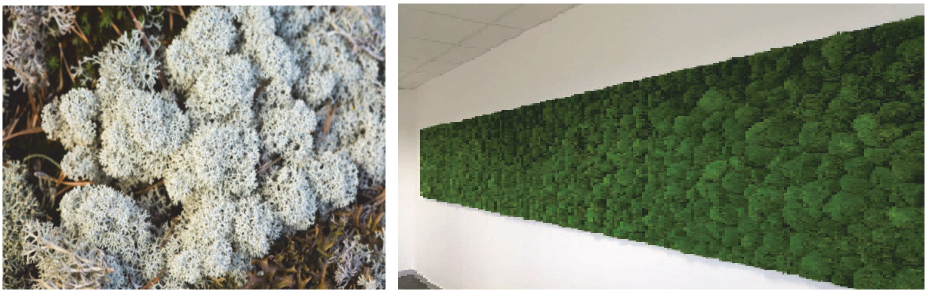

Fig. 3. Reindeer lichen in nature (on the left) and as an interior green wall (on the right)

Essentially, a collection of potted plants in the individual soil-cells are subject to the same changes that are faced by most houseplants: soil compaction, climatic stress, and soil nutrient replenishment (Egea et al. 2014). It is worth emphasizing that currently the role of HVAQ system engineers in the process of selecting specific plant species for green wall indoor modules is marginal. Still, interior architects, in consultation with florists, decide on the species composition of biophilic installations. Thus, when creating modules and plant compositions, the most important are aesthetic issues, not practical use of greenery to improve the air quality.

4. Indoor biophilic installations – limitations of use

Despite many studies, the accuracy of results extrapolating from chamber experiments to real-world conditions is questionable. While the issues of designing the structure and arrangement of green wall systems (for aesthetic purposes) in indoor spaces have been developed very well, there are still no clear guidelines or recommendations regarding the employment of plants as indoor air purification systems. Just saying that plants are able to remove pollution from the air and improve the indoor climate is not enough if the problem is to be approached in a practical way. The obstacles to the wider use of biophilic installations as an indoor air purifier are the following issues:

- no clear data on how many plants of a given species should be used in the module to achieve an effective level of pollution reduction,
- what lighting conditions should be used for the plants of a given species,
- how to combine the functioning of green walls and HVAC systems,
- how to estimate the potential ventilation equivalence of the tested plants,
- how to control the operation of a biophilic installation under changing internal conditions.

5. Conclusions

While phytoremediation is a recognized way of air purification, the issue of its effectiveness under real conditions remains debatable. The challenges that this technique will face in the near future include: genetic modification of plants dedicated to individual pollutant, testing new substrates, fertilization and irrigation systems as well as systems for remote monitoring of the condition of installations. They will allow developing the guidelines and recommendations for ventilation engineers and interior architects. However, it should be remembered that biophilic installations, with the current state of knowledge, can be a support, rather than an alternative to the traditional air purification techniques. Hence, it cannot be expected that their pollutants removal efficiency will be as high as that of conventional mechanical systems.

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Abstract

This paper discusses the possibilities and limitations of using biophilic installations to improve the indoor air quality in residential and commercial spaces. Modular plant systems can provide the support or, in smaller facilities, even an alternative to the conventional indoor air purification techniques, such as filtration. The unquestionable advantage of green walls is their comprehensive influence on the indoor air quality by shaping both appropriate thermal and humidity conditions as well as the chemical air composition. However, these constructions are not mechanical systems and therefore, the effectiveness of these specific types of living air purifiers in removing gaseous pollutants and particulate matter cannot be expected to match the level of traditional systems.

Keywords:
indoor air quality, biophilic installation, phytoremediation, green walls

Wykorzystanie instalacji biofilicznych do poprawy jakości powietrza wewnętrznego

Streszczenie

W pracy omówiono możliwości i ograniczenia wykorzystania instalacji biofilicznych do poprawy jakości powietrza wewnętrznego w przestrzeniach mieszkalnych i komercyjnych. Roślinne systemy modułowe mogą stanowić wsparcie lub w mniejszych obiektach alternatywę dla konwencjonalnych technik oczyszczania powietrza wewnętrznego jakim jest filtracja. Niekwestionowaną zaletą zielonych ścian jest ich kompleksowy wpływ na jakość powietrza wewnętrznego poprzez kształtowanie zarówno odpowiednich warunków cieplno-wilgotnościowych jaki i składu chemicznego powietrza. Nie są to jednak układy mechaniczne i nie można oczekiwać, aby te swoistego rodzaju żywe oczyszczacze powietrza osiągały skuteczności w usuwaniu zanieczyszczeń gazowych i pyłowych na poziomie tradycyjnych systemów.

Słowa kluczowe:
jakość powietrza wewnętrznego, instalacje biofiliczne, fitoremediacja, zielone ściany

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Mathematical Model of Particle Free Settling in a Vortex Apparatus

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1. Statement of the problem

In the production of thermal insulating materials, various heat and mass transfer apparatuses are widely used, in particular vortex ones, where the final stages of the technology are performed – drying or burning of fine particles (Pavlenko & Koshlak 2017, Pavlenko 2018). The scheme of such a device is shown in Fig. 1.

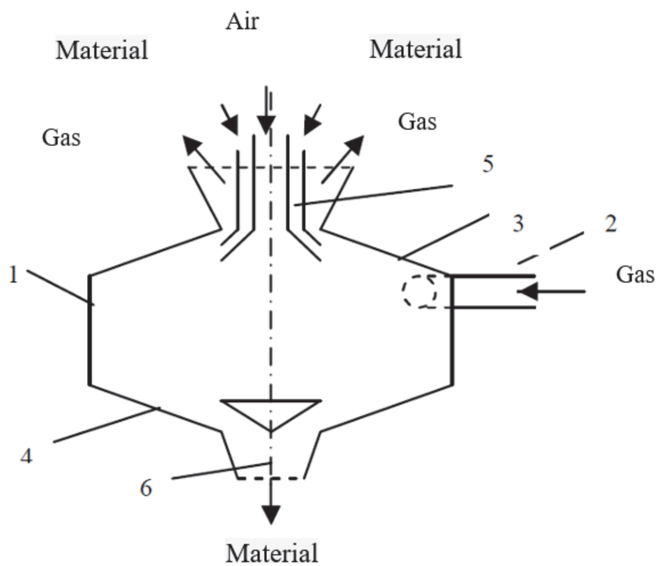

Fig. 1. Scheme of a vortex apparatus: 1 – body; 2 – lateral inlet pipe for gas supply; 3 – end upper wall; 4 – end bottom wall; 5 – feed hopper; 6 – discharge hopper

The vortex apparatus contains body 1 with lateral inlet pipe for heat transfer agent 2, connected tangentially to it, with end faces of the upper and lower walls 3 and 4, respectively, feed hopper 5 and discharge hopper 6.

Drying of materials in a vortex apparatus occurs during their free settling in the apparatus as a result of their interaction with air flows. Obviously, the longer the process, the more efficient it is.

2. Identification of previously unsettled parts of the general problem

A direct experimental study of the materials motion in vortex apparatuses is complicated by the process nonlinearity and non-stationarity. However, characteristics of the particle trajectories in the vortex apparatus can be determined by numerical modelling considering the available calculated velocity fields of the gas phase.

During drying, diameter of the particles changes, affecting the strength of their interaction with the gas phase. Available experimental data indicate an increase in the analysed particles diameter with temperature rise (Fig. 2). Thus, to determine trajectories of the introduced particles, it is necessary to calculate their temperature at the same time.

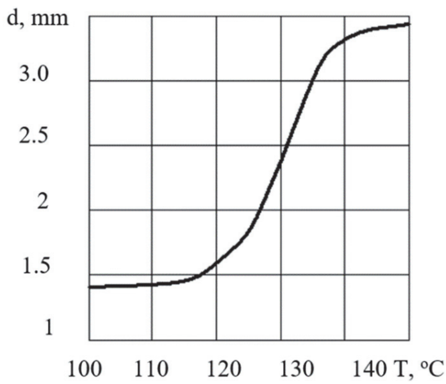

Fig. 2. Dependence of particle diameter d on temperature T

The efficiency of heat and mass transfer processes is largely determined by the ratio of geometric dimensions of this device, since hydrodynamic performance of the apparatus depends on them.

To rationalize technological parameters of the apparatus, as well as determine its efficiency, it is important to know the gas flow parameters (velocity and pressure components) in the entire volume of the apparatus.

Due to the specific apparatus design and gas supply, gas flows are substantially three-dimensional and largely perturbed. The experimental study of such flows is extremely difficult and requires large material costs.

On the other hand, an analytical solution to this problem is hardly possible without significant simplifications that can distort the entire process even at a qualitative level, therefore, in this paper we resorted to numerical modelling using the effective method of splitting by physical factors (Betyaev 2002). In this paper, this method, implemented in cylindrical coordinates in a three-dimensional formulation, is used to analyse the problem of gas dynamics study in a vortex apparatus.

3. Problem statement and methods of solution

In this paper, a complex mathematical model of the particle motion to be dried in a vortex apparatus with a simultaneous calculation of their temperature is developed.

Calculation procedure of the particle path under different conditions has been studied by many authors (see, for example: Betyaev 2002). In contrast to the specified works, in this paper the motion is calculated for the three-dimensional velocity field, obtained in the work (Mark 2011, Pavlenko & Koshlak 2019) for drying conditions in a vortex apparatus.

It is assumed that the particle falls vertically down with initial velocity v_o. When moving in the apparatus, a force acts on a particle:

$$\vec{F} = \vec{F_a} + \vec{F_s}, \tag{1}$$

consisting of buoyancy:

$$\vec{F_a} = (m - m^*)\vec{g}, \tag{2}$$

where m and m^* are particle mass, displaced air and resistance force:

$$\vec{F_s} = -CS\frac{\rho_r}{2}|\nu - \nu_r|(\vec{v} - \vec{v}_r), \tag{3}$$

where C is resistance coefficient, S is a unit cross section, ρ_r is its density, $\vec{v}, \vec{v}_r$ are particle and gas velocity respectively.

The equation of particle motion has the form:

$$\frac{d\vec{v}}{dt} = \vec{f}, \tag{4}$$

where $\vec{f} = \vec{F}/(m + km^*)$ and k are added-mass coefficients.

The process of a particle heating under the assumption of its sphericity is described by the one-dimensional equation of diffusive heat transfer:

$$\frac{\partial T}{\partial t} = a\frac{\partial}{r\partial r}\left(r\frac{\partial T}{\partial r}\right), \tag{5}$$

where T is temperature, a is a particle thermal diffusivity, r is distance to its centre (radial coordinate).

Convective heat transfer takes place at the particle boundary:

$$q = \alpha\left(T_p - T_g\right), \tag{6}$$

determining the boundary conditions for equation (5), where q is heat flow density at the particle boundary, T_p and T_g are particle surface temperature and surrounding gas phase, respectively, and α is heat transfer coefficient.

Coefficient α depends on particle diameter d and it is convenient to express it in terms of the dimensionless Nusselt number Nu: $\alpha = Nu\, \lambda_e/d$, where λ_e is effective coefficient of gas thermal conductivity, considering the turbulent nature of motion. Its value is selected based on the ratio (Lobanov 2013, Koshlak & Pavlenko 2019): $\lambda_e = C\, \rho_g\, v_e$, where C and ρ_g are gas thermal conductivity and density, ν_e is effective kinematic viscosity coefficient, determined by a three-parameter algebraic turbulence model in gas-dynamic calculation.

We consider the particle motion in cylindrical coordinates ρ, φ, z. In this case, equation (4) takes the form:

$$\frac{\partial \nu_\rho}{\partial t} = \frac{\nu_\varphi^2}{\rho} + f_\rho, \tag{7}$$

$$\frac{\partial \nu_\varphi}{\partial t} = \frac{\nu_\rho\, \nu_\varphi}{\rho} + f_\varphi, \tag{8}$$

$$\frac{\partial \nu_z}{\partial t} = f_z, \tag{9}$$

where the index of velocity and specific gravity means their component in cylindrical coordinates. For velocity components we have:

$$\nu_\rho = \frac{d\rho}{dt}, \nu_\varphi = \rho\frac{d\varphi}{dt}, \nu_z = \frac{dz}{dt}. \tag{10}$$

Numerically, system of equations (7)-(10) was solved using Euler-Cromer method,

$$\nu_\rho^{n+1} = \nu_\rho^n + \Delta t\left[\frac{\left(\nu_\varphi^n\right)^2}{\rho^n} + f_\rho^n\right],$$
$$\nu_\varphi^{n+1} = \nu_\varphi^n + \Delta t\left[\frac{-\nu_\rho^n \nu_\varphi^n}{\rho^n} + f_\varphi^n\right],$$
$$\nu_z^{n+1} = \nu_z^n + \Delta t f_z^n,$$
$$\rho^{n+1} = \rho^n + \Delta t \nu_\rho^{n+1},$$
$$\varphi^{n+1} = \varphi^n + \Delta t\left(\nu_\varphi^{n+1}/\rho^{n+1}\right),$$
$$z^{n+1} = z^n + \Delta t \nu_z^{n+1},$$

where n is sacrificial layer number, and Δt is time increment.

The inner part of the cylinder was chosen as the calculation region. When determining resistance force (3) of the unit motion in a gas flow, causing its helical motion, its cross-sectional area is preliminarily calculated $S = \pi d^2/4$ using graphical dependency defined in Fig. 1. For this, the particle temperature is calculated using an explicit difference scheme:

$$T_i^{n+1} = T_i^n + \frac{\Delta t a[(i-1)T_{i+1} - 2(i-1.5)T_i + (i-2)T_{i-1}]}{\Delta r^2}, \tag{11}$$

where Δt and Δr are time and radius increments, respectively, n is sacrificial layer number, i is spatial cell number (temperatures are calculated in the centre of cells). As the temperature, determining the particle diameter, average temperature for all cells is selected.

4. Results and discussion

A series of test calculations of the model was performed, indicating its qualitative adequacy to the analysed process (Fig. 3-5).

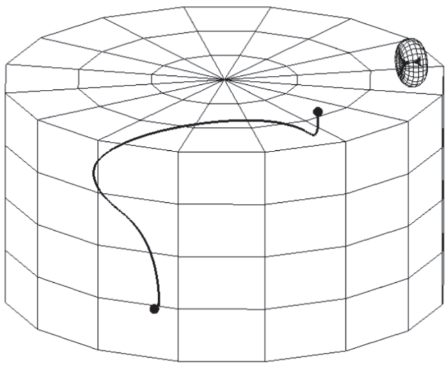

Fig. 3. Helicoidal particle path

The specific particle path depends considerably on the specific spot of its penetration into the vortex apparatus and is determined mainly (in addition to gravity) by vortex gas flows. So, being carried away by gas, a particle can make a helical motion (Fig. 3) until it leaves the apparatus.

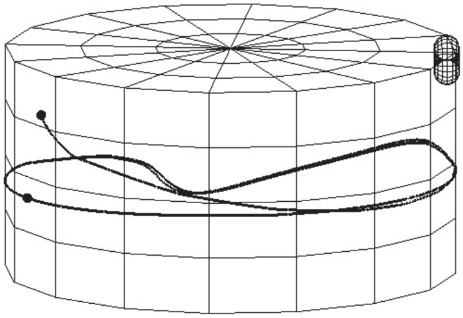

Fig. 4. Part of the quasi-stationary particle free settling path

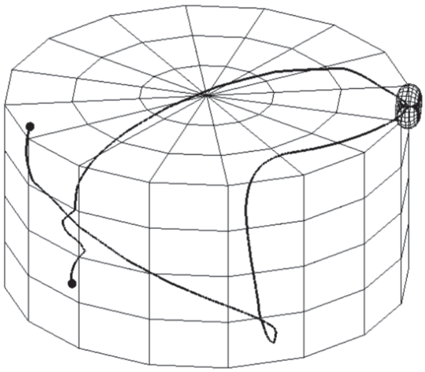

Fig. 5. Complex irregular particle path

However, numerical experiments show a rather irregular nature of particle motion. So, in the calculations, we observed both paths with stationary free settling sections (Fig. 4), as well as quite interesting variants of possible particle motions, such as, for example, as the variant, presented in Fig. 5. A particle under the action of gravity and gas flows can generally move down, and then, falling into ascending flows, again move upwards for a certain time. Finally, it leaves the apparatus.

The study of a large number of calculation results allows, still, (despite the irregularity of particle paths) to draw a qualitative conclusion that, in general, particles that fall into the vortex apparatus closer to the side wall are free settling for a longer period, and, consequently, they are dried longer, which is preferable from a technological viewpoint.

5. Conclusions

A complex mathematical model of heating and three-dimensional particle flow in a vortex apparatus was developed.

Analysing the obtained results, we can conclude that duration of the material particle heat treatment until it is completed, as shown in the figures above, can be different and depends, mainly, on the intensity of particle sweep with the heat transfer agent flow. In general, the obtained calculated information may serve as the basis for construction and optimization of the apparatus design from the viewpoint of energy usage reduction. The path configuration and its length determine overall dimensions of the apparatus and flow characteristics of the heat transfer agent. Depending on the required heat treatment intensity (and heat treatment intensity, as shown in the second section, determines the thermophysical properties of the finished product), the point of particle introduction and heat transfer agent velocity may vary.

Test calculations carried, performed according to the presented model, testify to its qualitative adequacy and possible use of this model to calculate various modes of material drying in vortex apparatuses.

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Abstract

A mathematical model of gas dynamics in a vortex apparatus during heat treatment is presented in the paper. The parameters of gas flows in the vortex apparatus, optimal ratios of the vortex apparatus geometric dimensions, as well as hydrodynamic parameters are determined, making it possible to develop effective design solutions of this equipment.

The mathematical model allows one to carry out computational experiments and determine particle trajectories, their temperature, particle size and humidity at various points in time and evaluate the dynamics of these parameters.

Using the calculation experiment method makes it possible to quickly and without financial costs determine the technological modes of heat treatment of dispersed material in vortex devices.

The obtained data can be used in calculation methods of heat and mass transfer vortex apparatuses

Keywords:
mathematical modelling, drying of particulates, vortex layer

Model matematyczny procesu swobodnego osadzania cząstek w aparacie wirowym

Streszczenie

W artykule przedstawiono matematyczny model dynamiki gazu w aparacie wirowym podczas obróbki cieplnej zdyspergowanych materiałów. Określane są parametry przepływów gazu w aparacie wirowym, identyfikowane są optymalne proporcje wymiarów geometrycznych aparatu wirowego, a także parametry hydrodynamiczne, które pozwalają opracowywać skuteczne rozwiązania konstrukcyjne tego sprzętu.

Model matematyczny umożliwia przeprowadzanie eksperymentów obliczeniowych i określanie trajektorii cząstek, ich temperatury, wielkości cząstek i wilgotności w różnych punktach czasowych oraz ocenić dynamikę zmian tych parametrów.

Zastosowanie metody eksperymentu obliczeniowego pozwala szybko i bez kosztów finansowych określić warunki technologiczne do obróbki termicznej rozproszonego materiału w urządzeniach wirowych o różnych konstrukcjach.

Uzyskane dane można wykorzystać w metodach obliczania urządzeń wirowych z wymianą ciepła i masy.

Słowa kluczowe:
modelowanie matematyczne, suszenie cząstek, warstwa wirowa

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The European Green Deal and its Impact on Regional Development Processes

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1. Introduction

The foundation defining the use of non-renewable resources is the principle of equal treatment of generations. When making decisions taking into account the social interest, there is no justification for treating the generations differently (Solow 1993, p. 57). Measures increasing the effectiveness of resource use or limiting the negative impact on the environment constitute only a shift of the boundaries of growth over time, and do not eliminate its barriers. Any consumption and increase in wealth, not justified by real needs, for the sake of enlargement, bring these limits closer. The mutually exclusive actions are the care for the needs of future generations and at the same time striving to increase wealth nowadays. Moving the boundaries of duration of human civilization on Earth requires broadly understood resignation from current consumption in favour of future consumption. In the light of the undisputed weaknesses characterising a market economy, the formulation of the following question remains justified: is it possible to decouple economic growth from negative environmental pressure and resource constraints?

A breakthrough in the perception of the processes of economy functioning was the publication of the 1st Report of the Roman Club "Limits to Growth" (Meadows 1972). The report initiated the creation of a concept for the functioning of the global economy, taking into account the resource constraint factor, the environmental consequences of management processes, and the development of global modelling. Concepts of functioning of the world economy expressing a new view on the process of management can be divided into those that challenge the idea of continuous economic growth (zero-growth theory) and those that anticipate the idea of continuous economic growth and give it a new dimension (sustainable development, Factor four, the EU concept of a low-carbon and resource-efficient economy, and the subject matter of this paper, the European Green Deal doctrine).

The aim of the paper is to analyse the theoretical aspects of the European Green Deal and to identify its potential impact on the Community's regional development processes.

2. Characteristics of the European Green Deal

In 2010, the European Commission presented a proposal to build a low-carbon and resource-efficient economy. The concept was a response to the immanent reality of resource scarcity and uncertainty about the phenomenon of climate change unknown to man. Civilisation developed during the Holocene, an interglacial period lasting for the last 10,000 years, during which global temperature and ocean levels were relatively stable (Hansen 2011). The problem of human adaptation to climate change has therefore not been addressed in the genome of the species, and the changes taking place seem to be something completely new, unrecognised and not fully realised. In societies, even among scientists, there is a problem of understanding the essence of the processes taking place, as well as the consequences of actions aimed at combating climate change and adapting to the changes taking place. Uncertainty relates to: the real direction of climate change; the real causes of the changes taking place and, consequently, the validity of the assumptions made about the relationship between human activity and climate change; the validity of the thesis that taking action to reduce GHG (greenhouse gases) emissions will stop the processes taking place (Piontek 2015).

The analysis of the presented strategic documents (Europe 2020) indicated strictly economic objectives of the concept. Over the past 30 to 40 years, the factors of economic growth in the European Community have been cohesion policy and the accession of new Member States. The capacity for further enlargement of the Community and the continuation of the cohesion policy in its current form, as well as the outflow of jobs to emerging economies, have forced the European Community to seek new drivers of economic growth in the long term.

The ten-year period of shaping and implementing new values led to the formulation of the European Green Deal doctrine (COM(2019)640). The purpose of the doctrine was expressed by Ursula von der Leyen, President of the European Commission: the European Green Deal is our new growth strategy – for a growth that gives back more than it takes away. It shows how to transform our way of living and working, of producing and consuming so that we live healthier and make our businesses innovative. We can all be involved in the transition and we can all benefit from the opportunities. We will help our economy to be a global leader by moving first and moving fast. We are determined to succeed for the sake of this planet and life on it – for Europe's natural heritage, for biodiversity, for our forests and our seas. By showing the rest of the world how to be sustainable and competitive, we can convince other countries to move with us (EC Press release, 11 December 2019). According to the adopted assumptions, economic growth and development are to be decoupled from the economy's carbon and resource consumption. According to its supporters, the idea is justified by empirical data on the functioning of the European economy over the past thirty years. Between 1990 and 2018, the EU reduced greenhouse gas emissions by 23%, while the economy grew by 61% (COM(2019)640 p. 4). This objective is to be achieved through action to leading to European climate neutrality in all areas of social and economic life by 2050 (Fig. 1).

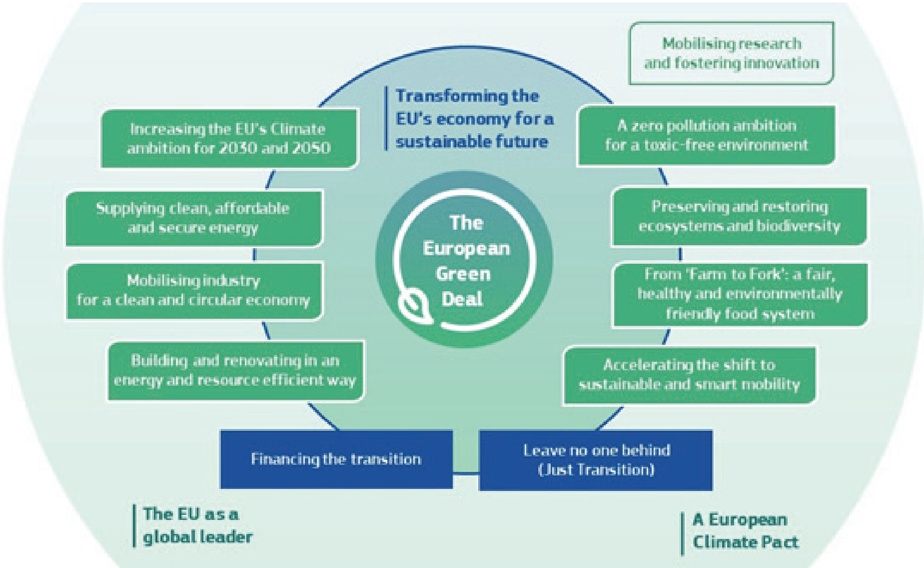

Fig. 1. Various elements of the European Green Deal
Source: (COM(2019) 640)

As political scene observers indicate, fighting with climate change gave the EU a new reason to exist. The very concept of the green deal is the result of the work of a network of experts and lobbyists in the fields of business, politics, and science (including Paul Polman, Laurence Tubiana, Teresa Ribera). The European Green Deal was presented under the conditions of a redefinition of investment strategies by the largest global corporations and a complete political reset in the EU following the simultaneous change of the European Parliament, the European Commission and the President of The European Central Bank

(Lombrana & Krukowska 2020). For example, in 2020, BlackRock, Inc.[1] CEO Laurence Fink in annual open letters (to chief executives of major companies – *A Fundamental Reshaping of Finance* (2020a) and to clients – *Sustainability as BlackRock's New Standard for Investing* (2020b)) announced that his firm would make investment decisions with environmental sustainability as a core goal (Fink 2020). At the same time BlackRock, Inc. declares the sales of $500 million of coal-related investments (Gandel 2020). As part of the strategy presented in 2020, BP p.l.c. is planning to reduce oil and gas production (a 40% reduction on 2019 levels) and pour a 10-fold increase in annual low carbon investment to $5 billion by 2030. BP p.l.c. tries to deliver on its promise of net zero emissions by 2050 and prepares for a world that uses much less oil (Ziady 2020). Particular attention is drawn to the statement of L. Fink, according to which *BlackRock has joined with France, Germany, and global foundations to establish the Climate Finance Partnership, which is one of several public-private efforts to improve financing mechanisms for infrastructure investment* (Fink 2020). It proves the close links between the European elite and global corporations. It also leads us to conclude that one of the hidden goals of the European Green Deal is to create new investment opportunities for global corporations redefining their strategies.

Implementation of The European Green Deal requires:

- redefining policies for clean energy supply across the economy, industry, production and consumption, large-scale infrastructure, transport, food and agriculture, construction, taxation and social benefits and
- increasing the value given to protecting and restoring natural ecosystems, to the sustainable use of resources and to improving human health (COM(2019)640).

The declared first action to build the European Green Deal is to set greenhouse gas (GHG) reduction targets ranging from 50 to 55% by 2030 (with reference to 1990). The existing binding target for the reduction of internal greenhouse gas emissions in the EU economy as a whole by 2030 is 40% and is distributed among Member States (OJ L 156/26).

A broad package of measures is provided for in order to achieve climate neutrality. The most important of these proposals is the use of the provisions of the Treaties, which allow the European Parliament and the Council to adopt proposals by ordinary legislative procedure, by qualified majority rather than by unanimity. As it should be concluded, the aim of the proposal is to minimise the possibility for individual Member States to object. The proposal substantially changes the conditions for membership of the Community, condemning

[1] BlackRock, Inc. – world's largest asset manager.

individual countries to the dictate of the majority. In addition, the following action is proposed:

- the creation of a European "climate law" that will create a strong commitment to the objective of climate neutrality and direct all EU policies towards the objective of climate neutrality, with all sectors playing their part in this process,
- carrying out changes to adapt climate policy instruments, including: consideration will be given to including new sectors in the EU ETS[2], Member States' emission reduction targets for sectors not covered by the ETS, the Regulation on emissions from land use, land use change and forestry and the Energy Taxation Directive (OJ L 283), will be revised,
- implementing policy reforms to encourage business and consumers to change their behaviour and sustainable public and private investment,
- as many countries contest the objectives set by the EU, there is a risk of carbon leakage. The Commission will propose a carbon border adjustment mechanism, for selected sectors, to reduce the risk of carbon leakage. The mechanism is to comply with World Trade Organisation rules and other EU international obligations. It will be an alternative to measures aimed to reduce carbon leakage existing under the EU ETS,
- introducing equitable transformation mechanisms, including the Just Energy Transition Fund (JET Fund). In the growth mechanism, the Fund will fulfil the functions currently performed by the Structural Funds and Cohesion Fund.

3. Economic and social dimension of the doctrine

The presented doctrine is an attempt to build a new economic, social and political order based on new paradigms, contesting the laws of physics, biology, and what is particularly important from the point of view of the undertaken problem of research law of economics. An example is the contestation of the Second Law of Thermodynamics. In the circular economy being part of the European Green Deal, recycling is intended to ensure the endless availability of resources for the growing European economy. Robert Solow, referring to the Second Law of Thermodynamics, indicates that the amount of non-renewable resources can only decrease (remain at the same level if they are not currently extracted). Recycling is only a tool to shift the barrier of resource scarcity and cannot be seen as a way to finally overcome it. *It is true even with regard to recyclable raw materials (...) that we will never get the whole pound of copper for secondary use from the pound initially used, nor the whole pound of copper from the pound after it has been used*

[2] EU Emissions Trading System

twice. (...) Thus, copper remains an exhaustible resource, despite the possibility of partial recycling (Solow 1993, p. 49).

The European Green Deal seeks internal re-coding. Creating an image of the world by deducing from a priori assumptions and treating its point of view as excluding competitive perspectives (similar features were also characteristic of earlier socio-economic concepts based mainly on Marxism) (Rojek 2008, p. 171). Following the example of Manicheism, he proposes a dichotomous perception of a world in which good (theorems, assumptions and dogmas forming the doctrine) are contrasted with evil (traditional values). The Green Deal doctrine is morally correct because it serves to eliminate the evil that results from the processes of man's management and existence.

It is characterized by apriorism and monism. The authors of the doctrine state the following apriori: *the atmosphere is warming and the climate is changing with each passing year. One million of the eight million species on the planet are at risk of being lost. Forests and oceans are being polluted and destroyed. The European Green Deal is a response to these challenges* (COM(2019) 640 final, p. 2). The theory of climate warming as a result of human activities and the possibility of counteracting it as a result of specific actions is considered to be the only "scientific world view" and points out to the public to believe as an unchanging and unquestionable dogma (see Annex 1). All different views (including results of scientific research) are rejected, while their authors are stigmatised and forbidden to express their views[3]. The climate truths expressed by the EU apply always, everywhere, and are final. There is an increasing tendency – already pointed out by Ludwig von Mises – to spread the paradigm that a country or government (in this case the EU) embodies everything good. Whoever accepts such a paradigm is considered to be an impartial researcher of social sciences, an educated and modern man. All those who oppose the paradigm are considered to be biased, steadfast, and biased (Mises 2012, p. 11). The media play a special role in promoting this paradigm. The European Commission declares that: *the EU can use its influence, expertise and financial resources to mobilise its neighbours and partners to join it on a sustainable path. The EU will continue to lead international efforts and wants to build alliances with the like-minded. It also recognises the need to maintain its security of supply and competitiveness even when others are unwilling to act* (COM(2019) 640, p. 2).

The European Green Deal was built on a dialectical approach, according to which the process of development of a society consists of three dialectical processes:

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[3] See: The Appeal of the Conference of Rectors of Academic Schools in Poland to take urgent, effective actions in response to the climate and environmental crisis, Warsaw, 27 September 2019.

- the creation of contradictions in the interaction between man and nature (i.e. contradictions in the process of exchange of human matter with nature),
- the emergence of contradictions between new and old production forces,
- the emergence of a contradiction between the new production relations (new economic base) and the old superstructure (Lange 1963).

The doctrine substantially rejects free market values, which are replaced by strong state (EU) interventionism in the course of management processes. Analysing the doctrine from the point of view of the theory of economic thought, it should be classified as an intermediate form combining features of Keynesism and centrally planned economy. As in the Keynesian theory, the basic assumption is to keep the welfare state and full employment with taxpayers' money. The responsibility for achieving the main goal lies with the public authority, which is granted the right to interfere in the entire economic life and shape the market processes taking place. The principle of effective demand is used, according to which the amount of national income and employment is determined by consumer and investment expenditure. Achieving full employment requires stimulating demand and shaping the propensity to consume (Keynes 2011, Wapshott 2013).

Intervention in the market mechanism is carried out using a wide range of instruments, including:

- instruments directly interfering with the market mechanism: restrictions on emissions, production restrictions, restrictions on use, market restrictions,
- instruments indirectly interfering with the market mechanism: design requirements, labelling requirements, extended producer responsibility, separate collection targets, dissemination of knowledge.

Using environmental protection to stimulate income- and employment-generating investments, eco-innovations are expected to become epoch-making and initiate the next Kondratiev cycle (Table 1).

Unlike earlier Kondratiev cycles initiated by technological innovations of exogenous type, the sixth cycle initiated by the EU is endogenous in nature. According to the Romer model, they are a response to market stimuli as well as to those contained in EU law (Romer 1990). Under the conditions of the European Green Deal, economic growth will be stimulated by factors created by the European Union. The speed and effectiveness with which the growth factors will be created, updated and implemented will determine how quickly and effectively the competitive advantage is achieved and maintained. The emergence of epochal innovations in environmental protection will be accompanied by the evolution of energy sources to meet the growing demand of the expanding economy. In the early part of the cycle, the energy demand is still met by fossil fuels and increasingly used nuclear energy. There is an ongoing effort to improve the energy efficiency of fossil fuel use processes. The use of traditional energy sources is accompanied by the development of renewable energy sources. Their importance in the energy balance continues to grow and in the final phase of the cycle they become the primary energy source.

Table 1. The sixth Kondratiev cycle in the concept of the European Green Deal

Cycle	Years	Growth phase	Duration	Epoch-making innovations	Basic fuels	Technological leaders	Economic leader
VI	2010 – 2060	2040/2050	50 years	Low carbon technologies Technologies that make economic growth independent of environmental resources	till 2035 – fossil fuels, nuclear energy from 2035 – renewable energy	Germany	European Community

Source: author's own work.

The EU's attempts at internal re-coding involve dangerous social and cultural changes which undermine the overarching human value and the traditional system of values derived from Europe's Christian roots. The social and political system that is being created has the characteristics of a religious state. Verification of the above mentioned claim requires carrying out:

a) an analysis of The European Green Deal in the context of the definition of religion,
b) a comparative analysis of the characteristics of a religious state with those of a socio-economic and political system as defined by The European Green Deal.

The European Green Deal meets the criteria of religion as defined by Erich Fromm. It constitutes a system of thoughts and actions shared by a certain group, which provides the individual with a system of orientation and an object of worship, the need for which is the original equipment of the human psyche. In this sense, objects of worship can be Christian God, an idea, a person, as well as the natural environment (Kamiński & Zdybicka 1974). As Nathan Söderblom points out, religion is the relationship of man to the transcendence in which they believe, on which they feel dependent, to which they express their attitude in prayer, trust, fear, sacrifice, and ethical behaviour (Kamiński & Zdybicka 1974). In the European Green Deal doctrine the absolute being is the Planet (Mother Earth, the environment). The man, expressing fear and caring for its good, should be oriented towards pro-ecological actions, able to make sacrifices and act ethically.

The religious character of the European Green Deal doctrine is proved by a comparative analysis of selected features of a religious state with features of the socio-economic and political system shaped by the EU, as presented in Table 2.

Table 2. Comparative analysis of the characteristics of a religious state with those of the European Green Deal

Selected features of a religious state	Features of the European Green Deal
Rejection by the state of neutrality (impartiality) in religious matters and adoption of a certain religious doctrine as state-related, official or dominant. An open declaration of a religious nature by the legislator of a given provenance is not a rule. Constitutions of religious states sometimes indicate the disappearance of the functional separation between the state and the official religion. The state assumes in particular the obligation to promote it	Climate action is the official and dominant area of interest and action of the European Union. The Union's institutions have taken on the responsibility of promoting it Compliance with the doctrine of climate change and ways to counteract it is the basis for setting and evaluating actions

Table 2. cont.

Selected features of a religious state	Features of the European Green Deal
Declaration in the constitution that a particular religion is a state religion	It is proposed to create the first European "climate law." In this way, the goal of achieving climate neutrality by 2050 will find its legal basis. In addition, climate law will ensure that all EU policies contribute to the objective of climate neutrality and that all sectors play their part in this process. References to environmental protection, Earth's sustainable development and climate change are already included in most of the EU legislation
In a religious state, broadly understood religious doctrine at least inspires the state law, including constitutional content. In extreme cases, the autonomy of the law established in relation to norms of a religious nature is excluded	Environmental values and objectives are governed by the EU law
The concern for the family resulting from religious motivations is also visible in the constitutions of Islamic states. The family is seen as a place for shaping traditionalist attitudes	The family and the individual are identified as a key factor in achieving climate objectives through their sacrifice. It is proposed that the family should not have children, that they should not consume products considered to be harmful to the climate (cessation of meat consumption, causing shame about flying planes, the so-called "flygskam" in Sweden)
A relatively frequent manifestation of their confessional character in the constitutions of religious states is the requirement of belonging to the official religion of the person holding the post of the head of state. Exceptionally, there is a requirement for the officers to practice the official religion	The values of green governance are accepted and supported by the vast majority of EU politicians as well as those in the Member States

Table 2. cont.

Selected features of a religious state	Features of the European Green Deal
The religious nature of the state results in undermining the organisational or functional distinctiveness of the state apparatus and the official faith, as indicated by some fundamental laws. An extreme case is the assumption by the religious authorities of the functions of state bodies	The implementation into the real sphere of the system of values expressed in Agenda 2030, The Paris Agreement and The European Green Deal is accompanied by the significant involvement of religious institutions, particularly Christian churches. In the teaching of the Catholic Church there is a gradual reorientation of teaching from God to the problems of the planet. The beginnings of the process are connected with Vaticanum II and *Pastoral Constitution on the Church in the Modern World Gaudium et spes*. As Jarosław Babiński points out, the documents and teachings of the post-conciliar popes have resulted in ecological issues occupying one of the main places in the teaching of the Catholic Church. They are particularly highlighted during the pontificate of Pope Francis, who constantly calls for ecological conversion, protection and care of all creation, action to halt global warming, and listening to the voice of the earth. As the Pope points out, humanity must not forget the history of exploitation of the South of the planet. It has caused a huge environmental debt as a result of the pillaging of resources and the excessive use of common environmental space for waste disposal. New concepts have been introduced to the teaching of the Catholic Church, such as ecotheology, integrative ecology, ecological culture, and ecological sin. Since 2015, the Catholic Church has celebrated the World Day of Prayer for the Care of Creation on September 1. Between 1 September and 4 October, within the international ecumenical initiative established by The World Council of Churches, the so-called Season of Creation (originally established in 1989 by Patriarch Dmitri I for Orthodox believers) is celebrated, where Christians of different faiths around the world unite in prayer, advocacy, and practical action to protect creation. The Catholic Church has also participated in this initiative since 2015. In connection with Lent in Germany in 2020, the Archdiocese of Berlin and the dioceses of Eichstätt, Hildesheim and Rottenburg-Stuttgart encouraged 'climate fasting' (Fastenaktion für Klimaschutz und Klimagerechtigkeit 2020). Protestant Church also participates in this initiative

Table 2. cont.

Selected features of a religious state	Features of the European Green Deal
A particular expression of the state's commitment to the promotion of religious doctrine is the organisation of religious education in public education	Teaching about climate change is an integral part of the teaching of children and young people. The authors of the European Green Deal declare that the European Commission will prepare a European Competence Framework to help develop and evaluate knowledge, skills and attitudes on climate change and sustainable development
The religious nature of the state often results in restrictions on freedom in religious matters	The EU introduces legal bans and restrictions on the use of products considered harmful to the climate. A representative example is the imposition of a new dietary pattern based on veganism
Saints have played an important role in shaping the European civilisation and the Catholic Church. Politically, they have contributed to the integration of the heritage of different cultures, to the spread of new styles of governance that depart from autocratic patterns, to the combination of politics and sanctity, or at times of crisis, to spiritual, philosophical, and political renewal. At the religious level, they teach faith, they are an example to follow for the faithful, they help believers to understand their own lives	The emerging climate religion is also looking for saints. The Swedish activist Greta Thunberg is one of the first 'saints'. For example, in Maria Poprzęcka's column entitled *Na oko: Greta d'Arc [Roughly: Greta d'Arc]*, Greta Thunberg is compared to the Catholic St. Joan of Arc. By comparing the two characters, the author points out their ability to move the wealthiest world, the fact that their contemporaries question their mental health, and the similarity of punishment. As indicated by the author, in the layman world the saints of the Lord were replaced by the Asperger syndrome and ADHD, and death at the stake has been replaced by the fire of hateful tweets, the immersion in a wave of disgusting memes, and annihilation by contemptible disregard. The equivalent of Joan of Arc's canonisation, in the case of Greta Thunberg, are to be her subsequent Nobel Prize nominations. This column was mentioned in one of the Polish textbooks for the second grade of high school. By placing the figure of the Swedish activist in the school textbooks, she performs the function of saints of the Catholic Church. She teaches faith, becomes an example and inspiration for the young generation, and helps them to understand and re-evaluate their lives

Source: author's own work; features of a religious state on the basis of (Borecki 2017) and (Misztal 2001); (Poprzęcka 2020); (Babiński 2011); (Laudato Si 2015); (Pope Francis 2020), (EURACTIV.com 2015); (EURACTIV.com 2019); (Morgan 2018); (Season of Creation 2020); https://www.klimafasten.de/

The attempts at internal re-coding are also connected with dangerous cultural transformations, in which the superior value of man over nature is questioned. In extreme cases, the coding takes the form of equating the suffering of Holocaust victims with the fate of farm animals[4]. Jennifer White, Senior Media Officer at PETA, during an interview on "*Good Morning Britain*," called for an end to addressing animals in ways that suggest species superiority. Among others she *has called on animal owners to stop using the word claiming it's a patronising term comparable to the treatment of women before feminism*. (GMB, 4 Feb. 2020) A Ukrainian woman in Wuhan stricken by SARS-Cov-2 coronavirus refused to evacuate because of a dog she could not take with her. (TVP INFO 2020) Attention should also be paid to the ideology of species equality, which fights against the belief in the superiority of human species and the resulting discrimination against animals (so-called speciesism). Those in favour of speciesism compare it with racism, sexism or the injustices of the feudal system. This ideology, among other things, states that: *discrimination based on species is just as arbitrary as any other discrimination based on an illogical criterion. Equality tainted by exclusions and arbitrary discrimination is by definition inequality, injustice. Therefore all sentient beings, regardless of species, must be included within the circle of moral consideration. This does not mean treating them all in an identical way but really taking their interests into account as if they were our own.* One of the forms of promoting ideology has been *World Day for the End of Speciesism* organised for six years on 29 August (WoDES 2020). Magdalena Środa in an interview given on 6 December 2019 on the Polish Radio Zet, recalling a book by Sue Donaldson and Will Kymlicki Zoopolis. *A Political Theory of Animal Rights* called for animals to be granted citizenship. She stated that: There are domesticated animals which should be treated as co-citizens, then there are liminal, border animals which live with us, for example, rats**,** cockroaches or something like that and they should have refugee status. And there are wild animals that should have the status of citizens of sovereign states (Radio Zet 2019). As Paweł Jędrzejewski points out, *the complex cultural mechanism of people's perception of themselves and animals, however, acts as a two-person swing on playgrounds for children. When one child rises, the other has to fall down.* When – even for humanitarian reasons – one wants to raise the status of an animal, comparing it to a human being, the status of a human being has to decrease. There is no escape from this (Jędrzejewski 2019). The opposition expressed to equating the status of humans and animals cannot be interpreted as acceptance of the abuse of animals, the lack of concern for their welfare or the destruction of biodiversity.

[4] See: publication by Sylwia Spurek, MEP, of a graphic by Jo Frederiks depicting cows in camp striped uniforms of Auschwitz-Birkenau prisoners.

4. Influence of the European Green Deal on regional development processes in Member States

The implementation of the European Green Deal in the real world will have significant consequences for the Community's regional development. These consequences will undoubtedly be both positive and negative. They are currently not sufficiently identified and recognised. The declared effects of the realisation of the European Green Deal are: providing clean, affordable and secure energy; mobilising the industry sector for a clean, closed-loop economy; building and renovating in an energy and resource-efficient way; speeding up the transition to sustainable and intelligent mobility; creating a fair, healthy and environmentally friendly food system; protecting and restoring ecosystems and biodiversity; zero emissions for a non-toxic environment. Achieving the effects requires an additional investment of €260 billion per year, which represents about 1.5% of the Community GDP in 2018. This expenditure will have to be sustained over the next thirty years (COM(2019) 640).

In further considerations, regional development will be defined as the process of development of economic potential, increase in competitiveness of economic entities and the standard of living of the countries' inhabitants, in their regional decomposition, which takes place as a result of transforming factors and resources into goods and services, ensuring economic security (cf. Gorzelak 1989, Serafin 2001, Nelson 2013, Płaziak Rachwał 2015). Regional development factors are divided into exogenous and endogenous factors. The detailed analysis of regional development process factors (with particular emphasis on entrepreneurship) presented by Tomasz Rachwał covers three groups, the first two of which are exogenous and the third one is endogenous:

- general tendencies of civilisation development: development of information society; building the knowledge-based economy; volatility of market systems under the influence of innovative processes; increased importance of advanced technology products,
- global (international): international economic, social and political situation; affiliation to international groupings (mainly economic and political, e.g. the EU); economic and political relations between countries, including neighbours; conditions and possibilities of international flows (products, services, capital, knowledge/technology, population/labour resources); European Union development policies (including regional policy, in relations to the SME sector and others), as well as the quality and effectiveness of EU institutions and instruments; infrastructural development (with supranational functions),

- internal (national, regional, local): political and social system, internal political power and stability of the political scene; quality and level of qualifications of political elites (legislative and executive); efficiency of administrative structures and relations between society and power (trust level); size, quality and structure of resources: natural, capital, human (employment); social structures – the intellectual potential of society and the resources of human and social capital; social climate for stimulating and developing entrepreneurship; population structures (including age, nationality, education) (Rachwał 2018).

In the processes of regional development, endogenous and exogenous factors coexist and there are two-way interactions between them. The economic policy is based on the use of exogenous factors to strengthen endogenous factors.

Factors of national competitiveness should be sought by asking what determines productivity and the rate of its growth at the level of individual industries and countries. A detailed analysis of economies makes it possible to indicate significant differences between them, and consequently to identify the characteristics of a nation that contribute to the competitive advantage of its enterprises. These features are at the same time factors of a country's competitive advantage. The European Green Deal is an exogenous factor through which the European Commission aims to impose a single development scenario on all Member States and their regional systems. As a result, there is a real threat of destroying the national characteristics which are indicated by Michael Porter in the theory of competitive advantage of particular nations (Porter 1990). The threat requires particular attention in the context of potential further EU exits and the break-up of the Community in the 2050 perspective.

Among the positive effects of the implementation of the doctrine one should indicate the development of new industries and related jobs. Industries with a strong potential for development and job creation are: research and development, IT, renewable energy, organic farming, electromobility, and construction. An increase in employment is also to be expected in the government and local government administration, which will be directly related to new administrative, reporting and control responsibilities. The development of the sectors indicated will be accompanied by a drop in demand and a collapse in the sectors currently operating (e.g. traditional car industry, animal husbandry). Thus, the use of development opportunities resulting from the European Green Deal by individual countries and regions is conditional on becoming a leader in pro-climate innovation and requires rapid adaptation processes. This particularly applies to countries and regions characterised by a high share of declining industries in the economy. Failure to meet this condition will result in countries and regions becoming recipients of technologies and products only, and their opportunities for development will be limited. The political risk of dominance of large Community countries (the Germany-France duo) over other countries is confirmed by the path of adoption of new regulations without unanimity, as indicated in the guidance document.

As already indicated, the pursuit of climate neutrality will require significant financial resources from individual countries and regions. These funds will be European Union funds provided under the support programmes, as well as own resources of the individual entities. The future resources of the EU budget will come from new own revenues provided by the Member States and will consequently deplete their national budgets. The concentration of Member States' and their constituent regions' own resources on climate neutrality objectives also raises a real risk of underfunding of alternative development areas.

The European Green Deal involves revolutionary changes in both public and private value systems. According to the theory of competitive advantage of Michael Porter's economy nations, evolving economies go through four stages of development: development stage based on production factors (land, labour, capital), development stage based on investments and the currently ongoing development stage based on innovations. The last development stage indicated will be the one based on national assets (e.g. natural resources). Countries without access to resources will be deprived of development opportunities (Porter 1990). The implementation of the European Green Deal leads to the destruction of the value of natural resources and national assets (buildings, infrastructure) owned by states and regions. Those considered harmful to the climate become useless and worthless (e.g. fossil fuels). They require cessation of use and/or replacement with new ones ensuring climate neutrality. As a consequence, wealth will be transferred to countries offering new technologies.

A similar process will apply to private property. Currently, it can be traced back to the impairment of electric cars currently offered on the market. The life span of the cars offered on the market with traditional internal combustion drive ranges from several to over twenty years. The life of electric vehicles has been reduced to 8 years, which is directly related to the battery life and cost of battery replacement (Table 3).

The range of offered cars decreases with each subsequent charge, and thus their usefulness decreases. For example, in the Nissan Leaf, a 24 kWh battery loses around 20% of its capacity within 5 years. The capacity loss rate of the newer 30 kWh battery is even higher, reaching 20% in the first 2 years of use. The exception is Tesla cars, where during the first 50,000 miles (80,000 km) there is a decrease in battery capacity of about 5%. The 10% drop in battery capacity only occurs after about 186,000 miles (300,000 km) (Nowak 2018).

Table 3. Examples of battery replacement costs in electric cars

Make of vehicle	Purchase price (in PLN)	Cost of battery replacement (in PLN)	Manufacturer's guarantee
Nissan LEAF	from 155,000 (promotional from 118,000)	96,950	8 years / 160,000 km
Renault ZOE	from 124,900	approx. 90,000	8 years / 160,000 km
BMW I3	from 168,900	80,091	8 years / 100,000 km
SMART EQ	from 96,900	from 36,700; original 54,000	8 years / 100,000 km
Volkswagen GOLF	from 165,690	86,373	8 years / 160,000 km
Hyundai KONA electric	from 152,900	149,600	8 years / 200,000 km

Source: author's own work with the use of: (Żuchowski 2019), dealer offers as of 18 February 2020

After 8 years of use or driving, depending on the brand, from 100,000 to 200,000 km, the manufacturer's battery warranty ends. The possible replacement of batteries involves a cost to the owner of the car equivalent to 50% to 100% of the value of the new car. Thus, the market value of the car falls to zero. It is more advantageous for the consumer to buy a new car than to invest in battery replacement in a worn-out vehicle. Forcing consumers to replace their vehicles frequently causes negative environmental effects related to unjustified production of new cars and their transport to future users to be completely ignored.

The environmental performance of the activities and technological solutions proposed under the European Green Deal also raises important questions. For example, GHG emissions from electric cars over their entire life cycle are determined by the following factors: the technology used to produce the energy consumed during the production and operation of the car, the process of production and recycling of batteries (including the acquisition of raw materials).

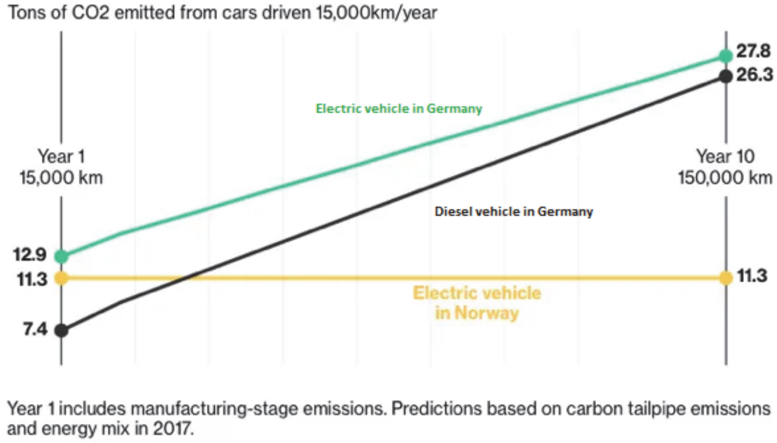


Fig. 2. Benchmarking analysis of emissions from electric and conventional cars in Germany and Norway
Source: (Rolander, Starn, Behrmann 2018)

According to Berryll Strategy Advisors′ study, building a 500 kilograms EV car battery in a fossil fuel-powered factory would result in up to 74% more carbon emissions than producing an efficient traditional vehicle (Rolander, Starn, Behrmann 2018). For example, with the current structure of energy sources in Germany, the total emissions of an electric car (carbon footprint including the production stage) will be lower than those of a conventional car after more than 10 years of operation (over 150,000 kilometres). In Norway, where about 98% of electricity is obtained from hydropower, the period is about 2.5 years (Figure 2) (Rolander, Starn, Behrmann 2018). It should be noted that the geographical conditions in Norway affecting the structure of energy production are unique.

The use of electric cars by both individuals and businesses also entails significant costs for the loss of time spent recharging vehicles. Unlike traditional vehicles, charging an electric vehicle in fast charging stations to the level of 80% takes about an hour, using a 7.2 kW wallbox – 4 hours, and less than 13 hours from the home network (values for Skoda Citigoe Iv) (Skoda-Auto 2020). The use of electric cars at their current range and recharging time significantly extends the travel distance. For companies, it is associated with a loss of efficiency and competitiveness. Employees who use electric cars in the course of their work will have to take numerous and long breaks to recharge their cars. Until progress is made on battery capacity and durability, electric cars should be seen as urban vehicles for individuals. The basic category of cars used should be hybrid cars. They make it possible to reduce the negative impact of transport on the environment, while at the same time their usefulness corresponds to that of traditional cars. In the long term, it seems justified to postulate the development of hydrogen drive technology.

5. Conclusions

The concept of planned obsolescence, presented by Bernard London in 1932, was used to stimulate the economy in the European Green Deal doctrine, as an attempt to counteract the Great Depression of the 1930s. In his study, diagnosing the causes and course of the crisis, he observes that: *I would have the Government assign a lease of life to shoes and homes and machines, to all products of manufacture, mining and agriculture, when they are first created, and they would be sold and used within the term of their existence definitely known by the consumer. After the allotted time had expired, these things would be legally "dead" and would be controlled by the duly appointed governmental agency and destroyed if there is widespread unemployment. New products would constantly be pouring forth from the factories and marketplaces, to take the place of the obsolete, and the wheels of industry would be kept going and employment regularized and assured for the masses* (London 1932, p. 2). Bernard London saw the causes of crisis in the behaviour of consumers, who, guided by rationality, make full use of their goods without succumbing to marketing or fashion. He proposed the administrative determination of the useful life of each product, at the end of which products would be considered *legally "dead"* and transferred to a government agency for destruction. As a result, consumers would have to re-purchase individual goods at strict intervals, thus ensuring continuity of production and employment. Similar solutions are at the heart of the European Commission's proposal presented in the European Green Deal. Compliance with the objectives of climate neutrality will be a criterion for determining the legality of the use of goods owned by societies.

The mechanism presented serves to stimulate investment that generates income and employment. The expected pro-ecological innovations should initiate the next (sixth) Kondratiev cycle. The EU activity in the area of shaping the factors of economic growth and development, and combating climate change justifies the continued existence of the European Community. The existence of this has been challenged in real terms by Brexit and the different perceptions of individual Member States of the sphere of values and ideas that underpin the EU. An observed dispute over fundamental values is taking place between supporters of Christian values expressed by the founding fathers and supporters of neo-Marxist values. The crisis of the EU's existence has also been caused by economic problems, the problem of migration, acts of terror committed by non-integrating immigrants. A significant problem is also the misunderstanding of the specific development and social, regional, and economic conditions in individual countries by the Brussels elite and the leaders of the largest countries of the Community (Germany and France).

The form and manner in which European politicians will present further GHG reduction targets resembles an auction (who gives more!). Every few years, successive European politicians initiate a process of adopting increasingly ambitious reduction targets. The current targets for 2021-2030 were only adopted in 2018 (see: OJ L 156/26) In fact, the proposals are in line with the investment strategies of the world's largest corporations, as evidenced by the BlackRock, Inc. with France, Germany, and global foundations agreement. Proposals are analysed to a limited extent in terms of real possibilities to reduce emissions, much less the risk of destroying the European economy.

The European Green Deal is an exogenous factor through which the European Commission aims to impose a single development scenario on all Member States and their regional systems. As a result, there is a real danger of destroying the national characteristics which determine the competitiveness of individual countries. The implementation of the European Green Deal in the real world will have significant consequences for the Community's regional development. These consequences – currently unrecognised – will be both positive and negative. Among the positive effects of the implementation of the doctrine one should indicate the development of new industries and related jobs. The European Green Deal involves revolutionary changes in both public and private value systems. Attention is also drawn to attempts at internal re-coding, which pose a threat to dangerous social and cultural change.

In the case of Poland, a separate path of climate and energy transformation, taking into account national conditions, the needs of the society and the economy, has been negotiated in relation to the remaining Community Member States.

Annex 1

The dogmatic perception of the climate warming theory is evidenced by the fact that its supporters a priori reject both extremely different scenarios of the course of climate processes and the same as assumed, but more or less pessimistic. Objective facts provided by science, indicating a possible different course, intensity and factors causing the observed climate change (other than the anthropogenic factor) are ignored. Numerous scientific studies are carried out in a way that aims to prove the thesis adopted in advance (including the most famous affair called Climategate). While rejecting an approach based on ‘political correctness,’ it must be stated unequivocally that a broad analysis of the available results of climate and palaeoclimatic research does not make it possible to verify positively both the hypothesis of warming and the opposite hypothesis. The theory of climate warming by its supporters (scientists and politicians) is treated as a strong stimulus to the development of an economy based on ecological innovations, by others as a recipe for disaster (see: Hansen, Sato 2011).

As indicated in the article, climate variability is an immanent feature that has had a significant impact on life since its beginning. Since the beginning of the Earth's existence, both temperature and greenhouse gas concentrations have been changing. The current CO_2 level in the atmosphere is one of the lowest in the planet's history (Piontek 2011).

Climate processes are first and foremost the result of an ongoing and complex process of varying natural factors. Among these factors, the key role is played by changes in the intensity of solar radiation, resulting from changes in solar activity. The influence of changes in solar activity on the course of climate processes on the Earth is confirmed by historical and climatic research (see Piontek 2011).

The 25th solar cycle started in 2020 – according to NASA's forecast presented on 12 June 2020 – will be the weakest of the last 200 years. The maximum of this next cycle – measured in terms of sunspot number, a standard measure of solar activity level – could be 30 to 50% lower than the most recent one (Tabor 2019). The solar activity will therefore be comparable to that of the Dalton minimum period (Figure 3). This forecast was revised on 9 December 2019 by The NOAA/NASA co-chaired, international panel to forecast Solar Cycle 25. The panel agreed that Cycle 25 will be average in intensity and similar to Cycle 24 (NOAA 2020). Notwithstanding the scientific dispute over the course of Solar Cycle 25, a trend of decreasing solar activity is observed from Solar Cycle 19 (Figure 3).

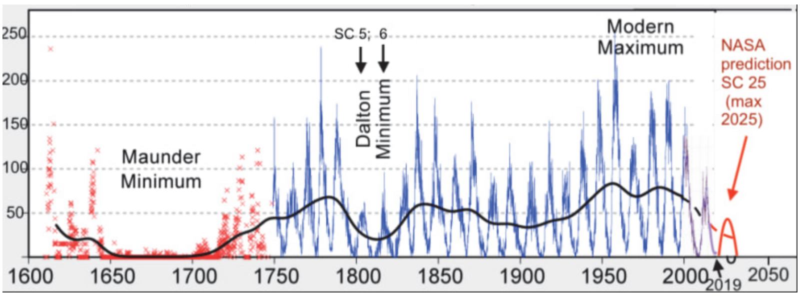
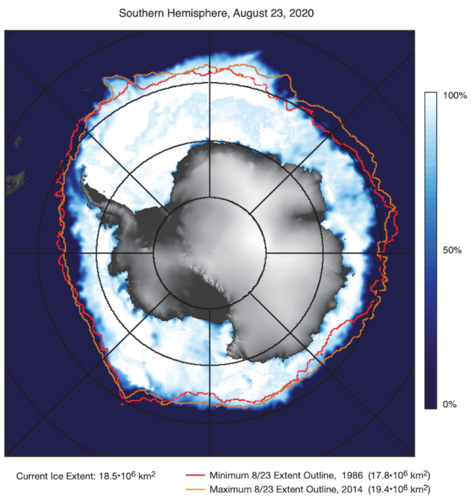


Fig. 3. NASA prediction Solar Cycle 25
Source: (https://www.iceagenow.info/a-repeat-of-the-dalton-solar-minimum/nasa-prediction-solar-cycle-25/)

In a situation of further decrease of solar activity – analogous to the Maunder's and Dalton's minimum – significant natural (not anthropogenic) climate changes leading to global cooling are to be expected in subsequent decades (solar cycles). This process will be expressed in the blurring of the differences between the seasons, irregular rainfall, intense and violent floods, storms, droughts, hailstorms, mild winters, as well as frost and snowfall during the summer.

The fact that the weather is destabilising, or the Arctic ice cap is significantly shrinking, is undeniable. At the same time, the extent of the Antarctic ice sheet has been stable over the recent decades. For example, as of 23 August 2020, the ice area in the Southern Hemisphere was 16.4 x 10^6 km^2 and was higher than the 1979-2020 average (16.2 x 10^6 km^2) and the minimum of 1986 (15.5 x 10^6 km^2) (Figure 4) (Comiso and others 2020). During the period of research, record levels of cover were observed in 2014, a period of widespread recognition of the theory of global warming.



10-year averages between 1979 and 2018 and yearly averages for 2012, 2014, and 2020 of the daily (a) ice extent and (b) ice area in the Southern Hemisphere and a listing of the extent and area of the current, historical mean, minimum, and maximum values in km^2

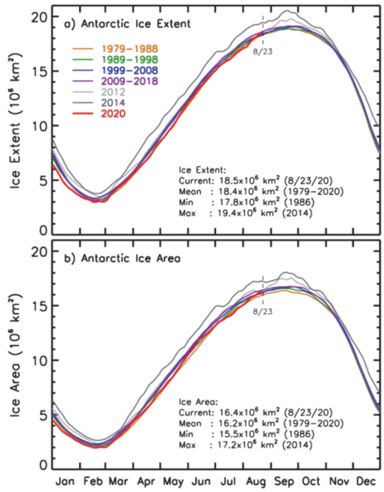


Fig. 4. Antarctica Sea Ice Cover
Source: (Comiso and others 2020)

In May and June 2020 in the mesosphere, at polar latitudes (60N-80N) and mid-latitude (35N-55N), temperatures reached their lowest values in 14 years of research history (Figure 5). On June 3, 2020, the temperature – at a latitude of 83°N and altitude of 83 km – reached only 140°K (measured using the MLS[5] method) (Figure 5) (Phillips 2020). After M. Schwartz it should be indicated that the upper tropospheric temperature is particularly important to climate feedbacks involving the regulation of humidity and clouds. Some climate models show temperature in the mesosphere to be particularly sensitive to climate change (Schwartz 2020).

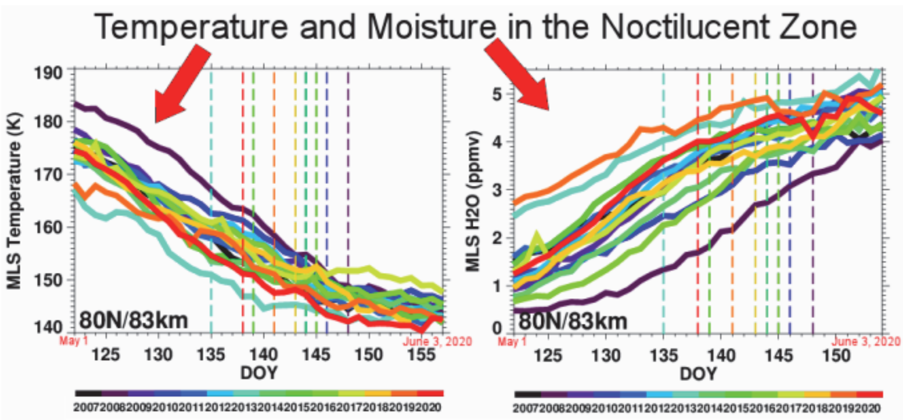


Fig. 5. Temperature of the Mesosphere – May, June 2020
Source: (Phillips 2020)

There is no doubt that there is a connection between the temperature of the mesosphere and the course of the summer in the northern hemisphere in 2020 and the winter in the southern hemisphere. In July, snowfall in the southern regions of Norway caused more than 10 metres of snowfall and a serious flood risk (Figure 6) (NRK 2020).

[5] Microwave Limb Sounder

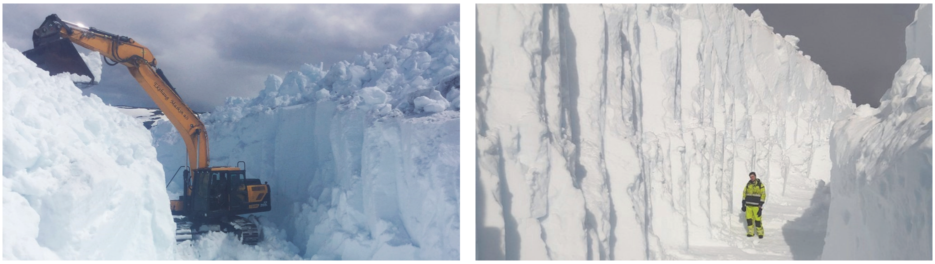


Fig. 6. Snow removal – southern Norway – July 2020
Source: (NRK 2020)

The Oppland County (Norway), located at an altitude of 2000 m, has a record low temperature of -6.3°C[6] (Celestial J. 2020b). At the same time, unprecedented snowfalls were recorded on 5 August in northern Tasmania (Jackson 2020). The Australia Bureau of Meteorology noted record low temperatures in central West Queensland in May (Al Jazeera 2020). In the second half of August, very intense Antarctic air brought to historic cold and snow across wide swaths of South America (DGW 2020).

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[6] An earlier record was noted in 1964, at the turn of the 19th and 20th solar cycle, also at a time of falling solar activity.

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Abstract

The aim of the paper is to analyse the theoretical aspects of the European Green Deal and to identify its potential impact on the Community's regional development processes. The paper presents the objectives and assumptions of the doctrine and its global dimension. The theoretical foundations of the doctrine in economic and social dimension have been defined. An attempt was made to identify and analyse the impact of the European Green Deal on regional development processes in the European Community. Regional development has been defined as the process of development of economic potential, increase in the competitiveness of economic entities and the standard of living of the countries' inhabitants, in their regional decomposition, which takes place as a result of transforming factors and resources into goods and services, ensuring economic security. The influence of the European Green Deal on factors of economic growth and development, factors of competitive advantage of countries, system of both public and private value (natural resources, national assets), transformations in the structure of economies (emerging and declining industries), as well as costs necessary to make the doctrine a reality were indicated.

Keywords:
the European Green Deal, climate neutrality, regional development,
factors of economic growth

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Responsible Pro-Environmental Management in an Organization: a Case Study

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1. Introduction

The basic stipulation of environmental management consistent with the requirements of ISO 14001: 2015 standard is to improve the relationship between the effects of human activities and natural environment. Maintaining balance requires uniform management, access to environmental resources, rational use of natural resources and to tackle negative effects of economic activity (Al-Kahloot et al. 2019, Lira et al. 2019, Loste et al. 2019, Maletic et al. 2015).

The aim of this publication is to present, on the example of a selected organization, the adaptation to the implementation of the ISO 14001: 2015 environmental management system and the analysis of the obtained benefits by said organization as a result of the system's implementation (De Camargo et al. 2019, Koukaou et al. 2019, Hernandez-Vivanco et al. 2019, Henrykowski 2008).

Environmental management strategy is based on the following elements: waste reduction at the source, waste management, waste prevention and reduction of pollution that enters the environment (Wolniak 2017, Vries et al. 2012, Vidovic et al. 2019). Environmental management is a response to the EU environmental policy and its states to more effectively and efficiently address environmental issues at the national, regional and local levels (Todaro et al. 2019, Apiworathanakorn et al. 2019, Andrei et al. 2019). The implementation of principles based on sustainable development are an important element of the national environmental and socio-economic policy (Sari & Kamalia 2019). The environmental strategy is a socio-economic policy that is implemented to maintain balance between the economic development and environmental resources. In practice, this means adapting economic development to the resilience of the environmental. The aim of this behaviour is to maintain environmental resources in healthy condition for the present and future generations (Pacana 2017, Pacana et al. 2017, Paulraj & Jong 2011).

The environmental management system can be understood as a part of the overall organization management system that includes the following: the organizational structure, responsibility, planning, procedures, rules of conduct, processes and resources needed for the development, implementation, review and maintenance of the created environmental policy. Environmental management is, therefore, one of the management techniques that enables an organization to keep the burden on the natural environment as low as possible (Malindžák et al. 2017, Treacy et al. 2019, Bober et al. 2017).

Identification of the environmental aspects is a basic element of the implementation, functioning, design and improvement of the environmental management system. These aspects may have an impact on the environment (Chiarini 2013). Well-defined environmental aspects are the basis for the proper functioning of the environmental management system in an enterprise. They determine the benefits that an organization will obtain from the implemented system. Through a comprehensive examination of the environmental aspects and presentation of sources of threat, it is possible to determine ways to minimize their impact on the environment (Olkiewicz 2018, Olkiewicz & Wolniak 2018). The decision to implement the ISO 14001: 2015 system must be the first step taken by the top management. The second significant step is the involvement of the management. This involvement determines the success of the implementation and the functioning of the environmental management system in an enterprise (Wolniak & Sędek 2009, Woźniak et al. 2010, PN-EN ISO 14004:2016). The implementation of the environmental management system should be planned in detail. It is also necessary to specify next stages of works and their deadlines (Wu et al. 2020, Satror et al. 2019, Searcy et al. 2012).

An effective environmental managements system is the one that brings measurable results of introduced changes in an organization, with the simultaneous increase of the company's value (Chiarini 2019). The benefits resulting from the implementation of ISO 14001: 2015 standard can be divided into external, internal, marketing and administrative (Psomas et al. 2011, Qi et al. 2015, Mijatowic et al. 2019, Olkiewicz 2020). Through the implementation of the environmental management system, the organization's undertaken marketing activities become easier and the perception of the company by clients and contractors improves (Elafi 2019). The company's reputation enhances as so does its credibility in conducting its business under applicable law. This gives the company an opportunity to compete in markets where there are high expectations in the areas of environment. In addition, the organization can effectively use public relations tools (Džubáková 2019, Nemati et al. 2019, Ni 2019). If the administrative obligations are well documented after the implementation of the system and there are benefits resulting from the access to investments loans in the area of environmental – then an organization will continue to develop (He & Shen 2019). In such situation, the number of external audits on the utilization of the environment is reduced and the costs of insurance premiums drops. This constitutes an elimination of penalties resulting from non-compliance with legal and other requirements related to environmental issues (Pirju 2019, Pacana & Ulewicz 2017).

Implementation of the theory and practices applied in accordance with the ISO 14001 standard involves a lot of effort from the top management and employees of an organization. The advantage of implementing this system is that the company is improving in the eyes of its current and future customers. The application of the standard certainly builds an advantage over competition and the local community will look favorably to the organization's activities. A company with clear objectives, an organizational policy and instructions helps to improve its self-esteem and makes it aware that it operates in accordance with the principles of environmental protection (Olkiewicz et al. 2015, Olkiewicz et al. 2019, Waxin et al. 2019).

2. Methodology

The research presented in this publication was based on a selected company operating on the local market in the area of a broadly understood scope of waste management and cleanliness maintenance. Currently, the company employees 70 workers, including 20 administrative employees. The company operates under commercial law.

As part of its activities related to the management of the municipal waste management, the company offers comprehensive refuse collection and solid waste management services, i.e. high-volume waste, post renovation waste, debris. The methods of selective waste collection implemented by the organization reduce the amount of waste going to landfills. Clients from the industrial sector are offered a comprehensive service in the area of waste collection and management generated at their enterprises. The company ensures proper management of generated waste in accordance with the applicable law.

This publication analyzed source documents obtained from the company, presents the results of in-depth interviews and uses a questionnaire method. Owing to this, environmental aspects were developed, the environmental policy was defined and an environmental example programme was developed. The organization's effectiveness to date and customer feedback was analysed through a survey. This case study allows to learn more about the possible benefits and expected results, which the company can achieve through the implementation of the environmental management system.

The performed initial environmental review covered the following areas: emissions into the air, dust, gases, noise, heat or smell, solid and liquid waste. Questions also included the company's legal framework, decisions required by law, permits, occupied area, machines, type of service, products, raw materials used in the company and emergency situations.

The initial company review was carried out by using a list of questions. During the review, decisions undertaken by the organization, permits and compliance of activities with applicable law were analyzed. The review also included a physical inspection of the area covered by the system with in-depth interviews with people employed in specific organizational units and knowledge in the case study area.

Fifty-eight clients of the analyzed organization took part in the survey. The duration of the survey lasted for one month. The participants of the survey were customers of the services supplied by the enterprise. Out of the fifty-five participants, thirty-five said that they were satisfied with the provided services. This amounts to 60% of satisfied customers. However, 26% gave a negative response and 14% had no opinion about the provided services.

3. Preparation to implement an environmental management system in the company

The areas verified by the environmental review allowed to conclude that the researched company holds permits, decisions and other documents that are necessary to carry out its activities in accordance with the applicable law in environmental management. The company has not yet been fined for exceeding the emission limits laid down in decisions and permits. Waste is collected in accordance with the applicable law and is collected and transported by specialised vehicles designed for this purpose.

All documents which may be needed at a later time are described and archaized, e.g. waste characterization sheets. The company has an adequate amount of road transport to perform its activities professionally and in accordance with the legal requirements and requirements set by interested parties. The raw materials used are stored in bendable packaging. After their use they are collected by a supplier with a permission to recover them. The company keeps records of waste received, collected and stored. In addition, the organization maintains records of electricity consumption. Emission processes to air are defined, thus the company has to pay environmental fee annually.

In summary, the company analyzed in this publication is well on its way to optimize its activities and to cover the enterprise partly with the environmental management system. The organization's aims are to cover their service provision with environmental management system in the area of collection and transport of municipal waste, collection and transport of hazardous and non-hazardous waste and road maintenance in the summer and winter time. Therefore, it is necessary to visualize and specify environmental aspects, aims and tasks, which after the decision to implement the ISO 14001: 2015 system, will be approved by the organization's management. After the initial review of the company, it was concluded that activities can be undertaken to implement the environmental management system.

Through the identification and evaluation, the following significant environmental aspect of the organization were identified:

I. The identified direct aspects include:

- pollution of natural environment with dust and gases through the emission of gases from the boiler on the premises of the administration facility and the transport and storage base,
- pollution of natural environment with waste caused by the production and storage of hazardous and non-hazardous waste at the transport and storage base connected with the operation of vehicle repair facility,
- water and soil pollution caused by the production of industrial sewage connected with the operation of a car washer,
- emissions of air pollutants in connection with the combustion of fuels in specialized vehicle engines,
- water and soil pollution due to the removal of rainwater and snowmelt sewage from the transport and storage base,
- water, soil and air pollution caused by non-hazardous waste storage at the transport and storage base connected with waste collection activities,
- water and soil pollution due to fuel and oil leakage from vehicle tanks,
- water and soil pollution caused by storage of mixtures in connection with winter road maintenance,
- air, soil and water pollution with a threat to human health in connection with the risk of fire on the company's premises.

II. The identified indirect aspects include:

- reduction of the amount of hazardous waste stored on a landfill site in connection with the collection of batteries and accumulators,
- reduction of the amount of hazardous waste stored on a landfill site in connection with the collection of electrical and electronic equipment,
- ensuring compliance with the requirements of waste management,
- reduction of the amount of hazardous waste stored on a landfill site (including ensuring appropriate waste recovery rates) in connection with the collection of municipal and selectively collected waste,
- raising public and customer awareness about waste management.

The designated environmental aspects allow to identify easily the company's environmental policy, i.e. a document that underpins the implementation and improvement of the environmental management system.

The current direction indicates the progressiveness against the adverse impact on the environment. This document serves as an important commitment of top management towards the environment.

The researched company has the required decisions and permits under applicable law. These decision and permits are:

- water-legal permit,
- decision to collect waste,
- decision to generate waste on the premises of transport and storage base,
- decision to transport waste.

The organization also has entries into the register of regulated activity for the collection of municipal waste in communes in which it conducts business activity. This entry is required under the Act to maintain cleanliness and order in communes. The company is also listed in the register of the Chief Inspector for Environmental Protection in relation to the provisions of the Act on waste management of electrical and electronic equipment. In addition, the organization is entered in the register of gas emissions to air kept by the National Centre for Emissions Balancing and Management.

Environmental effects will be monitored in accordance with the frequency, scope and methods precisely specified in the held decisions or permits. The water-law permits specify the deadlines for testing, the quality of rainwater, snowmelt and industrial sewage that is discharged to surface waters. The company conducts research on specified dates. The organization is committed to the principle of rational waste management and meets all legal requirements in the area of records and waste management. The company performs the reporting obligations for gas emissions into the air, waste management and transport-related reports. Environmental fees are paid annually under the applicable regulation in a given year. At present, the company did not incur any sanctions in the form of penalties for failing to meet legal requirements in the area of environmental protection.

To implement an environmental management system, its aims and tasks should be based on the company's specific environmental policy. Objectives and tasks must relate to the previously identified environmental aspects of significant nature. The environmental programmes of the analyzed organization were developed based on the objectives identified in the environmental policy approved by the company's management. The company's credo was defined as: We work well to ensure that the natural environment is clean.

Environmental programmes were established by the organization in accordance with the previously identified environmental aspects of significant nature with applicable technical requirements and company's technical capabilities in mind. Table 1 presents key environmental programmes for enterprise X, planned (hypothetically) to be implemented for the year 2018 and beyond.

Table 1. Environmental programs implemented by the organization

No	Environmental objective	Task	Environmental aspect or/and effect on the environment	Deadline
1	No losses in stored waste	Implementation of waste inventory control. Purchase and installation of monitoring cameras	Environmental aspect	2018
2	To raise awareness of the local community in the field of environmental protection	Conducting lessons in primary school on the subject of: pro-ecological behaviour regarding waste management	Collecting hazardous and non-hazardous waste at the premises of the transport and storage base	2018
3	Improvement of the company's image, improvement of aesthetic features of the company.	Planting 60 trees/shrubs and flowers over the length of 50 meters on the company's premises	Environmental aspect: improved control over waste collected at the base premises.	2018
4	Reduction of water pollution. Protection of soil by eliminating the produced sewage spill	Sealing the washer area by pouring a concrete floor	Environmental aspect: improved control over waste collected at the base premises.	2018
5	Protection of groundwater, surface waters and soil by securing the salt dump	Construction of retaining wall that prevents leaching of salt into the storm water drainage system	Impact on the environment: raising awareness of future customers/society in the field of proper waste management	2018-2020

Table 1. cont.

No	Environmental objective	Task	Environmental aspect or/and effect on the environment	Deadline
6	Protection of groundwater, surface waters, soil through prevention of possible leaks (fuel, oil) from means of transport	Elimination of defects in the paved road on the transport and storage base premises	Improvement of waste segregation at the source – improved recovery of raw materials	2018-2020

The pie chart in Figure 1 illustrates the opinions of respondents about pro-environmental actions undertaken by the company, e.g. promoting waste segregation at source. Vast majority of the respondents (88%) considered these activities to be significant. This means that the activities undertaken by the organization in the area of waste segregation at source are a right direction in the promotion of pro-ecological activities. Only 2% of the respondents said that there is no need for the company to promote pro-ecological activities. It may be presumed that these people do not segregate waste and consider doing it unnecessary. In addition, 10% of the respondents had no opinion in this matter.

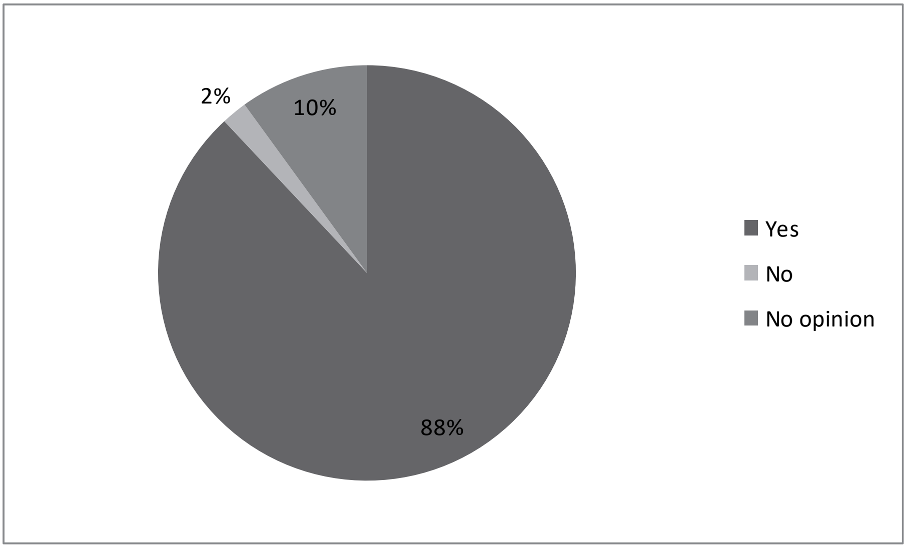

Fig. 1. The importance of promoting co-friendly activities

The bar chart presented in Figure 2 illustrates the percentage of people who have a positive attitude towards promoting pro-ecological activities undertaken by the company. The research shows that 86% of respondents have a positive attitude towards the promotion of pro-ecological activities of the organization aimed at gaining trust of the company's stakeholders. In the opinion of the rest of the surveyed group, pro-ecological activities will not increase their confidence in the company and its activities.

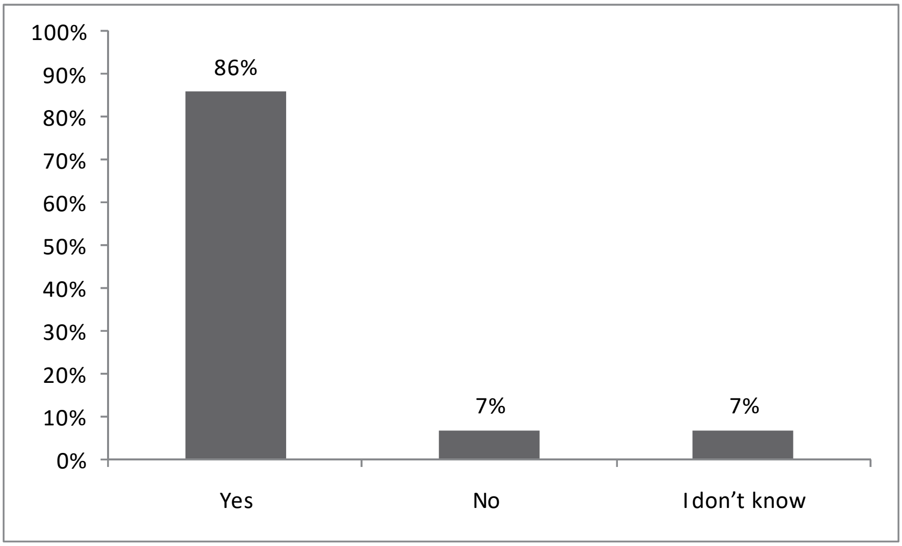

Fig. 2. Increasing customer trust through ecological activities

Figure 3 shows the opinion about the company's image concerning its environmental policy. Over 83% of the respondents said that the organization's environmental policy has an impact on the external image of the company. Only 10% of the surveyed people were of different opinion and the rest of the respondents stated that the do not know whether this type of influence exists.

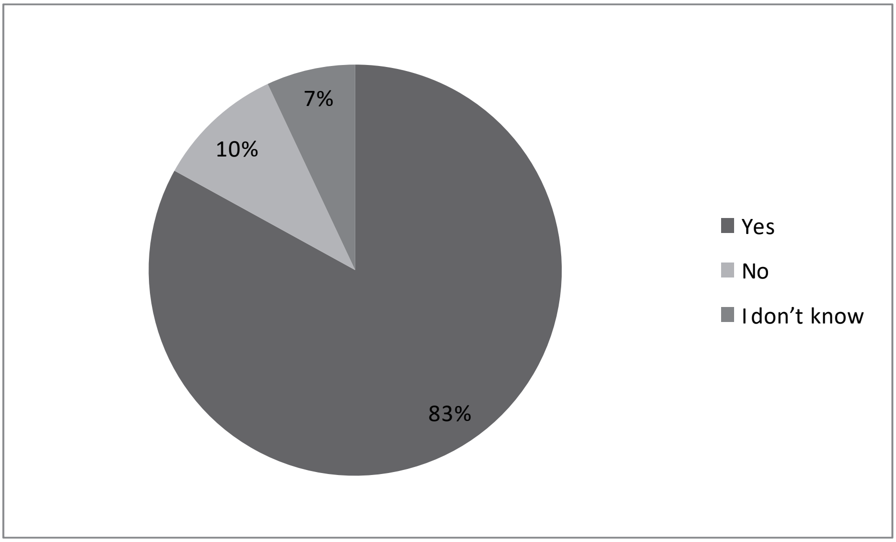

Fig. 3. Environmental Policy and the image of the organization

4. Benefits from the implementation of an environmental management system in the surveyed organization

The data presented in Figure 4 illustrate the potential benefits the company can achieve after the implementation of an integrated environmental system in the opinion of the respondents and stakeholders. The largest percentage (28%) was observed in the number of services provided by the company. An increase in customer confidence in the company (22%) was placed second. Subsequently, the respondents provided the following answers: improved functioning of the organization (16%), improved environment status around the company's premises (14%) and increased attractiveness of the organization (12%). Only 9% of respondent ticked the answer about the reduction of operating costs.

An efficiently functioning organization, confirmed by the presented survey results, and an effective environmental management system will generate measurable benefits, which will also be reflected in the financial, managerial and marketing sphere.

The internal benefits of the surveyed company include a reduction in charges incurred for utilizing the environment, thus a reduction in the amount of generated waste. Reduction of the consumption of water, energy or raw materials can also contribute to the increase of economic effects of the company. Another internal benefit is an increase in employees' ecological awareness and their increased involvement in the organization's activities. Specific procedures allow the company to limit the risk of malfunction in the company.

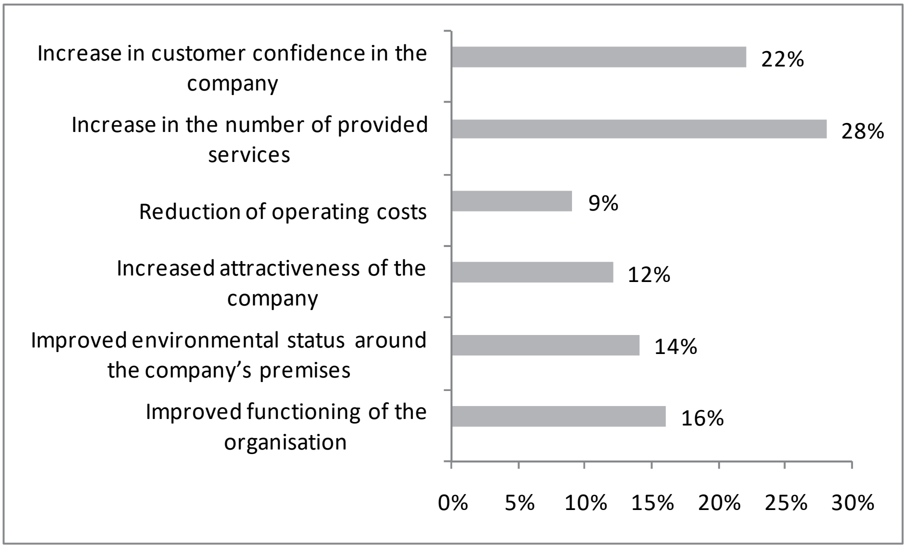

Fig. 4. Expected benefits after the implementation of the ISO 14001 system

A measurable external benefit of the company is the improvement of the state of natural environment around the company's premises, which will contribute to the improvement of relations and to enable direct dialogue with the local community. This will increase the company's competitiveness and customer confidence in the organization. The enterprise has an opportunity to identify and enter new markets.

An environmental performance indicator can be used to determine measurable effects of the company's environmental performance expressed with the following formula: R = A/B.

The letter A indicates the overall annual input/impact in the given area, whereas letter B indicates the overall annual output of the organization. The indicator for the company's overall annual output is the same for all the fields.

Table 2 shows selected environmental output indicators, which the company can use to measure its environmental effects.

The results presented in Table 2 illustrate measurements and results prior to the implementation of the system.

Table 2. Environmental performance indicators

Indicator	A				B		C		
		Unit	2014	2015	2014	2015	2014	2015	Unit
Energetic efficiency	Total direct electricity consumption	MWh	153.6	147.3	197	201	0.780	0.733	MWh per person working for the company
Effective use of materials	Annual mass flow of various materials used in the company (office paper)	Mg	1.974	2.260	197	201	0.010	0.011	Mg per person working for the company
	Annual mass flow of various materials used in the company (mixtures for winter road maintenance)	Mg	7072	3820	197	201	35.899	19.005	Mg per person working for the company
	Annual mass flow of various materials used in the company (chemical agents – for cleaning and disinfecting containers)	Mg	0.675	0.33	197	201	0.003	0.002	Mg per person working for the company
	Annual mass flow of various materials used in the company (paints, solvents)	Mg	0.323	0.583	197	201	0.002	0.003	Mg per person working for the company
Water	Total annual water consumption	m^3	3058	3339	197	201	15.52	16.61	m^3 per person working for the company

The company's environmental objectives that were previously designated, environmental tasks (environmental programme), identified environmental aspects and specified environmental policies allowed for the definition of measurable indicators for environmental performance presented in Table 2. These indicators determine the effectiveness of environmental activities undertaken by the organization.

Environmental performance indicators allow to illustrate the degree of a harmful impact an organization can have on the environment and present products manufactured by the company (waste, by-products) that have adverse effects on natural environment.

The indicators defined in Table 2 provide the necessary information for the external stakeholders and the management of the company. The correct interpretation of the results allows the top management to make the right decisions in the organization. The company is obliged to prepare environmental reporting after the implementation of the system. In such a situation, it is essential to analyse and modify the environmental indicators specified in this publication. These obligations impose costs that have to be borne by the organization. In the future, however, this will generate additional benefits for the company.

5. Conclusions

This publication presents a case study of responsible environmental management on the example of a Polish organization having the objective of municipal waste management. The results of conducted analyses allow to conclude that the organization is well prepared for the implementation of the environmental management system under the requirements of ISO 14001: 2015 standard. A number of activities were carried out during the initial preparation of the organization for the implementation of the system, i.e. review of the functioning documentation, review of the organization and an analysis of significant environmental aspects. The designated environmental aspects made it possible to develop environmental policy.

The carried-out survey indicates that the pro-ecological activities undertaken by the organization will bring numerous benefits. The benefits can include, inter alia, increased customer confidence, improved image of the organization and thus an increase in the number of services provided by the company. Environmental performance indicators will be carried out for the assessment of the functioning of the implemented environmental management system. This will allow an effective identification of the areas that require improvement

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Abstract

This publication presents a case study of responsible environmental management on the example of a Polish organization having the objective of municipal waste management. The results of the conducted analyses allow to conclude that the organization is well prepared to implement an environmental management system compliant with the requirements of ISO 14001:2015 standard. This publication presents and characterises environmental programmes which are implemented by the organization.

The purpose of this publication is to present, on the example of a selected organization, the adaptation to the implementation of the environmental management system compliant with ISO 14001:2015 standard and to analyse the benefits obtained by the organization as a result of implementing the environmental management system. The carried-out surveys suggest that pro-environmental activities undertaken by the organization will bring numerous benefits. The benefits can include, inter alia, increased customer confidence, improved image of the organization and thus an increase in the number of services provided by the company. Environmental performance indicators will be carried out for the assessment of the functioning of the implemented environmental management system. This will allow an effective identification of the areas that require improvement.

Keywords:
environmental management, ISO 14001, certification, environmental aspects, management, benefits of certification

Odpowiedzialne zarządzanie pro-środowiskowe w organizacji: studium przypadku

Streszczenie

W publikacji przedstawiono analizę przypadku odpowiedzialnego zarządzania środowiskowego na przykładzie polskiej organizacji zajmującej się gospodarką odpadami komunalnymi. Wyniki przeprowadzonych analiz pozwalają na stwierdzenie, że organizacja jest dobrze przygotowana do implementacji systemu zarządzania środowiskowego zgodnego z wymaganiami ISO 14001:2015. W publikacji przedstawiono i scharakteryzowano programy środowiskowe jakie są realizowane przez organizację.

Celem niniejszej publikacji jest przedstawienie na przykładzie wybranej organizacji dostosowania do wdrożenia systemu zarządzania środowiskowego ISO 14001:2015 oraz analiza korzyści uzyskiwanych przez organizację w wyniku wdrożenia systemu zarządzania środowiskowego. Przeprowadzone badania ankietowe sugerują, że działania proekologiczne realizowane przez organizację pozwolą na uzyskanie licznych korzyści.

Między innymi mogą one przyczynić się do zwiększenia zaufania klientów, poprawić wizerunek organizacji jak również w efekcie spowodować wzrost ilości usług wykonywanych przez przedsiębiorstwo. W celu analizy funkcjonowania wdrożonego systemu zarządzania środowiskowego będzie się prowadzić analizę wskaźników efektywności środowiskowej, które pozwolą na efektywne wskazywanie obszarów możliwej poprawy i ich udoskonalanie.

Słowa kluczowe:
zarządzanie środowiskowe, ISO 14001, certyfikat, aspekty środowiskowe, zarządzanie, korzyści certyfikacji

MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

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Experimental Determination of Optimum Mixture Design of Lightweight Concrete

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1. Introduction

Over the past few decades the increased use of lightweight concrete (LWC) for the structural elements has become a more and more important aspect of the modern construction industry (Rumsys et al. 2018). Despite many undoubted advantages like good thermal properties and low density (Liu et al. 2019), concrete fully made with the lightweight aggregate exhibits significant reduction in mechanical properties (Han & Xiang 2017). For instance, during pull-out test LWC is characterized by about 70% smaller bond strength between rebar and matrix than normal-weight concrete (NWC) (Alexandre et al. 2014). Compressive strength of concrete decreases with increase of lightweight aggregate content. The compressive strength of structural LWC is about 60% smaller than NWC at 28 days of curing when coarse aggregate is fully replaced with expanded clay aggregate (Aarthi et al. 2019). Considering the applications of LWC and NWC in structures and differences in material properties between them, the interfacial performance needs further study (Huang et al. 2019). All above facts inspired authors to conduct research programme dedicated to determine optimum mixture design of lightweight concrete.

2. Materials, experimental methods and specimens preparation

During the research programme following materials were used for the LWC preparation: aggregate consisted of expanded clay granules, Portland cement CEM I 42.5R which was used as a binder, tap water and superplasticizer (in case of selected mixes). Crushed (in industrial grinder - see Fig. 1) expanded clay granules were used as fine aggregate 0-4 mm. Expanded clay granules 4-16 mm were used as coarse aggregate. Superplasticizer reduced the amount of water by about 20% (in case of selected mixes). The research tests procedures were based on European and Japanese standards (see Table 1). The research programme was divided into two stages. During the first stage four different lightweight aggregate compositions (mix-1 to mix-4) were prepared. Based on these aggregates four LWCs (LWC-1 to LWC-4) were cast. Consistency, density, compressive strength and splitting tensile strength were tested for all four LWC. After an analysis of the achieved characteristics one LWC was qualified for the second stage of the research programme. During this part of the research programme more sophisticated properties of LWC in question were tested such as dynamic modulus of elasticity, flexural strength, shear strength and abrasion resistance.

Fig. 1. Industrial grinder used for crushing lightweight aggregate granules

Table 1. The research test procedures

Type of test	Standard number	Stage
Consistency	EN 12350-3:2001*	I
Density	EN 12390-7:2011*	
Compressive strength	EN 12390-3:2011*	
Splitting tensile test	EN 12390-6:2011*	
Dynamic modulus of elasticity	EN 12504-4:2005*	II
Flexural strength	EN 14651:2007*	
Shear strength	JCI-SF6:1984**	
Abrasion resistance	EN 13892-3:2005*	

* – European standard, ** – Japanese standard

The adopted design of experiment is summarized in Table 2 where number of specimens utilized for each test, their shape and dimensions are listed. The apparatus used for compressive strength and splitting tensile strength together with cubic specimens are shown in Fig. 2. Flexural and shear strength tests results are presented in Fig. 3.

Table. 2. Number of specimens, their shapes and dimensions used in the research tests

Type of test	Specimen shape [cm]	Number of specimens	
		in one test	overall
Density	–	6	24
Compression strength	cube 15x15x15	8	32
Splitting tensile test	cube 15x15x15	8	32
Dynamic modulus of elasticity	cylinder ⌀15x30	10	10
Flexural strength	beam 70x15x15	6	6
Shear strength	cuboid 30x15x15	12	12
Abrasion resistance	cube 7.1x7.1x7.1	3	3

Fig. 2. The strength apparatus (left) and specimens (right) used for compressive strength and splitting tensile strength tests

Fig. 3. Apparatus and specimen during flexural strength test (left) and shear strength test (right)

3. Research test results

Four different lightweight compositions prepared for the research programme are presented in Table 3. All aggregate compositions didn’t exceed the diameter of 16 mm. Mix 1 and 2 were characterised by maximum volume of the voids and minimum tightness. The dust content, sand content and water absorption was highest for the mix 3. Fine aggregate grading significantly affects the concrete properties in the hardened state (Katzer & Kobaka 2009b). The large surface area of the fine aggregate increases the amount of water necessary to wet all the solids (Katzer & Kobaka 2009a). Three of four aggregate mixes (except mix 3) were characterised by fineness modulus by Kuczynski within the recommended range 5-7.5. Fineness modulus by Hummle varied from 110.8 for mix 3 to 136.9 for mix 2.

The created four LWC mixes are thoroughly described in Table 4. The w/c ratio varied from 0.45 to 0.54. The consistency of fresh LWC was tested using ordinary VeBe method. The results of the VeBe test are shown in Table 5. Fresh LWC no. 1 was too liquid to be established by VeBe method (the fresh mix cone collapsed during tests preparation). LWC no. 2 was characterised by V2 consistency class, fresh LWC no. 3 and 4 were characterised by V3 consistency class according to EN 206:2016 standard.

Table 3. Properties of the aggregate mixes used for LWC creation

No	Property	Units	Mix 1	Mix 2	Mix 3	Mix 4
1	Voids volume	%	40	44	32	36
2	Water absorption (by weight)	%	18	21	26	22
3	Tightness	–	60	56	68	64
4	Median diameter (Katzer 2012)	mm	1.65	2.9	0.88	1.34
5	Dust content ($d \leq 0.125$ mm)	%	10.46	9.73	19.7	12.3
6	Fine grains content ($d \leq 0.5$ mm)	%	25.3	16.7	37.4	27.78
7	Sand content ($d \leq 2$ mm)	%	41.1	27.17	56.6	48.8
8	Fineness modulus by Kuczynski	–	5.25	5.63	4.76	5.14
9	Fineness modulus by Hummle	–	125.5	136.9	110.8	122.2

Table 4. Composition of the LWC

LWC	Aggregate		Cement	Water	w/c	Admixture
	Fine	Coarse				
	[kg/m^3]				–	[kg/m^3]
1	560	560	370	200	0.54	–
2	480	620	410	220	0.54	–
3	790	320	460	220	0.48	10.1
4	730	420	510	230	0.45	11.3

Table 5. Consistency tests results based on VeBe method

Mix no.	Test result [s]	Consistency class
1	0	–
2	3.5	V2
3	9.6	V3
4	6.1	V3

Particle size distribution test results are shown in a chart form in Fig. 4. The characteristics of all aggregate mixes in question were not compliant with the concrete aggregate recommendations yet in the case of mix 3 and 4 the differences were not significant.

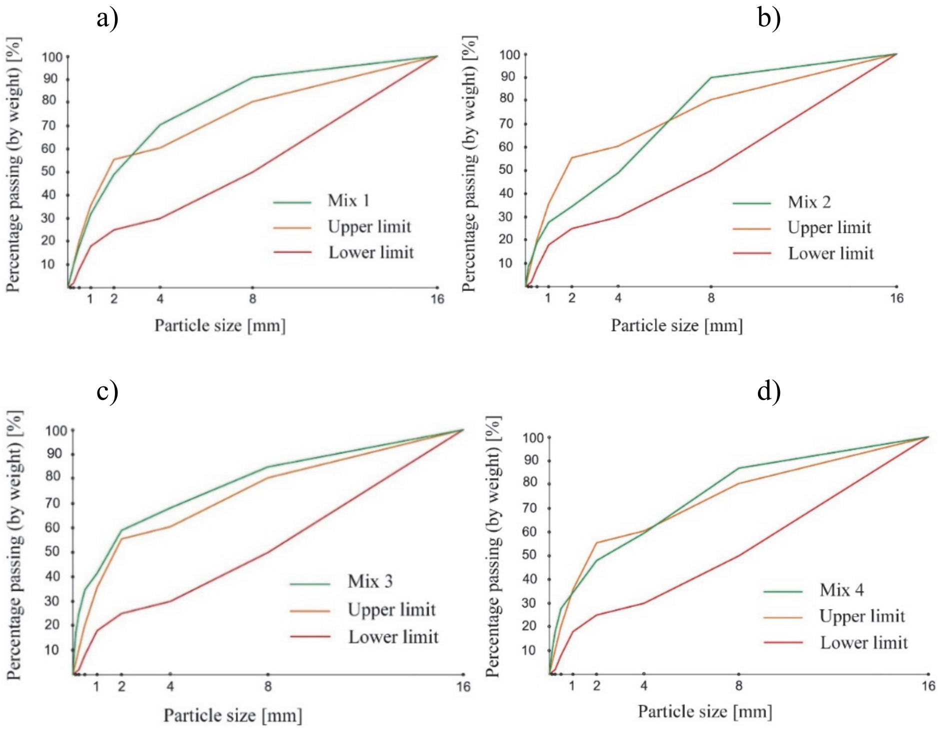

Fig. 4. Particle size distribution curves of customized aggregate compositions used: a) mix 1, b) mix 2, c) mix 3 and d) mix 4

4. Analysis of the test results

LWC-1 and LWC-2 were characterised by the lowest density (see Fig. 5) but also the lowest compressive and splitting tensile strength (see Figs. 6 and 7). LWC-3 was characterised by the highest density, compressive and splitting tensile strength. LWC-4 was characterised by lower density (by 22%), compressive strength (by 39%) and splitting tensile strength (by 21%) than LWC-4.

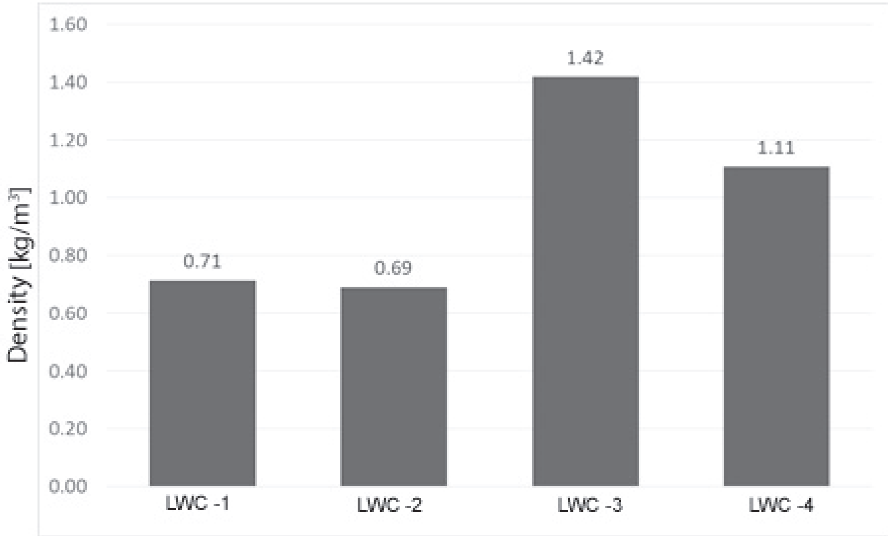

Fig. 5. Density of LWC

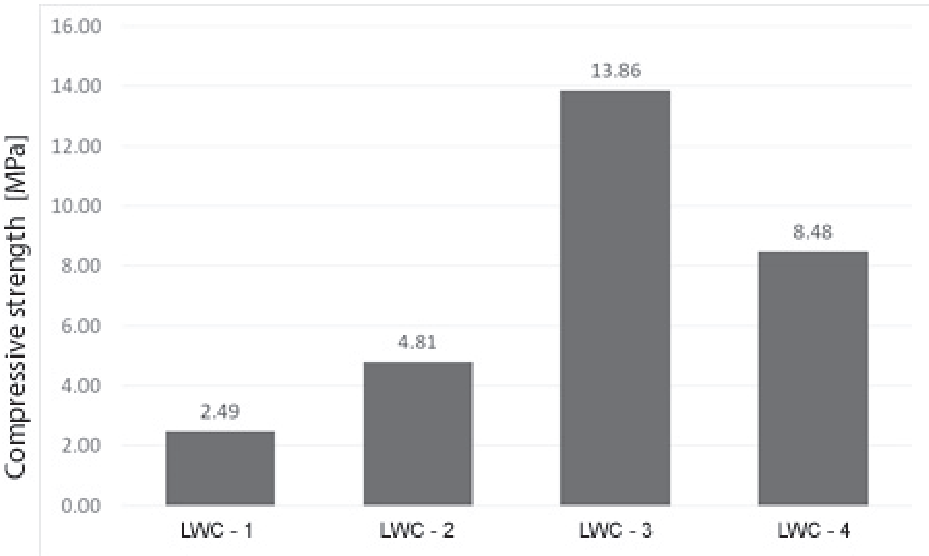

Fig. 6. Compressive strength of LWC

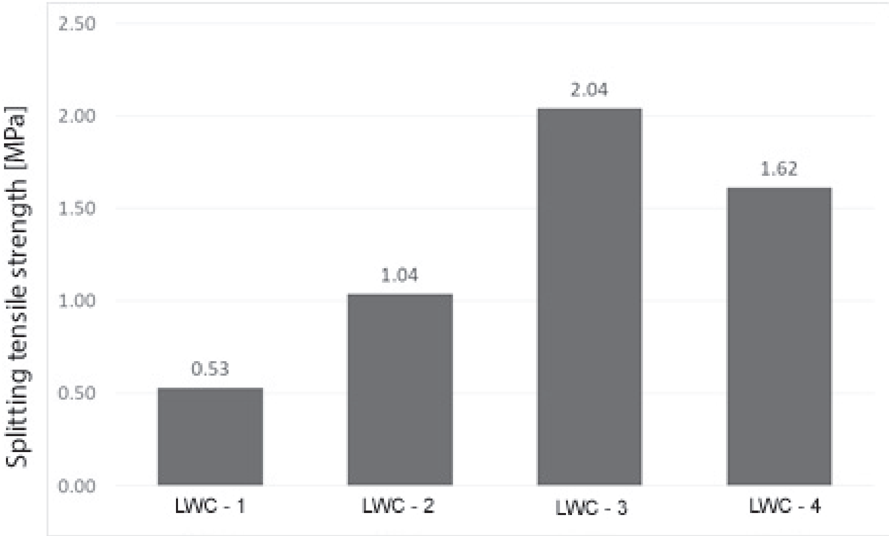

Fig. 7. Splitting tensile strength of LWC

Due to relatively high compressive and splitting tensile strength, low density of hardened concrete (equal 1.11 kg/m^3) LWC-4 was chosen for the second stage of the research programme. During the second stage such properties as dynamic modulus of elasticity, flexural strength, shear strength and abrasion resistance were of interest. The achieved results are presented in Table 6. Abrasion resistance measured in [cm^3/cm^2] was equal to 9.07 so according to EN 13813:2002 standard A12 abrasion resistance class can be assigned to this LWC-4.

Table 6. Selected properties of LWC-4

Property	Value
Dynamic modulus of elasticity [GPa]	6.21
Flexural strength [MPa]	8.48
Shear strength [MPa]	1.35
Abrasion resistance A [cm^3/cm^2]	9.07

5. Summary

The density and compressive strength are the key parameters in case of LWC. Low density is often accompanied by poor strength which can be observed in the test results of LWC-1 and LWC-2. LWC-3 was characterised by relatively high compressive and splitting tensile strength but also high density. LWC-4 was characterised by lower strength than LWC-3 but also over 20% lower density which was the reason for choosing this mix for the second stage of research. Additional tests of multiple properties such as dynamic modulus of elasticity test, flexural strength test, shear strength test and abrasion resistance have proven usefulness in providing experimental determination of LWC optimum mixture design.

The authors would like to thank mister Konrad Szulc for the help during preparation of the specimens and conducting some of the testing procedures.

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Rumsys, D., Spudulis, E., Bacinskas, D., & Kaklauskas, G. (2018). Compressive strength and durability properties of structural lightweight concrete with fine expanded glass and/or clay aggregates. *Materials*. DOI: https://doi.org/10.3390/ma11122434

Abstract

This paper describes the mixture design of lightweight concrete. The authors proposed lightweight concrete based solely on expanded clay aggregate. Commercially available expanded clay granules (used as coarse aggregate) were supplemented with crushed expanded clay granules (which played the role of fine aggregate). The created mixes were differentiated by particle size distribution of lightweight aggregate and the amount of used cement. Properties of both fresh concrete mixes and hardened composites were of interest. The tested properties were as follows: consistency, density, compression strength, splitting tensile strength, dynamic modulus of elasticity, flexural strength, shear strength and abrasion resistance. Experimental results have shown some satisfactory mechanical characteristics of concretes in question.

Keywords:
lightweight aggregate, expanded clay granules, lightweight concrete, properties, research testing

Eksperymentalne określanie optymalnego projektu betonu lekkiego

Streszczenie

Artykuł opisuje projektowanie betonu lekkiego. Autorzy zaproponowali projekt betonu lekkiego wykonanego wyłącznie na bazie kruszywa keramzytowego. Dostępne na rynku kruszywo keramzytowe (użyte jako kruszywo grube) uzupełniono pokruszonym kruszywem tego samego rodzaju (pełniącego rolę kruszywa drobnego). Utworzone mieszanki kruszyw różniły się uziarnieniem kruszyw i zawartością cementu. Zbadano właściwości zarówno świeżej mieszanki betonowej jak i stwardniałego betonu takie jak: konsystencja, gęstość, wytrzymałość na ściskanie, wytrzymałość na rozciąganie przy rozłupywaniu, dynamiczny moduł sprężystości, wytrzymałość na rozciąganie przy zginaniu, wytrzymałość na ścinanie i odporność na ścieranie. Wyniki badań eksperymentalnych wykazały zadowalającą charakterystykę zbadanych właściwości.

Słowa kluczowe:
kruszywo lekkie, keramzyt, beton lekki, właściwości, badania

MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

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Analysis of the Use of Undervolting to Reduce Electricity Consumption and Environmental Impact of Computers

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1. General information

The point of undervolting is to reduce the voltage of the processor or graphics card without reducing their performance. This is possible because factory preset voltages are voltages set for low quality chips that require higher voltage to work properly. This way more manufactured processors can be used. It should be noted that current technology of manufacturing processors, even though they are very modern and are subject to numerous restrictions, do not guarantee that each processor will be the same high-quality sample. In case when the computer is equipped with a good quality processor, the voltage of the processor can be significantly lowered (Gizopoulos et al. 2019).

The analysis of the literature shows that undervolting is used nowadays to optimize the power consumption of complex FPGA (Salami et al. 2018, 2019) or processors (Koutsovasilis 2020). Undervolting not only brings with it the profit resulting from the optimal electrical energy consumption, but also contributes to lowering the temperature and noise of electronic devices and allows to change the frequency of digital circuits. The above-mentioned reasons are also applicable to modern WiFi sensors, which are dedicated to the circuits used in the Internet of Things applications (Kalau et al. 2014, Kalau et al. 2015). Undervolting is also a method of optimizing such unusual devices as crypto mining rigs (Oğuzhan et al. 2020).

Considering the analyzed literature on the subject, the presented work describes the significance of undervolting, presents practical ways of its implementation, and in particular shares the results of experiences that have not been previously presented in the literature in such an approach and scope. The detailed description and the range of experiences in which undervolting was approached as a method of electricity reduction in large computer infrastructure are presented in the following chapters of the paper.

The use of undervolting is very important because it reduces the problem of wasting electricity by electronic devices and the disposal of computer equipment. In the case of processors, excessive voltage affects the amount of heat generated by the processor. The result is high temperature of operation of both the processor and other computer components. This has a negative impact on the life span of components making them degrade faster. This requires frequent replacement of computer parts, the disposal of which is problematic.

The advantage of the undervolting is that it only requires a one-time configuration of the computer workstation by the administrator. This operation does not interfere with the use of other energy saving methods and may work alongside them. Undervolting works particularly well in combination with Intel AMT technology, as this technology allows for remote, real-time monitoring of the status of the computer (Muc et al. 2018, Intel, Tan et al. 2007). It is also worth noting that when the administrator uses the appropriate undervolting software, the configuration that reduces the processor's power consumption is automatically turned on when the computer is started (Hartung et al. 2019). No user involvement is therefore required. This is a very important, because the experience of the authors concerning other energy saving methods (Muc et al. 2018) shows that users are reluctant to follow the recommendations of the administrator or supervisor of computer equipment for the correct and ecological use of the workstations.

Undervolting of the processor consists in changing the voltage offset. This results in a voltage drop for all processor states (e.g. idle, load, heavy load). The voltage reduction results in lower power consumption, TDP (Thermal Design Power) and decreased noise (the cooling system operates more quietly because it dissipates less heat) (Kalau et al. 2014, Kalau et al. 2015). Processor manufacturers provide dedicated software for changing processor’s parameters, which, among other things, allows performing undervolting operations in an easy way. Undervolting is not a dangerous operation – it should not damage the processor (Kalau et al. 2016). If the processor is assigned too low voltage, the component will report the misconfiguration to the BIOS and shut down the computer. The voltage configuration is stored only in the operating system (a profile is created which starts with the operating system). This means that if the voltage is set too low during testing and the changes are not saved (only the test profile is set), then after turning the computer off and on everything will return to normal. However, it is important to thoroughly test the created profile before it is permanently saved and set as the default profile. If by mistake the voltage is set to low and the profile is saved, the operating system will use it every time it starts – this means that if the incorrect profile causes the computer to shut down, the computer will reboot every time the system is started. In that case, the misconfiguration can be repaired by running the system in emergency mode and removing the profile used. When undervolting the processor, it should be loaded with synthetic tests (e.g. with the Small FFT test of the Prime95) (Kalau et al. 2016). An example of a synthetic test is shown in the Figure 1.

Processor undervolting should be done in steps. In the first step, lower the voltage values on the core by 20 mV and see if the machine is stable. Then the voltage should be lowered by another 20 mV (after lowering the voltage by 100mV, it should be lowered step by step by 10 mV) until the machine becomes unstable. After selecting the appropriate value, set the same value for the processor cache. If an error occurs after the processor cache voltage has been lowered, the cache voltage should be slightly increased by e.g. 10 mV or 20 mV and the tests should be repeated. It is also worthwhile to do undervolting of the integrated graphics processor (iGPU), but the reduction is usually much smaller than the core and cache (usually about half of the reduction of core and cache).

Processor manufacturers provide tools to customize processor performance. For Intel processors, Intel XTU (Fig. 2) can be used, while for AMD processors AMD Ryzen Master can be used. There are third party programs, i.e. ThrottleStop (Fig. 3), that allow the change of CPU clock parameters and voltages, but these are not applications designed by CPU manufacturers and the configuration made in them can be unstable or harmful to the chip.

The undervolting operation can also be performed by changing the processor's voltage in the BIOS. Unfortunately, on most motherboards, the firmware is limited and does not offer this option. It should also be noted that if the wrong configuration is used and saved in the BIOS memory, irreparable damage to the computer is possible.

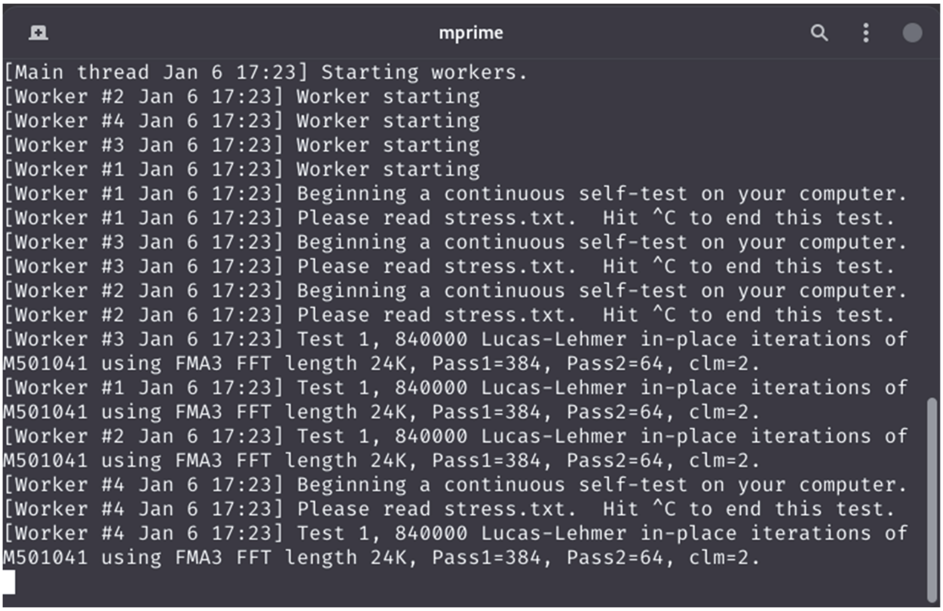

Fig. 1. Synthetic test with Prime95

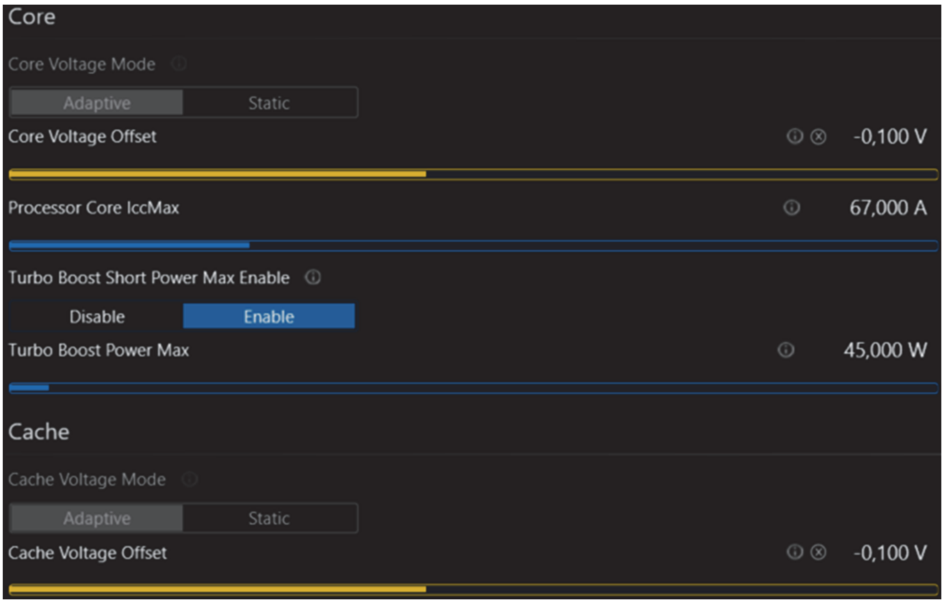

Fig. 2. Intel XTU interface – shows the common software options that are used for undervolting

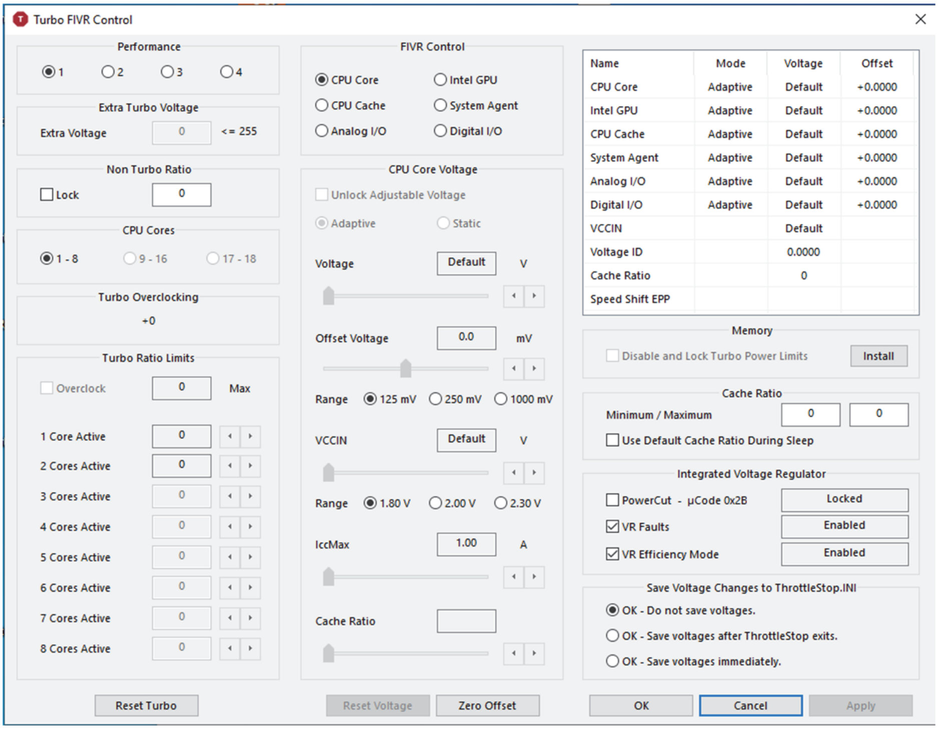

Fig. 3. ThrottleStop interface

2. Testing workstation

To assess the efficiency and applicability of undervolting, computers located in universities laboratories were used. There were two laboratories, each equipped with 20 identical computer workstations in terms of hardware configuration. The laboratories were used by students of a university in Gdańsk. One of the computer laboratories was used for computer graphics classes and the other one for application programming classes. The use of two laboratories allowed to compare results of undervolting for less loaded computers (programming classes) and for heavily loaded computers (computer graphics classes).

In computer laboratories, the standard computer unit is equipped with Intel Core i5-6600 processor cooled by SilentumPC Spartan Pro heatsink with a single fan, Patriot RAM (two units with a total capacity of 8 GB), HDD, SilentumPC Vero M1 power supply.

The maximum power consumption of a single RAM is 3.7 W (average consumption is about 1.0-1.5 W), power consumption of HDD is 6 W. When calculating the theoretical power consumption of a computer workstation, the power consumption of the monitor and peripheral equipment should also be taken into account. In this case, the testing workstation's monitor has an average power consumption of 25 W. The peripherals, i.e. mouse and keyboard, are connected to USB 2.0, so the maximum consumption of each of these peripherals is 0.5 W. The maximum power consumption of a cooling system equipped with three fans is 9 W (the maximum power consumption of a single fan is estimated at 3 W), however, it should be noted that the maximum power consumption occurs only when the fans operate at maximum speed – the average power consumption of the fans can be estimated at 3-4 W.

The Intel Core i5-6600 processor has a 65W TDP (Thermal Design Power) (Intel ARK). It is a 4-year-old unit (premiered in the third quarter of 2015) made in 14 nm lithography, with 4 cores and 4 threads at 3.3 GHz base clock (in 3.9 GHz Turbo mode).

3. Processor undervolting

The assessment of undervolting effectiveness and possibilities was made in to experiments on computer units described above. The first experiment can be described as static and the second as a dynamic. In the static experiment, the possibility of undervolting was evaluated on the basis of the specification of the computer parts in the computer unit. Knowing the specification of a computer unit, it is possible to assess its potential in terms of undervolting and potential energy gain. In the second experiment, the efficiency of undervolting was studied in two university laboratories – one with programming classes and the second with computer graphics classes. This experience consisted of recording the laboratory computers' processor load and measuring the electricity consumed. The experiment was carried out for computers with not undervolted processors and then repeated after performing the undervolt.

In a static experiment, the processor was undervolted. Voltage Offset values were reduced by 20 mV in steps until the value at which the processor stopped working properly was reached. After a 240 mV voltage reduction, processor errors occurred during the synthetic tests. Core Voltage Offset and Cache Voltage Offset were set to -220 mV and Processor Graphics Voltage Offset to -110 mV. After several hours of synthetic tests, this setting was found to be fully stable. The operation was performed with Intel Extreme Tuning Utility (Intel XTU). Figure 4 shows the profile created.

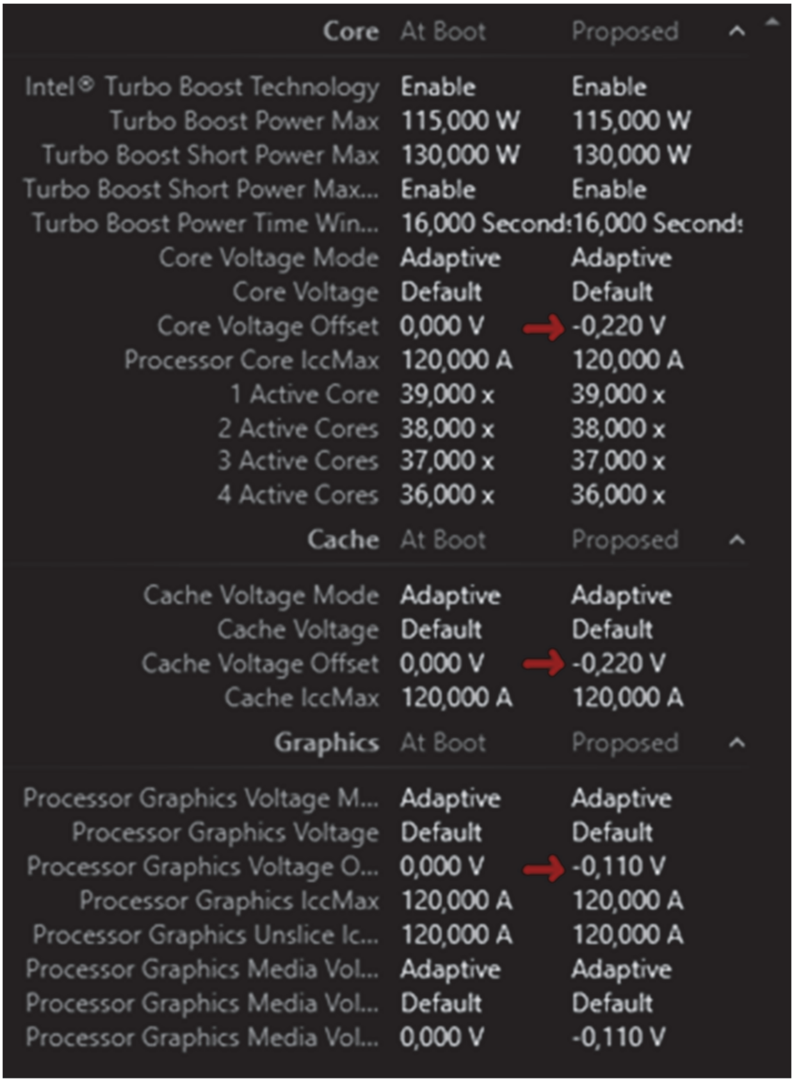

Fig. 4. XTU profile of Intel Core i5-6600 processor, where Proposed shows values of created test profile

The reduction of the voltage on the processor's core and the processor's cache by 220 mV resulted in a significant reduction of the processor power consumption and the amount of heat generated. Figure 5 shows a comparison of power consumption and temperatures.

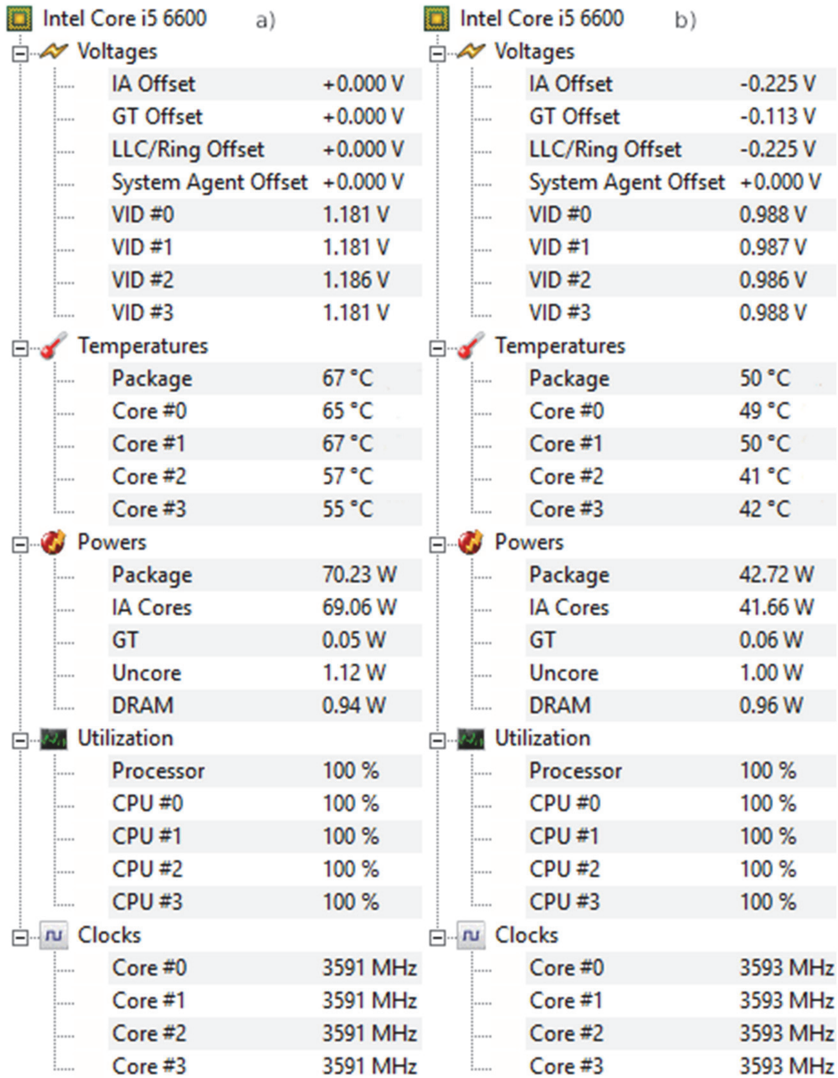

Fig. 5. Comparison of power consumption and temperature of the i5-6600 CPU at default voltage (a) and reduced voltage (b) by 225 mV on the core and cache and 113 mV on the iGPU

As shown in Figure 5 before undervolting, the processor, when loaded with a set of synthetic tests (Prime95, Small FFT test) on all cores, had a power draw close to 70 W (Powers → Package indicator) and maintained a temperature of 67°C (Temperatures → Package indicator) on the cores. The processor has been able to achieve 3600 MHz at all cores – this is the maximum clock speed that this unit can achieve (3.9 GHz Turbo mode is activated when only one core is loaded). This means that during the test, the processor was not restricted by security features (there was no Thermal Throttling, Power Throttling and Current Throttling Limit). After undervolting (IA Offset, GT Offset, LLC/Ring Offset indicator) core and cache voltage was reduced by 220 mV (in fact 225 mV) and iGPU by 110 mV (in fact 113 mV) and with all cores loaded with the same set of tests, the processor kept the clock speed at the same level, but with a power consumption of 43 W and core temperature of 50°C.

This means that after undervolting, the processor is able to perform tasks with the same performance, but at maximum load it draws 27 W less power and generates less heat.

Of course, the difference in power consumption will be different for a different degree of load. For medium load (in CAD programs), the undervolted CPU drew about 16 W less. Figure 6 shows a comparison of power consumption at medium load.

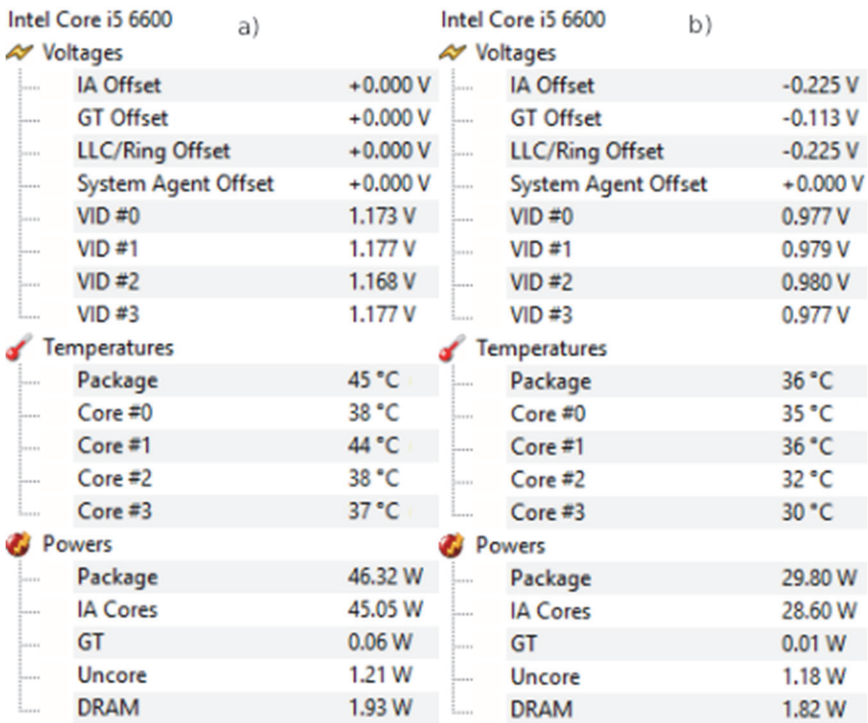

Fig. 6. Comparison of power consumption of i5-6600 CPU on medium load; a) in factory configuration, b) after undervolting

4. Processor undervolting in laptops

Not all computer laboratories are equipped only with desktop computers. Often laptops are used. Laptop processors are built differently than desktop processors. Manufacturers must take into account battery life and low efficiency cooling system (related to compactness of construction). For this reason, laptop processors are built as energy-efficient units. Unfortunately, the energy-efficient design of the processor is usually associated with a lower core clock speed and fewer threads. Undervolting operations on these processors are usually significantly more difficult, due to the already low base voltage. Undervolting of such processors is possible, but it is marginal and usually does not produce tangible results. However, there are series (marked as HQ) of processors for laptops, which are characterized by high performance – in this case the energy efficiency has been put aside. These notebooks are mainly designed for calculations, graphic processing, 3D modeling and simulation studies. These types of laptops are used in the computer laboratories of universities. To show the effectiveness of undervolting processor of such computer devices, the Intel i7-7700HQ processor with TDP of 45 W (Intel ARK). was also undervolted.

For undervolting purposes, Core Voltage Offset has been changed to -0.100 V, Cache Voltage Offset to -0.100 V and Processor Graphics Voltage Offset to -0.055 V. Figure 7 shows the profile created.

As can be seen in Figure 8 before undervolting, the processor, with power consumption close to 45 W and with all cores loaded with a set of synthetic tests (Prime95, Small FFT test), achieved a clock speed of 2700 MHz. After undervolting (IA Offset, GT Offset, LLC/Ring Offset indicator) core and cache voltage was reduced by 100 mV (in fact 102 mV) and iGPU by 55 mV (in fact 56 mV), with all cores loaded with the same set of tests, the processor kept the clock speed of 3000 MHz with the same power consumption.

This is due to the compactness of laptops. Unfortunately, laptop cooling systems, due to the small size of the fans and heat sink, do not conduct heat away from the processor efficiently enough. For this reason, there is the mechanism of Thermal Throttling – as a result of too high processor temperature, its clock speed are reduced (Liu et al. 2018, Zhang et al. 2019). Undervolting reduces the heat emitted by the processor, so the processor is able to maintain a higher clocks speed before the Thermal Throttling mechanism is activated.

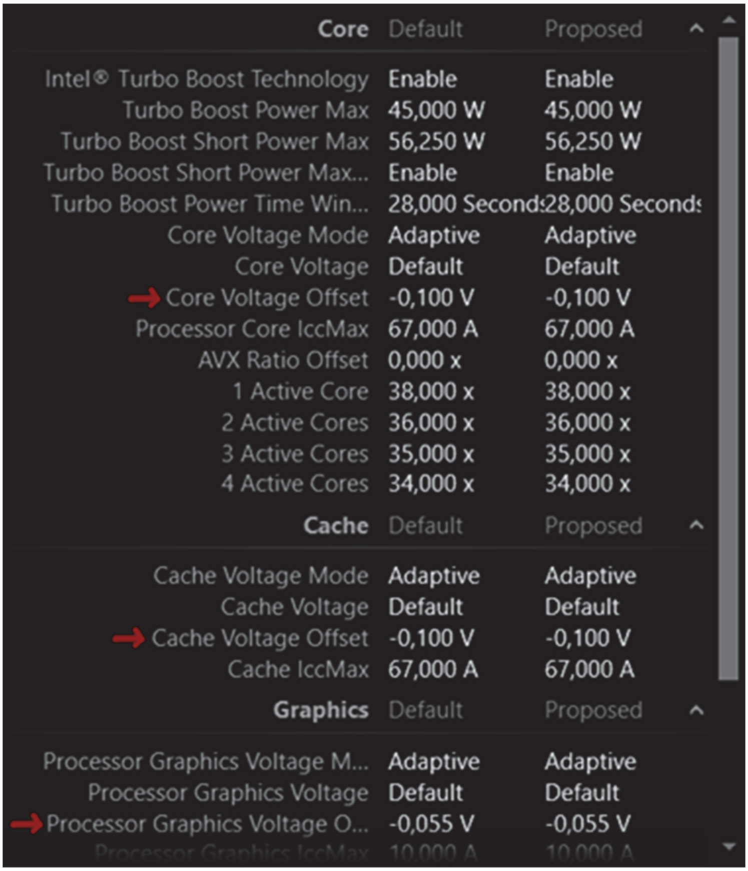

Fig. 7. XTU profile of Intel Core i7-7700HQ processor, when Default and Proposed values are the same, the profile is saved and will be used after system reboot

Figure 8 shows a comparison of the power consumption, clock speed and processor load during synthetic tests before and after undervolting.

This means that after undervolting, the processor runs at a higher clocks speed and is able to perform tasks faster. If the processor was running on the same clocks speed as before undervolting, it would draw less power. Unfortunately, in reality, as a result of undervolting, the laptop's maximum processor temperature reached will not be lowered. Undervolting will enable the processor to work more efficiently, but despite the reduction of generated heat, the cooling system will still not be able to dissipate it effectively enough. However, the lifetime of the processor will be significantly improved as the processor will perform calculations faster and run at high temperatures for shorter periods of time.

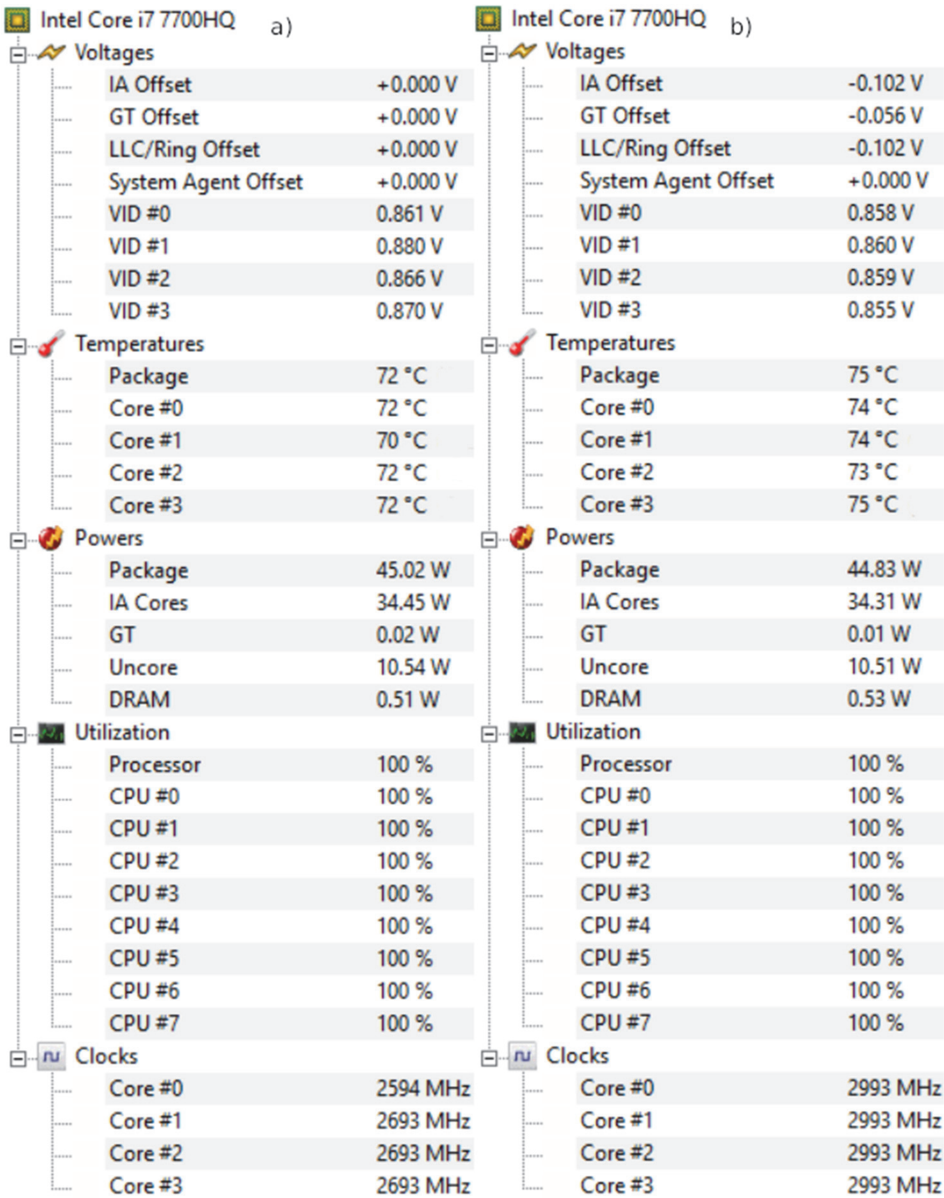

Fig. 8. Comparison of i7-7700HQ CPU performance at default voltage (a) and reduced voltage (b) by 102 mV on core and cache and 56 mV on iGPU

5. Environmental research

For the purpose of verifying the influence of undervolting on the power consumed by the computers in the computer laboratories, the power consumption of the computers in the laboratory without undervolting and with undervolting was measured.

Two computer laboratories were selected to carry out the experiments and their computers' power consumption was measured. In the first laboratory programming and computational techniques (conducted in the Matlab environment) classes took place. In the second laboratory there were graphic processing and CAD modeling classes. Both laboratories were equipped with a power meter covering only stationary units of computer workstations, excluding monitors and projectors located in the rooms.

In order to facilitate the measurement of power consumption, unnecessary components, i.e. optical drives, additional PCI-E expansion cards, etc., have been disconnected from computers. Peripheral devices, i.e. keyboard, mouse and USB flash drive, are connected to active USB hubs with separate power supply. To avoid measurement error, the theoretical power consumption of a single computer unit was calculated before testing, based on the manufacturer's power consumption data of each component. Calculations were made in different states (idle, load, heavy load) of the CPU without and with undervolt. The values thus established were a model to which the results obtained at later stages of research were compared.

The next step was to carry out measurements for computers with a processor factory configuration and for computers with a undervolted CPU. The research was conducted over a period of two months (October and November 2019). The tests included 160 hours of computers operation – 80 hours of computers with CPUs on factory configuration operation and 80 hours of computers with undervolted CPUs. The results of power consumption were obtained from two computer laboratories, which differ in the tasks performed by the students and the intensity of processor use during these tasks. The research has shown that the computers in the second laboratory for graphics and CAD modeling classes consume more power.

With the prepared model, for 80 hours of measurement from each laboratory, only the measurement time was taken into account, in which the computers performed intensive work and the number of used computers in the rooms was the same. The measurement time during which the computers were powered on but not used or the processor was in a state of inactivity or low activity was discarded. In this way, the measurements were limited to 50 hours of intensive processor usage of computers in each laboratory.

Figure 9 shows a diagram of the power consumption of computers from the first laboratory after CPU undervolting compared to computers' power consumption from the first laboratory before CPU undervolting.

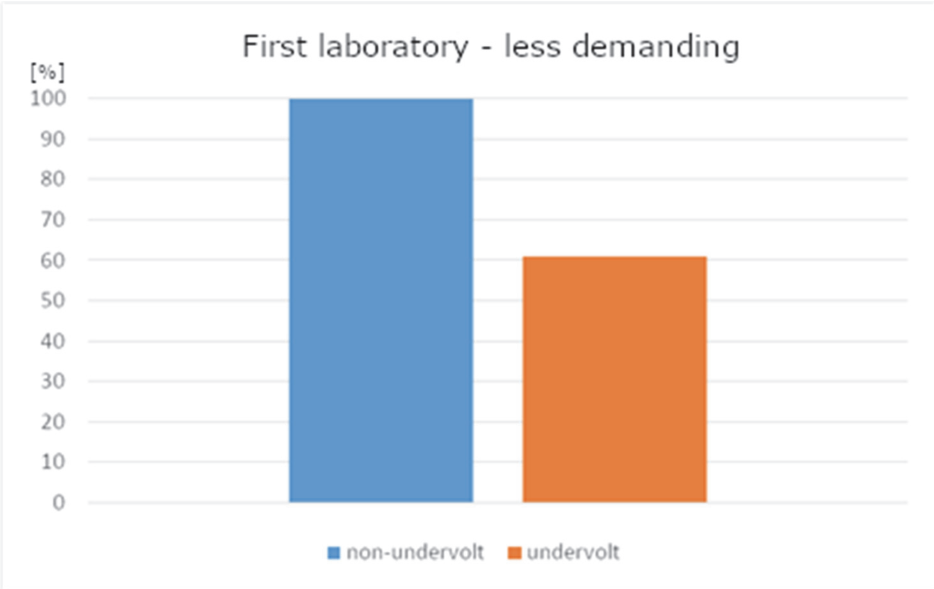

Fig. 9. Power consumption of computers after undervolting compared to computers before undervolting – first laboratory (programming and computational techniques)

Figure 10 shows the power consumption of computers from the second laboratory after CPU undervolting compared to computers' power consumption from the second laboratory before CPU undervolting.

Analyzing the results shown in Figures 9 and 10, it was noted that the energy gain of a computer unit with undervolted CPU is greater when computers perform tasks intensively and the processor is continuously loaded – in the second laboratory, there were graphics and CAD modelling classes that required continuous rendering, which intensely and continuously loaded the processor. In the case of tasks with lower processor intensity, the profit is lower – in the first laboratory, there were programming and computational technique classes, which require calculations only when compiling source code or running scripts.

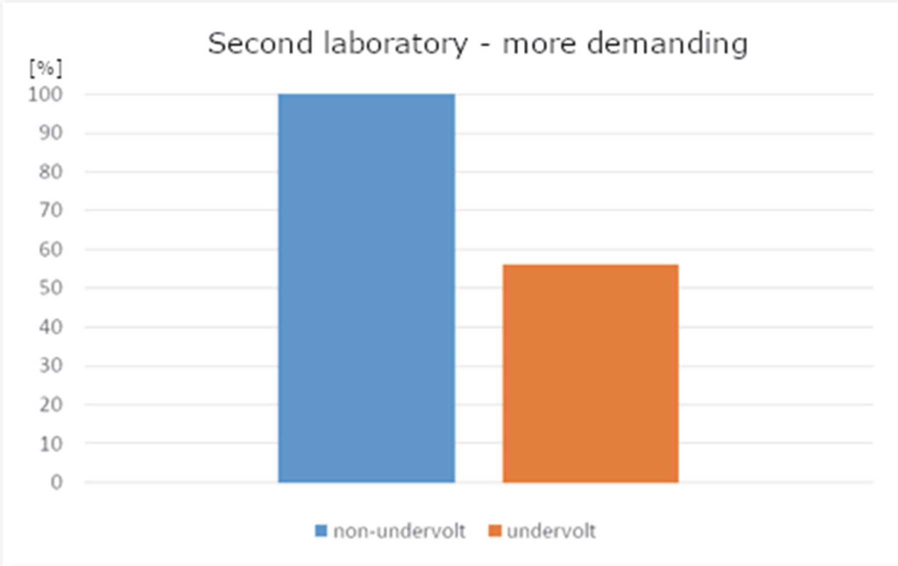

Fig. 10. Power consumption of computers after undervolting compared to computers before undervolting – second laboratory (graphic processing and CAD modeling)

6. Conclusion

Undervolting allows reducing CPU voltage. There are many reasons why this is desirable. The voltage reduction leads to a reduction in power consumption. In the case of a processor, the energy drawn is given away in the form of heat – this means that a reduction in voltage reduces the generated heat. Lowering the temperature in which the computer operates leads to benefits in relation to the service life of the component being used – the processor running at lower temperatures will degrade much slower. Lowering the temperature also relieves the cooling system. In the case of passive cooling there will be no difference in power consumption. However, with active cooling, the power consumption will be reduced. Each active cooling system is equipped with fans whose task is to take the heat from passive elements of the cooling system and transfer it outside the computer unit. With undervolting, the processor emits much less heat, which means that the cooling system will be able to dissipate the heat at reduced fan speed. The fans draw less power at lower rotating speed.

Reducing the heat generated by the processor also affects other computer components. In most computers, air circulation is common to all elements. This means that the air heated by the processor spreads in the central unit increasing the operating temperature of the other components, thus shortening their service life.

For laptops with insufficient cooling capacity, CPU performance is limited due to temperature limits. When the temperature limit is reached, the processor's clock speed is reduced to the level where the processor emits as much heat as the cooling system is able to discharge. Undervolting reduces the amount of heat generated by the processor, allowing the processor to run at higher clocks speeds before the temperature limits are reached. This means that by performing undervolting operations on the processor in the laptop, the performance and speed of completing the tasks is increased, which results in shortening the processor's operation at high temperatures time.

The use of undervolting is particularly important in school and university computer laboratories and in enterprises, because limiting the heat generated by multiple computer workstations in the same facility has a real impact on room temperature. The noise generated by fans of cooling systems installed in computers is also reduced. Reducing room temperature and noise can have a positive impact on the comfort of employees and students, and will save on air conditioning costs. With a large number of computers in the room, the reduction in power consumption is significant and brings about measurable savings. Increasing the life of computer components reduces the cost of repair or possibility of hardware replacement.

Undervolting should also be used in houses and flats. The benefit of reducing the electricity consumption of a single computer station may not be convincing enough, but it is worth noting that more than one computer is very often used in a single house or flat. At the scale of a block of flats or a housing estate, the profit from the electricity saved would be significant. However, for the household members, it may be more important to reduce the heat generated than the profit from reduced power consumption. Especially in summer, in a small room with a few hours of intensive use of the processor (in a home environment it can be computer gaming) the heat generated can cause discomfort.

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Abstract

This paper presents a method of lowering the processor's voltage and temperature in which the computer operates by performing an operation called undervolting. By using undervolting it is possible to reduce electricity consumption and the amount of heat generated by computer workstations by up to 30%. This problem is particularly relevant for institutions that use a large number of computers. The more the computers are subjected to the higher computational load, the more effective the mechanism of undervolting is. Undervolting the processor does not reduce its performance, but lowers its operating temperature, has a positive impact on its life span and power consumption. Maintaining a low temperature of operation for computer hardware is essential to reduce operating and repair costs. The paper also presents the results of environmental research aimed at assessing the validity and effectiveness of undervolting.

Keywords:
undervolting, energy saving, electric energy, power consumption, generated heat, processor

Analiza wykorzystania undervoltingu do redukcji zużycia energii elektrycznej w urządzeniach komputerowych i oddziaływania na środowisko

Streszczenie

W pracy przedstawiono metodę obniżania napięcia procesora i temperatury pracy komputera poprzez wykonanie operacji zwanej undervoltingiem. Przez zastosowanie undervoltingu można obniżyć nawet o 30% zużycie energii elektrycznej i ilość wydzielanego ciepła przez stanowiska komputerowe. Problem ten jest szczególnie istotny w przypadku instytucji, które korzystają z dużej liczby komputerów. Skuteczność mechanizmu jest tym większa im komputery poddane undervoltingowi są bardziej obciążone obliczeniowo. Wykorzystywanie undervoltingu w konfiguracji procesora nie zmniejsza jego wydajności, a obniża jego temperaturę pracy, wpływa pozytywnie na jego żywotność i zużycie energii elektrycznej. Utrzymanie dobrej kultury pracy sprzętu komputerowego jest kluczowe, by obniżyć koszty eksploatacji oraz napraw. W pracy przedstawiono również wyniki badań środowiskowych, których celem była ocena zasadność i efektywności stosowania undervoltingu.

Słowa kluczowe:
undervolting, oszczędzanie energii, energia elektryczna, pobór prądu, generowane ciepło, procesor

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Greenhouse Gas Emissions by Agriculture in EU Countries

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1. Introduction

Air pollution means the release of solid, liquid, gaseous, foreign substances into the atmosphere or natural substances present in excessive amounts that may adversely affect human health, climate, living nature, soil and water or cause other environmental damage. Air pollution comes from both anthropogenic (artificial) and natural sources. Emission of pollutants determines the mass of a substance introduced directly into the environment both from natural sources (e.g. as a result of volcanic eruptions, erosion of the earth's surface, etc.) and from anthropogenic sources (fuel combustion processes, industry, agriculture) (Elsom 1987, 1992, Farmer 2002, Bartra et al. 2007, Ionel et al. 2008, Popescu & Ionel 2010, Rokicki 2016, 2017). The amount of substances introduced into the environment and the variability of emissions over time for a given emitter, as well as the spatial distribution of emitters significantly affect the quality of air in a given area (Bereitschaft & Debbage 2013, Rodríguez et al. 2016, Lu et al. 2018).

Pollution from agriculture is a special type of surface emission. They concern emissions from machines, crops (from plants and mineral and artificial fertilizers used in production), breeding, farms, meadows (Novotny 1999, 2006, Buckley & Carney 2013). The main pollutants emitted in agricultural areas, in particular from production farms, include NH_3, N_2O, as well as odors (Bauer et al. 2016, Giannadaki et al. 2018).

2. Literature overview

The emission of pollutants in the European Union in the years 2000-2017 decreased mainly regarding the emission of SO_x, PM, O_3 and NO_2 in the air. The largest reduction was achieved for SO_x (by 77%), and the smallest for NH_3 (9%). While there was seen a reduction for classical air pollutants there is no reduction trend for greenhous gases (EEA 2019a). Activity in the agricultural sector is expressed in gross value added (GVA) in euro. Gross value added is a measure of the value of goods and services produced by a given sector (Eurostat 2019). In 2017, EU agriculture accounted for 92% of emissions NH_3, 54% CH_4, 15% of PM_{10} and 8% NO_x particles. Agriculture was the sector in which the reduction of pollutant emissions was the lowest in 2000-2017 (a decrease by less than 10%) (EEA 2019b, 2019c).

In the years 2000-2017, emissions of air pollutants showed a significant separation from economic activity measured by the value of GDP, which was desirable due to environmental protection and increased productivity. Every euro of GDP generated was associated with ever lower emissions of air pollutants in subsequent years (Brand 2016, Crippa et al. 2016, Guevara 2016, Rokicki et al. 2018, EEA 2019a, Koszela et al., 2019). EU countries were diverse in terms of GDP volume, specialization in production (including agriculture), socio-economic characteristics and innovation (Chapman & Meliciani 2017).

Greenhouse gas emissions from agriculture increased more slowly than emissions from other human activities. The increase took place mainly in developing countries due to the increase in total agricultural production there. About 60% of all CO_2-equivalent greenhouse gas emissions (metric GWP 100) from agriculture were related to animal husbandry. Their biggest source was enteric fermentation, as a result of which methane was emitted. Emissions from the use of fertilizers were also significant. It was the fastest growing source of emissions in agriculture. In addition, plant cultivation (including for animal feed) was also responsible for the emission. There was a scattering of nitrogen compounds not collected by plants and decaying crop residues from agriculture. Nitrous oxide mainly comes from soils, but also from plant and animal production. Emissions from agriculture also concerned the use of energy to power agricultural machinery and equipment (Duxbury 1994, Burney et al. 2010, Leip et al. 2014, 2015).

As a rule, an increase in unit yield in agriculture leads to an increase in the share of nitrogen in feed or in fertilizing crops. There are also differences depending on the animal species (Smith et al. 2013, 2014). The conducted research indicates differences in air pollution resulting from the growth of agriculture in individual EU countries. The greatest impact of agricultural growth on concentration of $PM_{2,5}$ occurred in Bulgaria, Romania and Italy (Giannakis et al. 2019).

Simulations show that a large reduction in $PM_{2,5}$ levels can be achieved by reducing emissions from agriculture, in particular ammonia (NH_3) from the use of fertilizers and animal husbandry. In Europe and North America, this impact is not as great as in Asia (Pozzer et al. 2017). The emission of ammonia to the atmosphere can be reduced by using, among others low-emission techniques of distributing and storing fertilizers as well as keeping and feeding animals. In animal production, you can use a breed that emits less methane in the digestion process, shorten the length of beef cattle, increase the proportion of cow grazing, or use more organic feeding. In plant production, it is possible to select appropriate varieties of plant species that have greater potential for binding carbon and nitrogen, increase the share of plants having a more efficient photosynthesis process and growing faster, which will reduce carbon dioxide emissions (Cole et al. 1997, Steinfeld & Gerber 2010, Thornton & Herrero 2010, Havlík et al. 2011, 2014, Herrero et al. 2013, Bryngelsson et al. 2016, Lamb et al. 2016).

3. Aim, materials and methods

The main purpose of the paper is to show the relationship of greenhouse gas emissions by agriculture with economic development and agricultural production parameters in the European Union. The specific objectives are: to present the diversity in greenhouse gas emissions in countries, to show the dynamics of changes in this area, to determine the regularity between the level of economic development, resources and the volume of agricultural production, and greenhouse gas emissions in EU countries. The paper presents a hypothesis according to which in the EU countries in 2004-2017, greenhouse gas emissions resulted unambiguously from the volume of agricultural production carried out in the country. In work was using EU-28 CO_2-equivalent in tons using GWP 100. The volume of agricultural production can be measured in various ways. Several measures were adopted in the study, i.e. value of agricultural production, value of animal production, area of agricultural crops, including the main crops, and the population of main animal species. Gross value added of agricultural production is the difference between global agricultural production and intermediate consumption. Intermediate consumption includes the value of agricultural products used for production purposes, coming from own production and from purchase. All EU Member States were selected for research as of December 31, 2017 (28 countries). The research period concerned the years 2004-2017. The sources of materials were EUROSTAT data, literature on the subject. The following methods were used to analyze and present materials.

The Gini coefficient is a measure of unevenness (concentration) of distribution of a random variable. When the observations y_i are sorted in ascending order, the coefficient can be represented by the formula (Dixon et al. 1987):

$$G(y)=\frac{\sum_{i=1}^{n}(2i-n-1)*y_i}{n^2*\overline{y}} \tag{1}$$

where:
n – number of observations,
y_i – value of the "i-th" observation,
$\overline{y}$ – the average value of all observations, i.e. $\overline{y}=\frac{1}{n}\sum_{i=1}^{n}y_i$

The Lorenz curve determines the degree of concentration of a one-dimensional random variable distribution (Dagum 1980). With sorted observations y_i, which are non-negative values $0\le y_1\le y_2\le ...\le y_n$, $\sum_{i=1}^{n}y_i>0$, the Lorenz curve is a polyline which apexes (x_h,z_h), for h = 0,1,…, n, have the following coordinates:

$$x_0=z_0=0, \qquad x_h=\frac{h}{n}, \qquad z_h=\frac{\sum_{i=1}^{h}y_i}{\sum_{i=1}^{n}y_i} \tag{2}$$

The Gini coefficient determines the area between the Lorenz curve and the diagonal of a unit square multiplied by 2.

In the case of a nuclear density estimator, the nucleus is such a function K : R -> [0,∞] that (Kulczycki 2005):

1) $\int_{-\infty}^{\infty}K(x)dx=1$,
2) K(0) >= K(X) for each R,
3) K – symmetrical to zero.

A nuclear estimator is a function $\hat{f}_n(x)=\frac{1}{nh}\sum_{i=1}^{n}K(\frac{X-X_i}{h})$, (3) where h is a constant called a bandwidth for h > 0.

The Doornik-Hansen test was used to determine compliance with the normal distribution (1994):

$$DH = z_1^2 + z_2^2 \tag{4}$$

where:
z_1 – transformed skewness,
z_2 – transformed oddity.

Pearson's linear correlation coefficient is a measure of the strength of a straight line relationship between two measurable features. It is expressed by means of the following formula (Jajuga & Walesiak 2004):

$$r_{XY} = \frac{C(X,Y)}{\sqrt{S_X{}^2 \cdot S_Y{}^2}} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{n}(y_i - \bar{y})^2}} = \frac{C(X,Y)}{S_X \cdot S_Y} \tag{5}$$

where:
C(X,Y) – covariance between the X and Y features,
S_x^2 – X feature variance,
S_Y^2 – Y feature variance,
S_x – X feature's standard deviation,
S_Y – Y feature's standard deviation.

The linear correlation coefficient can be considered as normalized covariance. Correlation always takes values in the range (-1, 1).

4. Research results

Greenhouse gas emissions from agriculture can be shown for all gases. Then, the gas emissions are converted into CO_2-equivalent in tons using GWP 100. The greenhouse gas emissions from agriculture calculated in this way contain the following types of pollution: CO_2, N_2O, CH_4, HFC, PFC, SF_6, NF_3. The largest emitters of greenhouse gases from agriculture included France, Germany, Great Britain and Spain. Poland and Italy followed. When analyzing individual types of greenhouse gases from agriculture, only the order of the countries in the top six changed slightly. Table 1 presents the dynamics of changes in greenhouse gas emissions from agriculture in EU countries in 2004-2017. The results are ordered in descending order of the dynamics of changes in total greenhouse gas emissions. In addition, dynamics indicators for basic types of gases emitted by agriculture, i.e. carbon dioxide, methane and nitrous oxide, are also presented.

The largest increase in greenhouse gas emissions from agriculture occurred in developing countries, including Latvia, Bulgaria, Estonia, Hungary and Poland. In turn, the largest decreases in emissions were recorded in southern European countries. In developed countries, there were slight declines or increases in emissions. When analyzing only selected gases, it turned out that there was very large variation. For example, in Latvia, carbon dioxide emissions from agriculture increased by 13 times in 2004-2017, in Luxembourg they almost tripled. The largest decreases were recorded in Cyprus (by 55%) and in the Netherlands (by 40%). In the case of methane emissions, the changes were smaller. This gas is mainly emitted by ruminant animals, i.e. its emission should be quite well correlated with animal population. Usually changes in the population do not occur very quickly and rapidly. In the case of nitrous oxide, the rapidity of changes in emissions of this gas as a result of agricultural activities was not large. This may indicate stabilization of plant production and the level of plant fertilization. Given the EU as a whole, greenhouse gas emissions from agriculture have not fallen much. The exception was carbon dioxide, which emissions increased slightly.

Table 1. Dynamics indicators of greenhouse emissions from agriculture in the EU in 2004-2017 (2004 = 100) (EUROSTAT)

Countries	Dynamics indicators of greenhouse emissions from agriculture in 2004-2017			
	total greenhouse gases	carbon dioxide	methane	nitrous oxide
Latvia	120.19	1395.06	117.85	119.40
Bulgaria	119.43	176.36	81.02	144.32
Estonia	117.82	144.22	108.64	126.13
Hungary	110.34	140.05	102.19	115.27
Luxembourg	108.36	282.06	114.12	96.34
Poland	108.04	68.68	107.96	111.72
Lithuania	105.26	110.18	88.33	121.14
Czechia	104.56	192.97	95.55	109.88
Ireland	103.09	135.44	105.09	97.85
Austria	102.84	112.23	101.68	104.64
Germany	102.70	117.42	100.10	104.42
Netherlands	102.01	59.34	110.65	88.78
Sweden	101.46	103.50	94.65	108.20
Portugal	101.15	212.88	103.70	95.24
Slovakia	100.36	211.62	84.60	113.66
Finland	100.01	71.65	100.66	101.62
Slovenia	99.75	78.13	102.02	95.86

Table 1. cont.

Countries	Dynamics indicators of greenhouse emissions from agriculture in 2004-2017			
	total greenhouse gases	carbon dioxide	methane	nitrous oxide
France	97.21	106.30	97.33	96.62
Denmark	96.68	137.21	94.97	97.32
Belgium	96.22	107.32	98.92	92.21
Italy	94.83	74.36	102.38	84.28
United Kingdom	94.13	79.01	94.66	94.78
Romania	92.15	91.56	89.42	98.09
Spain	91.99	116.12	88.00	98.90
Malta	88.34	156.00	89.51	90.91
Greece	85.69	93.97	89.61	80.95
Cyprus	84.79	44.21	89.49	77.78
Croatia	84.25	106.83	83.86	83.64
EU-28	98.71	101.03	97.66	99.98

The distribution of greenhouse gas emissions from agriculture was also examined and was found to be uneven. To determine the degree of concentration of greenhouse gas emissions from agriculture in European Union countries, the Gini coefficient was used. The data refers to the beginning of the study period, i.e. 2004 and the final year, 2017, and the number of observations was 28. The results were presented for four types of emissions, i.e. total, carbon dioxide, methane and nitrous oxide. The Gini coefficient for total greenhouse gas emissions from agriculture in 2004 calculated from the sample was 0.59, while the estimated coefficient for the population was 0.61. This means a large concentration of these gases in several EU countries. If the study was repeated for 2017, the results were slightly lower (coefficient from the sample = 0.58, and estimated for the population = 0.61). Therefore, there were no significant changes in the distribution of this type of greenhouse gas emissions. In addition, greenhouse gas emissions from agriculture in 2017 are presented on the Lorenz concentration curve (Fig. 1).

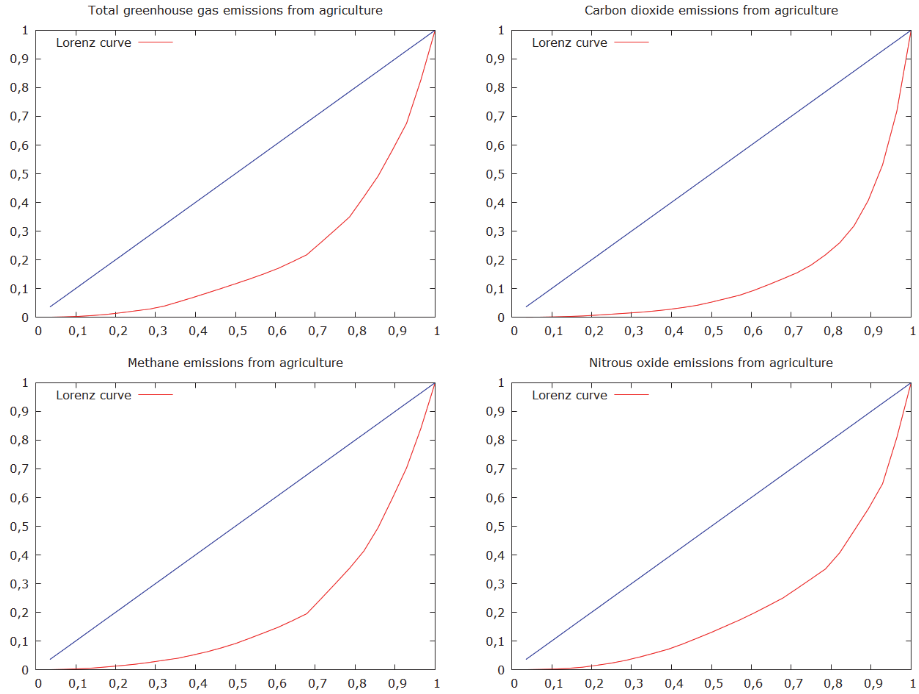

Fig. 1. Lorenz curve for greenhouse gas emissions from agriculture in EU countries in 2017

A similar approach was taken for individual greenhouse gases. For CO_2, the highest emission concentration was achieved, because in 2004 the coefficient from the sample was 0.73, and the estimated 0.75. In 2017 it was 0.71 and 0.74 respectively. The methane emission from agriculture in 2004 was strongly concentrated in several EU countries (coefficient from the sample 0.60 and estimated 0.62), similarly to nitrous oxide (coefficient from the sample 0.58 and estimated 0.60). In both cases, identical Gini coefficients were achieved in 2017. The presented results show that greenhouse gas emissions from agriculture were concentrated in several EU countries. The first four countries were the largest in terms of agriculture, i.e. France, Germany, Great Britain and Spain. In addition, in 2004-2017 the concentration factor was maintained, which means a great stabilization of the structure.

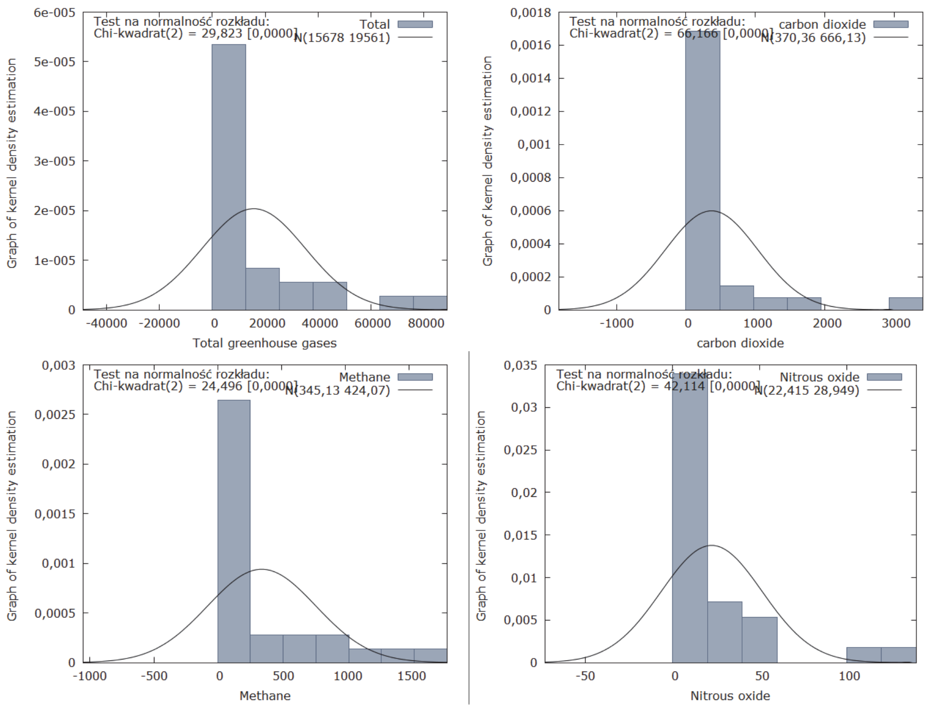

Fig. 2. Graph of kernel density estimation for greenhouse gas emissions from agriculture in EU countries in 2017

The smallest countries were of little importance in the structure of greenhouse gas emissions from agriculture. This is also confirmed by the density plots (Fig. 2). For all greenhouse gas emissions from agriculture in CO_2 equivalent for 19 countries, which accounted for 68% of all countries, emissions were less than 12,691 thousand tons of CO_2 in 2017 (in total, only 120 million tons were emitted in this group of countries, which accounted for only 27% of greenhouse gas emissions from agriculture in the EU). Greenhouse gas emissions from agriculture were not in line with the normal distribution. There were very similar relationships for methane emissions. In 19 countries with the lowest emissions, the emission of 25% of methane produced by agriculture in the EU was concentrated. For nitric oxide emissions, 19 countries in the lowest emission range achieved 30% of total EU gas emissions from agriculture. In the case of only CO_2 emissions, as many as 23 countries (82% of countries) were in one group, in which the emission was not higher than 487,000 tons in 2017. Total emissions from this group accounted for 5.6 million tons, or 54% of emissions throughout the EU.

Table 2. Pearson's linear correlation coefficients between greenhouse gas emissions from agriculture and selected economy and agriculture parameters

Parameters	Pearson's linear correlation coefficients for types of greenhouse gases			
	total greenhouse gases	carbon dioxide	methane	nitrous oxide
Correlation coefficients between the volume of greenhouse gas emissions from agriculture and				
GDP value	0.905	0.899	0.908	0.867
value of agricultural production	0.937	0.780	0.939	0.912
value of animal production	0.967	0.870	0.964	0.942
total UAA (ha)	0.857	0.660	0.873	0.820
total arable land (ha)	0.872	0.709	0.855	0.873
total area of permanent grassland (ha)	0.823	0.638	0.873	0.744
total area of permanent crops (ha)	0.386	0.130	0.452	0.309
cattle population	0.974	0.892	0.960	0.962
sheep and goat population	0.523	0.342	0.614	0.404
pig population	0.775	0.686	0.775	0.752
consumption of inorganic nitrogen fertilizers (mineral)	0.973	0.917	0.936	0.988
consumption of inorganic phosphorus fertilizers (mineral)	0.819	0.641	0.824	0.795
manure production from farm animals (in tonnes of nitrogen)	0.987	0.870	0.989	0.958
manure production from farm animals (in tonnes of phosphorus)	0.988	0.883	0.985	0.963

A p-value <0.01 was achieved for all correlation coefficients

In order to determine the relationship between the volume of greenhouse gas emissions from agriculture in the European Union and the agricultural and economic parameters (in total there were 14 such parameters) that could be associated with it, Pearson's linear correlation coefficients were calculated (Table 2). P = 0.01 was used as the limit of significance. Correlation coefficients were calculated for EU countries in the years 2004-2017. The study attempted to check the correlation that does not indicate that a given factor affects another, but that there is a strong or weak relationship between them.

All the results obtained turned out to be significant. Very strong positive relationships of greenhouse gas emissions from agriculture with the value of GDP and most agricultural parameters were found. This demonstrates the very high interdependence of the economic and agricultural situation with the amount of greenhouse gas emissions generated in agriculture. In general, the relationships were weaker in the case of CO_2 emissions, especially in relation to the total area of permanent crops, sheep population. These two parameters were the least correlated with other types of greenhouse gas emissions from agriculture. This may be due to the small share of such crops in the total agricultural area and suggests that the changes in production and fertilization level may outweigh the changes in land use for arable cropping. The share of sheep and goats in the animal population was also small. Particularly high positive relationships were achieved in the relation of greenhouse gas emissions from agriculture (various types) with the value of animal production, cattle population, consumption of inorganic (mineral) nitrogenous fertilizers, manure production from livestock in tons of nitrogen, as well as in tons of phosphorus. Such results show a large association of greenhouse gas emissions from agriculture, especially with animal production.

5. Conclusions

Nowadays, the reduction of greenhouse gas emissions is an important issue. Agriculture is one of the branches of the economy that contributes to high emissions. Therefore, it is important to determine the relationships at the macroeconomic level. The research allows the following conclusions to be drawn.

1 Greenhouse gas emissions from agriculture slightly decreased across the EU in 2004-2017. The changes, however, varied. As a rule, greenhouse gas emissions from agriculture increased in developing countries, while they remained at a similar level in developed countries. CO_2 emissions increased in the EU-28, but changes in individual countries varied widely. For other emission parameters (methane, nitrous oxide) the changes were not very large, there was less variation between countries in the dynamics of change.

2 There was a large concentration of greenhouse gas emissions from agriculture in several EU countries. The situation was stable, because from 2004 to 2017 the level of concentration did not change much. The top four emitting countries were the largest in terms of economic agricultural output, namely France, Germany, Great Britain and Spain.

3 All agricultural and economic parameters that were compared with the greenhouse gas emissions from agriculture were statistically significant. This indicates that the parameters selected for the calculations are good and that there is a close positive relationship.

4 The presented studies allow to state that the level of greenhouse gas emissions from agriculture depends on the economic situation and the terms of agriculture in the country. Regularities were in many cases straightforward, as for the relationship between greenhouse gas emissions from agriculture and the value

of animal production, cattle population, and the use of mineral fertilizers and manure production. This close relationship resulted from the fact that animal production was the part of agriculture that generated the most greenhouse gases.

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Abstract

The main objective of the paper was to show the relationship of greenhouse gas emissions by agriculture with economic development and agricultural production parameters in the European Union. All EU Member States were selected for research purposefully. The research period concerned the years 2004-2017. The sources of materials were EUROSTAT data, literature on the subject. For the analysis and presentation of materials, descriptive, tabular, graphic methods, dynamics based on a constant basis, Gini concentration coefficient, concentration analysis using the Lorenz curve, Pearson's linear correlation coefficients were used. Agriculture is one of the major economic sectors responsible for greenhouse gas emissions. In 2004-2017, emissions from this section slightly decreased in the EU. There was a wide variation between countries. Economically developing countries increased emissions, while developed countries maintained them at a similar level. Greenhouse gas emissions were highly concentrated in several EU countries. These were the countries with the most developed agriculture. In the years 2004-2017, there were no changes in the level of emission concentration. The level of greenhouse gas emissions from agriculture depended on the economic and agricultural situation in the country. The regularities were in many cases straightforward, as for the relationship of greenhouse gas emissions from agriculture with the value of animal production, cattle population, and the use of mineral fertilizers and manure production. This close relationship resulted from the fact that livestock production was the part of agriculture that generated the most greenhouse gases.

Keywords:
agriculture, EU, greenhouse gases, pollution reduction, methane, carbon dioxide

Emisja gazów cieplarnianych przez rolnictwo w krajach UE

Streszczenie

Celem głównym pracy było ukazanie zależności emisji gazów cieplarnianych przez rolnictwo z rozwojem gospodarczym i parametrami produkcji rolniczej w krajach Unii Europejskiej. W sposób celowy wybrano do badań wszystkie kraje członkowskie Unii Europejskiej. Okres badań dotyczył lat 2004-2017. Źródłami materiałów były dane

EUROSTAT, literatura przedmiotu. Do analizy i prezentacji materiałów zastosowano metody opisową, tabelaryczną, graficzną, wskaźniki dynamiki o podstawie stałej, współczynnik koncentracji Giniego, analiza koncentracji za pomocą krzywej Lorenza, współczynniki korelacji liniowej Pearsona. Rolnictwo jest jednym z ważniejszych działów gospodarki odpowiedzialnych za emisję gazów cieplarnianych. W latach 2004-2017 emisja wynikająca z tego działu nieznacznie zmniejszyła się w UE. Występowało duże zróżnicowanie pomiędzy krajami. Państwa rozwijające się gospodarczo zwiększały emisję, zaś rozwinięte utrzymywały ją na podobnym poziomie. Emisja gazów cieplarnianych była mocno skoncentrowana w kilku państwach UE. Były to państwa z najbardziej rozwiniętym rolnictwem. W latach 2004-2017 nie zaszły żadne zmiany w poziomie koncentracji emisji. Poziom emisji gazów cieplarnianych z rolnictwa był uzależniony od sytuacji gospodarczej i w zakresie rolnictwa w kraju. Prawidłowości były w wielu przypadkach prostoliniowe, jak dla relacji emisji gazów cieplarnianych z rolnictwa z wartością produkcji zwierzęcej, pogłowiem bydła, czy zużyciem nawozów mineralnych i produkcją obornika. Ten ścisły związek wynikał z faktu, że produkcja zwierzęca była tą częścią rolnictwa, która generowała najwięcej gazów cieplarnianych.

Słowa kluczowe:
rolnictwo, UE, gazy cieplarniane, redukcja emisji zanieczyszczeń,
metan, dwutlenek węgla

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Design Problems of the Hybrid Electric Power Supply System for Energy Balanced Floated House

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1. Introduction

If at least two different useful products can be produced in one process, then this process is called conjugated or combined (Szargut 1983, Szargut 2007). Particularly important associated processes are those in which heating products and electricity are useful products In the case of two products produced simultaneously in the combined process, there is talk about a cogeneration system, with three – trigenerative, and with a larger number of useful products – polygeneration.

Since the accession of Poland to the European Union, new trends in modern energy have been introduced and developed. Large, centralized systems of the combined economy (based mainly on combined heat and power plants) began to be replaced by local systems, so-called distributed generation. Distributed generation is understood to mean systems of small or medium size, including heating heat generation and electricity working in cogeneration (hence distributed cogeneration) (Malko 2004, Paskaa 2007) Classification of distributed generation systems (sometimes also known as a distributed generation – if the production of electricity and heat in cogeneration sources has power from about 1 MW to about a dozen MW) can be made taking into account various criteria. For example, according to the amount of power installed in the source: large distributed generation – 50-150 MW, medium distributed generation – 5-50 MW, small distributed generation – 1 kW-5 MW, distributed micro-generation – 1 W-5 kW; distinguishes due to the amount of power and location range distributed generation: pico generation (up to 2 kW of installed electrical power), microgeneration (up to 5 kW of power) and mini generation (up to 50 kW of power) (Charun 2015, Charun 2016).

Current, developed trends in the development of distributed generation point to the preference for the so-called hybrid manufacturing systems (HSW).

They are a combination of two or more different manufacturing technologies to obtain specific useful products. According to (Paska 2013), the concept of hybrid system was introduced into Polish legislation in the Regulation of the Minister of Economy of 18 October 2012 (Dz.U. 2012, poz. 1229), in the form of a record: a hybrid system is a generating unit producing electricity or electricity and heat, in which in the process in production, energy carriers produced separately in renewable energy sources are used, with the possibility of using auxiliary fuel and in energy sources other than a renewable energy source, working on a common collector and consumed jointly in this generating unit for the production of electricity or heat. In hybrid systems, for example, diesel generators (including diesel engines, small wind farms and solar cell batteries) are used. A typical example is the cooperation of solar panels with a wind energy generator. Other examples of hybrid systems are given in the literature, e.g. (Paska 2013, Paska 2005).

The problems described above fit into the design issues of the hybrid home power supply system (WH). In article (Charun 2020) selected design aspects of the heat extraction system using renewable energy sources (RES) using a compressor heat pump, with a lower heat exchanger placed in the surface water of the lake are given. This article presents hybrid systems, used to generate electricity for an example WH water house.

2. Aims of using hybrid systems in the WH

"House on the water" (WH) is a non-standard solution of a recreational and leisure facility in the form of a residential superstructure built on a float. Such a floating object is usually moored to a small pier or marina at the waterfront of a lake or river. Various global companies and Polish manufacturers WH offer various construction and installation solutions, without presenting detailed solutions. In most cases, the houses are powered by electricity from conventional coastal sources, which is fed in via power cables and used in the WH residential structure for heating, lighting, domestic hot water etc. This means that, in terms of power supply, the WH facility is organically dependent on external connections located on the waterfront.

The purpose of modernization changes introduced to the example of a WH house placed on a float 8 x 3.5 x 1 m (Charun 2020) was to reduce the energy dependence of WH on external power to the necessary minimum (excluding emergency cases). The name WH was obtained as "an energy-balanced floating house". The article (Charun 2020) presents some selected design aspects of heating such a house. Electricity is necessary not only to drive the compressor heat pump proposed in this solution but also for the living needs of residents.

The general assumption regarding the solution to the problem of independence from the external power supply has been turned towards the use of renewable energy sources (RES), especially wind energy and solar radiation.

In this way, the concept of using an electric hybrid system was obtained. The proposed hybrid power supply system includes the following basic components: wind turbines, photovoltaic panels, electricity storage system, control systems, intelligent control and measuring panels. The given set of elements is associated with the heating system using a heat pump cooperating with a renewable energy source (lake surface water).

A mini-scale distributed generation system in cogeneration was proposed as a classic form of the CHP (Combined Heat and Power) system. The hybrid solution uses renewable energy sources, and at the same time allows to achieve an increase in energy efficiency to the solutions used so far with external electricity supply from the waterfront.

3. Design assumptions for the hybrid system

The design assumptions for the hybrid electric power supply used for the WH floating home were:

- electricity demand to operate the receiving part of the installation,
- the scope of coverage of this demand by the generating elements of the system.
  - The hybrid system for the sample house WH was based on two subsystems obtaining energy from two different renewable energy sources, ie solar radiation energy – solar panel system and wind energy – wind turbine system. The interaction of both subsystems should cover the required demand
  - in the daily and annual cycle. To determine the size of actuators of both subsystems and installation instrumentation, balance sheets and analyzes were performed.
  - In the balance sheet of the receiving part of the electrical installation serving the WH residential structure, basic electricity receivers are specified, in particular: electric kitchen hob, household appliances, lighting, control system power supply, heat pump drive motor, etc. Balance, daily electricity demand, taking into account the factors their daily use and simultaneity of work is about 20.6 kWh/day.
  - A standard, a conventional floating house with similar dimensions of a residential superstructure requires a total electricity demand of about 7500 kWh/year. The use of the proposed hybrid power supply system should ensure significant savings in electricity consumption, obtained primarily through the proper selection and cooperation of executive elements of electricity generators, their control and all modernization measures. According

to preliminary simulations, the possibility of a daily reduction of electricity demand by about 85% was determined.

Based on the simulation analyzes, it was determined that obtaining the possibility of increasing the energy efficiency of the object requires the use of the hybrid system components listed in the following calculation conditions:

- wind turbines with a vertical axis of rotation with unit power of 50-150 W; turbine power is generated at an average airspeed of 2-3 m/s; according to the Weitbull Statistical Distribution. These wind speed parameters occur in Northern Poland for approximately 2500 hours/year. Due to the above, the possible power of wind turbines should be in the range of 200-600 W. It follows that in the estimated annual operating time, e.g. 4 wind turbines, energy in the amount of 500-1500 kWh/year can be obtained, i.e. 1.4-4.11 kWh/day;
- The photovoltaic subsystem should contain 4-6 photovoltaic panels with a maximum power of 250 W and real efficiency at an efficiency of approx. 10%. Normative sunshine duration in the conditions of northern Poland of 7.2 hours is assumed. in winter and 15.5 hours – in summer; the average calculated solar radiation energy value of 1065 kWh/m² was adopted, which will allow an annual energy yield of approx. 640 kWh/year, i.e. 1.75 kWh/day;
- in the calculations of cooperation of the hybrid system used to drive the compressor heat pump, it was assumed that the heat pump efficiency factor is COP = 3.5, generating a heating power of about 3.5 kW with an input power of about 1 kW.
- If the above-mentioned assumptions are met, the optimum yield should be: 5.86 [kWh/day] of electricity and 3.5 kWh of thermal energy. Assuming that the heat pump would work for 5 hours/day, almost all electricity can be allocated to the work of the heat pump, which would give 17.5 kWh/day of thermal energy. This results in a reduction of electricity consumption by 85.15% compared to the daily output value of 20.55 kWh. However, in extremely adverse weather conditions this figure can be as low as 15%.

Fulfilment of the above-mentioned design assumptions required a detailed analysis, taking into account statistical data of atmospheric parameters in the field of sunlight and windy conditions. Analyzes were carried out, for example, for the area of northern Poland in the coastal belt. Due to the limited volume of this study, only an outline of the methodology and some design calculations are provided.

3.1. Determination of wind energy resources in the WH foundation area

The basis for the wind installation design calculations was the distribution of average monthly wind speed values for the WH foundation basin. Values of this speed were determined for the windiness of the area located in the coastal belt from Łeba to Kołobrzeg. In the considered case, the results of the authors' research were carried out using the apparatus placed on a measuring mast with a height of 13 m located on the campus of the Koszalin University of Technology. The measurements were carried out over 12 months, with the test results in Table 1 taking into account the fact that in the case of the WH house wind turbines will be located at a height of up to about 3 m above the reference surface. In calculating the wind speed distribution as a function of height, the Sutton formula was used in the form (colective work 2008, Tytko 2016):

$$C_H = C_o \cdot \left(\frac{h}{h_o}\right)^{\alpha} \tag{1}$$

where: C_H – wind speed measured at the height of the [m/s], C_o – the speed at the height of ho (equal to 10 m) of the location of the anemometer, α – power exponent depending on the roughness class of the substrate and the averaging time (averaging values of 10 minutes were adopted, hence α = 0.20.

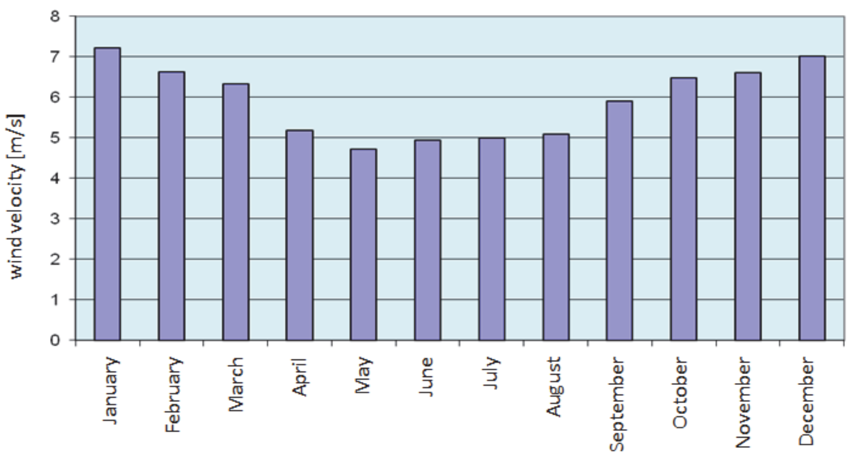

Fig. 1. Distribution of average monthly wind speed during the year at the WH foundation point at a height of 3 m

After the transformation of formula (1), the values of wind speed Co distribution at 3 m height were determined as average values in individual months of the year (Fig. 1). The average annual wind speed Cr was calculated from the formula:

$$C_r = \frac{\sum_{i=1}^{12} C_{o,i}}{12} \tag{2}$$

Using the statistical *Weibull* distribution, the frequency distribution of wind speeds at a given speed over a year was determined, according to the relationship:

$$f(x) = k \cdot C_r^{-k} \cdot x^{k-1} \cdot e^{-\left(\frac{x}{C_r}\right)^k} \tag{3}$$

where: x – wind speed at which the calculations were made [m/s], C_r – average annual wind speed [m/s], k – shape parameter (k = 3 was adopted).
Fig. 2 shows the wind speed distribution, depending on its frequency.

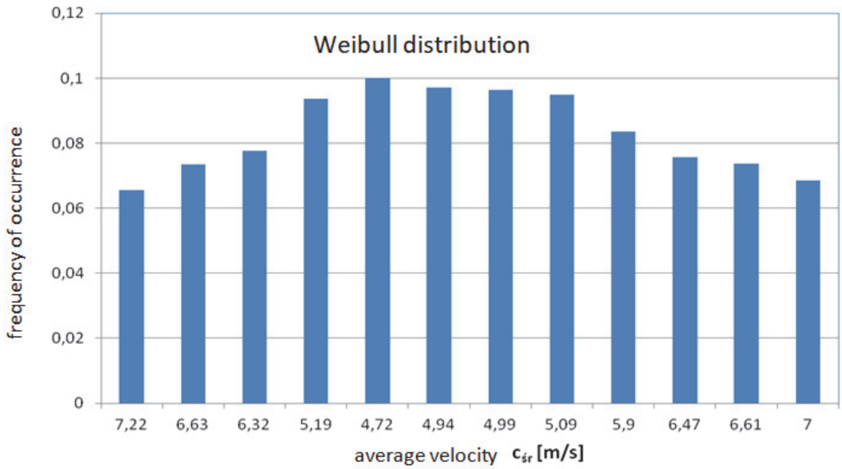

Fig. 2. Weibull distribution of wind speed depending on the frequency of occurrence

To determine the number of hours of the occurrence of individual values of wind speed, the percentage frequency of occurrence of these wind speeds was multiplied by the duration of the measurement (8760 hours/year). The results are presented in Table 1.

Table 1. Hourly amount of wind speed data occurrence

Velosity [m/s]	Frequency [Hz]	Grequency [h]
7.22	0.065646	575.06
6.63	0.073413	643.10
6.32	0.077645	680.17
5.19	0.093544	819.44
4.72	0.100115	877.01
4.94	0.097059	850.24
4.99	0.096359	844.11
5.09	0.094954	831.80
5.9	0.083501	731.47
6.47	0.075586	662.14
6.61	0.073684	645.47

Knowing the average monthly wind speed values and the terrain in the place where the wind turbine was founded, the amount of energy that could be generated by a given turbine was calculated based on the formula:

$$P_t = 0{,}5 \cdot \rho_{pow.} \cdot A \cdot c_p \cdot c_s^3 \tag{4}$$

where:
ρ_{pow} – air density (1.225 kg/m^3 was used for calculations), A – wind stream area [m^2], C – wind speed [m/s], c_p – wind turbine utilization coefficient. Further calculations were made using the methodology related to *Savonius* wind turbines (Jagodziński 1959, Wekesa 2016).

The maximum value of the power factor $c_{p,max}$ of the wind generator, using wind resistance usually does not exceed 0.2, which means that only 20% of wind energy can be used in devices such as the *Savonius turbine*. In practice, this value refers to the aerodynamic power achieved when the turbine is idling with a vertical axis of rotation. Consequently, the useful power achieved will be much lower and it can be assumed that it is close to the level of 50% of aerodynamic power.

Based on the applied calculation methodology, the power distribution possible to be obtained by one *Savonius* turbine in individual months of the year was determined – Table 2.

Table 2. Distribution of power generated by the Savonius turbine in individual months of the year

Month	Monthly average wind speed $C_{śr}$ [m/s] at a height of 3 [m]	The estimated amount of energy generated by 1 turbine [kWh/doba]	The estimated amount of energy generated by 4 turbines [kWh/doba]
January	7.22	2.43	9.70
February	6.63	2.23	8.91
March	6.32	2.12	8.49
April	5.19	1.74	6.98
May	4.72	1.59	6.34
June	4.94	1.66	6.64
July	4.99	1.68	6.71
August	5.09	1.71	6.84
September	5.90	1.98	7.93
October	6.47	2.17	8.70
November	6.61	2.22	8.88
December	7.00	2.35	9.41

a) b)

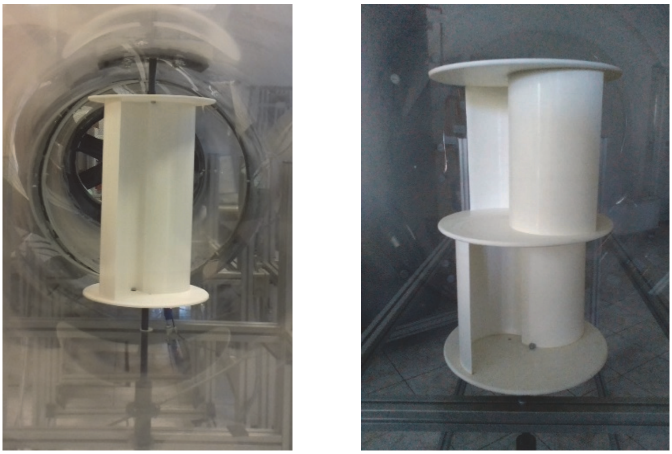

Fig. 3. View of model wind turbine rotors proposed in a hybrid system: a) Savonius, b) double Savonius

Power plant data:
propeller diameter – 50 cm
propeller length – 90 cm
wind-up speed – 1 m/s
working range – 1-20 m/s
weight – 8 kg
generator voltage – 12 or 24 V
PMG generator – weight 2 kg
generator power – 280 W

Fig. 4. View and technical parameters of the Savonius wind turbine – 280 W

Fig. 3 shows a model version of Savonius wind turbines. The project envisages the use of 4 Savonius turbines, the view and characteristics of which are shown in Fig. 4. This allows generating electricity in the amount of 6.3-9.70 kWh/day, with the average annual value of generated energy being. 2665 kWh/year for a set of 4 turbines. Even taking into account the reduction in turbine rotor operating speed, it is possible to obtain practically 3.32-4.85 kWh/day, i.e. 1332 kWh/year. To the planned demand specified at 500-1500 kWh/year, i.e. 1.4-4.11 kWh/day, the calculated amount of generated energy covers the planned demand.

3.2. Determination of solar energy resources in the WH foundation area

To estimate the local amount of solar radiation energy, several years of sun exposure studies are necessary.

The values of insolation were adopted from data obtained from the interactive Photovoltaic Geographical Information System (PVGIS). This system is based on data on the amount of solar radiation and terrain. The obtained values are shown in Fig. 5.

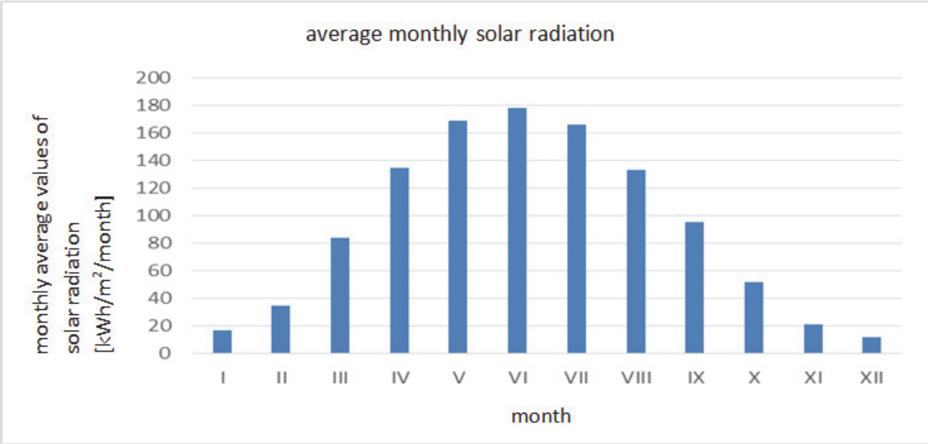

Fig. 5. Graph showing average monthly insolation values for the city of Kołobrzeg, data taken from PVGIS

Based on the above data, the annual value of sunlight for the city of Kołobrzeg was calculated:

$$E_{sr} = \Sigma E_{sm} = 16.8 + 34.8 + 83.7 + 134.7 + 169.2 + 178.2 + 165.9 + 133.2 + 95.7 + 52.2 + 21.1 + 11.9 = 1097.4 \text{ [kWh/m}^2\text{/year]}$$

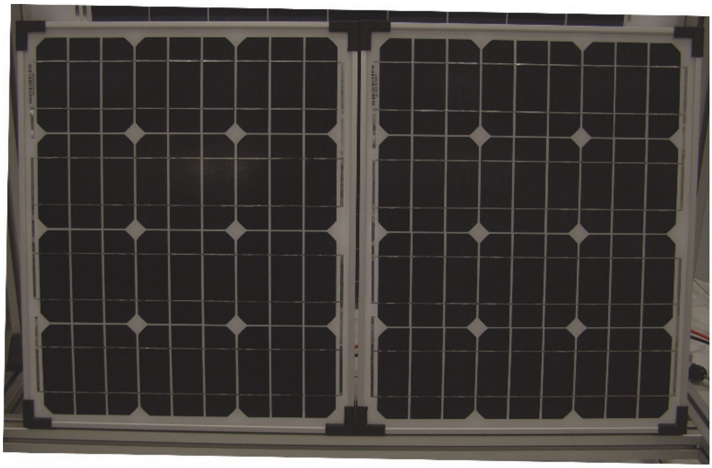

Fig. 6. View of monocrystalline panels in parallel connection

Fig. 6 shows a view of the proposed solar panel for use in a House on the Water. To obtain energy from solar radiation, the use of 6 monocrystalline photovoltaic panels with the following parameters is planned:

- rated power PMPP 290 W,
- rated voltage UMPP: 31.3 V,
- IMPP rated current: 9.25 A,
- open circuit voltage UOC = 39.3 V,
- short circuit current ISC 9.80 A,
- area: 1.47 m^2,
- efficiency η = 17.6%.

Electrical parameters were determined under standard test conditions (STC): 1000 W/m^2; 25°C; AM 1.5.

For real conditions, the efficiency of photovoltaic cells is assumed to be about η = 10% and the potential of useful energy from solar radiation H = 1097400 Wh/m^2 for one year (Kołobrzeg actinometric station). For the above parameters, it is estimated that it is possible to obtain 2.65 kWh electricity during the day. The following algorithm was used for the calculation:

$$H = \frac{1097400\left\|\frac{Wh}{m^2}\right\|}{365[day]} = 3006{,}58\left[\frac{\frac{Wh}{m^2}}{day}\right] = 3{,}01\left[\frac{\frac{kWh}{m^2}}{doy}\right], \tag{5}$$

$$\eta = \frac{P_{el}}{H \cdot A} = P_{el} = \eta \cdot H \cdot A, \tag{6}$$

$$P_{el} = 0{,}1 \cdot 3{,}01\left[\frac{\frac{kWh}{m^2}}{day}\right] \cdot 6 \cdot 1{,}47[m^2] = 2{,}65\left[\frac{kWh}{day}\right],$$

Compared to the planned amount of 1.75 kWh/day and 640 kWh/year over a 12-month scale, the calculated amount of energy that can be obtained from the proposed set of photovoltaic modules and solar radiation determined by PVGIS is much higher. It is on average 2.65 kWh/day and 969 kWh/year.

4. Design concept of hybrid system construction

Due to the uneven distribution of solar radiation in individual months of the year, there is a need to combine them with other electricity generators, e.g. wind turbines. In this case, two basic connection schemes are usually used:

1. photovoltaic generator + battery + inverter – connection by direct current lines,
2. photovoltaic generator and other elements, including receivers – connected to the AC system.

To the hybrid electric power supply system for the floating house WH, the second connection option was used. Fig. 7 shows an electrical diagram of connections of elements of the hybrid power supply system of the house on the WH water.

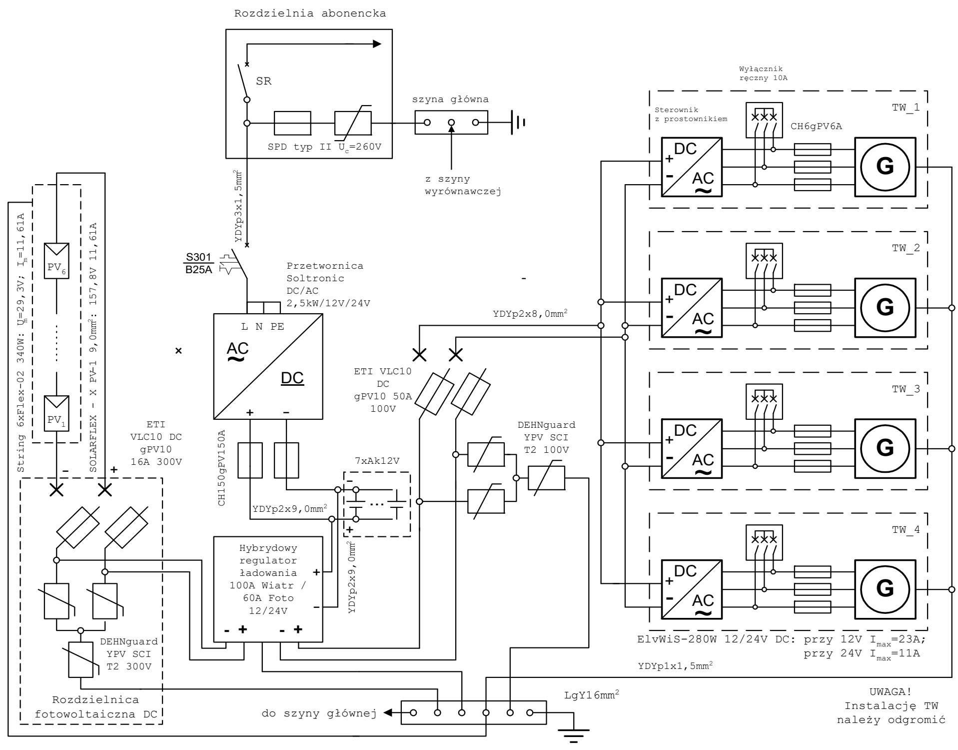

Fig. 7. Diagram of a hybrid electricity supply installation

The hybrid electric power system for WH was designed with the use of photovoltaics – monocrystalline photovoltaic modules type FLEX -02 340 W with a rated power of 340 Wp – 6 pcs. Connected to the system are 4 wind turbines of the Savonius type – ElvWiS III ALUMINUM. The electricity generated in the panels will be diverted via solar cables to the 100A wind 60A hybrid 48A photo 48/24/12V 8KW charging controller, and from it to the energy storage block (batteries with 6 pcs. 12 V). A set of four wind turbines is connected to this voltage regulator. The generated electricity, after converting it to DC 12/24 V through the voltage regulator, will supply the battery block. External devices are used to store electricity generated by a wind generator and photovoltaic panels in a battery. A hybrid controller having PWM wind and solar controller operation parameters will ensure cooperation with: max 5 kW wind generator, max 3 kW electric photovoltaic cells and a set of batteries.

Fig. 8 presents a general view of the WH assembled hybrid power supply system located in a separate WH superstructure room. All elements of the hybrid system were tested on laboratory stands and in operational conditions after the completion of WH assembly works. Research results will be the subject of a separate study.

Fig. 8. General view of the WH hybrid power supply system

5. Summary

The content of the study presents selected design problems of the hybrid electric power supply system for the recreation and leisure floating house WH moored at the lake quay located in the coastal belt in the Central Pomeranian area. The proposed power supply installation combines two independent systems for obtaining energy from renewable sources. The hybrid system is intended to make the floating object independent of the consumption of electricity from external sources located on the waterfront. The basic elements of the hybrid system are a subsystem of photovoltaic panels and a subsystem of wind turbines of the Savonius type with a vertical axis of rotation. The designed system not only performs the function of independence from external sources and the use of renewable energy sources (RES) but also shows significantly greater energy efficiency concerning dimensionally similar WH houses powered by external power cables. The proposed system, controlled by intelligent systems, is also a source of power for the compressor heat pump using the surface water of the lake as the lower heat source.

The present study was performed under in accordance with the application for funding by the National Centre for Research and Development No. POIR.01.01.01-00-0466/17 for the implementation of the project entitled "Construction of energy balanced floating leisure house" with Ekosun Paweł Czupajło company, based in Koszalin at 4 Boh. Warszawy Street, 75-211 Koszalin

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Abstract

Recreational houses (WH) of a recreational nature may constitute an offer for the development of non-standard forms of recreation proposed by the domestic tourist industry. The paper presents some selected design problems of heating an exemplary WH house. For central heating (central heating) and domestic hot water (domestic hot water), it is proposed to use a compressor heat pump. It works with the central heating installation (water underfloor heating) and hot water, and with a lower source in the form of surface water in the lake. The heat exchanger for the brine is immersed in the lake water. The methodology for calculating the dimensions of the lower heat exchanger was presented. It was proposed that it will be made in the form of two coils made of polyethylene pipes and WH float sides placed on both sides. The design solution presented in the paper meets the conditions for qualifying as using renewable energy sources (RES).

It should be noted that covering the demand for electricity for the WH house, including to drive the heat pump motor and for other living purposes in a residential superstructure, is also made using a hybrid system in the form of cooperation between wind turbines and photovoltaic panels. Problems regarding the WH hybrid electricity supply system will be the subject of a separate study.

Keywords:
floating house, renewable energy sources, designing, heat pump

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Assessment of the Variability of Rainwater Quality and the Functioning of Retention Reservoirs in the Urban Area

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1. Introduction

The rapid development of urban agglomerations in many countries results in significant environmental changes and the deformation of local hydrological cycles. Compacting technical infrastructure and increasing the share of sealed surfaces in urban space means reducing infiltration of rainwater to the ground, limiting retention, rapid outflow and, as a consequence, a decrease in the quantity and deterioration in the quality of water resources (Congying 2012, Geiger & Dreiseitl 2001). Changes in land use, combined with more and more extreme weather events (global climate change), lead in some urbanised catchments to the accumulation of rainwater, which in turn should be safely collected and directed to the right receivers. The increase in non-uniformity of flows with simultaneous unsatisfactory throughput of sewerage networks results in hydraulic overloads and local flooding (Hlavínek & Zelenakova 2015, Huang et al. 2015). In this context, the unreasonable development of technical infrastructure becomes an indirect threat to… the technical infrastructure (e.g. housing, transport, and communications).

Pollutants in rainwater and snowmelt runoff are another significant problem. Some authors emphasize that rainwater can be a major threat to the environment – including direct water receivers (Barałkiewicz et al. 2014, Yuan et al. 2017, Zubala 2018). The degree of water pollution depends, among other things, on the way of land use and topography, type, method of maintenance and operation of sealed surfaces, traffic intensity, degree of air and drained surface pollution, precipitation characteristics and the quantity and quality of sediments in sewerage systems. Performing an accurate forecast of runoff quality is very difficult due to the presence of so many different factors. There is no typical composition of rainwater. However, due to the possibility of significant negative impacts on the environment (pollution) and technical infrastructure (hydraulic overload), it is necessary to develop and implement effective rainwater management systems in urban agglomerations (precautionary and preventive principles).

A good solution may be storage (delaying outflow) and pre-treating rainwater at the place where it appears. The application of uncomplicated devices which are based on the use and intensification of natural self-purification processes, as well as reducing the intensity of outflow to the receiver, is justified in economic and environmental terms. Permeable surfaces, wells and infiltration basins, grit chambers and settlement tanks can be given as examples (Barszcz 2015, Fuchs et al. 2013, Geiger & Dreiseitl 2001, Langeveld et al. 2012). In the case of the availability of larger areas, detention ponds and wetlands with sedimentation, flotation, sorption and biological decay of pollution are used (Herrmann 2012, Liu et al. 2014, Moore & Hunt 2012). Their operation consists in slowing down the flow of liquid, which allows the sedimentation of solid particles (the use of gravity forces). In infiltration systems, rainwater additionally infiltrates into the ground where purification also takes place. The participation of microorganisms and aquatic vegetation is very important in self-purification processes.

It is necessary to conduct permanent qualitative monitoring in the case of terminal devices from which rainwater goes directly to natural receivers. Data obtained in various conditions and places in the world will allow not only a thorough understanding of the phenomena occurring in these facilities but also enable the preparation of reliable review papers and define project recommendations increasing the reliability of specific technologies. These issues are particularly important in developing countries, where the problem of rainwater management has been often postponed.

The aim of this work is to assess the variability of the quality and to compare the degree of pollution of rainwater collected and pre-treated in two reservoirs in the agglomeration of Lublin, with the simultaneous estimation of possible environmental threats. The functioning of the analysed reservoirs was assessed in the context of a different construction and ways of land use. Changes in weather conditions prevailing during the study period were taken into account. Reservoir 1 (R1) has a permeable bottom and collects runoffs from a section of national road. Reservoir 2 (R2) is a sealed concrete structure in which rainwater is collected from a housing estate. Large variation in some factors may determine the variability of retained water quality. The quality of rainwater and percentage differences in the content of pollutants in various aspects (e.g. between objects, within an object, in different periods) were determined as a part of three-year study. An attempt was also made to assess the basic technical and operating parameters of both systems after several years of functioning and the legitimacy of using specific solutions.

The collected data should be a valuable material for scientists in the field of environmental protection and water management, as well as for designers and users of rainwater management systems.

2. Materials and methods

2.1. Study area

Lublin is located in south-eastern Poland (the Lublin Upland macro-region), where it serves as the central hub of the agglomeration. It is the fastest growing and largest city on the eastern side of the Vistula River, with an area of 147 km^2 and about 340 thousand inhabitants. Important international transport routes intersect here and there are many industrial plants of various industries (including automotive, machinery, construction, and food industry). Residential, commercial and service buildings, recreational areas and road infrastructure have been growing particularly quickly in recent years in Lublin (SO 2017).

The studied rainwater reservoirs were built in 2006 (R1) and 2005 (R2). They are situated in the bottoms of dry loess valleys. The first one connects with the Bystrzyca valley – the main river of the Lublin City (R1), and the second with the Czechówka River valley – the Bystrzyca tributary (R2). This part of the city belongs to the highly sculptured mesoregion of the Nałęczów Plateau with soils that are very susceptible to water erosion (surface washes, numerous valleys and ravines, escarpments). Height differences reach several dozen metres (Harasimiuk et al. 2008). In both valleys, there is an increasing urbanization process leading to partial devastation of the area.

Observations have shown that trees and shrubs occur in small quantities on drained surfaces, which relates specifically to the national road. This results from the functions and progressive changes in land use (including the expansion of a new housing estate). Synanthropic plant communities, adapted to living in a strongly transformed environment, are predominant here. In the catchment basin of reservoir 2 there are also small home gardens with decorative vegetation.

R1 is located in the immediate vicinity of the drained section of national road no. 19 (Fig. 1). The road cuts across the dry valley. The size of the drainage area is approximately 10 ha (slight changes in recent years due to modernization), with the impermeable part constituting nearly 80% of the total (roadways, pavements). The rest falls on narrow, sodded stripes. In the vicinity of R1 there are also local roads, crop fields and wasteland. The housing estate from which water flows to R2 is mostly located on the southern slope. Its area is about 14 ha – a large part is occupied by roofs, tight roads and parking spaces (Fig. 1). The biologically active surface constitutes about 50% of the analysed area. The size of the tight surfaces of both catchments is similar. There are construction projects being carried out within the housing estate. Water erosion and the outflow of loess material to the rainwater drainage system may be facilitated by the lack of proper protection of exposed soil and by the steep slope. In the vicinity of R2 there is also a crop field, allotments and wasteland.

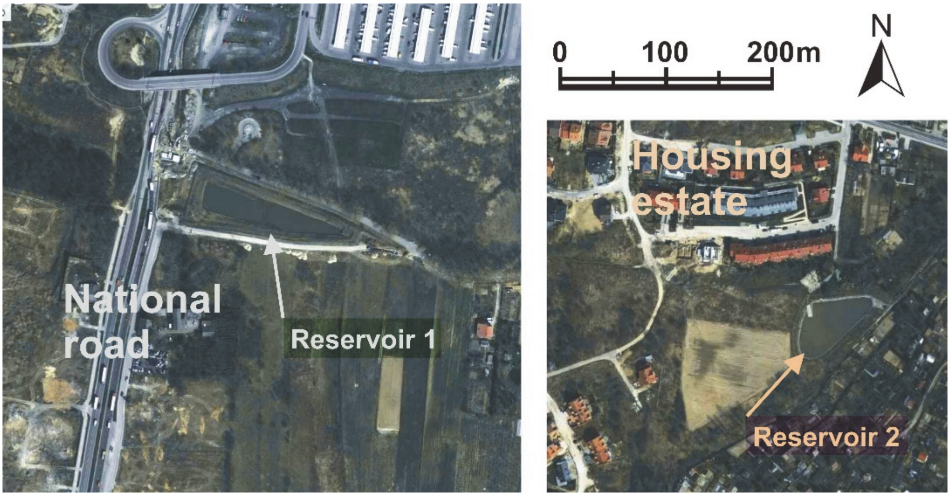

Fig. 1. Location of the analysed rainwater reservoirs with fragments of drained areas (www.geoportal.gov.pl)

2.2. Climatic conditions

Table 1 presents the most important data on climatic conditions in the study area. In the analysed period, the annual sums of precipitation were varied and they ranged from 533 to 792 mm. The years 2013 and 2014 were more abundant in precipitation than the average year in the period 1971-2010. The differences were 53 and 194 mm respectively. The last year of study was exceptionally dry – compared to the average for many years, the sum of precipitation was by 65 mm lower. Exceptionally high temperatures of atmospheric air were also recorded that year. The average annual temperature was 9.4°C and was higher than the average for many years by 1.7°C. In 2013-2014, higher sums of atmospheric precipitation were noted down in the first half of the year (I-VI) and they exceeded 60% of the annual rainfall. In the last year of study, total rainfall in both half-years was almost identical. Analysis of data from many years (1971-2010) showed the prevalence of precipitation in the second half-year (VII-XII). During the research period, exceptionally high monthly precipitation occurred in May – the maximum sum of 240 mm was registered in 2014 (30.3% of annual rainfall). The minimum monthly rainfall did not exceed 10 mm (X 2013 and VIII 2015).

Relatively low sums of rainfall were also recorded in February (Table 1). According to Kaszewski (2008), the average annual number of days with snowfall in Lublin is 48. However, the average annual number of days with snow cover varies from about 60 to 80 days in the Lublin region. In the analysed period, average annual air temperatures were higher than in the average year over many years (Table 1). This may be a symptom of general climate warming trends. A distinct increase in temperature is visible from year to year. In 2013 and 2014, the coldest month was January. In 2015, a slightly lower temperature was recorded in February; however, throughout the year the average monthly temperature did not fall below 0°C. The highest average air temperatures occurred in the summer months (mainly VII), which is in line with the values for many years.

Table 1. Monthly and annual sums of atmospheric precipitation and average air temperatures during the study period (2013-2015) against the background of average climatic conditions over many years (1971-2010) (CSO 2014, 2015, 2016)

	Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
Precipitation (mm)	2013	62	34	55	46	106	113	88	17	41	7	63	19	651
	2014	67	15	43	54	240	77	76	90	29	24	23	54	792
	2015	51	14	45	28	114	18	43	7	90	47	48	28	533
	1971-2010	32	30	37	39	63	69	82	69	63	43	38	33	598
Temperature (°C)	2013	-4.1	-1.3	-2.5	7.9	14.8	17.8	18.5	18.6	11.5	9.8	5.1	1.3	8.1
	2014	-3.0	1.2	6.0	9.7	13.4	15.6	20.3	17.8	14.2	9.2	4.2	-0.2	9.0
	2015	0.6	0.4	4.7	7.9	12.4	16.7	19.3	21.8	14.6	6.8	4.7	3.3	9.4
	1971-2010	-3.1	-2.0	2.0	8.0	13.5	16.1	18.5	17.7	13.0	7.8	3.0	-1.6	7.7

2.3. Rainwater reservoirs

Drained surfaces are located largely on slopes, which facilitates the gravitational transport of rainwater to reservoirs (use of existing height differences). Their task is to receive, collect and pre-treat liquids. The following self-purification processes may take place in the reservoirs: filtration (only R1), sedimentation, mixing, dilution, sorption, oxygenation, biological reactions (R1 and R2). Such phenomena are common in the aquatic environment.

R1 is a recessed earth structure with an area of 0.34 hectares and a capacity of 9,860 m^3 (significant oversizing). From the north it is closed by a high, grass-covered dyke made of native soil. The reservoir has a permeable bottom overgrown with submerged aquatic vegetation. The design of the structure takes into account the maximum flow rate – 1.5 $m^3 \cdot s^{-1}$ and an instantaneous volume of discharged water – 1,800 m^3 (flow through underground sewers). If necessary, rainwater can be partially transferred from the reservoir using a concrete drain monk. The receiver is a reinforced channel, which is also a girdling ditch (Fig. 2).

R2 is also a recessed earth structure. The object was designed for a maximum flow rate of 1.24 $m^3 \cdot s^{-1}$ and an instantaneous runoff volume of 1,608 m^3 (inflow through underground channels and shallow open gutter) (Fig. 2). The area of R2 is 0.23 ha, and the active volume is 2,013 m^3.

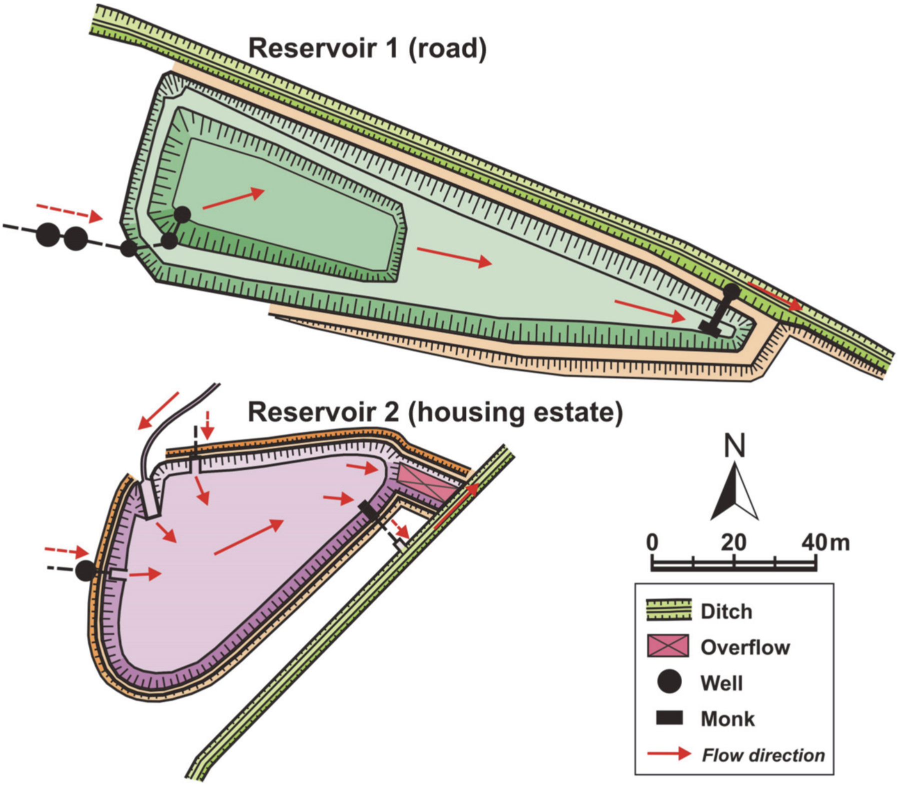

Fig. 2. Schemes of the analysed rainwater reservoirs

R2 bowl was sealed with concrete (geo-grid filled with concrete) for fear concerning the stability of the loess ground and due to the presence of neighbouring residential buildings (Fig. 3). This completely eliminates the infiltration process. The reservoir has the function of a settling tank; however, a layer of sediments has formed on the bottom that enabled the development of aquatic vegetation. Water is discharged into the periodic watercourse after temporary detention. Drainage is possible thanks to the use of a steel riser (monk) and safety overflow.

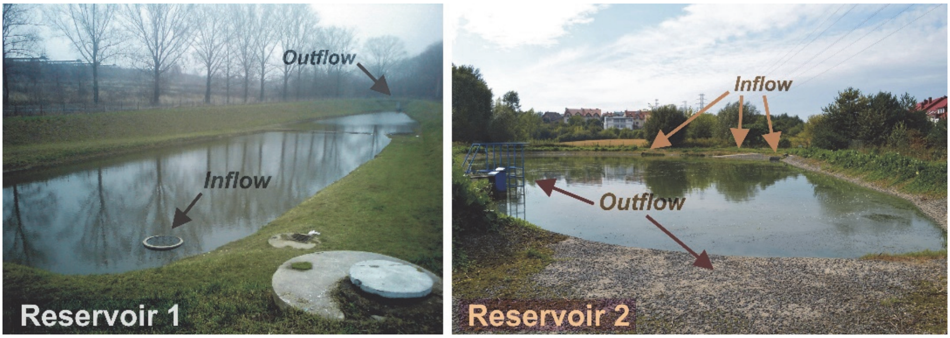

Fig. 3. General view of rainwater reservoirs

Underground rainwater sewers supplying water to the studied reservoirs are equipped with street inlets, inspection chambers and pre-treatment facilities (grit chamber, settling tank, separators). Both reservoirs are protected by a steel fence. The use of objects entails, among other things, regular mowing of vegetation, filling cavities in dikes, maintaining the tightness of weirs, cleaning of separators, grit chambers and settling tank, control and repair of ditch enhancements. During the study period bottom sediments were not removed from reservoirs.

2.4. Sampling and analysis

The analysis of rainwater quality variables was conducted seasonally for three years (12 measurement terms, 24 samples). The same number of samples was taken each year. The periods between rainwater runoffs were consistently selected. Samples were collected on the same day in both reservoirs (time difference: half an hour). The intake was carried out 1 meter from the shore in the middle of the length of the reservoirs (the side with inflow), using a sampling bailer. Both reservoirs contained water on all measurement dates. The research was carried out in the Laboratory of Water and Wastewater at the University of Life Sciences in Lublin. The following indexes were determined in the water samples: temperature, electrolytic conductivity (by conductometry), pH (by potentiometry), total suspended solids (by drying and weighing), dissolved oxygen (O_2), 5-day Biochemical Oxygen Demand – BOD_5 (by dilution), Chemical Oxygen Demand – COD (by dichromate method), ammonium ions (NH_4^+), nitrates (NO_3^-), nitrites (NO_2^-), phosphates (PO_4^-), sulphates (SO_4^-), iron (Fe^+), potassium

(K^+), and chlorides (Cl^-) (photometric determination). Chemical components (e.g. nutrients) were determined by means of photometers: MPM 2010 (WTW) and LF 300 (Slandi). Physical properties were determined using a multi-parameter Thermo Orion meter. In assessing the quality of rainwater, the extreme and average values of the analysed indicators were determined for each checkpoint. The statistical variability of obtained results was determined based on the values of standard deviation and coefficient of variation. The non-parametric Mann-Whitney test was used to compare the variable quality of rainwater in both reservoirs (significance levels $\alpha = 0.05$ and $\alpha = 0.10$). The percentage differences in the content of contaminants in the analysed objects were also determined.

3. Results and discussion

The quality of rainwater collected in reservoirs 1 and 2 is characterised by high variability (Table 2). The variability shown in this article is compatible with results obtained in other rainwater management facilities in the region (Zubala 2013, 2018). Significant differences were found in the case of conductivity, NH_4^+, NO_2^-, PO_4^-, SO_4^-, Fe^+, K^+, Cl^- (different distributions of values of the analysed features) (Table 2). Higher values of conductivity, NH_4^+, SO_4^- and Cl^- were observed in reservoir 1 (R1), receiving rainwater from a part of the national road. The percentage differences in mean values of given variables were recorded between reservoirs: 63.8, 24.9, 58.0 and 65.0%. The reservoir 2 (R2), which is supplied with rainwater from the housing estate, was more contaminated with NO_2^-, PO_4^-, Fe^+ and K^+. When comparing both reservoirs, the percentage differences of average concentrations were particularly high in the case of the last three indicators – they amounted to 282.8, 167.7 and 235.7% respectively. Despite the fact that on most measurement dates, COD and NO_3^- values were higher in rainwater R1, there were no incompatibilities in the distribution of these characteristics in statistical analysis. The high variability coefficients in R1 were characteristic of suspended solids, NH_4^+ and K^+ (above 100%), while in R2 of suspended solids and NO_3^- (NO_3^- as much as 205.6%). In both reservoirs, the smallest variation related to the pH value (about 10%).

Table 2. Characteristic values of rainwater quality indicators in reservoirs 1 and 2 (R) in 2013-2015 (statistical significance of differences in quality variables was determined for α = 0.05 and α = 0.10 – Mann-Whitney test)

Variables	R	Min.	Max.	Average	Median	Standard deviation	Variation coefficient	Important difference
Temperature (°C)	1	1.0	26.0	12.8	14.0	9.2	72.5	–
	2	1.0	25.5	13.3	14.5	9.2	69.2	
Conductivity ($\mu S \cdot cm^{-1}$)	1	265	3,985	1,122	841	1,051.3	93.7	+
	2	60	1,373	406	276	373.2	92.0	(α=0.05)
pH	1	7.6	10.1	8.8	8.8	0.9	10.6	–
	2	7.9	9.9	8.6	8.4	0.7	7.8	
Suspension ($mg \cdot dm^{-3}$)	1	4	114	29	18	35.4	120.8	–
	2	5	121	38	24	38.5	100.4	
O_2 ($mg \cdot dm^{-3}$)	1	2.4	13.7	8.9	9.5	4.2	47.2	–
	2	5.4	12,9	9.7	10.8	2.9	29.7	
BOD_5 ($mg \cdot dm^{-3}$)	1	1.4	13.1	7.1	6.9	3.9	55.2	–
	2	3.2	10.5	6.5	5.4	2.6	41.0	
COD_{Cr} ($mg \cdot dm^{-3}$)	1	13	173	61	47	44.6	73.7	–
	2	7	181	60	42	54.8	91.9	
NH_4^+ ($mg \cdot dm^{-3}$)	1	0.052	2.281	0.558	0.202	0.7	130.2	+
	2	0.258	0.876	0.419	0.387	0.2	38.4	(α=0.05)
NO_3^- ($mg \cdot dm^{-3}$)	1	0.102	1.659	0.594	0.323	0.6	98.3	–
	2	0.088	2.181	0.290	0.115	0.6	205.6	
NO_2^- ($mg \cdot dm^{-3}$)	1	0.056	0.625	0.254	0.161	0.2	72.1	+
	2	0.059	0.691	0.374	0.372	0.2	51.6	(α=0.10)
PO_4^- ($mg \cdot dm^{-3}$)	1	0.010	0.100	0.051	0.048	0.03	53.7	+
	2	0.018	0.561	0.197	0.170	0.1	71.7	(α=0.05)
SO_4^- ($mg \cdot dm^{-3}$)	1	3	36	13	9	9.8	78.5	+
	2	2	9	5	6	2.4	45.3	(α=0.05)
Fe^+ ($mg \cdot dm^{-3}$)	1	0.24	1.33	0.54	0.46	0.3	57.1	+
	2	0.14	3.77	1.44	1.05	1.1	74.6	(α=0.05)
K^+ ($mg \cdot dm^{-3}$)	1	1.3	21.9	4.6	2.4	5.7	124.2	+
	2	1.4	48.2	15.4	12.0	12.2	78.8	(α=0.05)
Cl^- ($mg \cdot dm^{-3}$)	1	20.4	98.0	65.4	77.7	25.7	39.3	+
	2	6.4	78.6	22.8	14.1	21.7	95.0	(α=0.05)

Rainwater quality forecast is difficult to perform due to a variety of factors and phenomena within the drained catchment and in sewerage systems. Their dynamics and variability may determine the variability of the content of pollutants in rainwater reservoirs. A relationship between the method of use, as well as the degree of pollution of urban space and the quality of outflow rainwater has been demonstrated in some papers (Goonetilleke et al. 2005, Liu et al. 2013). Existing weather conditions or the construction and operation of a rainwater retention system may also be of great importance (Gong et al. 2016, Zubala 2018).

Rainwater collected in the studied reservoirs was characterised by poor quality on most measurement dates. The indicator decreasing water quality in R1 was conductivity. The highest values were achieved in the winter months with a maximum of 3,985 $\mu S \cdot cm^{-1}$ in 2015 (Table 2). In the winter of 2013, the conductivity value was 2,321 $\mu S \cdot cm^{-1}$, and in 2014 – 825 $\mu S \cdot cm^{-1}$. Although the conductivity in R1 decreased in the subsequent months of a given year, in spring 2013 and 2015 its level exceeded 1,000 $\mu S \cdot cm^{-1}$. The average conductivity value in rainwater of R2 was only 406 $\mu S \cdot cm^{-1}$ and only on one measurement date it exceeded 1,000 $\mu S \cdot cm^{-1}$ (1,373 $\mu S \cdot cm^{-1}$ in March 2015). Such high conductivity is associated with meltwater runoff, carrying high loads of pollutants. According to Ociepa et al. (2015) such phenomena are linked primarily with the long time of snow retention and gradual accumulation of subsequent portions of pollutants, including measures to protect roads against glazed frost. During these periods a significant increase in the content of chlorides was also observed, which is especially true for R1. The maximum level of Cl^- in R1 was 98.0 $mg \cdot dm^{-3}$, and in R2 78.6 $mg \cdot dm^{-3}$. Sodium chloride (NaCl) is widely used in Poland to reduce slipperiness after snowfall. The necessity to ensure transport safety means that it is likely to use much more salt within the national road than in a housing estate. Consequently, in R1, the average concentration of Cl^- was 65.4 $mg \cdot dm^{-3}$, and in R2 only 22.8 $mg \cdot dm^{-3}$. The average annual content of Cl^- did not decrease in R1 below 75 $mg \cdot dm^{-3}$ in 2013 and 2015. Placing large doses of salt on drained surfaces can have a negative impact on the environment (Corsi et al. 2015, Rivett et al. 2016). The increase of salt concentration in the soil prevents the roots of plants from taking up water, causing them to dry up. It can also be destructive to soil decomposers and disturb the functioning of freshwater ecosystems (rainwater receivers).

A worrisome high pH was found in the analysed rainwater. The average value in R1 was 8.8 and 8.6 in R2. The maximum values were about 10 in both reservoirs (Table 2). Alkalization of rainwater is probably due to the presence of alkaline dust and salinity within the basins. The processes occurring in the sediments of the sewerage system and the studied reservoirs may also be of great importance. The sediments have not been removed from the reservoirs from the moment they were put into operation. A thick layer accumulated on the bottoms, which is moved during intense water flows. This is evidenced by a significant increase in turbidity during and after violent storm and meltwater runoff. The highest concentration of suspended solids in both reservoirs were found in the first year of the study (2013). Maximum concentration were 114 (R1) and 121 $mg \cdot dm^{-3}$ (R2). The amount of suspended solids in water R2 was higher than that in R1 in most measurement date. For R2 catchment a major problem was inadequate securing of construction sites and unpaved roads located on a steep slope (especially in 2013). As a result of water erosion, larger quantities of loess dust penetrated into the sewage system and the reservoir, which may be confirmed by the yellow colour of rainwater in some periods. Increased suspension content was usually observed in winter and spring (thaws, pollutants wash-off after winter). The lowest mean annual concentrations of the analysed component were recorded in 2014. In R1 and R2 its values were 10.5 and 15.5 $mg \cdot dm^{-3}$, respectively. The year 2014 was characterised by heavy rainfall. Total rainfall significantly exceeded the average for many years (Table 1). Relatively large runoff occurred in November 2013 (63 mm). It is likely that suspended solids were washed off from drained surfaces and contaminants were partially diluted in retention reservoirs (inflow of clear liquids) during those periods (Lee et al. 2002, Liu et al. 2013). The reduction of average values in 2014 also referred to other variables: conductivity, NH_4^+, NO_2^-, SO_4^-, Fe^+, K^+ and Cl^-. On respective dates, the conductivity was only 60 $\mu S \cdot cm^{-1}$ (R2), the concentration of the suspension did not exceed 5 $mg \cdot dm^{-3}$, and NO_2^- 0.06 $mg \cdot dm^{-3}$ (R1 and R2). Fe^+, K^+ and Cl^- decreased to: 0.14 (R2), 1.3 (R1) and 7.0 $mg \cdot dm^{-3}$ (R2).

Some authors have shown strong affinity between suspended solids in rainwater and nutrients (Song et al. 2019, Vaze & Chiew 2004). According to them, nitrogen and phosphorus (N, P) are most often transported with finer and slower settled fractions. It was found that the concentration of N and P increased with an increase in the concentration of suspended solids and in water turbidity. In the reservoirs analysed in this work, similar connections were observed only on a few measurement dates. In the case of R1, they mainly concerned NH_4^+ and NO_2^-, while in R2 – NO_2^- and PO_4^-. R1 was more loaded with NH_4^+ than R2 (on average 24.9%), while higher concentrations of NO_2^- and PO_4^- were found in R2 (on average 47.0 and 282.8%). In R1 rainwater the average concentrations of most nutrients were higher in winter than in summer. Relatively high percentage differences were found for NH_4^+ (70.0%) and PO_4^- (40.7%). The average NO_2^- values remained at a similar level in both seasons. The only increase in pollution in the summer season was observed in 2015 and it concerned mineral forms of nitrogen. Different phenomena occurred in R2. The average concentrations of NH_4^+, NO_2^- and PO_4^- in summer time were higher than in winter. Differences reached even several hundred percent depending on the year and component. Downward trends in summer were found only in the case of NO_3^- (on average

86.0%). It is difficult to determine the reason for the increase in the concentration of nutrients in water of R2 in summer. According to some authors, the outflow of N and P from the catchment during the growing season should be smaller than in winter (Arheimer et al. 1996, Birgand et al. 2007). This is related to the ability to capture nutrients by autotrophs that form biogeochemical barriers in the basin. However, the share of biologically active areas is strongly reduced within the territory where the studied reservoirs are located. The drainage area is also small, and the take-over and transport of rainwater into the sewage system are very fast. The natural and economic systems analysed in the literature are more extensive and are characterised by a large variety of spatial development forms. In the studied rainwater reservoirs, the risk of eutrophication was mainly due to high NO_2^- concentrations. The maximum values were between 0.6 and 0.7 $mg \cdot dm^{-3}$. Relatively high average annual concentrations fell in 2013 (R1 and R2) and 2015 (R2) – exceeded 0.44 $mg \cdot dm^{-3}$. There was also a disturbing increase in NH_4^+ (maximum 2.28 $mg \cdot dm^{-3}$ in R1) and PO_4^- (maximum 0.56 $mg \cdot dm^{-3}$ in R2) on certain measurement dates. During those periods, the outflow of rainwater into ditches should be blocked (use the reserve capacity).

The average O_2 content in the analysed rainwater was satisfactory and was 8.9 (R1) and 9.7 $mg \cdot dm^{-3}$ (R2). In all years, high saturation of O_2 in R1 was maintained in winter and spring (7.8-13.7 $mg \cdot dm^{-3}$), and in R2 in winter, spring and summer (7.0-12.9 $mg \cdot dm^{-3}$). The worst condition was observed in autumn. The average O_2 concentrations were then 4.9 (R1) and 5.7 $mg \cdot dm^{-3}$ (R2). High levels of dissolved oxygen were found after many days of intense rainfall, taking place immediately before the liquid samples were taken. During the study, a gradual decrease in the average annual oxygen content in the examined rainwater was observed. Biochemical processes occurring in the growing layer of bottom sediments, as well as the elevated temperature of the retained liquid might be the cause (Dojlido 1995). During the tests, the average annual air temperature gradually increased (Table 1). This may result in negative phenomena within rainwater reservoirs in the future – for example, the intensification of anaerobic processes and the emission of gaseous pollutants into the atmospheric air. The presence of odours was noticeable in the vicinity of R2 in the warm months of the last year of research. If the weather trends persist, this nuisance may be significant if more rainwater reservoirs are built. This particularly applies to the territory of housing estates and travel service areas. Water was characterised by the greatest turbidity in this period. The phenomena characteristic of phytoplankton bloom have been observed (Fig. 4).

Fig. 4. Increase in turbidity of rainwater in the analysed reservoirs during the warm season

Despite the relatively high average concentration of dissolved O_2, BOD_5 and COD reached alarming levels in the analysed rainwater. The average values of these indicators were 7.1 and 61 $mg \cdot dm^{-3}$ in R1, and 6.5 and 60 $mg \cdot dm^{-3}$ in R2 (Table 2). In both reservoirs, a particularly high demand for O_2 occurred in spring and summer. In the warm season in R1, the average BOD_5 and COD values were higher by 34.7 and 184.1% compared to the cool season. In R2, these differences were even higher and amounted to 38.6 and 231.3%, respectively. The obtained results may indicate a high load of organic pollutants (Dojlido 1995). Artificial oxygenation using mechanical, chemical (Imhoff & Imhoff 2006) or biological methods could be a way to eliminate oxygen problems. Floating treatment wetlands are becoming increasingly popular among biological methods. At the same time, they demonstrate high efficiency in the elimination of other contaminants, e.g. N and P (Chang et al. 2012, Wang & Sample 2014). It is also important to successively remove bottom sediments, which unfortunately was not implemented in the case of the analysed objects. Sludge quality tests should be undertaken in order to determine the environmental hazard on their part and possible participation in secondary pollution of retained rainwater.

With the exception of the slight odour nuisance in the case of R2 (last year), during the study period no negative environmental impact of the analysed reservoirs was observed. Although R1 is an earth reservoir, made of local loess material, no over-standard deformations and displacements of individual elements as well as subsidence of adjacent land were found. No cracking and traces of caving were noticed in the body of the embankments. This may indicate a lack of intensive infiltration of rainwater into the ground and dikes. Despite the large inclination of slopes, erosive damage is also not observed. Dense vegetation effectively protects their surface (Fig. 3 and 4). R2 is a tight, concrete reservoir in which no infiltration takes place. This means that the risk of the described phenomena is very low. During the research period, no influence of R2 waters on the lowest located objects of the housing estate was found. Natural gravel and stones were sunk in the fresh concrete during construction, which improves the aesthetics of the reservoir. Shrub and tree planting also positively influenced its landscape values (Fig. 3 and 4). R2 should in principle perform the function of a classic open settling tank due to its sealing. However, after more than ten years of operation, its bottom completely captured the aquatic vegetation by succession (Fig. 5). The deposition of a thick layer of sediments with a loess suspension was a favourable factor. Currently, the reservoir resembles an artificial marsh ecosystem. Such solutions are considered as factors enhancing biodiversity in a poor, urbanised landscape (Herrmann 2012, Kazemi et al. 2011, Le Viol et al. 2009, Zubala 2018).

Fig. 5. Intensive plant development on the sealed bottom of reservoir

The basic principles of maintaining and operation of the analysed reservoirs are respected. As a result, no problems were observed in the operation of individual devices and the entire systems (including correct tightness of hydraulic closures and patency of inflow sewers). Supervision over the flow of rainwater is carried out properly. The need to remove bottom sediments from reservoirs should be considered. Their presence may hinder the precise control of the quality of collected and pre-treated rainwater (re-suspension and secondary pollution). Improving the quality of rainwater in the future would allow them to be used for economic and environmental purposes in the immediate vicinity of reservoirs (e.g. surface cleaning, green areas irrigation). According to many authors, this is an element of integrated and rational management of water resources (Mitchell et al. 2007, Pennino et al. 2016, Tao et al. 2014, Yu et al. 2013).

4. Summary

Retention and treatment of rainwater in the place of their formation contributes to reducing the load on sewage systems. However, it should be remembered that the very construction and operation of rainwater reservoirs can also be associated with environmental impact and irreversible changes in ecosystems (terrain relief, soils, surface and underground waters, landscape). The intensity of these processes depends on many factors, which are sometimes difficult to determine before putting the object into use. For this reason, it is necessary to constantly monitor and evaluate the functioning of existing infiltration reservoirs, settlers and constructed wetlands. This article shows a high variability of rainwater quality collected in the Lublin agglomeration reservoirs. Among the analysed indicators, suspended solids, NH_4^+, NO_3^- and K^+ were characterized by a significant differentiation of values (above 100%). The lowest variation was found for pH (approximately 10%). Rainwater from the section of the national road had higher conductivity, NH_4^+, SO_4^- and Cl^- than the water from the housing estate. In the second case, there was a greater load of NO_2^-, PO_4^-, Fe^+ and K^+. The analysed rainwater was characterized by poor quality on many measurement dates. Conductivity was a major threat, mainly related to meltwater runoff from the national road (maximum 3985 $\mu S\cdot cm^{-1}$). Alarmingly high was the pH (maximum 10.1) and the concentration of suspended solids (maximum 121 $mg\cdot dm^{-3}$). In some cases, an increase in the content of nutrients was observed – especially NO_2^-, NH_4^+ and PO_4^-. During these periods, the outflow of rainwater from reservoirs should take place under special control due to the risk of eutrophication. The relationships between the quality of retained waters and weather conditions or seasons of the year was also noted. For example, in the year with the highest precipitation sums, the average concentration of suspended solids, NH_4^+, NO_2^-, SO_4^-, Fe^+, K^+ and Cl^- decreased in the reservoirs. The conductivity was similar. This phenomenon results from rinsing the basin and diluting contaminants in reservoirs. In cold seasons, there was always an increase in the concentration of dissolved oxygen, as well as the values of conductivity and Cl^-. In spring and summer, the demand for oxygen increased (BOD_5 and COD) and oxygen deficits occurred. In the following years, a decrease in the average annual oxygen content in rainwater was observed. This may be related to biochemical processes occurring in the thick layer of bottom sediments and increasing average annual air temperatures and heating of retained waters. There is a periodic odour nuisance in the case of a reservoir in a housing estate. The use of open rainwater reservoirs near human settlements may be problematic if these trends persist and the sediments are not systematically removed.

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Abstract

Three-year observations made it possible to assess the degree of pollution and variability in quality of rainwater collected in two reservoirs in the Lublin agglomeration (south-eastern Poland). The studied objects are characterised by different construction, size, hydraulics and type of drained surface. In particular, a large variation in water quality indicators was observed for suspended solids, NH_4^+, NO_3^- and K^+. Higher conductivity, NH_4^+, SO_4^- and Cl^- was found in the reservoir receiving rainwater from the national road, compared to the water from the housing estate. In the second reservoir, a higher load of NO_2^-, PO_4^-, Fe^+ and K^+ was observed. Among the analysed variables, the most disturbing values were recorded for conductivity, pH, suspended solids, oxygen indicators, NO_2^-, NH_4^+ and PO_4^-. The liquid flowing into the reservoirs during snowmelt was characterised by high pollution. In the year with the highest sum of atmospheric precipitation, there was a reduction in medium concentrations of many quality variables (flushing effect, dilution of pollutants). An increase in oxygen demand and oxygen deficits were observed in warm seasons. An emission of inconvenient odors in the vicinity of the reservoir in the housing estate was also observed. These phenomena may be intensified in the case of improper use of the system (e.g. when bottom sediments are not removed) and further increase of air temperatures. Under such conditions, the possibility of using open rainwater reservoirs near human settlements becomes questionable.

Keywords:
rainwater, water pollution, retention reservoir, environmental protection

Ocena zmienności jakości wód opadowych i funkcjonowania zbiorników retencyjnych na terenie zurbanizowanym

Streszczenie

Na podstawie trzyletnich obserwacji dokonano oceny stopnia zanieczyszczenia oraz zmienności jakości wód deszczowych gromadzonych w dwóch zbiornikach na terenie aglomeracji Lublina (Polska południowo-wschodnia). Badane obiekty charakteryzują się różną budową, wielkością, hydrauliką i rodzajem powierzchni odwadnianej. Szczególnie duże zróżnicowanie wskaźników jakości wody dotyczy zawiesiny, NH_4^+, NO_3^- i K^+. W zbiorniku na wody deszczowe z drogi krajowej stwierdzano wyższą przewodność, NH_4^+, SO_4^- i Cl^- niż w wodach z osiedla mieszkaniowego. W drugim zbiorniku obserwowano większe obciążenie NO_2^-, PO_4^-, Fe^+ i K^+. Wśród analizowanych zmiennych najbardziej niepokojące wartości osiągała przewodność, pH, zawiesina, wskaźniki tlenowe, NO_2^-, NH_4^+ i PO_4^-. Wysokim zanieczyszczeniem charakteryzowała się ciecz dopływająca do zbiorników w trakcie roztopów. W roku z najwyższą sumą opadów atmosferycznych nastąpiło zmniejszenie średnich koncentracji wielu zmiennych jakości (przemycie zlewni, rozcieńczenie zanieczyszczeń). W ciepłych porach roku obserwowano wzrost zapotrzebowania na tlen i pojawianie się deficytów tlenowych. Stwierdzono też emisję odorów w sąsiedztwie zbiornika w osiedlu mieszkaniowym. Przy niewłaściwej eksploatacji systemu (m.in. brak usuwania osadów dennych) i dalszym wzroście temperatur powietrza zjawiska te mogą nasilać się. W takich warunkach możliwość stosowania otwartych zbiorników wód deszczowych w pobliżu siedzib ludzkich staje się wątpliwa.

Słowa kluczowe:
woda deszczowa, zanieczyszczenia wód, zbiornik retencyjny, ochrona środowiska

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A Comparative Analysis of Approval Driving Tests in the Context of Carbon Dioxide Emissions on the Example of Selected Passenger Cars

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1. Introduction

The global progress of civilization, which has been observed over recent decades, apart from technological development, also has negative effects, largely on the natural environment. Progressing urbanization, development of the energy, industry and transport have contributed to a significant deterioration in the quality of the ecosystems that surround us, including atmospheric air (Tritscher et al. 2020). The most serious and one of the priority problems is the excessive emission of carbon dioxide into the atmosphere, which contributes to an increase in the average temperature on Earth (Wang et al. 2020). The increased greenhouse gas emissions, including a large share of carbon dioxide – which accompanies virtually all fuel-to-energy conversion processes – are considered a major anthropogenic factor that deepens the greenhouse effect (Anderson et al. 2016).

From 1990 to 2019, global carbon dioxide emissions increased by over 60%. Table 1 summarizes the increase in global carbon dioxide emissions in the years 1990-2019.

The largest CO_2 emitters are China (approx. 27%), the United States (approx. 14.5%) and India (approx. 6.8%). Together, the EU-28 Community countries are responsible for around 10% of the gas discharge into the atmosphere. In 2017, Poland ranked 5th among the European countries with the highest CO_2 emissions. What is worse, the European Environment Agency has reported that our country has recorded the largest increase in carbon dioxide emissions compared to all EU member states (EEA Report No. 5 2018).

Table 1. Total global carbon dioxide emissions in 1990-2019

	CO_2 emissions [Mt]								
	22,182	23,007	24,559	29,255	33,067	35,463	36,153	36,573	36,810
Years	1900	1995	2000	2005	2010	2015	2017	2018	2019

Source: Author's own study based on: Global Carbon Atlas (1990-2019) http://www.globalcarbonatlas.org/en/CO2-emissions

According to the Global Carbon Project (GCP), 36.81 billion tonnes of CO_2 ($GtCO_2$) were emitted into the atmosphere in 2019. It means an increase of only 0.24 $GtCO_2$ (0.6%) compared to 2018.

The increase in global emissions in 2019 was almost entirely caused by China. This country has increased its CO_2 production by 0.26 $GtCO_2$. The rest of the world has reduced its emissions by -0.02 $GtCO_2$. This was due to a reduction in coal consumption in the US and Europe, as well as a slowdown in the Indian economy compared to previous years (Friedlingstein et al. 2019).

Transport is responsible for approximately 25% of CO_2 emissions, of which 70% is road transport. This sector is closely connected with practically every branch of the economy, which translates into increased dynamics of its development. The number of motor vehicles and road networks is constantly increasing, which translates into increasing negative environmental effects. In 2016, passenger cars were responsible for about 60% of total emissions, while trucks and vans only for 38%. On the example of Poland, it can be seen that the increase in the number of passenger cars is significant. In 2012, the number of passenger cars in Poland was 18,744,400, while in 2017 this number increased to 22,569,900 (PZPM Report 2018, Central Statistical Office of Poland 2019). Therefore, an increase of over 20% was recorded. The numerous advantages of road transport and the increased demand for broadly understood mobility contribute to increasing the number of vehicles on the road. According to the data of the General Directorate for National Roads and Motorways (GDDKiA), the volume of traffic on national roads is also increasing. The general traffic measurement carried out in 2015 (this measurement is carried out every 5 years) showed an increase in traffic on national roads by 14%. The average daily traffic in 2015 for motor vehicles was 11,178 vehicles per day, compared to 9,888 vehicles per day in 2010 (Opoczyński 2016).

As early as 1992, the world already took action to reduce greenhouse gas emissions, including carbon dioxide, during the United Nations Framework Convention on Climate Change. The basic resolutions of the convention concerned national strategies for reducing greenhouse gas emissions – the preparation of such strategies and their consistent implementation, the inventory of emissions, the preparation of reports related to the implementation of the Convention's postulates as well as the commitment to conduct research in the field of climate change (United Nations Framework Convention 1992). Another important document was the Kyoto Protocol to the United Nations Framework Convention on Climate Change, drawn up at Kyoto in December 1997, which set binding quantitative and qualitative targets for reducing greenhouse gas emissions (Kyoto Protocol 1997).

The European Union has taken consistent action in the context of the fight against climate change by adjusting its environmental policy to global commitments (Fuss et al. 2020). On December 12, 2015, COP21 was held, which was a meeting of the parties to the United Nations Framework Convention on Climate Change. The international proceedings were concluded with an agreement on maintaining the average temperature rise on earth at 2°C, compared to the period before the industrial revolution (UN FCCC/CP/2015/L.9 2015). Therefore, the European Community has committed itself to reducing greenhouse gas emissions, including CO_2, by 40% compared to 1990 levels. The time horizon was set for 2030 (Schleussner et al. 2016). Such stringent reduction levels have an impact on all sectors, including road transport (Krause et al. 2020).

In the road transport sector, aspects of emissions from vehicles have been regulated by EURO standards (1-6) since 1993. Introduced by relevant European directives, they have set binding limits for individual chemical compounds for newly manufactured vehicles. To verify cars in terms of the amount of emitted substances, the NEDC (New European Driving Cycle) approval test was performed. The procedure was developed in the 1980's, while it was officially used since the early 1990's (Mock et al. 2014).

In its updated phase, the test was divided into 2 parts – the urban cycle and the extra-urban cycle. The urban part, which was supposed to reflect driving in agglomerations, lasted 13 minutes, during which time the vehicle covered a distance of about 4 km. In this part there were 4 consecutive phases of accelerating the vehicle to the speeds of 15, 32 and 50 kph, followed by a stop of the vehicle. After repeating this cycles four times, the extra-urban cycle followed, typical for non-residential areas and motorways. This part lasted 6 minutes and 40 seconds and the vehicle covered about 7 km at that time. It included accelerating the vehicle to the speeds of 70, 100 and 120 kph. This part was carried out once, without stops, only with a reduction of the speed to 50 kph.). Based on this test procedure, the fuel consumption and emission of individual exhaust components from the tested vehicle were determined (Barlow et al. 2009, Regulation No 83 of the UNECE 2012).

Unfortunately, this test was characterized by quite a generalization and at some point did not at all reflect the real road conditions or the dynamics of modern cars, which has changed a lot since the 1990's. Along with increasingly stringent environmental standards, it was necessary to introduce a new test procedure that would be reliably testing exhaust emissions of motor vehicles. From 2008, work began on a new approval test and from September 1, 2018, the WLTP (Worldwide Harmonized Light Vehicles Test Procedure) approval procedure was introduced into widespread use for all newly manufactured vehicles to be driven within the territory of the European Union. The WLTP test distinguishes three categories of vehicles and the criterion is the power factor per vehicle mass [kW/t]. Currently, only cars from the third class are offered on the European market. The procedure includes 4 driving phases: low (average speed: 18.9 kph), medium (average speed: 39.4 kph), high (average speed: 56.5 kph) and very high (average speed: 94.0 kph). Stops are also included. The whole procedure lasts 30 minutes, during which time the car covers a distance of 23.25 km, which is more than twice as much as in the previous test. The WLTP also takes into account the equipment and tires mounted on the vehicle and is performed in more reliable temperature ranges, as for European conditions. In addition, the test will be different for each car because it takes greater account of its dynamics. All this is to be reflected in the precision of the results obtained and their compliance with real conditions on the road (Orynycz et al. 2020). Table 2 below summarizes the main differences between the two approval tests.

As seen in the above table, the tests differ significantly, which may have a large impact on the results obtained on their basis. In this paper, it was decided to compare both test procedures on the example of a passenger car powered by biofuels and diesel. The choice of the vehicle was dictated by its urban character as well as the variety of fuels with which it can be supplied. The value of emitted carbon dioxide was chosen as the assessment parameter, due to the increasing restrictions on its reduction. The research used a simulation model that reflects the movement of the vehicle according to the given test procedure.

Table 2. Differences in the NEDC and WLTP homologation test procedures

Parameter	NEDC	WLTP
Development/Introduction	Developed in the 1980's, introduced at the beginning of the 1990's.	Developed from 2008, introduced from 1 August 2018.
Driving cycles	Urban cycle 65% and extra-urban cycle 35%	Low, medium, high and very high cycles. Urban cycle share – 52%, extra-urban cycle share – 48%
Duration	20 min	30 min
Total distance	11 km	23.25 km
Average speed	34 kph	46.5 kph
Maximum speed	120 kph	131 kph
Gear shift	According to schedule, in specific points	Individually, depending on the vehicle being tested
Remarks	No distinction between versions of equipment, tyres installed or other factors	Allows for vehicle equipment, tyres installed and other factors affecting exhaust emissions

Source: Author's own study based on (https://wltpfacts.eu/, Mock et al. 2014, Kroyan et al. 2020)

2. Methodology

The simulation model was developed in the SciLab environment. It is an open source scientific software that enables one to perform complex numerical calculations and build computational algorithms in a user-friendly manner. The unquestionable advantage is the ability to create block diagrams, each of which is based on mathematical equations and becomes a small element of a large simulation system. It is possible for the program to solve complex differential equations, linear and nonlinear systems, and optimize the resulting algorithms, which makes it a useful tool, also for structurally complex models. To build a simulation model of carbon dioxide emissions from the vehicles in question, the Xcos package was used, which corresponds to the Simulink package of the competitive Matlab environment and employs block diagrams to reflect the vehicle operation and dependencies in its mechanical systems (Czemplik 2012, Jaroszyński et al. 2014). Those research methods, based on computer simulations, are characterized by numerous advantages such as repeatability of results, the possibility of quick and costless modification of data and the acquisition of large amounts of data in a relatively short time (Łatuszyńska 2011).

The simulation model used the technical parameters of a Fiat Panda 1.3 MultiJet passenger car with a diesel engine. The Fiat Panda, equipped with a modern diesel engine of 1.3 liters, reaches its maximum power of 55 kW at 4,000 rpm and the maximum torque of 190 Nm is already achieved at 1,500 rpm. Diesel engines have different working characteristics than gasoline engines and achieve maximum torque sooner and in the lower RPM range. Fuel consumption for this car, according to the catalog data, is respectively: in the urban cycle 4.7 [l/100 km], in the extra-urban cycle 3.5 [l/100 km], while in the mixed cycle the fuel consumption is 3.9 [l/100 km] (FCA POLSKA SA 2015). Table 3 below lists the technical parameters of the engine in question.

Table 3. Technical parameters of 1.3 MultiJet engine

Parameter	Unit	MultiJet II
Engine cylinder capacity, Vss	cm^3	1251
Cylinder layout	–	in-line
Number of cylinders, c	–	4
Diameter of cylinder, D	mm	69.6
Injection type	–	direct, multistage

Table 3. cont.

Parameter	Unit	MultiJet II
Compression ratio, e	–	16.8 : 1
Piston stroke, S	mm	82
Maximum engine power, Ne	kW	55
Engine speed at maximum power, nN	rpm	4000
Maximum engine torque, Me	Nm	190
Engine speed at maximum torque, nM	rpm	1500
Rotational speed on idle gear, nbj	rpm	850±20

Source: Author's own calculations based on (Zembowicz 2010, Ambrozik et al. 2012)

In order to properly conduct the test procedure, it was necessary to implement appropriate fuel parameters and their consumption characteristics. The following conventional fuel and its alternative substitutes were used in the simulation to additionally assess the reduction potential of popular biofuels: diesel, fatty acid methyl esters (FAME), butanol (butyl alcohol). These substances were tested as self-contained fuel as well as mixtures with diesel oil. Table 4 below lists the properties of the fuels mentioned.

Table 4. Parameters of fuels used in the simulation

	Combustion parameters		Elemental composition		
	Calorific value [MJ/kg]	Air demand [g_{air}/g_{fuel}]	Carbon content [%]	Hydrogen content [%]	Oxygen content [%]
Diesel oil (ON)	44	14.5	86.5	13.4	0.0
Rapeseed oil (RO)	38.0	12.5	77.6	11.7	10.5
FAME (FAME)	37.0	12.5	78.0	12.0	10.0
Butanol (B)	33	11.2	64.8	13.5	21.6

Source: Author's own study based on (Baczewski et al. 2004, Gwardiak et al. 2011, Jóźwiak et al. 2006, Żółtkowski et al. 2015)

The above fuel and engine parameters as well as the course of approval tests were input into the simulation model being developed, which was used to obtain the results of carbon dioxide emissions from individual vehicles powered by various fuels. The results obtained refer to direct emissions during the test. In order to be able to refer to the reference values specified in the EURO standards, it was necessary to convert them into a unit appropriate for the standard – gram per kilometer [g/km].

The diagram of the model used to perform the computer simulation has been presented in Figure 1.

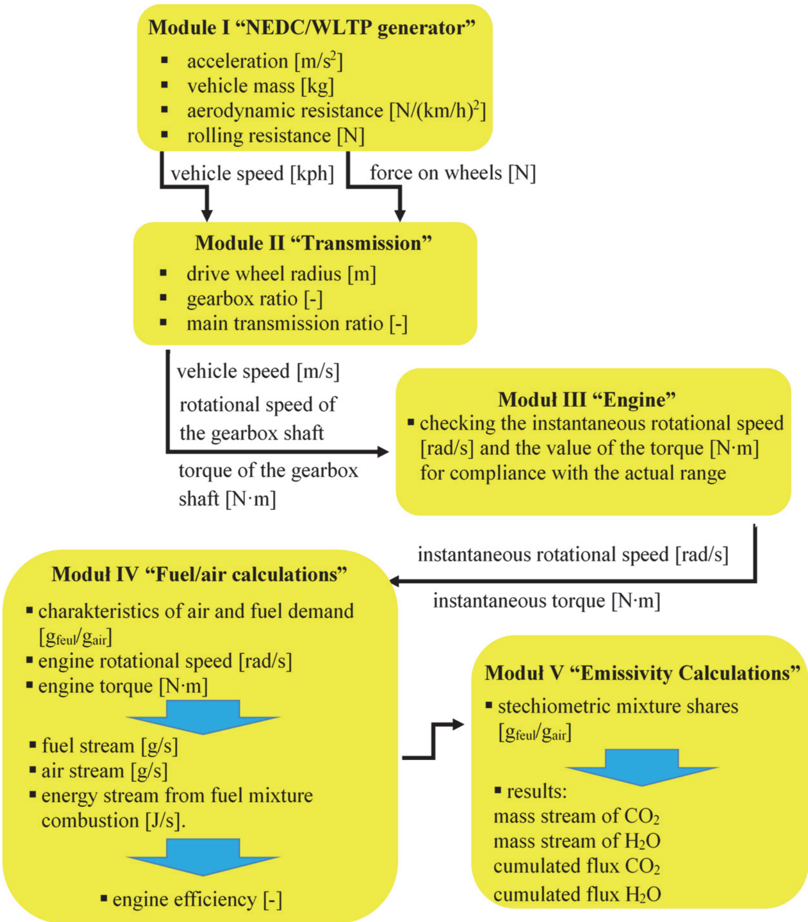

Fig. 1. Structure of the simulation model for CO_2 emissions from the NEDC and WLTP tests; Source: Author's own study

The model was divided into five modules, each of which was responsible for providing the results necessary to determine carbon dioxide emissions from the vehicles tested. Each of the modules presented in the diagram is described below:

- Module I "NEDC/WLTP generator" – Based on vehicle data such as mass, rolling resistance or aerodynamic resistance, the block provides the parameters characteristic for each driving test in the form of vehicle speed and wheel force.
- Module II "Transmission" – This block uses data on vehicle wheel size (dynamic diameter), transmission system ratios in relation to the rotational speed and ratios for the torque. On this basis, it generates signals such as: the speed at which the vehicle moves, the torque of the gearbox input shaft and its rotational speed.
- Module III "Engine" – Based on this module, the parameters obtained so far, such as the instantaneous speed and the instantaneous torque, are verified. It is essential that both of these factors should be within the designated ranges, allowed for a given engine. Any values that deviate from the acceptable ranges are directed to extreme parameter blocks and do not participate in further simulation stages.
- Module IV "Fuel/air calculations" – The block is based on the implemented hourly characteristics of the fuel and air demand and uses the torque and rotational speed values obtained in the previous block. It then calculates the fuel and air flow necessary to carry out the correct combustion process and the energy stream from the conversion of the fuel-air mixture.
- Module V "Emissivity calculations" – Taking into account the share of individual elements in the mixture, such as hydrogen, carbon and oxygen contained in the fuel mixture, mass streams of carbon dioxide and steam are determined and then their cumulative values are set.

3. Research results and discussion

The simulation model, developed according to the above scheme, renders it possible to map the movement of the vehicle according to the given driving test. It is therefore possible to carry out the experiment including the "start-stop" system installed in the vehicle and to determine the desired values of carbon dioxide emissions for fuels with different properties. Figure 2 below presents a summary of the charts obtained from module I and II, which reflect the values of individual parameters as the vehicle completes a given driving cycle. Part "A" refers to the NEDC test, while "B" refers to the WLTP. The parameters included here are: the vehicle speed (v [kph]), the distance traveled by the car (d [km]), resistance forces (F [N]) and the current gear ratio, i.e. the gear in which the vehicle is moving (p [-]).

The following comparison illustrates the significant difference between the two procedures in each of the aspects mentioned above. Even at first glance it can be inferred that the WLTP provides much more parameters than its predecessor and reflects the dynamics of the vehicle movement far more precisely. The courses of the speed of the car in each of the tests are consistent with the courses published in the available literature, which may lead to a conclusion that the model is working properly and provides reliable data. The further part of the results compares fuel consumption as a function of the additive share and carbon dioxide emissions as a function of the additive share. For these results, the functioning of the "star-stop" system was taken into account, which is fitted as standard equipment of the tested vehicle.

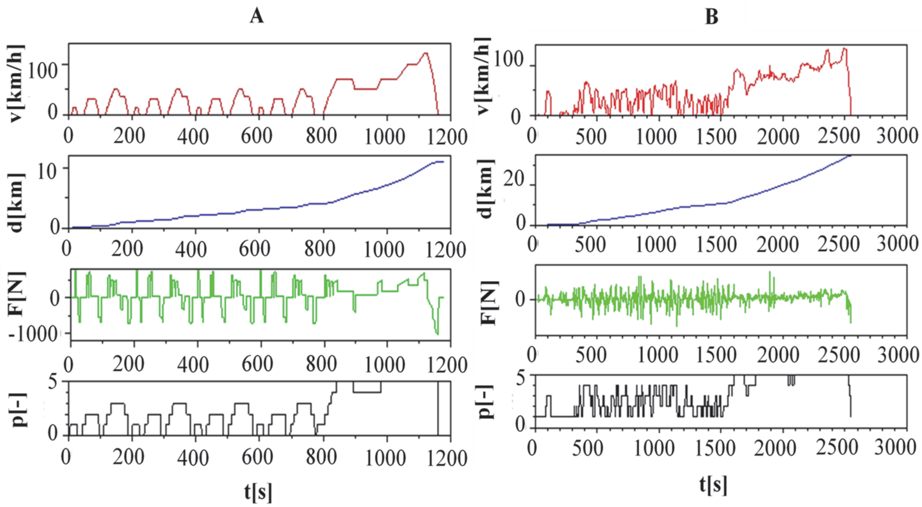

Fig. 2. Parameter courses obtained from modules I and II for NEDC (A) and WLTP (B) tests; Source: Author's own study

The vehicle under analysis has a five-speed gearbox. Therefore in figure 2 for p [-] the maximum value is 5. The figure shows the full range of changes of p [-] values.

3.1. Fuel consumption in the NEDC and WLTP tests – "start-stop" system disabled

Figure 3 summarizes the consumption of individual fuels and their mixtures [kg] by the vehicle in test A) NEDC and B) WLTP. This list does not include the operation of the system responsible for switching off the engine when the vehicle is idle (stationary).

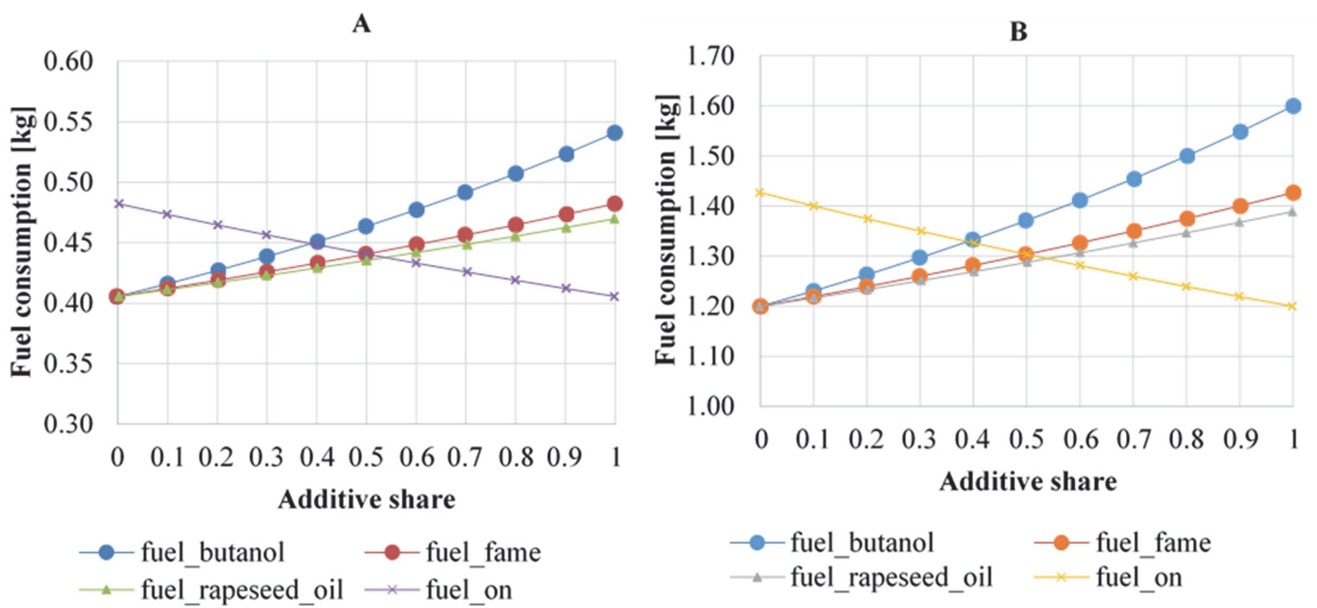

Fig. 3. Consumption of fuels and their mixtures in NEDC (A) and WLTP (B) tests (“start-stop” system disabled);
Source: author’s own study

Based on the above graphs, a significant difference can be seen between the vehicle's consumption of individual fuels and their mixtures. Higher consumption in the WLTP test is correct though, due to the test distance being more than twice as long. Therefore, the difference obtained is obvious and the results obtained are correct. Both in the WLTP and NEDC tests, it can be seen that the increasing share of the additive in the mixture with diesel oil increases the consumption of the carrier and the highest values are achieved by biofuels as 100% powering fuel.

3.2. Fuel consumption in the NEDC and WLTP tests – "start-stop" system enabled

The Figure 4 shows the consumption of various fuels and their mixtures [kg] by the vehicle in the A) NEDC and B) WLTP tests while the "start-stop" system is enabled and shows its operation when the car is stationary.

With reference to the previous charts, a clear difference can be noticed in reducing the vehicle's fuel consumption. For pure butanol, the value of the carrier used in the NEDC test without the engine immobilization system is 0.54 kg, while with its participation it is merely 0.48 kg. The downward trend applies to all fuels and is a natural consequence of a break in the engine operation, therefore it does not combust fuel. In the WLTP procedure, a decrease in fuel consumption can also be seen, with the "start-stop" system running. However these differences are smaller due to the reduced number of stops and the longer test distance.

The following part presents the results of carbon dioxide emissions for individual fuels and test procedures, also taking into account the operation of the "start-stop" system in the vehicle.

3.3. Carbon dioxide emissions in the NEDC and WLTP tests – "start-stop" system disabled

Below (Fig. 5) are the results of carbon dioxide emissions for individual alternative fuels, and their mixtures with conventional diesel for the A) NEDC and B) WLTP test procedures. This option does not include the functioning of the "start-stop" system.

It can be seen that in the WLTP test emission values are about 4 times higher than for the NEDC test. When comparing the selected biofuels in both tests, butanol showed the lowest CO_2 emissions. Rapeseed oil gave intermediate results, while the highest concentration of carbon dioxide was provided by fatty acid methyl esters. This value increased along with the increase of this additive in a mixture with conventional diesel oil.

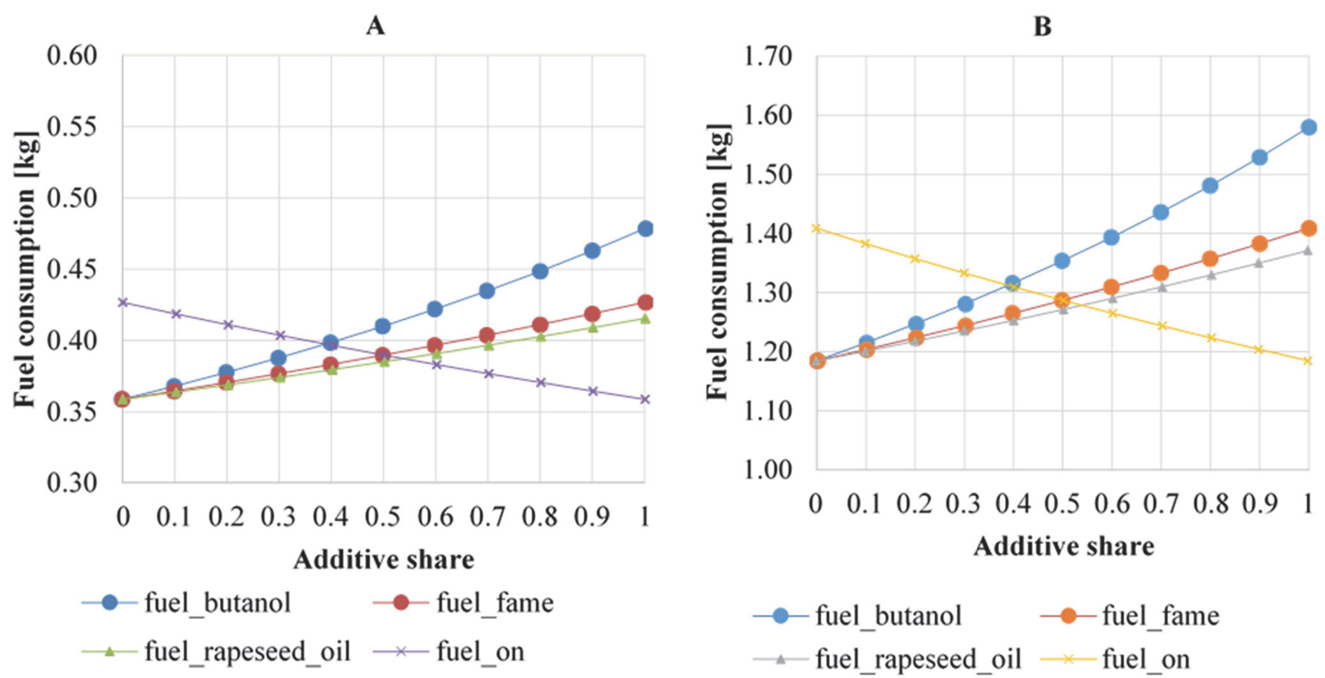

Fig. 4. Consumption of fuels and their mixtures in the NEDC (A) and WLTP (B) tests (“start-stop” enabled);
Source: author’s own study

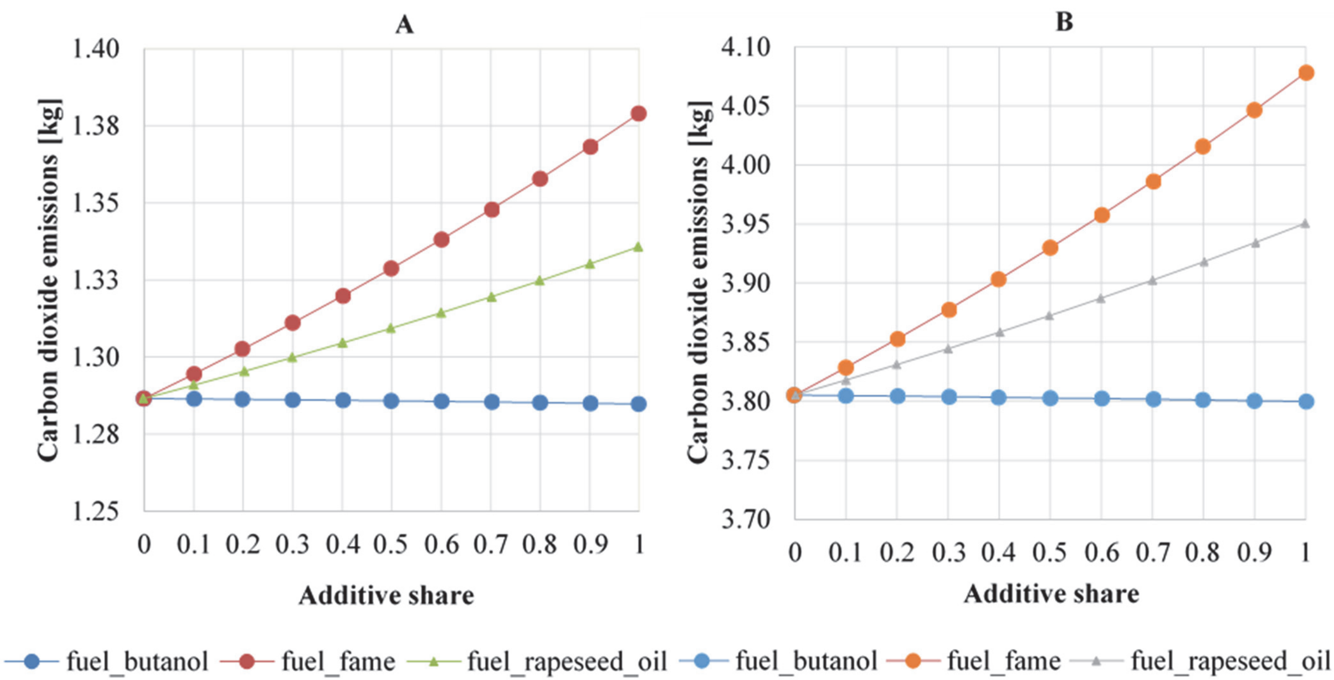

Fig. 5. Carbon dioxide emissions from individual fuels in the NEDC (A) and WLTP (B) tests (“start-stop” disabled); Source: author’s own study

3.4. Carbon dioxide emissions in the NEDC and WLTP test – "start-stop" system enabled

Fig. 6 summarizes the results of CO_2 emissions for selected A) NEDC and B) WLTP test procedures when the "start-stop" system is enabled.

It can be clearly seen that there is a favourable difference compared to not stopping the engine when the vehicle is stationary. In addition, as in the case of previous results, carbon dioxide emissions were much higher for the WLTP procedure than for the NEDC. This is obviously due to the vehicle's longer operation and fewer stops in the new test.

3.5. Summary of results

In the above form, it is impossible to objectively compare both methods due to the numerous differences in both schedules. As mentioned earlier, the new approval test has a much longer distance to be covered by the vehicle as well as different dynamics of movement. Therefore, Table 5 summarizes the results obtained for 100% fuels in both tests and converted them into a reference unit. This unit is strictly defined in EURO standards and is expressed as gram of substance per kilometer of road [g/km]. For the passenger car in question, the permissible value of carbon dioxide specified in the EURO standard is 130 g/km (Regulation (EC) No. 443/2009).

The above results show that no fuel exceeds the permissible level of carbon dioxide emissions in 100% content. It was evident in earlier graphs that alternative fuels as self-contained carriers show the highest emissivity, hence the values of emitted carbon dioxide for their pure forms were used for this comparison. With reference to the comparison of the values for both tests, it can be stated that:

- The values of carbon dioxide emitted for individual fuels depend on the functioning of the "start-stop" system.
- When engine sleep is off, this emission is lower for WLTP than NEDC.
- When the "start-stop" system is active, emissions in the new test procedure are higher. This may be related to the number of stops, of which are there are fewer in WLTP.
- In both tests, regardless of the system being on or off, the highest direct CO_2 emissions were attributed to FAME fatty acid methyl esters.
- Butanol was the fuel with the lowest emissions.

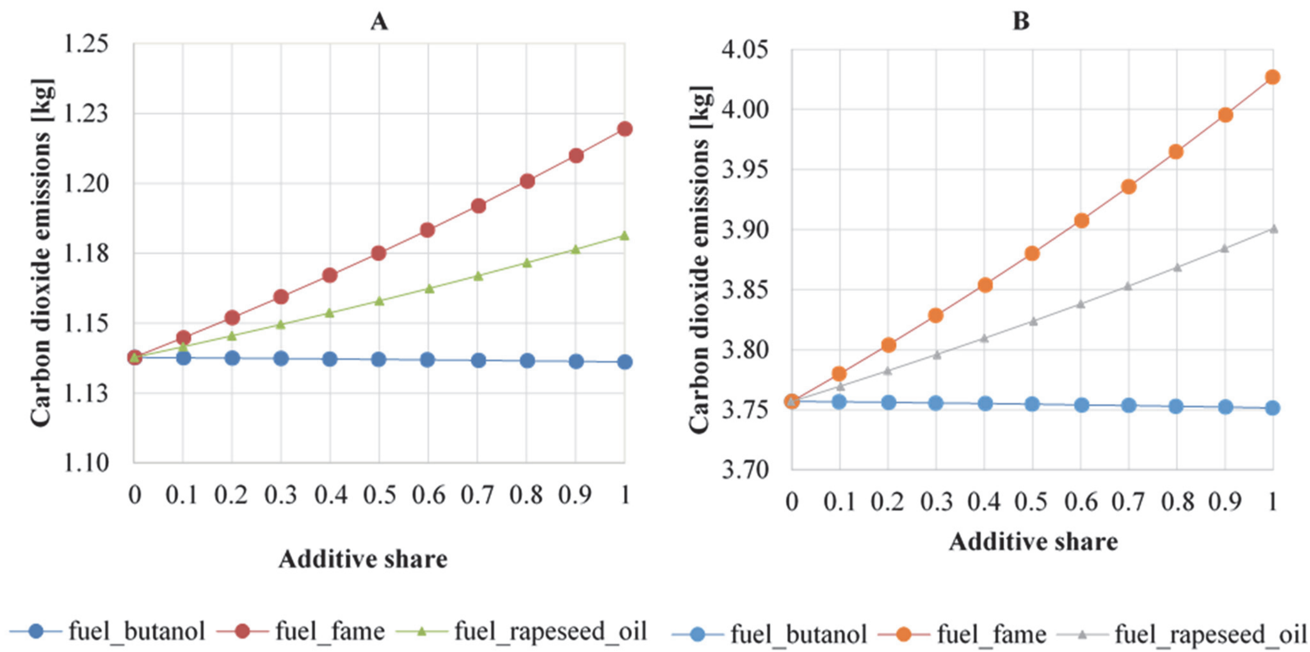

Fig. 6. Carbon dioxide emissions from individual fuels in the NEDC (A) and WLTP (B) tests ("start-stop" enabled);
Source: author's own study

Table 5. Summary of CO_2 emission results in NEDC and WLTP drive tests: Diesel oil (ON); Fatty Acid Methyl Esters (FAME), Rapeseed oil (RO); Butanol alcohol (B)

Driving test used	NEDC							
Distance in the test [km]	11.03							
Start/stop system	OFF	OFF	OFF	OFF	ON	ON	ON	ON
Fuel used	ON	FAME	RO	B	ON	FAME	RO	B
Carbon dioxide emission CO_2 [kg]	1.286	1.378	1.335	1.284	1.137	1.219	1.181	1.136
Reference unit [g/km]	116.591	124.932	121.034	116.410	103.083	110.517	107.072	102.992
Driving test used	WLTP							
Distance in the test [km]	34.68							
Start/stop system	OFF	OFF	OFF	OFF	ON	ON	ON	ON
Fuel used	ON	FAME	RO	B	ON	FAME	RO	B
Carbon dioxide emission CO_2 [kg]	3.805	4.078	3.95	3.799	3.757	4.026	3.900	3.751
Reference unit [g/km]	109.717	117.589	113.898	109.544	108.333	116.09	112.456	108.160

4. Summary

The deteriorating condition of the natural environment, including the air that surrounds us, influences the formation of climate policies of many countries and communities. Road transport, as a serious source of emissions, also in the field of carbon dioxide, is subject to increasingly restrictive regulations designed to limit its negative impact on ecosystems.

One example of changes in the transport sector was the introduction of a new approval procedure for motor vehicles to be put into service in the European Union. The comparative analysis of the new test with the previous procedure showed:

1. The new WLTP approval test should bring much more accurate results than the previous NEDC test, due to its assumptions in terms of time, distance, driving conditions and individual treatment of each vehicle
2. Research on carbon dioxide emissions from diesel oil and its alternative fuels has yielded equivocal results, depending on the activity of the vehicle's "start-stop" system.
3. For the engine sleep system turned on when the engine was idle, more emissions were recorded in the WLTP test.
4. For the switched off system, this emission was higher in the previous test procedure
5. When remaining within one test, it is clear that the "start-stop" system will reduce the amount of carbon dioxide emitted to the atmosphere.
6. It is worth mentioning that considering the results without a "start-stop" system is quite theoretical due to the fact that this system is in the basic equipment of the car, so it can be assumed that the WLTP test provided more objective results and the NEDC procedure simply lowers them.

The developed driving cycle test simulation tool uses data on actual fuel parameters (calorific value, chemical composition) and their mixtures. This allows for forecasting the change in exhaust gas emissions when using a different fuel mixture.

The simulation of engine operation takes into account the actual characteristics of specific fuel consumption as a function of speed and torque, which allows for the precise determination of momentary operating parameters and emissions under dynamic engine operation conditions during driving cycle tests. In the literature, the solutions used so far have mostly used averaged values resulting from vehicle exploitation.

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Abstract

This paper presents a comparison of two approval tests for a passenger car, both the current procedure and its predecessor. The car that was the subject of the study received a roadworthiness certificate based on the NEDC test, however, the emission results were compared with the new test procedure. The analysis showed the significance of the "start-stop" system in the conducted tests, however, assuming the original equipment of the car (active "start-stop" system), the WLTP test showed higher CO_2 emissions, which did not exceed the permissible emission standard for this model specified in the relevant regulation.

Keywords:
engine, CO_2 emission, NEDC, WLTP

Analiza porównawcza homologacyjnych testów jezdnych w kontekście emisji dwutlenku węgla na przykładzie wybranych samochodów osobowych

Streszczenie

Niniejsza praca przedstawia porównanie dwóch testów homologacyjnych dla samochodu osobowego, zarówno aktualnie obowiązującą procedurę jak i jej poprzednika. Samochód, który był obiektem badań, świadectwo dopuszczenia do ruchu otrzymał na podstawie testu NEDC, jednakże porównano wyniki emisji z nową procedurą testową. Dokonana analiza wykazała istotność systemu „start-stop" w przeprowadzonych badaniach, zakładając jednak oryginalne wyposażenie auta (aktywny układ start-stop) test WLTP wykazał wyższą emisję CO_2, jednakże nie przekroczyła ona dopuszczalnej dla tego modelu normy emisyjności określonej w stosownych przepisach.

Słowa kluczowe:
silnik, emisja CO_2, NEDC, WLTP

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Presentation of Experimental Biomass Gasification with Minimizing Gibbs Free Energy Mathematical Model

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1. Introduction

Thermochemical processing of biomass is the effective way of producing combustible gas (synthetic gas) The use of biomass by gasification has many advantages:

- using a wide range of biofuel and combustible waste types, even the wastes with the high moisture content,
- reduction in atmospheric pollution by using biofuels,
- the possibility of increasing the efficiency of equipment.

Today the technology of pyrolysis and gasification of need to be upgraded.

The synthesis of biogas is implement by various methods, for example, by the method of biochemical oxidation of raw materials, as presented in work (Kaosol & Sohgrathok 2013). This way makes it possible to get similar products (Malakahmad et al. 2013, Puah et al. 213), but these methods are not appropriate for all types of raw materials. Moreover it is difficult to predict the composition of the synthesized gas (Pavlenko & Koshlak 2019, Lavrov 1957).

Technological plants and systems for generating generator gas by biomass gasification currently need to be improved. There are methods to predict the composition of the generator gas and then its performance depending on the device parameters. The issue of processes are reflected in the works of many authors (Christus Jeya et al. 2014, Koroneos & Lykidou 2011) and others. Inthat papers, the experimental research of the gasification of solid fuels are shown, however the development of methods for predicting the composition of synthetic gas and determining the best parameters of the process has not been touched.

The method of predicting the composition of the gas is a big challenge for synthesis technologies, when it rise up the efficiency of the gas generator. To create a method for predicting the composition of the gas, we took as a basis the works of the authors (Zainal et al. 2001, Yang et al. 2006), where the energy characteristics of the resulting gases were evaluated. From our point of view it is highly important to know the composition and the influence of every component on the energy characteristics of the gas. It will allow to optimize the composition and predict the basic thermal characteristics. That was our main goal. In this article, we present the results of experimental research of multifactorial biomass gasification processes and the model of gasification based on the Gibbs free energy function.

2. Mathematical model and its solution

The main task of the research is to create a model of the biomass gasification process for predicting the composition of the synthetic gas and the parameters of the technology using a parameter – maximum thermodynamic efficiency. To do this, the following tasks must be done:

- investigate the whole processes of the gasification of biomass in installations with fluidized bed,
- go through a physico-chemical analysis of gasification processes,
- experimentally check the mathematical model.

The actual process of gasification depends on many parameters. Existing mathematical models of this process usually consider only some of them, so the modeling is not very accrue. The most of models are bulid on experimental data or hypotheses and correspond only with certain process.

In all existing approaches to mathematical modeling of the gas synthesis by gasification, the method for minimizing the free Gibbs energy should be considered. It does not need specification and choosen of specific gasification reactions (Jarungthammachote & Dutta 2008) and only takes into account the starting and end products of the process. This method is more suitable for viewing complex systems in which a large number of reactions occur. The method is based on the research of the equilibrium state of all those involved in the reactions of the gasification process.

The point of the method is the use of the thermodynamic potential of the system, the change of which goes to the minimum value under the condition of its equilibrium. The isobaric and isothermal potential (Gibbs energy) of a system of ideal gases is presented in the equation (1). Knowing the pressure in the gasification chamber is 1 ata, the properties of the gases approximate those of an ideal gas, we write equation (2) in developed form. The issue of defining the composition of a synthetic gas with an equilibrium state of the system comes to the search for a composition that correlate to the minimum value of the function (Gtot → min) expressed by equation (3) under certain limiting conditions. The boundary conditions for this method of modeling the gasification process are the equations of the mass and energy balances of the elements of the system.

3. Basic simplifications of the mathematical model

The application of the thermodynamic equilibrium method require certain simplifications, the most important of which are presented:

- the time of passing of all gasification reactions is enough to get an equilibrium among all the gasification products,
- all gases involved in the gasification process have the properties of an ideal gas,
- the proportion of components of biomass which does not exceed 1%, and ash are not considered,
- the components of the synthesis gas produced are CO_2, CO, H_2, H_2O, CH_4, C_2H_4, C_6H_6, N_2.

1) Taking humidity into account. In most research on the gasification process, the authors do not take into account the humidity of the air supplied to the reactor, since their proportion will not be significant. However, the amount of moisture flowing in with the blowing air can reach 7% relative to 1 kg of fuel. This amount of moisture has a significant impact on the efficiency of the gasification process and should be considered in the mathematical model of the gasification process.
   The w_{air} is determined by the dependence (total water mass per kg of dry fuel) and is presented in equation (4).
2) The presence of an unreacted carbon residue. In (X Li et al. 2001) it was experimentally proven that with increasing temperature in the reactor and the same parameters, the CO_2 concentration decreases in favor of CO. To produce 1 kmol of CO, you need twice as much oxygen as for the formation of 1 kmol of CO_2 with the same amount of carbon. Therefore, oxygen shows in the composition of other gas components (H_2O) or remains in the free form (O_2). However, gasification products contain practically no free oxygen in their composition under various gasification conditions, and the H_2O concentration decreases with increasing temperature in favor of H_2. Therefore its sensible to talk about an increase in carbon conversion with increasing temperature. An increase in the rate of conversion of carbon also takes place with an increase in the amount of moisture entering the reactor (Skoulou et al. 2008, Miao et al. 2013, Pavlenko 2019).

The proposed model proposes to determine the amount of non-gasified carbon residue through empirical relationships obtained based on the results of the experimental studies carried out.

The obtained dependence is presented by equation (5).

This regression equation is obtained after statistical processing of experimental data. We assumed that the total carbon balance contains the main components CO, CO_2, CH_4, C_2H_4, C_6H_6 and unreacted carbon (C). It is obvious that the amounts of these components will depend on the factors mentioned above, the values of which have changed in the experiments within: α_{bio} = 0.05-0.5; T = 800-1000°C; W = 5-50%.

3) Hydrocarbon yield based on empirical define. The emissions of such components as methane and other hydrocarbons (C_nH_m) cannot be well predicted using a stoichiometric model. Even if the relatively low yield of hydrocarbon compounds is not neglected, this has a considerable influence on the prediction of the yield of other components of the synthesis gas. Because of the fact that some of the hydrogen (H) and carbon (C) do not lead to the formation of molecules of the type (C_nH_m) but to the formation of other gas components, this cause an overestimation of the concentration of the combustible components of the synthesis gas in the stoichiometric model. It is proposed to determine the yield of some hydrocarbons based on empirical relationships that have been compiled from the results of experimental studies. The resulting dependence for the molar yield of CH_4 under the above experimental conditions is represented by equation (6).

4) Assuming non-adiabatic process conditions. Most of the work deals with the gasification process under adiabatic conditions (without heat loss or additional heat input). During real operating conditions, heat losses are unavoidable, and with a low input of the gas generator, heat losses can significantly reduce efficiency.

In the mathematical model, such components as heat losses in the gas generator are included in the energy balance equation, which offers the possibility of a more precise and comprehensive evaluation of the gasification process.

3.1. Equations of mass balances

The general mass balance equation for every jth element in the system containing M elements represents equation (8). The gasification process can be modeled without dividing it into stages and only considering the start and end products of the process that shows equation (7).

3.2. Equation of energy balance

The general equation of the energy balance for the gasification is equation (9) and its expanded form is equation (10) while the energy of the all elements of the system includes its energy of formation and the physical heat that is presented by equation (11).

The Lagrange multiplier use the Gibbs function and link all the conditions in equation (12).

The partial derivatives for each component of the synthetic gas equal zero and creates a system of equations (12) that solution makes it possible to determine the composition of the generator gas under certain conditions of gasification. Since the mole yield of CH_4, C_2H_4, and C_6H_6 is determined by empirical relationships, they will enter the system (13) as constant values for the chosen conditions of running the gasification process.

In the system of equations (13), in addition to the variables x_1, x_2, x_3, x_4, the value of the free Gibbs energy (G_{fi}^{0}), the value of which depends on the temperature, is also taken into account. In this case, the temperature of the system can be determined from the general equation of the energy balance (10) and is a function of the final composition of the generator gas.

This task is solved by an iterative method.

Experimental investigations of the gasification process were driven in a fluid bed generator. Based on the results of experiment, the material and energy balances of the process were created for various gasification conditions, on the basis of which the efficiency of the gas generator and the quality of the thermochemical treatment of biomass could be fully assessed what Figures 1-4 shown. The lines marked with the letter "S" indicate the humidity of the biomass 14%, "S +" – humidity 35%.

The data obtained are presented on Figures 1-4. The lines shows calculated data, points are experimental.

$$
\begin{cases}
Gtot = \sum x\mathrm{i} \cdot \mu\mathrm{i} \quad (1) \\
\mu i = G\ RT\ P0f\ i + ln\mathrm{P}\ i \quad (2) \\
G_{tot} = \sum x_i \cdot \left(H_{fi}^0 - TS_i^0\right) + RT \sum x_i ln \frac{x_i}{\sum x_i} \quad (3) \\
w_{air} = \frac{d_{air}\alpha_{bio}m_{bio}\left(M_{O_2} + 3{,}76M_{N_2}\right)}{M_{H_2O}1000} \quad (4) \\
\gamma = 1 - \{0{,}63(0{,}589\alpha_{bio} + 0{,}641)(0{,}001T + 0{,}51)(0{,}0003W' + 0{,}963)\} \ (5) \\
CH_4 = 0{,}0678(0{,}0722 - 0{,}0314\alpha_{bio})(23{,}34 - 0{,}0097T)(0{,}0003W' + 0{,}9626) \ (6) \\
\mathrm{CH_bO_cN_d} + \alpha_{bio}m_{bio}(O_2 + 3{,}76N_2) + wH_2O + qV_{SG} + f\{V_{FG} + (\alpha_{sg} - 1)m_{sg}(O_2 + 3{,}76N_2)\} = \\
= \gamma C + x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + x_6C_2H_4 + x_7C_6H_6 + zN_2 \ (7) \\
\sum_{i=1}^{N} h_{ji}n_i^{out} + A_j^{out} = \sum_{i=1}^{N} h_{ji}n_i^{in} + A_j^{in} \quad (8) \\
\sum_{i=1}^{n} Q_i^{in} = \sum_{i=1}^{n} Q_i^{out} \ (9) \\
\mathrm{H_{bio}^{in}} = \mathrm{w_{bio}H_{w_{bio}}^{in}} + \mathrm{w_{air}H_{w_{air}}^{in}} + \mathrm{w_{steam}H_{w_{steam}}^{in}} + \alpha_{\mathrm{bio}}\mathrm{m_{bio}}\left(\mathrm{H_{O_2}^{in}} + 3{,}76\mathrm{H_{N_2}^{in}}\right) + \\
+\mathrm{qH_{SG}^{in}} + \mathrm{fH_{FG}^{in}} + \mathrm{Q_{ex}} = \\
= \gamma\mathrm{H_C^{out}} + x_1\mathrm{H}_{H_2}^{\mathrm{out}} + x_2\mathrm{H}_{CO}^{\mathrm{out}} + x_3\mathrm{H}_{CO_2}^{\mathrm{out}} + x_4\mathrm{H}_{H_2O}^{\mathrm{out}} + x_5\mathrm{H}_{CH_4}^{\mathrm{out}} + \\
+x_6\mathrm{H}_{C_2H_4}^{\mathrm{out}} + x_7\mathrm{H}_{C_6H_6}^{\mathrm{out}} + z\mathrm{H}_{N_2}^{\mathrm{out}} + Q'_{ach} + Q_{loss} \ (10) \\
H_i = \Delta H_{fi}^0 + Q'_i \ (11) \\
L = G_{tot} - \sum_{j=1}^{M} \lambda_j \left(\sum_{i=1}^{N} h_{ji}x_i^{out} + A_j^{out} - \sum_{i=1}^{N} h_{ji}x_i^{in} - A_j^{in}\right) (12)
\end{cases}
$$

$$
\begin{cases}
\frac{\partial L}{\partial x_1} = RT \cdot ln\left(\frac{x_1}{\sum x_i + z}\right) + G_{fH_2}^0 + \lambda_H(2q - 2) = 0; \\
\frac{\partial L}{\partial x_2} = RT \cdot ln\left(\frac{x_2}{\sum x_i + z}\right) + G_{fCO}^0 + \lambda_C(q - 1) + \lambda_O(q - 1) = 0; \\
\frac{\partial L}{\partial x_3} = RT \cdot ln\left(\frac{x_3}{\sum x_i + z}\right) + G_{fCO_2}^0 + \lambda_C(q - 1) + \lambda_O(2q - 1) = 0; \\
\frac{\partial L}{\partial x_4} = RT \cdot ln\left(\frac{x_4}{\sum x_i + z}\right) + G_{fH_2O}^0 + \lambda_H(2q - 1) + \lambda_O(q - 1) = 0; \\
1 - \gamma + q(1 - \gamma) + f(1 - \gamma) = x_2 + x_3 + x_5 + 2x_6 + 6x_7; \\
(b + 2w)(1 + q + f) = 2x_1 + 2x_4 + 4x_5 + 4x_6 + 6x_7; \\
c + 2\alpha_{bio}m_{bio} + w + q(c + 2\alpha_{bio}m_{bio}) + f\left(c + 2\alpha_{bio}m_{bio} + w + 2\alpha_{sg}m_{sg}\right) = \\
= x_2 + 2x_3 + x_4.
\end{cases} \quad (13)
$$

where:
G_{tot} – the Gibbs energy of the system, kJ/kmol; μ_i – the chemical potential of the component of the system, kJ/kmol; x_i – the amount of substances in the component of the system, kmol.
P_i – the partial pressure of the ith component of the system, Pa; R – the universal gas constant, kJ/(kmol · °C); T – the temperature of the system, K;
G_{fi}^0 – the standard free Gibbs energy of the formation of the component, kJ/kmol.

$H^0_{f\,i}$ – enthalpy of formation of the i-th component of the system, kJ/kmol;
S^0_i – entropy of the i-th component of the system, kJ/(kmol · K).
d_{air} – moisture content of air, g/kg; α_{bio} – coefficient of excess air in the process of gasification; m_{bio} – the amount of oxygen for stoichiometric combustion of 1 km of biomass, kmol; M_i – molecular mass of the i-th component, kg/kmol.
W'– the total mass of H_2O is given by 1kg of dry gasified fuel, kg (H_2O)/kg (dry biomass); γ – amount of carbon that remained in the ash residue, kmol.
x_1, x_2, x_3, x_4, x_5, x_6, x_7, z – predicted yield H_2, CO, CO_2, H_2O, CH_4, C_2H_4, C_6H_6, N_2, relatively, kmol; V_{SG} – total yield of volatile components in the gasification process, kmol; q – Synthesis gas recycling ratio in gas generator, units;
m_{sg} – amount of oxygen for stoichiometric combustion of 1 kmole of generator gas, kmol; V_{FG} – amount of combustion products during stoichiometric combustion of 1 kmole of synthesis gas, kmol; w – total H_2O entering the gas generator, kmol; h_{ji} – the number of atoms of the j-th element in the i-th gas or liquid component of the system; n_i^{in}, n_i^{out} – the amount of substance of the i-th gas or liquid component at the entrance to the system and at the output from the system, kmol;A_j^{in}, A_j^{out} – the number of atoms of the j-th element in the solid form, per 1 kmol of biomass at the entrance to the system at the output of the system, respectively; Q_i^{in} – energy flow at the entrance to the gasification plant, W; Q_i^{out} – energy flow at the outlet from the gasification unit, W; $\mathrm{H}^{\mathrm{in}}_{\mathrm{bio}}$ – total energy of the dry part of the biomass, kJ; $\mathrm{H}^{\mathrm{in}}_{\mathrm{w_{bio}}}$ – total energy of moisture of biomass, kJ; $\mathrm{H}^{\mathrm{in}}_{\mathrm{w_{air}}}$ – the total energy of the water of the blown air supplied to the gas generator kJ; $\mathrm{H}^{\mathrm{in}}_{\mathrm{w_{steam}}}$ – total energy of water vapor for gasification, kJ; $\mathrm{H}^{\mathrm{in}}_{\mathrm{O_2}}$, $\mathrm{H}^{\mathrm{in}}_{\mathrm{N_2}}$ – total energy O_2 and N_2 of air, kJ; $\mathrm{H}^{\mathrm{in}}_{\mathrm{SG}}$ – total energy of the recycled generator gas, kJ; $\mathrm{H}^{\mathrm{in}}_{\mathrm{FG}}$ – the total energy of the combustion products entering the gas generator, kJ; $\mathrm{Q_{ex}}$ – additional energy entering the gas generator from external sources, kJ; $\mathrm{H}^{\mathrm{out}}_{\mathrm{C}}$ – the total energy of the carbon residue, kJ; $\mathrm{H}^{\mathrm{out}}_{H_2}$, $\mathrm{H}^{\mathrm{out}}_{CO}$, $\mathrm{H}^{\mathrm{out}}_{CO_2}$, $\mathrm{H}^{\mathrm{out}}_{H_2O}$, $\mathrm{H}^{\mathrm{out}}_{CH_4}$, $\mathrm{H}^{\mathrm{out}}_{C_2H_4}$, $\mathrm{H}^{\mathrm{out}}_{C_6H_6}$ – total energy H_2, CO, CO_2, H_2O, CH_4, C_2H_4, C_6H_6 as gasification products, kJ; Q'_{ach} – loss of heat with ash, kJ; Q_{loss} – loss of heat to the environment (from the body of the gas generator), kJ
ΔH^0_{fi} – standard enthalpy of formation of 1 kmol of the i-th component, kJ/kmol. Standard enthalpy of substance formation; Q'_i – physical heat of 1 kmol of the i-th component of the system, kJ/kmol; L – the Lagrange function of the system; λ_j – the Lagrange multiplier at the j-th element.

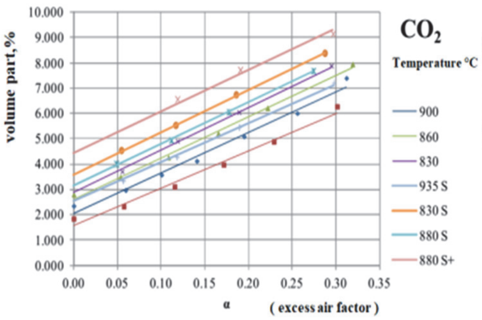

Fig. 1. Graphs for the CO_2 emission in the synthesized gas

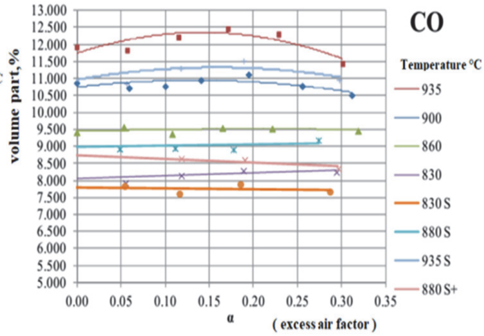

Fig. 2. Graphs for the CO emission in the synthesized gas

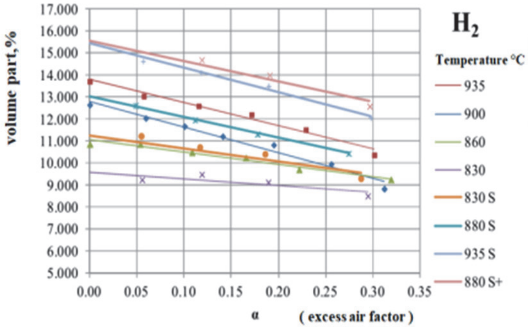

Fig. 3. Graphs for the H_2 emission in the synthesized gas

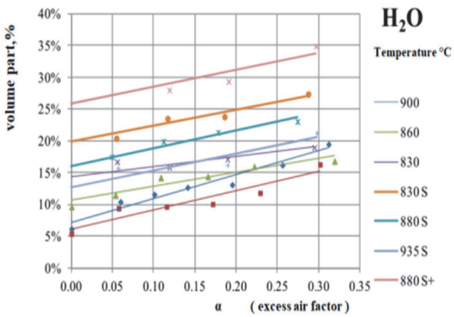

Fig. 4. Graphs for the H_2O emission in the synthesized gas

3.3. Checking the accuracy of the simulation

The accuracy of the mathematical model of the gasification process is checked using the experimental data. For this purpose, the correlation coefficients between the test and simulation results were determined under the same gasification conditions and the relative error of the data obtained.The starting data accepted for the modeling are identical to the conditions for carrying out experimental studies on biomass gasification. The results o are shown in Figures 5-8.

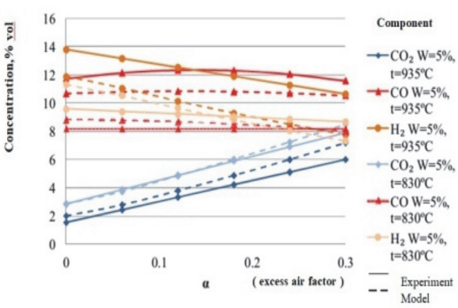

Fig. 5. Component output graph of synthesized gas with variable α and humidity W = 5%

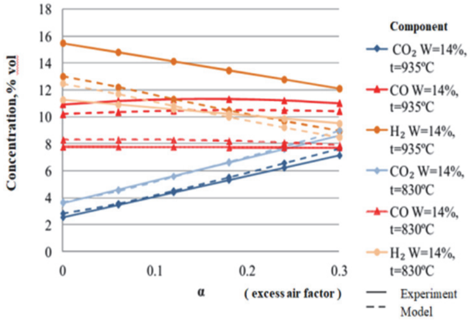

Fig. 6. Component output graph of synthesized gas with variable α and humidity W = 14%

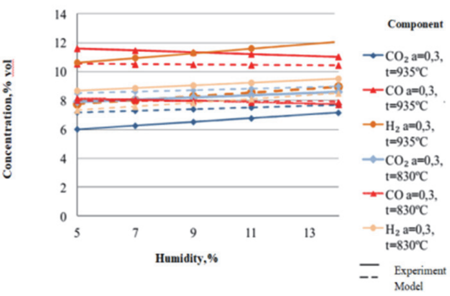

Fig. 7. Components output graph of synthesized gas at variable humidity

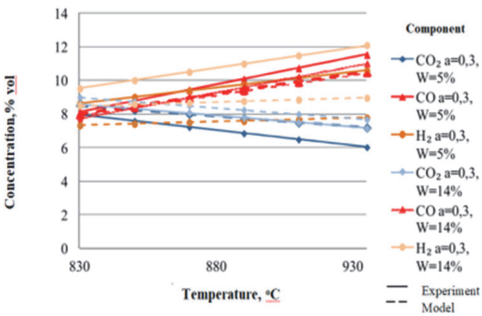

Fig. 8. Components output graph of synthesized gas at variable temperature

Analysis of the data obtained shows that the correlation coefficients between experimental data sets and arrays of simulation results are 0.99 and higher for the most of the experiments and only for few about 0.85...0.95. It is worth mentioning the high accuracy of the modeling for low temperatures process driven, the relative error in the modeling of the performance of the components of the generator gas is 5...10%. And a slightly higher error at high temperatures is 15...20%. An underestimation of the yield of the combustible components of the synthetic gas at high temperatures from the simulation results is characteristic. This accuracy is very high and enables an objective assessment of the impact of the parameters of the gasification process on the result.

Therefore, a new mathematical model of the gasification process of biomass was created, with the possibility to consider the thermodynamic efficiency of multifactorial influence (both separately and complex) on the energy properties and the composition of the generated gas. Another important achievement of this study is the optimization of the biomass gasification process by determining the operating states of the gas generator.

4. Conclusions

A large scope of experimental single and multi-factor experimental research on biomass gasification under different conditions has been done. The compensation of the energy losses of the gas generator took into consideration the dynamics of exothermic reactions of the oxidation of biomass. This allowed to understand the effect of separate regime factors of the gas generator on the composition of the synthetic gas. Based on the minimization of the function of the isobaric isothermal potential (Gibbs energy), a mathematical model of the biomass gasification process was developed. It predicted the composition of the generator gas and the technological parameters of the gas generator. The model obtained provides high reliability of the predicted composition of the synthetic gas, the process temperature and the excess air factor in the reaction zone of the gas generator. The results obtained can be used in the creation of biomass gasification industrial plants.

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Abstract

The paper consists the results from the conducted experiment and the mathematical model of it. The presented process is biomass gasification and the modelling is based on complex parameter that is maximum thermodynamic efficiency and use the Gibbs free energy function and Lagrange multiplier. Referring to European Union strategy in terms of energy use it is highly recommended to increase the share of renewable energy in total energy production. The biomass is one of the most important sources of energy. Listed above methods of mathematical calculations let as define the composition of the gas produced and the efficiency that was reached. Also the precision of the model was evaluated. The effect of the work done is the possibility to use it to state the best condition for the process of biomass gasification technology.

Keywords:
gasification, pyrolysis, biomass, regenerative energy, synthetic gas, mathematical modeling, Gibbs energy

Prezentacja eksperymentalnego procesu zgazowania biomasy z modelem matematycznym minimalizacji energii swobodnej Gibbsa

Streszczenie

Artykuł przedstawia wyniki przeprowadzonego eksperymentu i jego model matematyczny. Przedstawiony proces dotyczy zgazowania biomasy, a modelowanie opiera się na złożonym parametrze, jakim jest maksymalna wydajność termodynamiczna, z wykorzystaniem funkcji energii swobodnej Gibbsa i mnożnika Lagrange'a. Nawiązując do strategii Unii Europejskiej w zakresie zużycia energii, zdecydowanie zaleca się zwiększenie udziału energii odnawialnej w całkowitej produkcji energii. Biomasa jest jednym z najważniejszych źródeł energii. Wymienione powyżej metody obliczeń matematycznych pozwalają określić skład wytwarzanego gazu i osiągniętą wydajność. Oceniono także precyzję modelu. Efektem wykonanych prac jest możliwość określenia najlepszych warunków prowadzenia procesu technologii zgazowania biomasy.

Słowa kluczowe:
gazyfikacja, piroliza, biomasa, energia odnawialna, gaz syntetyczny, modelowanie matematyczne, energia Gibbsa

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Duration of a Design Rainfall for Urban Drainage System Modelling

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1. Introduction

Synthetic hyetographs are one of the basic sources of rainfall data for the hydrodynamic modelling of stormwater systems (Veneziano & Villani 2009, Cazanescu & Cazanescu 2009, Ellouze et al. 2009, Lu-Hsien et al. 2011). Especially in case of the deficiency of recorded rainfall data they are an alternative input data to series of historical rainfalls and stochastic models used for generating rainfall series (Licznar et al. 2011, Knighton & Walter 2016).

The use of hyetographs with simple design is particularly justified in analyzing at the stage of designing new stormwater systems. Due to the lack of possibility of calibrating the computer model, a significant uncertainty of the simulation results, related to the unverified selection of the values of model parameters, should be expected. In that case, using complex design rainfalls is not justified.

For selection of the sewer cross sections, rainfall data in the form of IDF (Intensity-Duration-Frequency) or DDF (Depth-Duration-Frequency) curves, describing the relation between the frequency of rainfall occurrence, the rainfall duration and respectively the rainfall intensity or rainfall depth, are used. These curves give information only about average intensity at a specified time. The use of rainfalls with intensity constant in time for hydrodynamic modelling may lead to underestimating of the calculated runoff (Alfieri et al. 2008). Synthetic hyetographs should represent the basic characteristics of real rainfalls, of which the most important is the variability in time. The greatest instantaneous rainfall intensity is called a peak. The location of the rainfall peak for real rainfalls is not constant and has a significant impact on the maximum outflow (Urcikán & Horváth 1984, El-Jabi & Sarrat 1991, Mazurkiewicz 2016). Synthetic hyetographs usually represents the rainfalls with one maximum intensity (peak).

Due to the availability of IDF or DDF curves, either for local or larger areas (a region or a whole country) (Kotowski et al. 2010, Fadhel et al. 2017, Kaźmierczak et al. 2017), in hydrodynamic modelling of the stormwater systems the hyetographs based on these curves are used. For transformation rainfall data from the IDF or DDF curves to the hyetograph, widely used are Euler hyetographs (Schmitt 2000) and Chicago method (Keifer and Chu 1957, da Silveira 2016).

The use of synthetic hyetographs involves a significant limitation. The frequency of occurrence, included in the IDF or DDF curves, refers only to the rainfall depth at a specified rainfall duration, so it cannot be assigned to any of the runoff characteristics (Adams & Howard 1986, Vigilone & Blösch 2009). This is particularly important in the design of stormwater systems, where for description of the conditions of the these systems the frequency of occurrence is used (EN752 2017), for example in case of pressurized flow for a specified surcharge level in the sewer. The assessment of the conditions of pressurized flow requires the determination of maximum runoff from the catchment. Thus, the hyetograph, that for a given frequency of occurrence will generate the worst conditions, i.e. maximum outflow, is need to be found.

For a given shape of the hyetograph, change of the rainfall peak, which has an impact on the value of the outflow (Dunkerley 2012), can be caused by changing the total rainfall duration. Therefore, determining the design rainfall duration, which will generate the greatest possible outflow, is necessary. For hydraulic calculation and selection of the sewers cross sections, it is recommended that the design rainfall duration should be equal to the flow time through the catchment (ASCE 1992, Crobeddu et al. 2007). For the purpose of hydrodynamic calculations, the design rainfall duration should be at least two times longer than mentioned flow time (Kaźmierczak & Kotowski 2012). Besides these general guidelines, a more detailed information concerning the selection of a design rainfall duration were not found in the literature. Due to this fact, the need of specified recommendations for the selection of the rainfall duration, in the opinion of the authors of presented publication, justifies the topic.

Two basic aims of the analysis were formulated.

- The first was the determination of the design rainfall duration, which generates maximum instantaneous outflow from the catchment.
- The second aim was the evaluation of the relation between the design rainfall duration that generates the maximum outflow and selected catchment characteristics. The knowledge of these relations is important from a practical point of view, and can be used for estimation of the design rainfall duration for selected catchment on basis of the knowledge of its characteristics.

2. Methods

2.1. Catchments

Analyses presented in the publication were made based on eight existing urban catchments located in Bydgoszcz (Figure 1). The catchment areas varied from 35 to 280 ha. Other chosen basic parameters of the catchments are shown in Table 1 placed in the further part of the paper. The receivers of the rainwater collected in the catchments are the Brda river (for catchments C1-C5), the Brda channel (for catchments C6 and C7) and the Vistula river (for catchment C8).

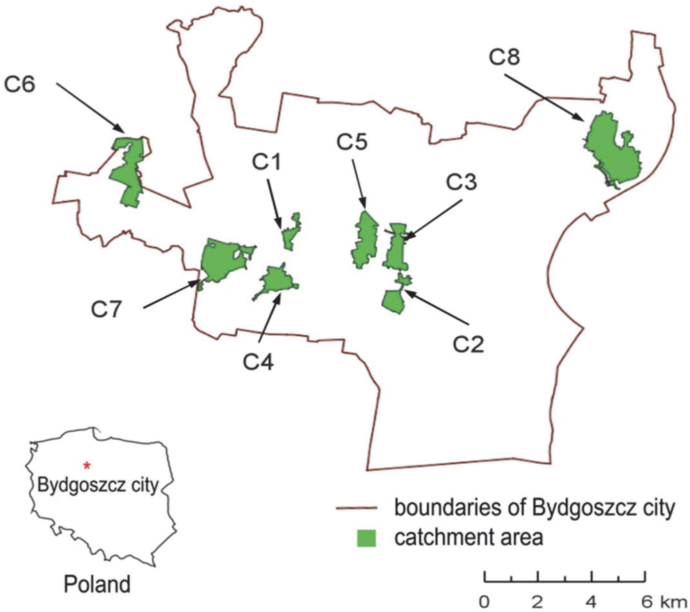

Fig. 1. The location of the catchments in Bydgoszcz

For rainfall-runoff simulations the hydrodynamic model SWMM5.1.013 was used (Rossman 2015). The catchment models have been developed and made available by MWiK in Bydgoszcz (Poland), the company that operates the described stormwater systems.

For three catchments (C3, C5 and C7) in 2016 the outflow measurements were carried out. Collected data together with data from the rainfall monitoring network in Bydgoszcz (also operated by the MWiK) allowed the calibration of models of these catchments. Values of the outflow obtained as a result of the outflow simulation and recorded outflow hydrographs were consistent.

Differences between the simulated and registered peak flows and the values of total outflow volume were compatible within the range of ±15%. These values were considered as acceptable and meeting the requirements concerning storm water system simulation models (UDG 2017). Rainfall data for catchments C3 and C5 were taken from one pluviometer located approximately 400-500 m from the catchments boundaries. In case of catchment C7 the pluviometer was located on the catchment area. All of the pluviometers registered the instantaneous rainfall intensity with the time step of 2 min. The outflow measurements were performed with the use of ultrasonic flow meters installed in the sewers close to the sewer outlets. The time step of registered outflow was also 2 min. For the models calibration the hydrographs for four rainfalls were used. These hydrographs were registered during the measurement campaign from May to July 2016.

All the catchments have very similar development and storm sewers, located on these catchments, are made of the same material, have similar age and are in similar condition. That gives grounds to assume that for all analyzed catchments the rainfall-runoff transformation will be performed under similar conditions.

For each catchment model the control cross section of main sewer, approximately 200-300 m before the sewer outlet, was chosen. For selected control cross section the outflow hydrographs were examined. For the purposes of the presented analysis, it was assumed that the outflow from the catchment would be represented by the outflow peak Q_{MAX}, that is the greatest value of the outflow calculated for a given rainfall. The use of the rainfall that generates the maximum outflow in the sewer outlet will cause the maximum outflows in other sewers, for which the flow time is shorter. That leads to assumption that the results consideration can be limited only to the outlet sewer characterized by the longest flow time.

It was assumed that analyzed catchment characteristics should have a clear interpretation and be easy to determine. It was decided, therefore, to use the four catchment characteristics: total catchment area A, the impervious area A_{IMP}, the longest flow path by the catchment L and the longest flow time through the sewers T_F (Table 1). Flow time T_F was calculated assuming steady flow and full flow conditions, described by a Manning's equation, for individual segments separately and summing the result. Taken into account during the T_F calculations, sewer characteristics (cross sections, slopes, roughnesses) were the same as in SWMM5.1.013 catchment models.

Table 1. Selected characteristics of the analyzed catchments

Catchment characteristics	Catchment description							
	C1	C2	C3	C4	C5	C6	C7	C8
A [ha]	34.8	63.9	71.3	78.3	112.6	157.3	172.1	280.2
A_{IMP} [ha]	23.9	25.3	20.2	35.4	30.4	37.6	44.5	91.1
L [m]	1520	1790	1780	1700	2250	3780	2900	3260
T_F [min]	12.4	29.3	21.7	26.9	29.4	67.6	34.8	38.2

2.2. Rainfalls

The runoff calculations were made for synthetic hyetographs of Euler type II (Schmitt 2000). The design of these hyetographs is characterized by a very simple transformation of data obtained from the DDF (or IDF) curve. The hyetograph on Figure 2a represents the rainfall intensities determined according to DDF curve as a ratio of rainfall depth increments to the duration of time step. To obtain the Euler hyetograph the maximum rainfall intensity should be set at 30% of the total rainfall duration (Figure 2b).

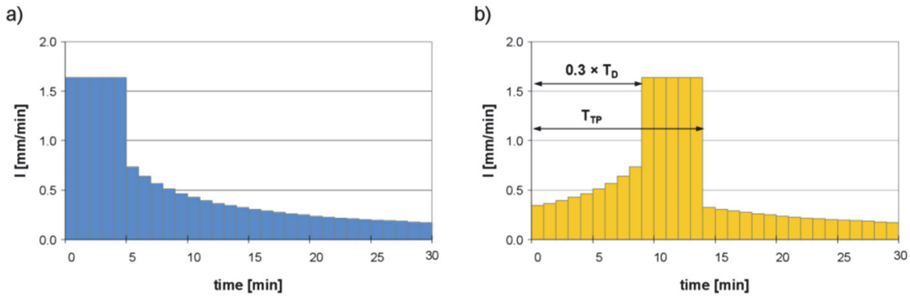

Fig. 2. Euler hyetographs design: rainfall intensities calculated directly from DDF curve (a) and Euler hyetograph with a rainfall duration T_D = 30 min (b)

As the basic DDF curve, the rainfall depth formula for Polish conditions developed by the IMGW (Bogdanowicz & Stachý 1998) was used. According to the recommendations for the Euler hyetographs, it was assumed that the beginning of the pulse with the maximum rainfall intensity was set at 30% of the total rainfall duration. In addition, a time to rainfall peak T_{TP} was concerned. The T_{TP} was represented by the part of hyetograph from the beginning of the rainfall to the end of the last pulse with maximum rainfall intensity (Figure 2b).

The design documentation of the storm sewer systems for analyzed catchments was not available. Moreover taking into account the probability of the changes in a catchment development from the time of sewerage systems realization, the simulations for design conditions were not performed. Hyetographs have been developed for the rainfall frequency of occurrence of c = 2 years. According to recommendations for sewerage systems design (EN752 2017), these rainfalls should generate outflows with the free surface, without hydraulic surcharges. Thus, the shapes of calculated hydrographs are not deformed and maximum outflows are not disrupted as a result of the flattering of the hydrographs during the pressurized flow and by backflow effects.

In the presented analysis, the hyetographs with the rainfall durations T_D from 15 min to 360 min were used. The increments of the rainfall duration were assumed as 15 minutes. The time step of reporting the calculation results and the time step of numerical calculation were set as 10 s.

The time step of hyetograph discretization was assumed as 1 min. The DDF curve (Bogdanowicz & Stachý 1998), used in calculations, allows the determination of rainfall duration of at least 5 minutes. Therefore the synthetic hyetograph peak is characterized by a constant intensity within 5 minutes (Figure 2).

3. Results and discussion

The outflow peak Q_{MAX} increases with the increase of rainfall duration T_D for all concerned values of T_D (Figure 3). After a certain value of rainfall duration, called the stabilization time in the further part of the paper, the increments of outflow peak slightly decreases.

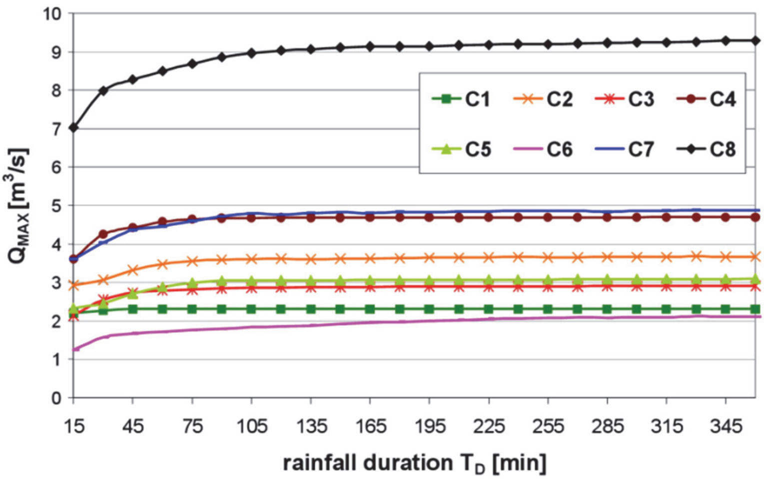

Fig. 3. The outflow peak Q_{MAX} as the function of rainfall duration T_D

In practice, determining the one value of the outflow peak may be impossible, because for longer rainfall durations a further increase of values Q_{MAX} may occur. For practical purposes it is important to specify a threshold value of rainfall duration, after which a clear decrease of outflow peak is noticed. Taking into account the graph of the function $Q_{MAX} = f(T_D)$ (Figure 4), this time was called the stabilization time T_{ST} and was identified with the design rainfall – the rainfall that generates the greatest runoff from the catchment as measured close to the sewer outlet. It was assumed that the stabilization time would be determined as the rainfall duration for which the calculated outflow peak is equal to 97% of the outflow value calculated for the longest analyzed rainfall duration (T_D = 360 minutes). The difference equal to 3% between the maximum outflow and the outflow corresponding to the stabilization time takes into account the accuracy of the outflow simulation represented as a Continuity Error in SWMM5.1.013.

The discrete form of function $Q_{MAX} = f(T_D)$ had been converted to continuous by using polynomial regression (Figure 3). The differences between the values of the outflow peak calculated during the SWMM5.1.013 simulations and based on a regression equations do not exceed 0.5%. Due to this fact, the stabilization time can be specified with an accuracy of 1 minute (Table 2) without the need of performing simulations of the outflows for all rainfall durations T_D (15-360 min).

Table 2. Determined flow times T_F, stabilization times T_{ST} and times to rainfall peak T_{TP} for analyzed catchments

Time [min]	Catchment description							
	C1	C2	C3	C4	C5	C6	C7	C8
T_F	12.4	29.3	21.7	26.9	29.4	67.6	34.8	38.2
T_{ST}	23.0	87.0	62.0	53.0	88.0	213.0	98.0	119.0
T_{TP}	11.9	31.1	23.6	20.9	31.4	68.9	34.4	40.7

In the next step, for determining the relations between the characteristics of the catchments and the stabilization time, the assessment of the correlation between these values was made (Figure 4). As a measure of the correlation, the Pearson correlation coefficient (PCC) was used (Table 3).

The correlation between the total area A or the impervious area A_{IMP} and the stabilization time was weak. For the longest flow path L the correlation was on a significant level. The highest correlation was observed for the flow time T_F.

Table 3. The values of the PCC and the coefficients α (for Equation 1) for the analyzed catchment characteristics

Catchment characteristic CC	PCC [-]	Coefficient α (Eq. 1)
A	0.582	0.670
A_{IMP}	0.346	2.051
L	0.909	0.041
T_F	0.988	2.963

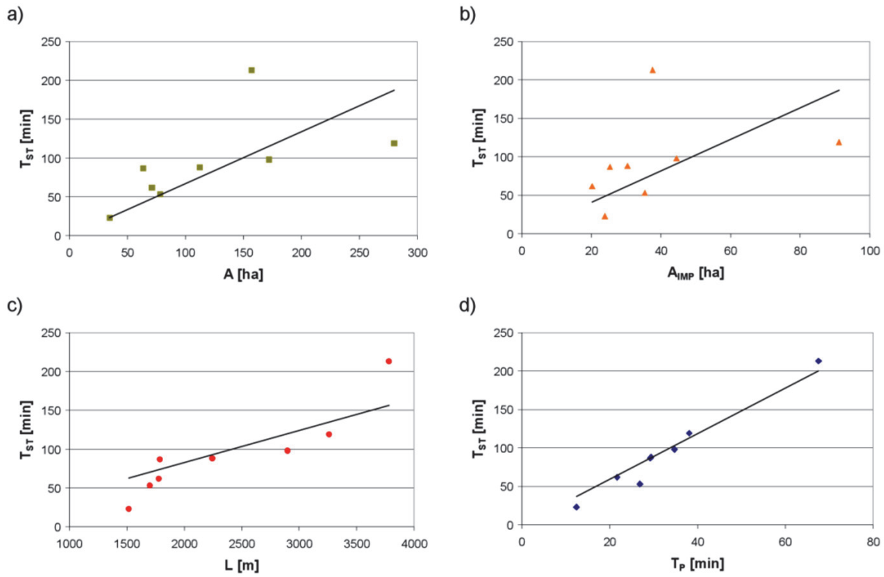

Fig. 4. The results of the analysis of the correlation between the catchment characteristics and the stabilization time T_{ST}

For rainfalls with relatively small intensities (such as included in the analysis for rainfalls with the frequency of occurrence c = 2 years) the surface runoff is only generated by the impervious area. Thus the impervious area is a characteristics of the catchment with the basic influence on the total volume of the outflow, while its impact on the outflow peak is the least significant (from among analyzed characteristics). An example might be a catchment C6, for which, despite a total area is more than four times greater (and the impervious area nearly twice greater) than for C1 (Table 1), the value of outflow peak is comparable to the outflow peak calculated for the catchment C1. It proves that in the rainfall-runoff transformation for an urban catchment, the greatest influence on the shape of the hydrograph has a flow phase in the sewer network. Between two analyzed characteristics that describe the sewer network (the flow path L and the flow time T_F) greater value of the Pearson correlation coefficient was calculated for flow time through the catchment T_F. According to the different characteristics of the sewers (cross sections, slopes, material), besides the flow path, an important issue is the flow velocity, which determines the flow time.

The proposed method of determination the flow velocity on basis of Manning's equation (for assumption of steady flow and full flow conditions) is a sufficiently accurate approximation of flow conditions in sewers in case of determining the design rainfall duration.

For the practical use of the observed relations between catchment characteristics and stabilization time T_{ST} it was assumed that this relation would take a form of a straight line:

$$T_{ST} = \alpha \cdot CC \tag{1}$$

where:
CC – selected catchment characteristics (A; A_{IMP}; L; T_F).

The value of the coefficient α for the Equation (1) for the flow time through the catchment T_F is close to 3 (Table 3). It means that the maximum outflow is generated by the rainfall with a duration approximately three times greater than the flow time T_F.

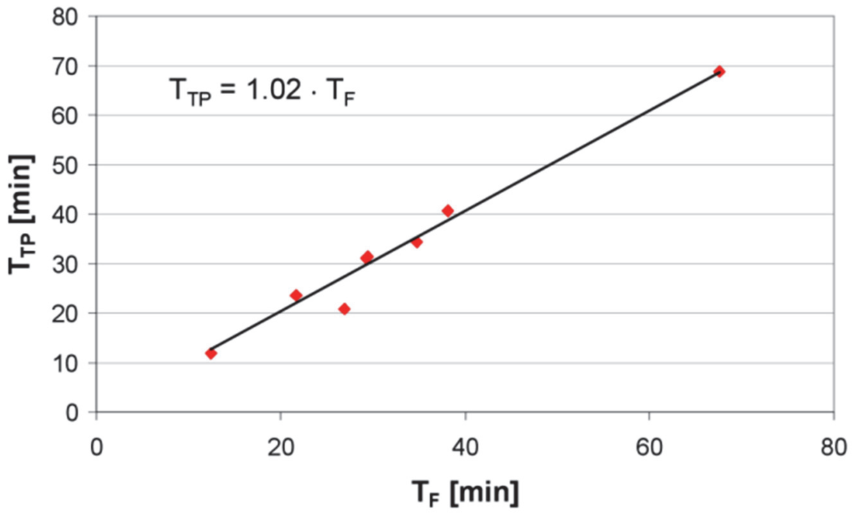

Fig. 5. Relation between the time to rainfall peak T_{TP} and the flow time through the catchment T_F

In the case of Euler hyetographs time to rainfall peak T_{TP} is approximately equal to 1/3 of the total rainfall duration. It suggests that a major role in choosing the duration of the design rainfall plays not only the total rainfall duration, but also the location of the rainfall peak. In order to confirm this observation, a linear regression between times T_{TP} and T_F was performed (Figure 5). The value of the slope of straight line is close to 1, what confirms the significant relation between the time to rainfall peak T_{TP} of rainfall generating the maximum outflow from the catchment and the flow time through the catchment T_F.

This relation is consistent with the principles of the stormwater systems design based on a Rational Formula (ASCE 1992). According to these recommendations, the design rainfall duration should correspond the flow time through the catchment. However, it should be noticed that in the case of the Rational Formula the rainfall with a constant intensity is used (so called block rainfall). The greatest outflow from the catchment will appear at the end of such a rainfall. In case of using synthetic hyetograph with the variable intensity in time, the maximum outflow will be generated at the end of the rainfall pulse with the greatest intensity. This time corresponds to the time to rainfall peak T_{TP} (Figure 2 b).

The knowledge about the relation between the design rainfall duration and the flow time through the catchment can be used in a hydrodynamic modelling of stormwater sewer systems. It can be particularly useful for stormwater sewer systems verification, when the model calibration cannot be performed due to the lack of outflow measurement data or when the historical rainfall data are not available. The relation between the design rainfall duration and the flow time through the catchment, presented in the paper, allows the easy selection the appropriate hyetograph for specified catchment. For determining the flow time through the catchment T_F any additional data are not required. The stormwater system parameters (sewer lengths, slopes, cross sections, material) are known at the stage of hydraulic calculations concerning stormwater systems.

4. Conclusions

The results of the presented analysis allow formulating the following conclusions:

1. The duration of the design rainfall, represented by the stabilization time T_{ST} is dependent on the flow time through the catchment T_F.
2. Time to rainfall peak T_{TP} for the design rainfall should corresponds to the flow time through the catchment T_F or be greater than this value.
3. The flow time through the sewers calculated for full flow conditions and the steady flow may be a measure of the flow time through the catchment.

The presented relations concern catchments with similar parameters to those used in the analyses. At the current stage of the analyses there are no grounds to extrapolation of the obtained results for other catchments with different size and sewer length. The generalization of the results requires calculations performed for larger number of catchments with different parameters. It is advisable to perform an outflow simulations for design rainfalls with a variable peak location, e.g. the Chicago design rainfall. It would allow to the clarification of relation between the hyetograph peak location and generated outflow from the catchment for specified rainfall duration.

The authors wish to thank the Miejskie Wodociągi i Kanalizacja company in Bydgoszcz for sharing their catchment models and measurement data.

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No potential conflict of interest was reported by the authors.

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Abstract

In the presented paper the determination of the design rainfall duration for which the outflow from the urban catchment reaches maximum intensity and the evaluation of the relation between determined design rainfall duration and selected catchment characteristics were discussed. The analysis based on the outflow simulation results in SWMM5 obtained for eight existing urban catchment located in Bydgoszcz (Poland) with area ca. 35-280 ha. The calculations were made for the Euler hyetographs with the rainfall durations from 15 min to 360 min and the rainfall frequency of occurrence c = 2 years. For each catchment the relations between the catchment characteristics (total area, impervious area, length of the flow path and the longest flow time through the sewers) and the rainfall duration were determined. It was shown, that the design rainfall duration, represented by the Euler hyetograph, should be at least three times longer than the flow time through the catchment.

Keywords:
design rainfall, hydrodynamic modelling, SWMM5, urban catchment, Euler hyetograph

Czas trwania deszczu obliczeniowego na potrzeby modelowania odpływu ze zlewni miejskiej

Streszczenie

W publikacji zaprezentowano wyniki analizy wpływu czasu trwania deszczu projektowego na wielkość maksymalnego odpływu ze zlewni oraz relacje między tym czasem a wybranymi charakterystykami zlewni (całkowitą powierzchnią, powierzchnią nieprzepuszczalną, długością drogi przepływu przez zlewnię i najdłuższym czasem przepływu przez sieć kanalizacyjną). Analiza obejmowała symulacje odpływu w programie SWMM5 dla ośmiu istniejących zlewni miejskich lokalizowanych w Bydgoszczy o powierzchniach od ok. 35 ha do ok. 280 ha. Symulacje przeprowadzono przy wykorzystaniu hietogramu Eulera o czasie trwania deszczu od 15 min do 360 min i częstości przewyższenia deszczu c = 2 lata. Dla każdej zlewni zbadano zależność między charakterystykami zlewni i czasem trwania deszczu. Wykazano, że czas trwania deszczu projektowego, reprezentowanego przez hietogram Eulera, powinien być co najmniej trzy razy dłuższy od najdłuższego czasu przepływu przez zlewnię.

Słowa kluczowe:
deszcz obliczeniowy, modelowanie hydrodynamiczne, SWMM5, zlewnia miejska, hietogram Eulera

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Composite Heat Exchangers for Boiling Heat Transfer Enhancement

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1. Introduction

Phase – change heat exchangers are commonly used in many industrial applications such as refrigeration systems, electronics cooling, and etc. In terms of boiling, this heat transfer mode is highly efficient in dissipating significant heat fluxes at small temperature differences. Considerable improvement in the value of heat fluxes can be achieved by the application of heat enhancing microstructures on heat exchangers such as metal wire meshes and metal – fibrous structures. These porous structures will be considered in the present paper.

Metal wire meshes can be successfully used for the production of high performance phase – change heat exchangers. In (Liu et al. 2001) tests of boiling heat transfer of methanol and HFE-7100 on a stainless steel mesh coating were described, while in (Brausch & Kew 2002a, Brausch & Kew 2002b, Brausch & Kew 2003) water and R-141b boiling was investigated – also on stainless steel mesh wicks. The coatings consisted of one, three and five layers of mesh. It was reported that the use of a single layer resulted in elevated heat fluxes in comparison to the smooth surface at low superheats. The paper (Franco et al. 2006) presents the research results of boiling heat transfer of R141b on different wire meshes that were made of stainless steel, aluminum, copper and brass. The application of the microstructure of a proper geometry enabled to obtain higher values of the critical heat flux (even 40% higher than for the smooth surface). The work (Li et al. 2006) deals with water boiling on surfaces covered with two to nine mesh layers. All meshed surfaces proved to enhance boiling in comparison with the smooth surface. A similar finding was reported in (Li & Peterson 2006), where test results of water boiling on a copper surface with a copper mesh can be found. In (Wong & Kao 2008) attention was given to heat pipes containing two – layered mesh wick coating. The authors reported that the fine mesh provids more nucleation sites. Also in (Liou et al. 2010) investigations were focused on multi-layer copper meshes sintered to the heat pipe surface with water as the working fluid. The paper (Diao et al. 2014) contains test results of evaporation/boiling on copper mesh of height 0.6-1.0 mm under different pressures. The highest enhancement of heat transfer with the application of the mesh reached about 32%.

Equally advantageous might be the use of porous metal – fibrous coatings. They are produced from metal fibers sintered to surfaces in the reduction atmosphere. In the monograph (Poniewski 2001) extensive test results for water, ethanol and R-113 on surfaces covered with copper fibrous microstructures of fiber diameter 50 μm and length 3 mm were provided. It was stated that the parameters of the porous layer significantly impact heat transfer performance. Other works (Wójcik 2004, Wójcik 2005, Wójcik 2009) focused on experimental investigations of water boiling on a tube covered with a copper – fibrous layer of 40% porosity. A significant enhancement was recorded for the porous microstructures. In (Kalawa et al. 2017) research results of pool boiling of distilled water on heater surfaces covered with coatings produced with stainless steel fibers were given. It was stated that the coating enhanced heat transfer in relation to the smooth surface (heat flux for the superheat of 10K was ca. 3.5 higher than for the smooth surface).

Currently, phase – change processes attract much scientific interest (Pavlenko & Koshlak 2019) including the thermal properties of porous media (Koshlak & Pavlenko 2019). In terms of heat transfer enhancement, literature provides much data on heat exchangers produced from the same material as presented in the above sections. The current paper experimentally analyses and compares composite elements made of two types of microstructures. The first ones consist of the copper base and the single bronze meshes of different aperture (distance between the wires). The second one is made of the copper base with the bronze meshes, on which copper fibers have been sintered. The aim of the paper is the determination of the thermal performance of such composite phase – change heat exchangers.

2. Material and method

The tests have been conducted on samples made of the copper base (a disk of 3 cm diameter), on which porous structures have been applied. The layers consist of a single mesh (Fig. 1) made of bronze.

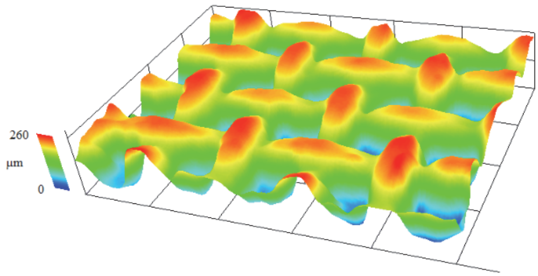

Fig. 1. 3-D image of the example mesh

Two kinds of meshes have been used – both have the wire diameter of 0.20 mm, while their aperture (distance between the wires) amounted to 0.40 and 0.63 mm. The bronze mesh surfaces have been reinforced with fine copper fibers. The diameter of the wires was 50 µm, while their length ca. 1 mm. Thus, samples of the copper base with bronze meshes of 0.40 and 0.63 mm with sintered copper fibers on top have been developed and investigated. All the specimens were sintered in the reduction atmosphere of hydrogen and nitrogen. During this process durable bonds are developed between joined elements.

The tests of boiling heat transfer have been performed on the experimental stand, whose main element has been presented in Figure 2.

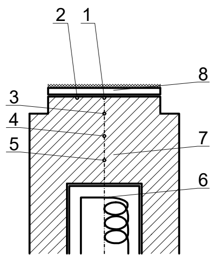

Fig. 2. Main unit of the experimental set-up: 1, 2 – thermocouples under the sample, 3, 4, 5 – thermocouples in the axis of the heating block, 6 – electric cartridge heater, 7 – copper block, 8 – sample with the mesh

The produced specimens in the form of copper discs, on which microstructural coatings have been sintered, were soldered to the copper heating block. An electric resistance heater was located in it to produce heat, which was later conducted to the samples (the block was insulated from the surroundings with high temperature insulation). The power of the heater was increased during the measurements using the autotransformer with given steps to provide a few data points which enabled to draw the boiling curves (which are a visual representation of the thermal performance of each sample).

The boiling curve is a dependence of heat flux vs. superheat (defined as the difference between the surface and saturation temperature of the liquid). The heat flux transferred to the samples was calculated using temperature readings recorded in the axis of the copper heating block (Fig. 2) with the Fourier's law of heat conduction. The temperatures under the sample were also recorded. As a result, the boiling curves could have been drawn. Boiling occurred in the thermally – resistant glass vessel located above the sample on the teflon plate. The generated vapour underwent condensation in the condenser located above it and was returned to the vessel gravitationally so that the liquid level above the sample was kept constant. The liquid temperature in the vessel was measured with a thermocouple. In the tests all thermocouples were of K type.

3. Results and discussion

The experimental analysis has been focused on determining the thermal performance of the designed samples in the nucleate boiling mode of heat transfer. Figure 3 presents the dependence of heat flux vs. superheat for the smooth copper surface and the copper samples with bronze meshes of different aperture of 0.40 mm and 0.63 mm. The meshes had the same wire diameter of 0.20 mm (thus, the same height).

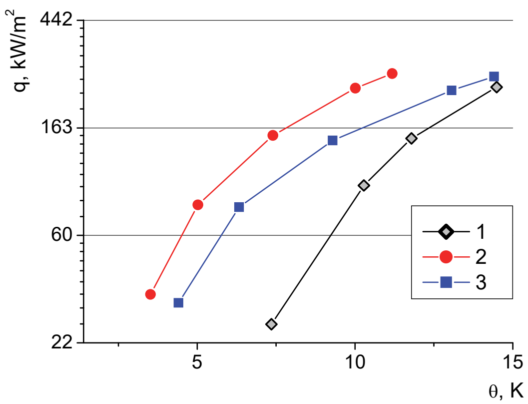

Fig. 3. Boiling curves for distilled water; 1 – smooth copper surface, 2 – bronze mesh of 0.63 mm aperture on the copper base, 3 – bronze mesh of 0.40 mm aperture on the copper base

As can be seen the application of the bronze meshes sintered to the copper base significantly improved heat transfer, leading to elevated heat flux values in comparison to the smooth surface test results. For the same superheat, the heat flux can be much higher than for the surface without any coating. The coarser mesh of larger distance between the wires (aperture of 0.63 mm) proved to be more effective in dissipating heat than the finer mesh of 0.40 mm aperture. It might be related to better removal of the vapour phase. The finer mesh probably hampers vapour and liquid flow in the area of high heat fluxes and the data points come close to the ones obtained for the smooth surface.

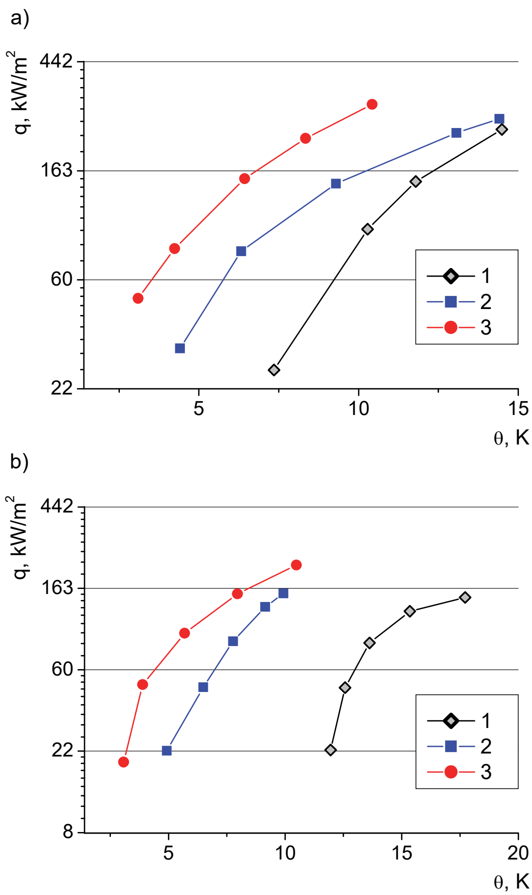

Fig. 4. Boiling curves for distilled water (a) and ethyl alcohol (b); 1 – smooth copper surface, 2 – bronze mesh of 0.40 mm aperture on the copper base, 3 – bronze mesh of 0.40 mm aperture on the copper base with copper fibers on top

Further enhancement of heat flux might be possible if additional passive techniques are used for the production of the heat exchangers. The porous microstructures consisting of the bronze meshes, on which fine copper fibers of 50 μm diameter were applied. A combination of the bronze mesh and copper metal – fibrous structure have proved to be even more efficient as indicated in Figures 4a and 4b for distilled water and ethyl alcohol, respectively.

As indicated in the above figures, the combined effect of the mesh and the fibers provided the most advantageous heat transfer conditions. The heat flux values for both boiling liquids are highest if copper fibers are sintered onto the bronze mesh of 0.40 mm aperture. The same phenomenon can be observed for the mesh of larger aperture as presented in Figures 5a and 5b.

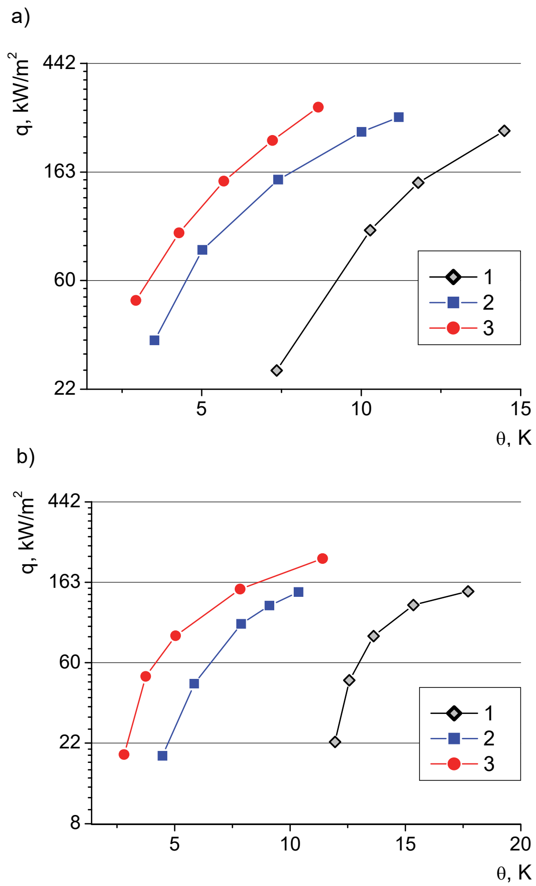

Fig. 5. Boiling curves for distilled water (a) and ethyl alcohol (b); 1 – smooth copper surface, 2 – bronze mesh of 0.63 mm aperture on the copper base, 3 – bronze mesh of 0.63 mm aperture on the copper base with copper fibers on top

The application of porous coatings might considerably increase heat flux transferred from the phase – change heat exchangers. It might be related to the combination of two effects. The first one is linked with the higher density of active nucleation sites (locations were vapour bubbles are grown) on the surface. Additional porous coverings increase the number of such sites and, thus, enhance heat transfer. The other factor might be the extension of the heat exchanger area due to the larger surfaces in the form of meshes and fibers covering the heaters. The nature of this phenomenon might be more visible if the enhancement factor is considered as the function of the superheat. It has been presented in Figure 6 (based on the heat flux data from Fig. 4a) as the enhancement ratio (ER). It is defined as the ratio of the heat flux transferred from the meshed surface of aperture 0.40 mm to the heat flux from the smooth surface (1), the ratio of the heat flux transferred from the surface with the mesh of aperture 0.40 mm and the fibers to the heat flux from the smooth surface (2) and the ratio of the heat flux transferred from the surface with the mesh and the fibers to the heat flux from the surface with the mesh only (3).

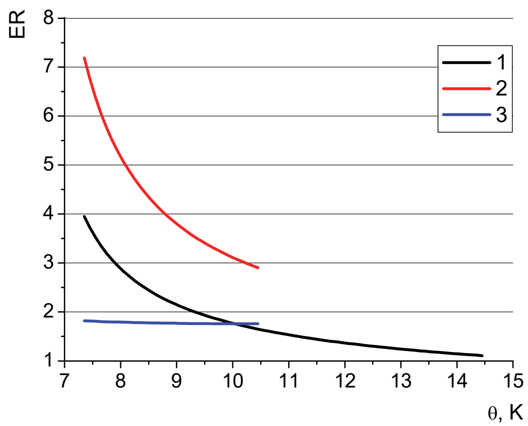

Fig. 6. Enhancement radio (ER) for distilled water – explanation of (1), (2), (3) in the text

The enhancement of heat transfer caused by the application of the porous microstructures resulted in heat fluxes over seven times higher – in the case of the bronze mesh layer covered with copper fibers. This effect diminishes as the superheat rises. It might be related to the fact that more nucleation sites become active on the smooth reference surface while the number of active nucleation sites on the microstructural surfaces is constant. Moreover, is it worth noting that the sample with both mesh and fibers performed much better than the specimen with the mesh only. The ratio of the heat flux transferred from the sample with the mesh and the fibers to the heat flux values of the meshed sample is almost constant (curve no 3 on Figure 6) and equals ca. 1.75. Thus, the additional effect of sintering the fibers, which extend the heat transfer area, is very advantageous. It slightly diminishes with increased superheat. This could be caused by more vapour being generated as temperature rises, which hampers the vapour and liquid flow within the produced porous layer.

4. Conclusions

The application of the investigated composite phase – change heat exchangers significantly enhanced heat transfer in comparison to the smooth surface without any coating. Particularly promising is the combined use of the mesh and the porous layer consisting of fine fibers. Sintering the components of the microstructures to each other and to the copper base reduces the thermal resistance and provides the development of the durable bonds between the jointed elements. It is especially important if the heat exchangers are located in vehicles or machines, which are subject to vibrations. The thermal performance of the tested heat exchangers with the porous layers is highest for small superheats and diminishes with rising heat flux. This phenomenon is also known for other microstructural coatings and should be considered during the design stage of new heat exchangers. Future works in this area need to cover high performance boiling agents such as nanofluids.

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Abstract

The paper deals with the development of high-performance composite heat exchangers made of different metals. The samples made of meshes and fine fibers have been sintered to the copper base in the reduction atmosphere to prevent oxidation. The test of boiling heat transfer performance have been carried out under ambient pressure with distilled water and ethyl alcohol as working agents. The obtained data indicates significant enhancement of heat flux of such composite heat exchangers in comparison to the smooth surface without any coating. The maximum heat flux for the microstructure covered heater has been several times higher than for the smooth surface. The enhancement has been observed to decrease as the temperature difference become higher.

Keywords:
composite heat exchanger, enhancement, porous layers

Kompozytowe wymienniki ciepła do intensyfikacji wrzenia pęcherzykowego

Streszczenie

Artykuł dotyczy badań wysokowydajnych, kompozytowych wymienników ciepła wykonanych z różnych metali. Próbki wykonano poprzez spiekanie w atmosferze redukcyjnej (w celu uniknięcia utlenienia) warstw siatkowych i drobnych włókien metalu z podstawą miedzianą. Badania przeprowadzono pod ciśnieniem atmosferycznym dla dwóch cieczy roboczych tj. wody destylowanej i bezwodnego alkoholu etylowego. Uzyskane wyniki wskazują na znaczące możliwości zwiększenia wymienianych gęstości strumienia ciepła dla wymienników kompozytowych w porównaniu do powierzchni gładkiej bez pokrycia. Maksymalne wartości gęstości strumienia ciepła odbieranego z powierzchni z mikropokryciem nawet kilkakrotnie przewyższały te, odbierane z powierzchni gładkiej. Intensyfikacja wrzenia zmniejszała się jednak w miarę wzrostu przegrzania.

Słowa kluczowe:
kompozytowy wymiennik ciepła, intensyfikacja, warstwy porowate

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Impact of Weather Conditions on the Operation of Flue Gas Ducts and the Gravitational Ventilation in Rooms with Gas Appliances

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1. Introduction

Contemporary systems for removing flue gases and used air should be selected so that there is no risk of accumulation of hazardous and harmful substances in human health. The use of energy from the combustion of organic fuel always involves the emission of compounds hazardous to health, which should be removed from the atmosphere of the room as soon as possible. We spend a significant part of our lives in apartments, and even relatively low concentrations of harmful substances can pose a serious threat to health. Efficient ventilation and an exhaust system is a guarantee of the safe use of gas appliances.

In Poland, flats are ventilated mainly in a gravitational way, where the exhaust takes place through gravitational ventilation channels, and the supply through disordered infiltration and ventilation. In this case, air exchange at the recommended level is very difficult to achieve. The efficiency of air exchange, and thus the concentration of harmful substances in rooms, largely depends on changing conditions – i.e. outdoor air temperature, atmospheric pressure, wind strength and direction, as well as the way the rooms are used.

2. Purpose of work and research methods

2.1. Purpose of research

Air is removed from the rooms as a result of the pressure difference between the room and chimney and the building's surroundings. This is the active pressure and expresses the so-called chimney draft, which is the basis for the operation of gravitational ventilation and proper operation of flue systems. The pressure value determines whether the combustion of fuel in gas appliances proceeds in the assumed way, the ventilation works properly, and the exhaust gases and used air do not tend to go back to the rooms (Larsen 2006).

The natural chimney draft depends on several factors, including:

- the difference in density of exhaust gas and air outside the building,
- construction, height and cross-sectional area of chimney,
- strength and direction of the wind,
- atmospheric pressure,
- building structure (roof) and building location relative to the other buildings, trees etc.
- terrain.

The proper operation of ventilation and flue systems depends on many variables whose interaction generates a large number of variants.

The author of the article set themselves the task of examining the impact of weather conditions on the operation of flue gas exhaust systems and ventilation in rooms with gas appliances.

2.2. Subject of study

In order to determine the impact of weather conditions on the chimney draft, the work of the ventilation and flue gas system in a 4-storey multifamily building located in Koszalin (II wind zone) (PN-EN 1991) was analyzed.

Fig. 1. Multifamily building with analysed apartments

Two apartments located on the ground floor and on the last floor were analysed. In each apartment there was a 4-burner gas cooker and a gas instantaneous water heater with a maximum power of 23.6 kW.

In the kitchen room, exhaust ventilation is carried out using a brick ventilation duct with a section of 140x140 mm, with a ventilation grille mounted under the ceiling. The air supply is carried out by means of an air grille installed in the door with a cross-section of 200x100 mm. Initially, the flats were fitted with ventilation hoods, however, due to the opinion of specialists citing the provisions of §150.9 of the Technical Conditions (Rozporządzenie 2002), they were abolished.

In the bathroom, the exhaust is carried out by means of a brick ventilation duct with a section of 140x140 mm, with a ventilation grille mounted under the ceiling. The air is supplied by means of an air grille installed in the door with a cross section of 200x100 mm.

Flue gas discharge from a gas flow water heater via a flue pipe Ø140 mm. The plan of the apartment is shown in Figure 2.

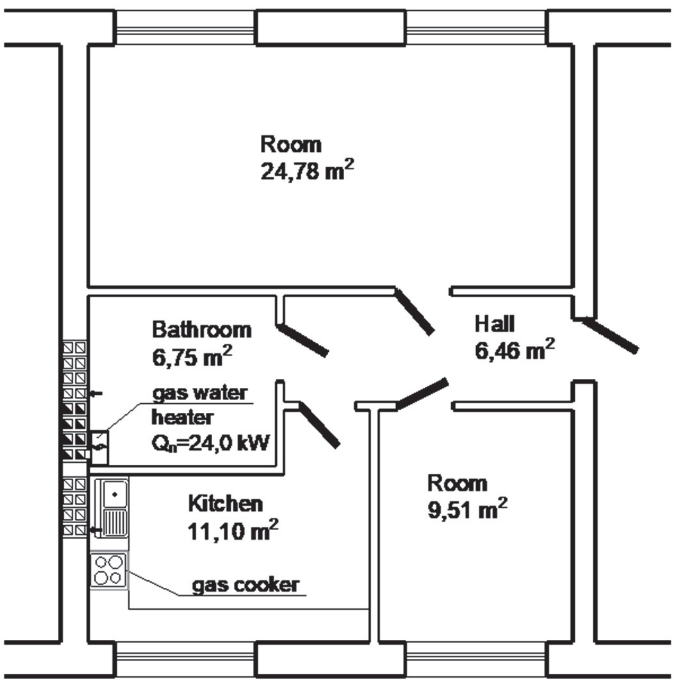

Fig. 2. Plan of a flat with gas appliances

2.3. Research methods and assumptions

2.3.1. Research methods

In order to determine the impact of weather conditions, meteorological data was analysed covering the period of 24 months, from January 2018 to December 2019.

In addition, in the last quarter of 2019, the results obtained were compared with the actual state during local visits. For this purpose, the multifunctional meter Testo400 type was used to measure ventilation air parameters.

2.3.2. Assumptions

The research assumed that due to the ajar window in the room and kitchen, the resistance to infiltration would be negligible, therefore their impact on the total value of displacement pressure was omitted. It was assumed that due to the short distance of the gas stove from the ventilation duct discharging used air, the air temperature in the duct will be 30°C. The bathroom has an air temperature of 25°C.

The flue gas temperature from the gas water heater is based on catalogue data and is 140°C

The required ventilation air flow for living needs was adopted on the basis of standards and it is 70 m^3/h for kitchens and 50 m^3/h for bathrooms (PN-83/B-03430+A3:2000).

Chimney draft disturbances are often a consequence of local atmospheric conditions, which determine the air flow around the building. Although wind is a factor conducive to chimney draft, under certain conditions it may cause a reduction or complete disappearance of the chimney draft. Such a phenomenon occurs especially often in the submontane (wind zone III) and coastal (wind zone II) regions (Żurański 2003).

To assess the impact of wind, it is necessary to know the external pressure exerted by the wind on the external surfaces of the building, as well as the pressure at the outlets of ventilation and flue pipes.

Due to the fact that the wind direction is characterized by high variability throughout the day, for the purposes of the analysis the wind blowing in the corner of the building was adopted. Windows, ventilation and exhaust ducts will be on the leeward side. The distribution of pressure coefficient values on the leeward façade and roof is shown in Figure 3.

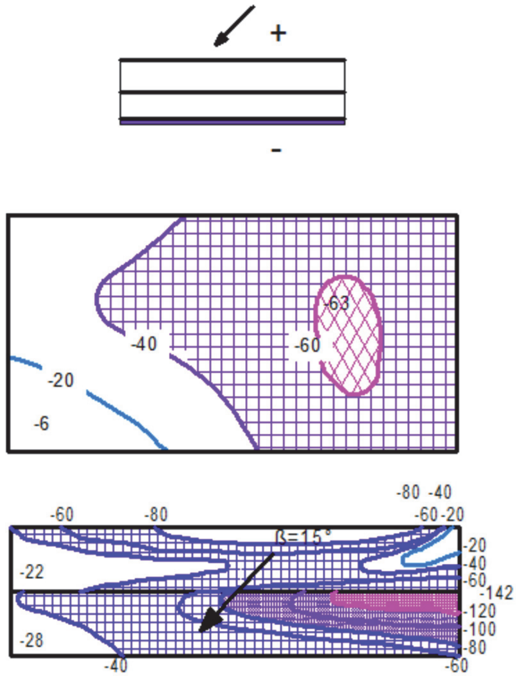

Fig. 3. Distribution of the value of the external pressure coefficient on the wall and roof of the building at the assumed wind direction (Jensen & Franck 1965)

3. Results of tests

The most adverse conditions and disturbances in the work of gravitational ventilation systems were observed in the summer. The equalization of outside and inside air temperatures is the main factor that interferes with proper air exchange in the room (Szkolenie 2014). In summer, however, the problem is not so much noticed, because users often open the windows, allowing fresh air to enter the rooms.

Abnormal operation of the ventilation system has already been observed at temperatures less than 10°C, especially in rooms located on the top floor. Sample results of the total positive displacement pressure and the actual exhaust ventilation air flow for the kitchen ventilation duct are presented in Table 1.

Table 1. Total pressure and actual air flows in the kitchen ventilation duct in 10.2019

Date	T avg. [°C]	ρ [kg/m^3]	Wind int. [km/h]	Pres. s. lev. [HPa]	Kitchen			
					Δp_c [Pa]		Vr [m^3/h]	
					fourth floor	ground floor	fourth floor	ground floor
03.10.2019	8.0	1.241	8.7	1007.3	1.015	4.752	38.03	45.61
04.10.2019	8.9	1.244	7.1	1012.8	0.995	5.099	37.64	47.24
05.10.2019	9.0	1.244	7.5	1012.4	0.980	5.193	37.36	47.67
06.10.2019	6.0	1.268	5.0	1021.3	2.122	8.073	54.98	59.44
07.10.2019	6.5	1.264	7.2	1020.2	1.961	7.693	52.86	58.02
08.10.2019	5.9	1.259	10.1	1013.6	1.831	6.993	51.06	55.32
09.10.2019	10.5	1.225	12.5	1003.5	0.122	2.632	13.16	33.94
10.10.2019	10.9	1.225	11.3	1004.2	0.051	2.676	8.52	34.22

From the obtained results it can be concluded that with gravitational ventilation it is very difficult to achieve the normative required flow of ventilation air. On 10.10.2019, the ventilation air flow was only 8.52 m^3/h, for the kitchen located on the fourth floor, which with the required 70 m^3/h is only 12% of the required level.

The situation was no better in a flat located on the ground floor, there the stream was 34.22 m^3/h, i.e. 49% of the required value.

Atmospheric pressure also plays a role. At low atmospheric pressure the decrease in the intensity of air exchange is clearly visible.

It would seem that in winter the problem with incorrect operation of ventilation systems will be marginal. All the more when a strong wind begins to blow outside, which increases the intensity of ventilation. In the first half of December in Koszalin, tests were carried out to determine the effect of wind on the chimney draft in bathrooms with gas water heaters installed. The measurement results are presented in Table 2.

On 07/12/2019, for the first time in a month, a reverse flow was observed in the bathroom room, located on the top floor. In the ground floor bathroom the string was correct. The temperature on this day was close to the temperature on 05.12, where no change in flow direction was observed. The decisive factor was the wind, which blew at an average speed of 17.7 km/h, with gusts of wind almost 60 km/h causing the outside air to be forced through the ventilation duct into the rooms and disturbing the correct air flow.

In the following days the wind did not reduce its speed, and the outside air temperature increased a few degrees. This caused interference in ventilation also in other rooms, both on the first and second floor.

Table 2. Total pressure in the bathroom ventilation duct depending on the wind in December 2019

Date	T [°C] avg.	ρ [kg/m³]	Wind [km/h]		Pres. s. lev. [HPa]	Δp_c [Pa]	
			Int.	Gust		fourth floor	ground floor
01.12.2019	1.5	1.287	9.20	36.0	1020.4	0.76	5.22
02.12.2019	1.7	1.281	13.10	32.4	1016.8	0.57	4.54
03.12.2019	2.3	1.285	9.30	46.8	1020.3	0.66	5.12
04.12.2019	4.2	1.274	15.20	43.2	1020.4	0.21	3.66
05.12.2019	4.4	1.274	11.70	—	1019.9	0.19	3.68
06.12.2019	2.2	1.273	16.40	43.2	1010.9	0.26	3.57
07.12.2019	4.5	1.249	17.70	57.6	1001.1	-0.68	0.43
08.12.2019	7.0	1.241	18.90	54.0	1003.1	-1.16	-0.46
09.12.2019	6.8	1.232	17.10	46.8	995.1	-1.46	-1.65
10.12.2019	5.1	1.254	18.00	54.0	1006.1	-0.56	1.15
11.12.2019	1.2	1.286	13.40	39.6	1017.8	0.74	5.25
12.12.2019	0.6	1.274	13.70	—	1005.8	0.34	3.80
13.12.2019	1.7	1.256	13.20	32.4	996.7	-0.29	1.44

Figure 4 shows the photo taken on 08.12.2019 in the bathroom room located on the ground floor of the building.

Fig. 4. Backward flow of ventilation air from the ventilation sheet in the bathroom on the ground floor

4. Interpretation of results

In order to strengthen (or reduce) the chimney draft during wind and to protect against reversal of draft, chimney caps are usually installed at the flue gas outlet. The obligation to use them in zones II and III according to (PN-EN 1991-1-4:2008) imposes a Regulation (Rozporządzenie 2002). The above obligation does not apply to ventilation. The pressure in the chimney base depends on the pressure on the roof and the wind speed in the area of the base (Opaliński & Rabczak 2003). If this speed is small relative to the reference speed, then the pressure difference between the chimney outlet and the apartment can reduce the displacement pressure or reverse the flow direction.

Flue gas receding due to the wind is primarily the result of an unfavourable pressure difference between the zone within the apartment windows and the pressure at the chimney outlet. This situation usually occurs when the wind blows on the corner of the building. On the leeward side, one-third of the length of the building creates the greatest negative pressure, and on the roof, in the area where there are usually chimney flue outlets, the negative pressure is relatively low. The flats on the leeward side are in an under-pressure area that may cause back-flow of flue gases (Żurański 2003.)

The effectiveness of ventilation depends on changing weather conditions. Therefore, it is very difficult to meet the requirements for the required ventilation air flows for living spaces.

It should be remembered that both the gas cooker and the instantaneous gas water heater belong to devices that take air necessary for the combustion process directly from the rooms in which they are installed. In these rooms, proper air exchange is of particular importance. In addition to the air necessary for hygiene and sanitary purposes, an additional amount of air necessary for the combustion process must be supplied.

If, when burning natural gas, the amount of air supplied is less than required, then harmful substances will appear next to carbon dioxide in combustion products. The more oxygen there will be, the less oxygen will be available during the combustion reaction.

4.1. Theoretical calculations

How important this task is, we can prove by calculating the amount of air that should be delivered to the gas water heater, which has average nominal power of 20 kW.

High-methane natural gas (E) consists in 97-98% of methane (CH_4). Other compounds, which are present in the natural gas in small amounts, for example propane, butane, carbon dioxide are of minor importance and to simplify they will be omitted from our considerations.

It requires a simple stoichiometric calculation to discover that for the combustion of 1 m^3 of gas (Shkarovskiy & Maliszewska 2018), the required amount of fresh air is 9.52 m^3.

Assuming that the amount of air that must be delivered to the device must be increased by 15%, (the excess-air ratio $\lambda = 1.15$), the actual volume of air delivered to burn 1 m^3 methane is equal:

$$9.52 \times 1.15 = 10.95 \text{ m}^3.$$

Assuming that the average calorific power of the gas is 10.35 kWh/m^3, and the efficiency of the burner amounts to 70-75%, can be determined the amount of gas, which has to be delivered to the water heater within one hour:

$$Q = 20.0 / (10.35 \times 0.74) = 2.57 \text{ m}^3/\text{ h}.$$

The quantity of air consumed by a water heater is equal:

$$2.57 \times 10.95 = 28.18 \text{ m}^3/\text{h}.$$

This is the required amount of fresh air, which has to be delivered in one hour to the gas water heater in the bathroom to enable it to function properly. This is the amount of air that must be additionally supplied, regardless of the air necessary for hygienic and sanitary purposes.

If the supplied amount of air is less than required when burning natural gas, a negative pressure will be created in the room and the air flow in the ventilation ducts will be reversed.

Improper operation of gas devices for the flow preparation of hot utility water, drawing combustion air from the room is the main cause of poisoning with carbon monoxide in residential premises. A drastic example is the reverse of the draft in the flue gas and the exhaust gas escaping into the room. Lack of adequate supply of air from the outside disrupts the operation of the gas heater.

During the combustion of gas in gas burners, numerous by-products are formed, the most important of which may be nitrogen oxides (NO_x) and carbon monoxide (CO).

Reversing airflow can be very dangerous. Polluted air along with harmful compounds is sucked in from ventilation ducts and re-introduced into the rooms. In addition, malfunctioning ventilation does not discharge gases (combustion products) that significantly affect human health. The following calculations will allow you to estimate the scale of the threat.

The flow of gas characterized by a calorific value of 37.60 MJ/m^3 with both burners (with a nominal power of 2.00 kW and 2.90 kW) operating simultaneously will be:

$$(2.00 + 2.9) \times 10^{-3}/37.60 \times 3600 = 0.469 \text{ m}^3/\text{h}$$

The expected flue gas stream entering rooms (at the theoretical unit volume of dry basis combustion products, which is 8.52 m^3/m^3) (Shkarovskiy & Maliszewska 2018), and taking into account that the standard 200 mg/m^3 is converted into $\alpha = 1$, will amount to:

$$0.469 \times 8.52 = 3.996 \text{ m}^3/\text{h}$$

In this way, the amount of nitrogen oxides going into the rooms of the kitchen can be equal:

$$3.996 \times 200 = 799.2 \text{ mg/h}$$

Assuming that the air exchange stream for a kitchen room with a window equipped with a gas stove will be 38 m^3/h (data from 03.10.2019), then the possible concentration of NO_x directly in the kitchen room will be (Maliszewska et al. 2019):

$$799.2/38 = 21.03 \text{ mg/m}^3$$

It is a value that significantly exceeds the permissible standards for the concentration of nitrogen oxides even for the working environment (Zarządzenie 1996, Rozporządzenie 2018) which undoubtedly affects the health of people staying in the room.

5. Conclusion

1. The efficiency of air exchange, and thus the concentration of harmful substances in rooms, largely depends on changing weather conditions – i.e. outdoor air temperature, atmospheric pressure, wind strength and direction.
2. It is very difficult to achieve the normative required ventilation air flow with gravitational ventilation. In adverse weather conditions it can be as low as a few percent of the required level or reach zero values.
3. Abnormal operation of the ventilation system has already been observed at temperatures less than 10°C, especially in rooms located on the top floor.
4. If during the combustion of natural gas the amount of air supplied is less than required, a negative pressure will be created in the room and the air flow in the ventilation ducts will be reversed, ventilation will not be able to discharge combustion products whose concentration in the room can significantly exceed the permissible standards.
5. Inverted gravitational draft can be very dangerous. Exhaust gas escaping from flue pipes may be sucked in and injected into the building, posing a risk to health and life.
6. The aim should be to install devices with closed combustion chamber in bathrooms where there is a risk of back draft.
7. Distribution of pressure factor values on walls and roof slopes given in the wind impact standards relate to the load on buildings and their elements. It is planned to extend the experimental research related to this issue to adapt it to the needs of ventilation.

8. Chimney cowls mounted on flue gas ducts with low wind may additionally reduce chimney draft, creating additional resistance.
9. In the literature, there is no data relating to changes in the temperature gradient in the exhaust gas flue. It is planned to expand the research related to this issue.
10. It is planned to supplement the experimental research with the analysis of data obtained with the help of programs for numerical modelling of CFD flow. Pre-construction tests could verify the relative location of buildings and help prevent unfortunate accidents due to poisoning.

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Abstract

Contemporary systems for removing flue gases and used air should be selected so that there is no risk of accumulation of hazardous and harmful substances in human health. We spend a large part of our lives in our apartments and even relatively low concentrations of harmful substances, that arise during the operation of gas appliances can pose a serious threat to health. The efficiency of air exchange, and thus the concentration of harmful substances in rooms, largely depends on many variables, whose interaction generates a large number of variants. The author of the article set themselves the task of examining the impact of weather conditions on the operation of flue gas exhaust systems and ventilation in rooms with gas appliances.

Keywords:
flue gas discharge system, ventilation, chimney draft, wind, indoor gas appliances, air quality

Wpływ warunków atmosferycznych na działanie systemu odprowadzenia spalin i wentylacji grawitacyjnej w pomieszczeniach z urządzeniami gazowymi

Streszczenie:

Współczesne systemy odprowadzania spalin i zużytego powietrza powinny być tak dobrane, aby w pomieszczeniach nie powstawało ryzyko gromadzenia się substancji niebezpiecznych i szkodliwych dla ludzkiego zdrowia. W mieszkaniach spędzamy znaczną część swojego życia i nawet stosunkowo niskie stężenia substancji szkodliwych, powstające podczas eksploatacji urządzeń gazowych, stanowić mogą poważne zagrożenie dla zdrowia. Skuteczność wymiany powietrza, a tym samym stężenie szkodliwych substancji w pomieszczeniach w dużej mierze uzależnione jest od wielu zmiennych, których wzajemna interakcja generuje znaczną liczbę wariantów. Autor artykułu postawił sobie za zadanie zbadanie wpływu warunków atmosferycznych na pracę systemów odprowadzenia spalin i działania wentylacji w pomieszczeniach z urządzeniami gazowymi.

Słowa kluczowe:
system odprowadzenia spalin, wentylacja, ciąg kominowy, wiatr,
urządzenia gazowe w pomieszczeniach, jakość powietrza

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Impact of a Small Wastewater Treatment Plant on the Sanitary State of Atmospheric Air

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1. Introduction

Wastewater treatment plants are a source of odours and microorganism emissions to the atmospheric air (Kołwzan et al. 2010, Sówka et al. 2015, Szyłak-Szydłowski et al. 2016, Sówka et al. 2017). The high density of buildings and errors in spatial planning cause that residents of buildings adjacent to municipal wastewater treatment plants are exposed to the emissions of chemical and microbial atmospheric air pollutants (Byliński et al. 2019, Paśmionka 2020). It may cause discomfort and fear of the health effects of exposure resulting from the treatment plant activities.

Bioaerosol emitted to the atmospheric air by opened wastewater treatment plants, especially municipal ones, may contain pathogenic and potentially pathogenic microorganisms for humans and livestock causing among others allergic reactions (Michalak & Pawlas 2012, Budzińska et al. 2013, Michałkiewicz 2018). Municipal wastewater is also a reservoir for antibiotic-resistant microorganisms (Huang et al. 2012, Osińska et al. 2019, Savin et al. 2019). The volume of bioaerosol emissions, and thus also the potential health risk, shows a dependence on the size of the treatment plant and the wastewater treatment technology used in it (Breza-Boruta 2010, Kołwzan et al. 2012, Rizzo et al. 2013). This justifies researching the health threat caused by the emission of bioaerosol into the atmospheric air by wastewater treatment plants and the dispersion of this type of pollution (Michalak & Pawlas 2012, Michałkiewicz 2018).

The aim of the study was to assess the impact of the new, just opend, small municipal wastewater treatment plant, located 300 m east of the nearest residential buildings on the sanitary condition of atmospheric air. In the vicinity of the investigated wastewater treatment plant, natural sources of microorganism emissions to the atmospheric air were located, including drainage channels filled with water and natural terrain obstacles (trees and forests), affecting the dispertion of pollutants emitted by the wastewater treatment plant.

2. Study object

The subject of the study was a municipal wastewater treatment plant (WWTP) serving approx. 20,000 PE (population equiwalent), with an average daily flow of approx. 2,300 m^3 located among arable fields. There is the forest on the south-west of WWTP. In the area of the investigated wastewater treatment plant, there are predenitrification chamber (67 m^3), 2 dephosphatation chambers (112 m^3 and 168 m^3), 3 denitrification chambers (343 m^3, 112.5 m^3 and 331 m^3), optional chamber (142 m^3), nitrification chamber (1432 m^3), and secondary settling tank (610 m^3). Treated wastewater is discharged into a drainage ditch. The wastewater treatment plant is equipped with a sludge dewatering station with a capacity of 10-12 m^3/h, working 6 days a week for 10 hours a day.

3. Materials and methods

The number of microorganisms suspended in the atmospheric air was determined by the sedimentation method, accordance with Polish standards no PN-89/Z-04111/01, PN-89/Z-04111/02, PN-89/Z-04111/03, and PN-89/Z-04111/08. Measuring stands 1-10 were located in the wind trail every 50 m, taking into account field conditions on the leeward side of the treatment plant. Control stands 11-13 were situated on the windward side (Fig. 1).

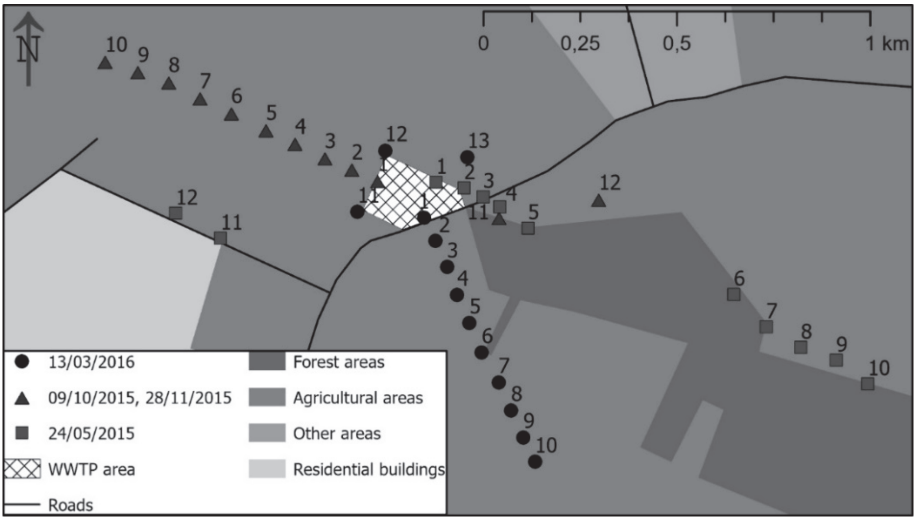

Fig. 1. Location of measuring stands

Four series of tests were carried out in the transitional periods of the year (spring and autumn), field tests were carried out between 9.00-12.00. Agarized microbiological media (BTL Polska LTD., Łódź, Poland) in Petri dishes (3 tiles with each substrate) with a diameter of 0.09 m were exposed to free-falling microorganisms for 15 min (media for psychro- and mesophilic bacteria and mold fungi) and 30 min (for actinomycetes) 1.30 m above the ground. Subsequently, the dishes with media were incubated at the temperatures indicated in Table 1.

Table 1. Microorganisms incubation conditions

Group of microorganisms	Microbiological medium	Incubation temperature [°C]	Incubation time [24 h]
psychrophilic bacteria	nutrient agar	22	3
mesophilic bacteria	nutrient agar	37	1
mold fungi	Sabouraud with chloramphenicol	26	3-5
actinomycetes	Pochon	26	3-5

After incubation, colonies grown on media were counted. The number of colony-forming units (CFU) in the unit of air volume was calculated according to the Omelian formula in the Gogoberidze modification (Polish standards – PN-89/Z-04111/02, PN-89/Z0411/3). Bioaerosol samples were taken in triplicate. The results are presented as the arithmetic mean for three replications. Standard deviation is also provided. During the tests, temperature and humidity of the air, wind direction and speed were determined (Table 2). The assessment of the sanitary state of the air around the tested wastewater treatment plant was made by comparing the concentration of microorganisms with the criteria recommended by PN-89/Z-04111/02 (Table 3), PN-89/Z0411/03 (Table 4) and the proposals of the Team of Experts on Biological Factors (Table 5).

Table 2. Meteorological conditions in the research area at 9 am

Atmospheric factor	24.04.2015	9.10.2015	28.11.2015	13.03.2016
air temperature [°C]	+18	+2	-3	+3
air humidity [%]	65	65	90	90
wind speed [m/s]	1.5	2.4	3.0	2-3
wind direction	NW	SW	SE	NNW

Table 3. Criteria for classification of atmospheric air pollution by bacteria according to PN-89/Z-04111/02 - in the scope related to the results of tests obtained in this work

Total number of mesophilic bacteria	Number of actinomycetes	Degree of atmospheric air pollution
<1000	<10	uncontaminated
1000-3000	10-100	moderately polluted
>3000	>100	heavily contaminated

Table 4. Classification criteria for atmospheric air pollution by fungi according to PN-89/Z-04111/03

Total number of fungi in 1 m^3 of atmospheric air	Degree of atmospheric air pollution
3000-5000	average clean atmospheric air, especially in the late spring and early autumn
5000-10000	pollution that may have a negative impact on the natural environment
>10000	pollution threatening the natural human environment

Table 5. Proposals for assessing the degree of microbial contamination of atmospheric air developed by the Team of Experts on Biological Factors (Górny 2010) – to the extent related to the results of research obtained in this work

Bioaerosol component	Degree of atmospheric air pollution	
	acceptable	unacceptable
mesophilic bacteria	≤5000 cuf/m^3	>5000 cuf/m^3
thermophilic actinomycetes	≤200 cuf/m^3	>200 cuf/m^3
Fungi	≤5000 cuf/m^3	>5000 cuf/m^3

4. Results and discussion

The research shows that the concentration of psychrophilic bacteria on the leeward side of the treatment plant varied in the range from 156±85 to 6587±1286 cfu/m^3, depending on the position and day of the inspection. Their concentration was higher than in control (average of all positions on the windward side of the treatment plant) at positions 1-10 on 24/04/2015, 7 and 9 o 9/10/2015, 1-2, and 4-10 on 28/11/2015, 2, 6, 8-10 on 13.03.2016 (Table 6).

Table 6. Concentrations of microorganisms at individual research stands (mean value for 3 repetitions with standard deviation)

Group of microorganisms	Number of measuring stand	Date of control			
		24.04.2015	09.10.2015	28.11.2015	13.03.2016
psychrophilic bacteria	1	1647±401	1577±88	4143±130	653±226
	2	1265±107	1543±214	329±149	1139±383
	3	2617±554	1877±270	156±85	224±91
	4	3675±946	1473±136	589±330	336±91
	5	1127±130	1993±425	572±42	1300±518
	6	1387±276	1872±278	1039±83	1792±436
	7	1300±147	6587±1287	729±184	989±778
	8	1851±70	2028±377	676±258	1531±161
	9	1647±249	6500±332	399±65	3453±2315
	10	4108±883	1300±85	555±98	597±185
	11	1005±65	2877±177	121±65	915±297
	12	919±191	2357±149	416±236	1773±140
	13	not tested	not tested	not tested	1344±992
mesophilic bacteria	1	763±214	1248±153	5997±978	87±25
	2	763±88	1144±112	1092±363	121±65
	3	953±498	1647±259	607±65	87±88
	4	1629±49	1317±201	1040±153	381±88
	5	416±185	2115±534	555±385	1300±42
	6	399±65	1491±161	624±112	1109±298
	7	659±209	6309±1349	676±195	399±107
	8	589±123	2357±107	451±172	693±356
	9	555±65	4628±663	121±49	1127±354
	10	1283±172	1473±65	347±49	243±149
	11	433±161	1421±25	399±25	225±172
	12	416±74	1577±177	364±42	797±307
	13	not tested	not tested	not tested	277±149

Table 6. cont.

Group of microorganisms	Number of measuring stand	Date of control			
		24.04.2015	09.10.2015	28.11.2015	13.03.2016
actinomycetes	1	104±56	165±65	9±12	9±12
	2	87±12	87±25	0±0	0±0
	3	225±80	520±21	43±25	43±25
	4	191±65	225±96	0±0	0±0
	5	130±0	295±12	26±21	26±21
	6	26±21	321±117	9±12	9±12
	7	69±49	849±96	17±12	17±12
	8	243±25	702±21	26±21	26±21
	9	182±56	702±21	17±25	17±25
	10	113±44	719±12	0±0	0±0
	11	113±12	745±107	0±0	0±0
	12	104±21	425±32	43±25	43±25
	13	not tested	not tested	not tested	9±12
Fungi	1	589±218	2704±321	52±42	205±140
	2	104±112	3155±283	52±42	485±132
	3	659±201	4632±410	69±65	355±115
	4	173±136	3744±405	284±21	411±115
	5	87±49	3744±258	451±218	317±132
	6	676±42	3380±195	607±177	672±229
	7	589±25	3033±298	1041±44	205±70
	8	1057±354	3397±172	711±123	1027±161
	9	555±218	4403±519	364±127	2150±454
	10	867±25	4039±177	485±49	3211±588
	11	295±49	3969±65	225±130	429±115
	12	277±25	3068±42	69±65	1045±53
	13	not tested	not tested	not tested	2949±294

The concentration of mesophilic bacteria on the leeward side of the wastewater treatment plant varied from 87±24 to 6309±1349 cfu/m^3, depending on the position and the day of the inspection. Their concentration was higher than in control (average of all positions on the windward side of the treatment plant) at positions 1-4 5 and 7-10 on 24/04/2015, 3, 5, 7-9 on 9/10/2015, 1- On November 8 28, 2015, 5-6 and 8-9 on March 13, 2016 (Table 6).

Concentrations of actinomycetes on the leeward side of the treatment plant varied from 0±0 to 719±12 cfu/m^3, depending on the position and day of the inspection. Their concentration was higher than in control (average of all sites on the windward side of the treatment plant) on sites 3-5 and 8-10 on 24/04/2015, 3, 7-10 on 9/10/2015, 3, 5 and 8 on November 28, 2015, 3 and 8 on March 13, 2016 (Table 6).

The concentration of mold fungi on the leeward side of the wastewater treatment plant varied from 52±42 to 4645±425 cfu/m^3, depending on the stand and the day of the inspection. Their concentration was higher than in control (average of all positions on the windward side of the treatment plant) at locations 1, 3, and 6-10 on 24/04/2015, 3-5, and 9-10 on 9/10/2015, 4-10 on 28.11.2015, 9-10 on 13.03.2016 (Table 6).

The concentration of microorganisms in the area and in the vicinity of wastewater treatment plants examined by other authors, serving from tens to hundreds of thousands of inhabitants were similar to those found in this work and were in the following ranges: 10^2-10^4 for psychrophilic and mesophilic bacteria, 10^1-10^2 for actinomycetes and 10^1-10^4 for mold fungi (Filipkowska et al. 2000, Breza-Boruta 2010, Kołwzan et al. 2012, Li et al. 2016, Paśmionka 2019, Paśmionka 2020). The authors of these studies also found that the concentrations of microorganisms at measuring points differed by the distance from the wastewater treatment plant as a whole and its individual elements, and depending on the day of the inspection. This phenomenon is seasonal in nature (Szyłak-Szydłowski et al. 2016). However, the formation of bioaerosol in a wastewater treatment plant and its distribution in the atmosphere as well as the survival of microorganisms in the atmospheric air depend on many factors, including:

- wastewater treatment technology used in a given treatment plant and its parameters, including: the intensity of wastewater mixing and aeration,
- variable meteorological conditions: wind speed and direction, solar radiation intensity, precipitation, air temperature and humidity
- topography around the wastewater treatment plant and the presence and distribution terrain barrier,
- the duration of the treatment plant's operation – its long-term operation may cause microbiological contamination of the soil and cause the secondary transport of microbial contamination from the soil (Korzeniewska 2011, Kołwzan et al. 2012, Michałkiewicz 2018).

In terms of the concentration of mold fungi, the air around the wastewater treatment plant was on average clean air according to PN-89/Z-04111/02, according to the classification proposed by the Team of Experts on Biological Factors, the degree of atmospheric air pollution around the treatment plant was acceptable (Górny 2010).

In terms of the concentration of mesophilic bacteria, the air was uncontaminated according to PN-89/Z-04111/02 at 23 sites on the leeward side of the treatment plant, moderately contaminated at 14 sites and heavily contaminated at 3 test sites during all four series of field tests (total 40 research positions). In terms of the classification proposed by the Panel of Experts on Biological Factors, the degree of air pollution with mesophilic bacteria was acceptable for 39 out of 40 test stands on the leeward side of the power plant (all series of field tests). The exception was the stand no. 1 located at the wastewater treatment plant fence on November 28, 2015.

In terms of concentration of actinomycetes, the air was uncontaminated according to PN-89/Z-04111/02 at 8 test stands on the leeward side of the treatment plant, moderately polluted at 16 stands and heavily contaminated at 16 stands. Concentrations of actinomycetes on 24/04/2015 and 9/10/2015 were higher than on 28/11/2015 and 13/03/2015. In the presented work, actinomycetes were incubated at 26ºC, in accordance with PN-89/Z-04111/02. At the same time, the Expert Team on Biological Factors (Górny 2010) concluded that air pollution by actinomycetes is acceptable when the concentration of thermophilic actinomycetes exceeds 200 cfu/m^3. This number of actinomycetes was found at 11 positions during the first two field tests, but it was not found during the last two field tests. It is not known, however, how many of these actinomycetes would be thermophilic actinomycetes.

The diversity of microorganism concentrations around the tested wastewater treatment plant did not decrease as a function of the distance from the emission source. It was similar in the case of the previously tested large wastewater treatment plant (Strzelecka et al. 2004). In both cases, this could be due to the presence of other sources of microorganism emissions to atmospheric air in the vicinity of the treatment plant. In the case of the small wastewater treatment plant currently under study, these were arable land without vegetation or scantily covered with emerging winter crops and numerous drainage channels filled with water and water collected in ground depressions. The plant was surrounded by obstacles such as mid-field tree stands, a forest with a dense undercoat, and a railway embankment about 1 m high. They could have changed the direction of air masses displacement from the plant together with bioaerosol lifted from its facilities.

5. Conclusion

The obtained research results indicate that the emission of bioaerosol from a small wastewater treatment plant, may cause changes in the concentration of microorganisms in the atmospheric air at a level close to natural sources. The threat to human health associated with this emission is, in such cases, the presence of pathogens in bioaerosol emitted by wastewater treatment plants (Korzeniewska 2011, Kołwzan et al. 2012, Michalak & Pawlas 2012) and microorganisms that show resistance to antibiotics (Rizzo et al. 2013). An effective solution to the problem is hermetization of the wastewater treatment plant (Michałkiewicz et al. 2009). However, this is an expensive investment. Periodic monitoring of the sanitary state of the air around wastewater management facilities is therefore justified. However, in many countries of the world, including Poland, there is no standardized methodology for this type of monitoring and the permissible concentrations of microorganisms in the air, as well as a clear statement that such monitoring is mandatory. The authors of other works have already addressed this problem (Górny 2010, Michałkiewicz 2018). It is also necessary to conduct further research to develop a set of microbiological indicators that will be used in routine monitoring of sanitary air in the area and in the vicinity of wastewater treatment plants.

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PN-89/Z-04111/01. Ochrona czystości powietrza. Badania mikrobiologiczne. Postanowienia ogólne i zakres normy.

PN-89/Z-04111/02. Ochrona czystości powietrza. Badania mikrobiologiczne. Oznaczanie liczby bakterii w powietrzu atmosferycznym (imisja) przy pobieraniu próbek metodą aspiracyjną i sedymentacyjną.

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Abstract

Wastewater treatment plants are the source of odour and microorganism emissions to the atmospheric air. Bioaerosol emitted by treatment plants may contain pathogenic microorganisms, antibiotic resistant microorganisms and cause allergies.

The aim of the study was to assess the impact of the newly created municipal wastewater treatment plant using the activated sludge method (approx. 20,000 PE, average daily flow of 2,300 m^3) on the sanitary state of atmospheric air. Numerous field obstacles (e.g. trees) and natural sources of microorganism emissions to the atmospheric air (e.g. drainage channels) were located in the vicinity of the wastewater treatment plant.

Bioaerosol samples (3 replicates) were taken in a wind trail at 10 test stands on the leeward side of the treatment plant and two control stands on the windward side of the treatment plant. Samples were taken by sedimentation on Petri dishes with microbiological mediums. Media was incubated at a temperature appropriate for the type of microorganisms (psychrophilic bacteria, mesophilic bacteria, actinomycetes, mold fungi), and then colonies growing on media were counted. The number of microorganisms per unit volume of air was determined according to the Omelian formula in the Gogoberidze modification. Four series of tests were carried out during the transition months (spring and autumn).

The concentration of microorganisms on the leeward side of the treatment plant in the following ranges amouted: psychrophilic bacteria: 156 ± 85 - 6578 ± 1286 cfu/m^3, mesophilic bacteria: 87±24 - 6309 ± 1349 cfu/m^3, actinomycetes: 0±0 - 719±12 cfu/m^3, mold fungi: 52±42 - 4645±425 cfu/m^3. These values were similar to those found in the area and in the vicinity of wastewater treatment plants examined by other authors. The concentration of microorganisms in the vicinity of the tested wastewater treatment plant did not show a downward trend as a function of distance from the wastewater treatment plant. This could be due to the presence of other sources of bioaerosol emissions to atmospheric air in the vicinity of the treatment plant (e.g. drainage canals, uncovered soil in plowed fields) and field obstacles that could have affected the movement of air masses (e.g. in-field woodland, forest, embankment Railway).

The obtained research results indicate that the emission of bioaerosol from a small wastewater treatment plant, may cause changes in the concentration of microorganisms in the atmospheric air at a level close to natural sources. However, the threats to human health caused by bioaerosol emitted from municipal wastewater may be higher. Therefore, it is justified to monitor the sanitary state of the air and the atmosphere at the wastewater treatment plant and in its vicinity, and conduct research to develop an optimal set of indicator microorganisms of this state.

Keywords:
bioaerosol, bacteria, fungi, air pollution, wastewater treatment

Wpływ małej oczyszczalni ścieków na stan sanitarny powietrza atmosferycznego

Streszczenie

Oczyszczalnie ścieków są źródłem emisji odorów i mikroorganizmów do powietrza atmosferycznego. Bioaerozol emitowany przez oczyszczalnie może zawierać mikroorganizmy chorobotwórcze, mikroorganizmy oporne na antybiotyki oraz powodować powstawanie alergii.

Celem pracy była ocena wpływu nowo powstałej oczyszczalni ścieków komunalnych oczyszczającej je metodą osadu czynnego, (ok. 20000 RLM, średni przepływ dobowy 2300 m^3) na stan sanitarny powietrza atmosferycznego. W sąsiedztwie oczyszczalni znajdowały się liczne przeszkody terenowe (np. zadrzewienia) oraz naturalne źródła emisji mikroorganizmów do powietrza atmosferycznego (np. kanały melioracyjne).

Próbki bioaerozolu (po 3 powtórzenia) pobierano w smudze wiatru na 10 stanowiskach badawczych po stronie zawietrzenj oczyszczalni i dwóch stanowiskach kontrolnych po stronie nawietrznej oczyszczalni. Próbki pobierano metodą sedymentacyjną na płytki Petriego ze zagaryzowanymi podłożami mikrobiologicznymi. Podłoża inkubowano w temperaturze odpowiedniej dla danego rodzaju mikroorganizmów (bakterie psychrofilne, bakterie mezofilne, promieniowce, grzyby pleśniowe), a potem liczono kolonie rosnące na podłożach. Liczbę mikroorganizmów w jednostce objętości powietrza określano według wzoru Omeliańskiego w modyfikacji Gogoberidze. Wykonano 4 serie badań w miesiącach przejściowych (wiosna i jesień).

Stężenia mikroorganizmów po stronie zawietrznej oczyszczalni mieściły się w przedziałach: bakterie psychrofilne: 156±85 - 6578±1286 jtk/m^3, bakterie mezofilne: 87±24 - 6309±1349 jtk/m^3, promieniowce: 0±0 - 719±12 jtk/m^3, grzyby pleśniowe: 52±42 - 4645±425 jtk/m^3. Były to wartości zbliżone do stwierdzonych na terenie oraz w sąsiedztwie oczyszczalni ścieków badanych przez innych autorów. Stężenia mikroorganizmów w sąsiedztwie badanej oczyszczalni nie wykazywało tendencji spadkowej w funkcji odległości

od oczyszczalni ścieków. Mogło to być spowodowane obecnością w sąsiedztwie oczyszczalni innych źródeł emisji bioaerozolu do powietrza atmosferycznego (np. kanałów melioracyjnych, odkrytej gleby na zaoranych na polach) oraz przeszkód terenowych, które mogły mieć wpływ na przemieszczanie się mas powietrza (np. zadrzewienia śródpolne, las, nasyp kolejowy).

Uzyskane wyniki badań wskazują, że emisja bioaerozolu z małej oczyszczalni ścieków, w niektórych przynajmniej przypadka, może powodować zmiany stężenia mikroorganizmów w powietrzu atmosferycznym na poziomie zbliżonym do źródeł naturalnych. Zagrożenia dla zdrowia ludzkiego spowodowane przez bioaerozol emitowany ze ścieków komunalnym mogą być jednak większe. Dlatego uzasadnione jest monitorowanie stanu sanitarnego powietrza atmosferycznego na terenie oczyszczalni ścieków i w ich sąsiedztwie oraz prowadzenie badań nad opracowaniem optymalnego zestawu mikroorganizmów wskaźnikowych tego stanu.

Słowa kluczowe:
bioaerozol, bakterie, grzyby, zanieczyszczenie powietrza, oczyszczalnie ścieków

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Waste Heat Recovery by Electric Heat Pump from Exhausted Ventilating Air for Domestic Hot Water in Multi-Family Residential Buildings

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1. Introduction

Research on waste heat recovery concerns many branches and is carried out in a wide range of subjects. Waste heat recovery is used, for example, in data centres (Luo et al. 2019) industrial installations (Hys & Wiak 2013) and in heating equipment from flue gases (Dudkiewicz & Fidorów-Kaprawy 2017, Dudkiewicz & Szałański 2019).

A specific type of waste heat recovery is the heat recovery from exhaust air in ventilation systems. This is a particularly important issue, because any building in which people occupy cannot be operated without ventilation, heating and increasingly often without cooling of the air. Air heating process requires a significant amount of energy and it is important to recover it as much as possible. Therefore, heat recovery in ventilation is the current subject of research (Jaber & Ezzat 2017, Jafarinejad et al. 2019, Kang et al. 2010, Mahajan et al. 2017, O'connor et al. 2016, Wang et al. 2016).

In Poland, heat recovery in ventilation systems has been the basis for changes in regulations and the method of reducing heating needs and operating costs of buildings for over a dozen years. Since 2002, heat recovery has been required by regulations in supply and exhaust ventilation systems with a capacity of at least 10 000 m^3/h (Dz.U. 2002 nr 75 poz. 690 2012). Then, by regulation (Dz.U. nr 201 poz. 1238 2008), of 2008, the regulation was made stricter and in mechanical supply and exhaust ventilation or comfort air conditioning systems with a capacity of 2,000 m^3/h and more, it became mandatory to use heat recovery devices for extract air (where possible – hygienic and air purity reasons) with an efficiency of at least 50%. Further changes were introduced by Regulation (Dz.U.

2013 poz. 926 2013) of 2013. The value of the above mentioned capacity was changed to 500 m^3/h.

It is worth emphasizing, that the requirements of the regulations do not apply to natural and mechanical exhaust ventilation systems. Similarly, most of the above mentioned publications on heat recovery in ventilation installations do not apply to such systems. In these systems, all the warm exhaust air is discharged into the atmosphere and is a significant residual of the waste heat potential.

Natural and mechanical exhaust ventilation systems are characteristic for multi-family residential buildings, which are a very important part of the Polish housing market. According to the National Census of Population and Housing 2011 (GUS 2011), there were over 530,000 multi-family buildings in Poland and 42.5% of all citizens living in them, of which almost 80% were located in buildings with 10 or more flats. In the European Union, about 42% of the population live in multi-family buildings, as reported by Eurostat (EUROSTAT 2019).

Waste heat recovery from exhaust air in extract air ventilation systems is technically difficult. In mechanical supply and extract ventilation systems, heat recovery is achieved by transferring heat from exhaust air to outdoor air in the heat exchanger in air handling unit through which both streams flow without the mixing of these streams. In exhaust ventilation systems, such a recovery of heat is not possible due to the multipoint inflow of outdoor air into the building through the supply air vents located in the building envelope. Because of the relatively low exhaust air temperature (about 20-24°C), direct use of this heat for building or domestic hot water heating is not is not technically feasible. In a building heating system, the water inlet temperature may range from 30°C to 80°C, and in a DHW system, the need for heating is from 10°C to 60°C.

A heat pump can be used to utilize low-temperature waste heat because it is a device which, with the cost of an additional portion of energy, allows to raise the temperature level of the recovered heat. Heat pumps have various applications. For example, to recover heat from extracted air from the kitchen, for heating of natural gas (Englart et al. 2019), in combined use with phase change materials (Pardiñas et al. 2017), in heat recovery systems from grey water (Liu et al. 2014), for water tempering in pools (Géczi et al. 2014), for thermal water preparation for fish technological processes (Suslov et al. 2015) and for additional heat recovery in a supply and extract mechanical ventilation systems (Pisarev et al. 2016).

In the literature, the topic of heat pumps is often discussed, developed and dealt with in various ways. The papers (Kowalski & Szałański 2019, Naldi, Dongellini, & Morini 2015, Dongellini, Naldi, & Morini 2015) present the influence of the climate of various cities on the results of calculations of seasonal energy performance of air heat pumps. The paper (Bohdal et al. 2015) concerns the technical, legislation and ecological aspects of the use of compressor heat pumps with particular consideration of the possibility of eliminating certain refrigerants. In (Dolna & Mikielewicz 2017) CFD analysis of the field type ground heat exchanger and its influence on the compressor heat pump performance was presented.

The authors propose the use of a heat pump to recover heat from the extract air as a potentially very beneficial option, as the lower heat source can be air with a constant and favourable high temperature value. The above was confirmed by examples from the literature review. If an air heat pump with exhaust air as the lower heat source is used, the efficiency of the air heat pump will be significantly higher than in the case of standard operation with outdoor air as the lower heat source (Cepiński & Szałański 2019). Therefore, the further part of the article presents an analysis of the use of air-to-water heat pump type to recover waste heat from the exhaust air from the exhaust ventilation system in a typical multi-family residential building and the use of this heat for the purposes of DHW and the impact of this solution on the energy performance of this building.

2. Requirements for buildings energy performance

On the basis of the EU Directive 2002/91/EC of 16 December 2002 on the energy performance of buildings (Directive 2002/91/EC 2002), in 2008, Polish legislation introduced the concept of energy performance and EP indicator for annual non-renewable primary energy demand for heating, ventilation, cooling, DHW preparation and lighting (Dz.U. 2007 nr 191 poz. 1373 2007; Dz.U. 2015 poz. 376 2015). Moreover, also in 2008, the regulation (Dz.U. nr 201 poz. 1238 2008) gave the method of determining the maximum permissible EP of a building. In May 2010, The European Parliament and The Council adopted the revised Directive "Energy Performance of Buildings" (Directive 2010/31/EU 2010), which further strengthened the requirements in this field. And in 2013, the Regulation (Dz.U. 2013 poz. 926 2013) introduced a gradual increase in EP requirements. The maximum EP limit values were stated as in force from the beginning of 2014, then from the beginning of 2017 and from the beginning of 2021. In 2017 (Dz.U. 2017 poz. 2285 2017), the date of application of the most strict future requirements was finally changed by one day - from the beginning of 2021 to the end of 2020.

The annual non-renewable primary energy demand EP [kWh/($m^2 \cdot a$)] is sum of the components for: heating and ventilation EP_H, domestic hot water (DHW) EP_W, cooling EP_C, lighting EP_L – except residential buildings.

The current values of components of maximum EP for different types of buildings are given in (Dz.U. 2017 poz. 2285 2017). Exemplary values for residential buildings are cited in Table 1. A specific type of waste heat recovery is the heat recovery from exhaust air in ventilation systems. This is a particularly important issue, because any building in which people occupy can not be operated without ventilation, heat

Table 1. Values of maximum EP components, kWh/(m^2·a)
(Dz.U. 2017 poz. 2285 2017)

	from 1st January 2017			from 31st December 2020		
	EP_{H+W}	ΔEP_C	ΔEP_L	EP_{H+W}	ΔEP_C	ΔEP_L
Single-family residential building	95	$10 \cdot A_{f,C}/A_f$	–	75	$5 \cdot A_{f,C}/A_f$	–
Multi-family residential building	85			65		

A_f – floor area of rooms with controlled air temperature (heated or cooled), m^2
$A_{f,C}$ – floor area of rooms with controlled air temperature (cooled), m^2
If the building does not have a cooling system, then $\Delta EP_C = 0$ kWh/(m^2·a).

In common residential buildings without cooling the energy performance depends on the non-renewable primary energy demand for heating, ventilation and for domestic hot water (DHW) preparation. According to (Dz.U. 2015 poz. 376 2015) the energy demand for heating and ventilation and the energy demand for DHW are calculated separately. To determine these values, the energy need is first calculated for the particular purpose. The efficiency of the particular installation is then taken into account to determine the final energy. Besides the final energy, the energy required to drive auxiliary devices such as fans, pumps and automatic control systems is also calculated. The results of final energy Q_k and auxiliary energy E_{pom} by the appropriate values of the non-renewable primary energy factor w_i. These values depend on the type of energy that covers the particular needs (for example: for grid electricity $w_i = 3.0$; for natural gas $w_i = 1.1$; for cogeneration district heating $w_i = 0.8$ (Dz.U. 2015 poz. 376 2015)). Finally, the non-renewable primary energy Q_p can be determined from the formula below:

$$Q_P = Q_k \cdot w_i + E_{pom} \cdot w_i \tag{1}$$

Non-renewable primary factor EP is calculated as:

$$\mathrm{EP} = \frac{Q_p}{A_f} \tag{2}$$

Final energy factor EK is calculated as:

$$\mathrm{EK} = \frac{Q_k}{A_f} \tag{3}$$

The final energy for heating and ventilation depends on the insulation of the building envelope, on glazing, on type and efficiency of heating system and on type of ventilation system. The final energy for DHW purposes depends on type of a building (residential, public, etc.) and on type and efficiency of DHW preparation system.

Current and future requirements presented in Table 1 are so high that when designing new multi-family residential buildings, despite proper insulation of the building envelope and application of energy-saving installation solutions, their fulfilment without the use of renewable energy sources (e.g. solar collectors for domestic hot water) or other unconventional solutions is often impossible.

The research on energy efficiency is still up to date. A study (Alzoubi & Malkawi 2019) showed that old vernacular buildings built in Jordan are better than modern traditional buildings in relation to energy performance. The paper (Stolarska 2019) describes the positive influence of a winter garden on the energy performance of a single-family building designed in a passive standard. There is also up to date topic of proper computation of energy performance of a building (Pasichnyi et al. 2019). Publication (Kowalski & Szałański 2018) presents the influence of the method of testing the airtightness of the whole building envelope and its particular zones on the result of energy performance calculations. Article (Kowalski & Szałański 2017) shows a comparison of the computational and actual energy performance of an exemplary single-family building.

Considering the high demand for new solutions improving the energy performance of buildings, this article shows the analysis of the heat recovery system of waste heat from exhaust air via a heat pump for DHW purposes.

3. Energy potential for heat recovery from exhaust air

The air exchange in the building is a must. According to the Polish standard (PN-B-03430:1983 1983), the minimum required exhaust air flow rates are, for example: for kitchens from 30 m^3/h to 70 m^3/h (depending on the number of occupants and type of oven), for bathrooms 50 m^3/h, for separate toilets 30 m^3/h, and for windowless auxiliary rooms 15 m^3/h. Consequently, for typical flats, the total minimum exhaust air flow rate may range from 80 m^3/h to 150 m^3/h. In exhaust systems, both natural stack ventilation and mechanical extract ventilation, the exhaust flow must be compensated for by external supply air. This air must be heated in the room to the indoor temperature required by the regulations and then is removed to the outside after assimilation of pollutants. Recovering waste heat from this air and using it for other heating purposes can improve the energy performance of the building. Table 2 shows the potential of heat recovery from extract air from dwellings with different total exhaust air flow rates and with different heat recovery rates from this air - different values of temperature drop of exhaust air on the evaporator of a heat pump. The given potential total heat recovery capacity values represent the potential capacity of the lower source of the heat pump. The higher temperature drop of exhaust air on evaporator and the higher relative humidity of this air, the higher potential total capacity of heat recovery is. Typical air-to-water heat pumps make the difference in temperature of the air flowing through the evaporator from about 5 K to about 10 K. Table 2 shows that a higher potential heat recovery rate can be achieved with heat pump designs that cool the exhaust air by approximately 10 K. Greater air cooling requires a larger evaporator heat exchange area, overcoming higher hydraulic resistances at the flow through the heat exchanger and additionally lower temperatures and evaporation pressures of the refrigerant. This results in a decrease of the energy efficiency COP of the heat pump.

The potential waste heat recovery capacity shown in Table 2 can be used for various purposes in a building. In order to determine the possibility of using this potential, the article analyses the possibility of using this heat in DHW system.

4. Description of an exemplary energy recovery system

With a heat pump it is possible to use the heat recovered from the exhaust ventilation system for both purposes:

- heating,
- preparation of DHW.

In both cases, it is possible to use heat pumps of the type:

- air-to-water,
- water-to-water,
- brine-to-water.

The heat pump can heat heating water or DHW:

- directly,
- indirectly using a medium and a heat exchanger or coil in the tank.

Table 2. Potential capacity for total heat recovery (potential capacity of the lower heat pump source) from exhaust ventilation air from typical dwellings

Description of the dwelling	Total exhaust air flow rate, m^3/h	Potential heat recovery capacity from exhaust ventilation air [1]					
		for 40% relative humidity of exhaust air		for 50% relative humidity of exhaust air		for 60% relative humidity of exhaust air	
		5 K[2]	10 K[2]	5 K[2]	10 K[2]	5 K[2]	10 K[2]
Apartment with bathroom, separate toilet and kitchen with gas cooker	150	0.25	0.50	0.25	0.57	0.25	0.73
apartment for more than 3 people, with bathroom, separate toilet and kitchen with an electric cooker	130	0.22	0.44	0.22	0.49	0.22	0.64
Apartment with bathroom and kitchen with gas cooker	120	0.20	0.40	0.20	0.45	0.20	0.59
Apartment for more than 3 people. with bathroom and kitchen with an electric cooker	100	0.17	0.33	0.17	0.38	0.17	0.49
Apartment for up to 3 persons. with bathroom and kitchen with an electric cooker	80	0.13	0.27	0.13	0.30	0.13	0.39

1) for the exhaust air temperature from bathrooms of 24°C and the temperature of 20°C from other rooms, was determined assuming the heat exchanger wall temperature of 2 K lower than the temperature of air leaving the heat exchanger

2) assumed decrease of exhaust air temperature on the evaporator of the heat pump

The paper presents an analysis of the possibilities and effects of heat recovery from exhaust air in a multi-family residential building via air-to-water heat pump and using this heat to indirectly heat (with a coil) the DHW stored in the tank. The diagram of the analysed system is shown in Figure 1. The exhaust air from kitchens, bathrooms and toilets is transported through ventilation ducts over the roof of the building. The heat pump evaporators are installed in the air stream. The heat is taken from the exhaust air by the evaporator of the heat pump. Then, it is transported to the condenser via the refrigerant of the heat pump. In the condenser, the heat is transferred to an intermediate fluid that heats up the water in the storage tank. In the storage tank, the domestic water is preheated in the lower coil. If the set point temperature in the tank is not reached, the domestic hot water is heated by an auxiliary heat source. The heat from the auxiliary heat source is transferred to DHW via the upper coil in the tank.

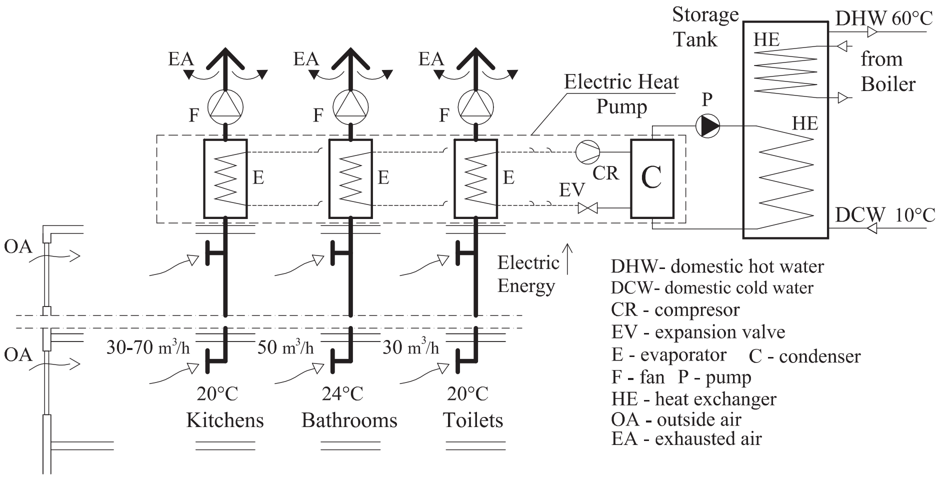

Fig. 1. Scheme of analysed solution

5. Simulation of an exemplary energy recovery system and its impact on the energy performance of a building

Computer simulations of the heat recovery system presented in Figure 1 were performed with the TRNSYS 17 software (Klein 2010) and using the TESSLibs 17 libraries (TESSLibs 17 2012). Table 3 shows the main modules used in the simulation.

Table 3. TRNSYS modules used in simulation

Type	Component name
938	Heat Pump Water Heater
534	Cylindrical Storage Tank with Immersed Heat Exchangers
1243	Water Draw Profile
742	Pump
911	On/Off Differential Controller
659	Auxiliary Fluid Heater With Proportional Control (Proportional Boiler)

The results of the simulation of heat recovery system operation were used to determine its impact on the energy performance of the building.

5.1. Assumptions for simulation

The system under consideration is automated. The heat pump operates in on/off mode. The flow temperature at the outlet of the heat pump is limited (to a value between 35°C and 50°C) by switching the heat pump on/off with a temperature hysteresis of 2 K. Additional heat source (boiler) operates with full capacity and binary control (ON/OFF) with hysteresis of 2 K.

The main assumptions for the simulations of the heat recovery system are presented below:

- simulations were carried out in the period similar to the heating season in Poland, i.e. from 1.10 to 30.04,
- separate hourly domestic hot water draw profiles for working days and weekends according to (Chmielewska 2017),
- value of the daily water draw 40 $dm^3/(occupant \cdot d)$,
- number of occupants 40,
- daily hot water draw of the building 1600 dm^3/d,
- the internal volume of the tank 700 dm^3,
- average coefficient of heat loss from the tank casing 0.51 $W/(m^2 K)$,
- heat transfer area of the lower coil (supplied by the heat pump) 6.5 m^2,
- heating medium flow through the lower coil (from the heat pump) 1500 kg/h,
- heat transfer area of the upper coil (supplied by an additional heat source) 3.0 m^2,
- heating medium flow through the lower coil (from auxiliary heat source) 2000 kg/h,
- auxiliary heat source capacity 12 kW,
- supply medium temperature from the auxiliary heat source 65°C,
- temperature of the exhausted air entering the heat pump evaporators 22°C,

- relative humidity of the exhausted air entering the heat pump evaporators 50%,
- total air flow rate of exhausted air through evaporators 1500 m^3/h,
- the air-to-water heat pump with coefficient of performance COP = 4.0 at entering water temperature 10.0°C, entering air temperature 21.7°C and entering air relative humidity 50.0% (technical data of the heat pump was assumed from the Type 938 module of the TRNSYS (Klein 2010) and TESSlibs software (TESSLibs 17 2012)).

A multi-family residential building with a basement and a flat roof was assumed for analysis. It can be a new building or an existing one after thermal renovation. The building has 5 storey, each storey has 3 flats. There is a staircase in the central part of the building. The building is very well thermally insulated. Heat transfer coefficients of building envelope meet the current requirements of Polish regulations (Dz.U. 2017 poz. 2285 2017) and are as follows: external walls U = 0.23 W/(m^2 K), the flat roof U = 0.18 W/(m^2 K), the ceiling of the basement U = 0.25 W/(m^2 K), windows U = 1.10 W/(m^2 K). The floor area (A_f) of the building is 1001.5 m^2, the internal volume of the building is 2503.8 m^3. Indoor air temperatures are as follows: rooms and toilets 20°C, bathroom 24°C, staircase 8°C.

There is mechanical exhaust ventilation in the building. A gas condensing boiler is the heat source for building heating. Two heat source variants are considered for DHW preparation. I – gas condensing boiler, II – gas condensing boiler and air/water heat pump with lower source as exhaust air from mechanical ventilation system The II variant is a proposal of the authors presented in this paper (Figure 1).

For the building model, an annual energy needs calculation was carried out. Calculations of primary energy were performed in line with the Polish methodology for determining the energy performance (Dz.U. 2015 poz. 376 2015).

5.2. Simulation results

5.2.1. Effect of limiting the outlet temperature from the heat pump on the energy effect

In the discussed example, the heat source for DHW heating is both the heat pump and the boiler. The heat pump supplying the DHW system through the coil located in the lower part of the tank is the first DHW heating stage. The boiler is a source of heat, which through the coil located in the upper part of the tank is always able to provide the preset DHW temperature equal to 60°C. Therefore, the heat pump can operate in the range from DCW temperature equal to 10°C to DHW temperature equal to 60°C. The temperature of the upper heat source of the heat pump affects its efficiency. As the temperature of the upper heat source increases, the COP decreases. A heat pump can run longer heating DHW to a higher temperature or shorter to a lower temperature. In the first case it will reach a lower value of the seasonal coefficient of performance (SCOP) and in the second case higher. Therefore, it is important to consider what is more energy efficient. Table 4 shows the effect of limiting the maximum outlet temperature of a heat pump on the energy effect.

Table 4. Simulation and calculation results – the influence of limiting the maximum outlet temperature of a heat pump on the energy effect

Limit temperature of heat pump outflow	SCOP	$E_{HPT}/(E_{BT}+E_{HPT})$	Operating time		EK_W[1)]		EP_W[1)]
			Heat pump	Boiler	kWh/(m² a)		
	–	%			Heat pump	Boiler	kWh/(m² a)
t_{max} = 30°C	3.36	39.6%	43.6%	32.7%	23.13	4.06	39.97
t_{max} = 35°C	3.19	48.9%	53.7%	28.9%	19.56	5.29	39.68
t_{max} = 40°C	3.05	56.9%	62.3%	25.4%	16.52	6.42	39.71
t_{max} = 45°C	2.93	64.1%	70.0%	21.7%	13.76	7.55	40.00
t_{max} = 50°C	2.82	70.4%	77.0%	18.5%	11.32	8.59	40.42

[1)] for DHW
E_{HPT} – energy delivered to the storage tank from heat pump
E_{BT} – energy delivered to the storage tank from boiler (auxiliary heat source)

Operating time of the heat pump and the boiler change significantly. This means that a different amount of electricity is used to operate the heat pump and gas to operate the boiler. That's why final energy for DHW preparation (EK_W) decreases with increasing heat pump outlet temperature. But this does not mean the same impact on primary energy, because it also depends on the value of non-renewable primary energy factors. The energy effect indicator was assumed to be the non-renewable primary energy factor for DHW (EP_W). The lowest EP_W value is reached for a 35°C supply flow temperature. It is worth noting that for all analysed heat pump outlet temperatures the amount of non-renewable primary energy consumed by the system is close.

The amount of non-renewable primary energy in accordance with formula (1) depends on the non-renewable primary energy factor w_i and the amount of final energy (Q_k). Since for the heat pump $w_i = 3.0$, which is much more than for the gas for which $w_i = 1.1$, even a much smaller amount of final energy consumed by the heat pump does not significantly affect the total primary energy. It should be noted that PEF (Primary Energy Factor) values in the EU are below 3.0 and decrease over the years. (Esser & Sensfuss 2016; Uwe R. Fritsche 2015).

5.2.2. Effect of the exhaust air humidity on the heat pump capacity and the building energy effect

In the analysed system, the exhaust air from the apartments is the lower source of the heat pump. As shown in Section 3, the potential heat recovery capacity from the exhaust air, and thus the capacity of the heat pump, is significantly affected by the humidity of this air. This is the result of using the condensation of water vapour from the air in contact with the evaporator of the heat pump. Therefore, if the relative humidity of the air increases, the power of the lower heat source of the heat pump can increase. The higher the power of the lower heat source of the heat pump, the higher the efficiency of the heat pump. Thus, a higher seasonal coefficient of performance (SCOP) of the heat pump improves the energy efficiency of the building.

Since the simulation is based on constant relative humidity of the exhaust air (50%), it was decided to check what influence the change of this relative humidity will have on the energy effect of the building. The operation of the system with relative humidity of the exhaust air equal to 40%, 50% and 60% was analysed (Table 5). The change of the relative humidity of the exhaust air from 40% to 60% results in a reduction of EP_W by 2.1%. Exhaust air humidity changes over time. This is a result of changes in the humidity of the outdoor air and the emission of water vapour inside the rooms. Therefore, the determination of changes in the humidity of the exhaust air requires detailed analyses and the formulation of many assumptions. In order to formulate conclusions in this article, they are not necessary, but they may be a stage of future research.

Table 5. Simulation and calculation – influence of the relative humidity of the exhaust air on the energy effect

Relative humidity of the exhaust air	SCOP	$E_{HPT}/(E_{BT}+E_{HPT})$	Operating time		EK_W [1)] kWh/(m² a)		EP_W [1)]
	–	%	Heat pump	Boiler	Heat pump	Boiler	kWh/(m² a)
RH = 40%	3.11	48.6%	55.5%	29.0%	5.38	19.67	40.10
RH = 50%	3.19	48.9%	53.7%	28.9%	5.29	19.56	39.68
RH = 60%	3.28	49.2%	52.0%	28.9%	5.17	19.47	39.24

Temperature limitation of the heat pump outlet to 35°C.
[1)] for DHW
E_{HPT} – energy delivered to the storage tank from heat pump
E_{BT} – energy delivered to the storage tank from boiler (auxiliary heat source)

5.2.3. Impact of the proposed solution on the energy performance of the building

The use of a gas boiler as a heat source for building heating and DHW preparation is one of the typical solutions in heating technology in Poland. The type of heat source and the type of fuel from which the heat is produced significantly influences the value of non-renewable primary energy consumed by the building (see Section 2). Table 6 presents the results of energy performance calculations for the building in two variants, I – the source of heat for space heating and DHW preparation is a gas condensing boiler, II – the source of heat for space heating is a gas condensing boiler, the source of heat for DHW preparation is a gas condensing boiler and an air-to-water heat pump. In the II variant, the heat pump covers 48.9% of the DHW preparation needs (see Tables 5 and 6). The use of a heat pump allows to reduce the amount of final energy for DHW preparation (EK_W) by 35.1% in comparison with variant I. However, the difference in primary energy consumption (EP_W) is much smaller and amounts only 9.1%. This is due to the large difference between w_i values for electricity and gas (see 5.2.1).

In the analysed case, the application of the proposed solution made it possible to meet the Polish regulations on energy savings. The EP_{H+W} factor for variant II is lower than the maximum limit value for multi-family residential buildings. The comparison does not cover all possible cases. The similar result obtained for variant I and II calls for further research, which will determine in which cases the application of the proposed solution is energetically but also economically justified.

Table 5. Comparison of the energy effect of a boiler and a heat pump

Variant	Heat source for space heating	Heat source for DHW preparation	EK_W [1)]		EP_W [1)]	EP_H [1)]	EP_{H+W}	$EP_{H+W(max)}$
			kWh/(m² a)					
			Heat pump	Boiler	kWh/(m² a)			
I	Boiler	Boiler	–	38.29	43.65	44.43	88.08	85.00
II	Boiler	Boiler/Heat pump[1)]	19.56	5.29	39.68	44.43	84.11	85.00

[1)] for DHW, [2)] for space heating
E_{HPT} – Energy delivered to storage tank from heat pump
E_{BT} – Energy delivered to storage tank from boiler (auxiliary heat source
Auxiliary energy calculated as for a boiler and distributed proportionally according to the share of two sources. Outlet temperature of the heat pump limited to 35°C, the exhaust air relative humidity is 50%

6. Conclusions

It was shown that using an air heat pump it is possible to recover waste heat from the exhaust air from the ventilation system of a multi-family residential building. This potential is high due to the large share of such buildings. By increasing the temperature level of the recovered heat with a heat pump, it can be used, for example, to preheat domestic hot water.

The proposed heat recovery system of waste heat from exhaust air via an electric heat pump for DHW purposes was analysed by TRNSYS 17 software. Based on the analysis for an exemplary multi-family building, it was concluded that in order to obtain a minimum primary energy consumption for the analysed system, it may be justified (depending on the local values of the non-renewable primary energy coefficients) to limit the outlet flow temperature from the heat pump. In the analysed case, in Polish conditions, the temperature of 35°C was determined. In comparison with using only a gas condensing boiler, the final energy amount for DHW preparation (EK_w) by 35.1% and primary energy consumption (EP_w) by 9.1%. n Poland, electricity is produced mainly from fossil fuels, which results in high consumption of non-renewable primary energy for its production. When a larger share of cleaner sources (e.g. PV) is used to generate electricity, the proposed solution results in a much greater reduction in the demand for primary energy.

Moreover, an increase in the relative humidity of the exhaust air increases the efficiency of the heat pump, which in the analysed range (40-60%) resulted in a change in both EP_W and EK_W, but only by about 2%.

The discussed topic has a very wide range of future research possibilities. Further research is planned to determine how to recover available waste heat with less energy input and for which installations in the building it should be used. In the future, different heat recovery system and heat pump configurations, including gas, will be analysed, as well as the use of waste heat also for space heating and the cooperation of heat pumps with other heat sources.

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Abstract

The article discusses the possibility of recovering waste heat from the exhaust air from the ventilation system of multi-family residential buildings. A system of waste heat recovery from the extracted air with an electric heat pump was proposed for the preparation of domestic hot water (DHW). The proposed system has been analysed in TRNSYS 17 software for exemplary multi-family residential building. The influence of exhaust air humidity and heat pump outlet temperature on the energy effect was analysed. For the analysed case and the Polish conditions of electricity production, a possible reduction of the final energy amount for DHW preparation (EK_W) by 35.1% and primary energy consumption (EP_W) by 9.1% was determined in comparison with the use of a gas condensing boiler only.

The factors influencing the energy effect of the system for the recovery of waste heat from the exhaust air were indicated. The authors specified directions of further research aimed at determining how to recover available waste heat from the exhaust air with lower energy expenditure and for which installations in the building they should be used.

Keywords:
air-to-water electric heat pump, waste heat recovery, heat recovery in ventilation, domestic hot water, TRNSYS

Odzysk ciepła odpadowego za pomocą elektrycznej pompy ciepła z wywiewanego powietrza wentylacyjnego do systemu ciepłej wody użytkowej w wielorodzinnych budynkach mieszkalnych

Streszczenie

W artykule podjęto temat możliwości odzyskania ciepła odpadowego z powietrza wywiewanego z systemu wentylacyjnego budynków wielorodzinnych mieszkalnych. Zaproponowano system odzysku ciepła odpadowego z powietrza wywiewanego elektryczną pompą ciepła dla potrzeb przygotowania ciepłej wody. Zaproponowany system przeanalizowano w oprogramowaniu TRNSYS 17 dla przykładowego budynku wielorodzinnego. Przedstawiono wpływ wilgotności względnej powietrza wywiewanego i temperatury zasilania pompy ciepłej na efekt energetyczny. Dla analizowanego przypadku i polskich warunków produkcji energii elektrycznej, wyznaczono możliwe zmniejszenie zapotrzebowania energii końcowej na przygotowanie ciepłej wody użytkowej (EK_W) o 35,1% i energii pierwotnej (EP_W) o 9,1% w porównaniu z zastosowaniem tylko gazowego kotła kondensacyjnego.

Wskazano czynniki wpływające na efekt energetyczny systemu do odzysku ciepła odpadowego z powietrza wywiewanego. Autorzy podali kierunki dalszych badań zmierzających do określenia jak odzyskać dostępne ciepło odpadowe z wywiewu przy mniejszym nakładzie energetycznym i do jakich instalacji w budynku je wykorzystać.

Słowa kluczowe:
sprężarkowa pompa ciepła powietrze/woda, odzysk ciepła odpadowego, odzysk ciepła w wentylacji, ciepła woda użytkowa, TRNSYS

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Results of Measurements of Pore Water and Air Pressure in Model Studies on an Flood Embankment Under Variable Water Saturation Conditions

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1. Introduction

A flood embankment is an artificial earth wall in the form of an escarpment-shaped fill, whose length is one of the characteristic parameters. Flood embankments are an important component of the system of protection of people, animals and material objects from flood. During its exploitation, a flood embankment is exposed to destructive factors – mainly changeable water saturation levels. This results in a rapid escape of air from the inside of an embankment, which is linked to the initiation of the destruction of the whole structure. The research discussed in the article was first conducted as part of the European Union Integrated Project called FLOODsite (*Integrated Flood Risk Analysis and Management Methodologies),* 2004-2009, Fourth Framework Programme of the European Union, coordinator: HR Wallingford, the United Kingdom, contract no GOCE-CT-2004-505420, and subsequently continued under the framework of the TROIAnet network, financed by the Polish Ministry of Science (2009) and a grant funded by the National Science Centre no NN 506 31 70 39 „Studies on changes in the earth microstructure and its influence on process of water flow and transport of pollutants in flood embankments", carried out in 2010-2013. Model tests were performed at the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk.

2. Research method

The research station (Fig. 1) was built by Abo Elela in 1996, but it was refurbished in 2006, which is when a system for measuring air and water pressure in soil pores was added (Abo Elela 1996). Another refurbishment took place in 2011, when the pressure recording system was modernized.

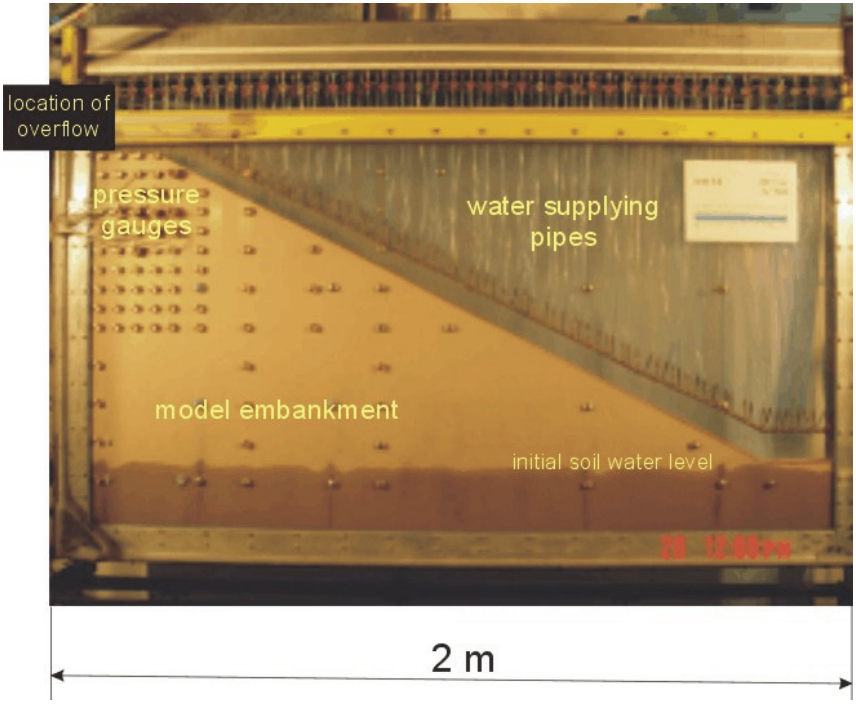

Fig. 1. Component elements of the research station

The knowledge of pressure changes inside the flood embankment model has not been adequately described in the literature. The work is an observation of phenomena occurring during changing hydration conditions with particular emphasis on changes in pore pressures within the model.

The main measurements of pressure were recorded on a model whose geometrical parameters are presented in Fig. 1. It was made of Lubiatowo sea sand, whose characteristics are presented in Table 1. The model was formed with the sand rain method (Kolbuszewski & Jones 1961, Zaradny 1993, 1994). The angle of inclination ($\alpha = 27°$) of the model (Fig. 2) is due to the need to load it in the limit state of load, which facilitated the observation of model degradation. More than 50 tests were conducted. The most representative was test No. 17, the results of which are shown below.

Variable	Value
Median d_{50}	0.25 mm
Filtration coefficient k_s	0.016 cm/s
Volume weight	17.0 kN/m^3

Table 1. Characteristics of Lubiatowo sand

The initial pressures in the unsaturated zone were calibrated to zero. During the modelling, the degree of compaction of the entire model was not verified, but based on previous experiments it was assumed that it was homogeneous. The model was formed in the ultimate limit state. Based on the observations of previous tests, it was found that the determination of the groundwater level had a small and negligible effect on the pore pressure measurements.

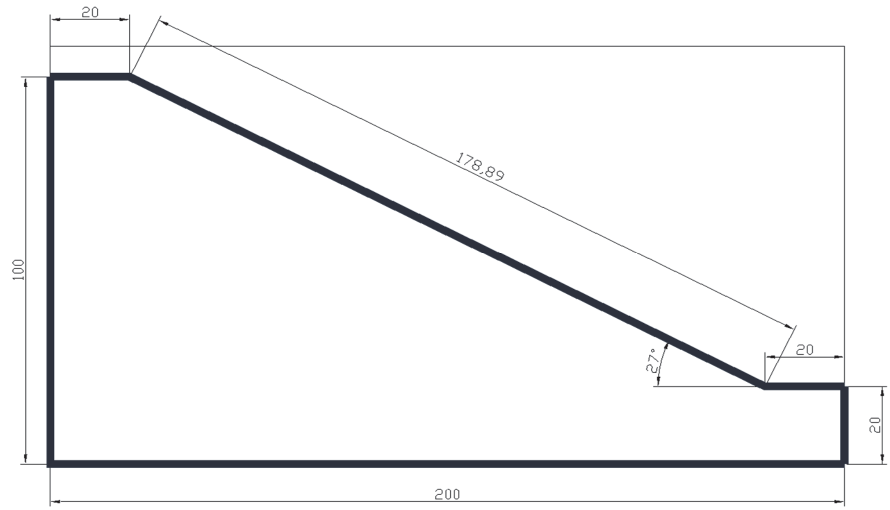

Fig. 2. The geometry of one of the slopes of the flood embankment model, adopted for the study (linear dimensions are given in [cm])

The modelling program included three simulated model irrigation methods:
1. intense rainfall – air slope,
2. water overflow through the crown of the flood embankment,
3. change of water level from the side of the upstream slope.

The type 1 experiment consisted in watering the flood protection model by introducing a rain generator into the measuring box. The type 2 experiment consisted of water overflow through the embankment crown – it was carried out for the air slope and various overflow expenses, and for the full embankment model. The type 3 experiment consisted in changing the water table level at different speeds, simulating a flood surge.

During tests simulating rainfall and overflow through the crown of the embankment (with a correspondingly large expenditure) or rapid lifting of the water table on the upstream side, i.e. in those experiments where the pore air was closed in the areas surrounded by irrigated soil and lost contact with the atmosphere, the appearance of open discontinuities in the form of air-filled gaps was observed in the model body. These fissures are called macropores because their dimensions correspond to a much larger (in the order of several thousand) number of soil grains.

Sensors SSC-3000 (SensorsTechnics, Germany), i.e. piezoresistance sensors (Fig. 3), set within the range of -1.0; +1.0 bar (-1000; +1000hPa), were used to measure the pressure. These sensors were dedicated to measuring overpressure.

Fig. 3. SSC3000 applied in the research, [http://www.sensortechnics.com]

A set of sensors installed in the head panel of a measuring box consisted of:

1. sensors to measure the air pressure in soil pores – no 1 to 6 (Fig. 4 – yellow colour),
2. sensors to measure the water pressure in soil pores – no 8 to 13 (Fig. 4 – red colour),
3. sensor to measure the atmospheric pressure – no 7 (installed outside the measuring box).

The sensors, supplied an electrical current of 1 mA, transmitted a signal indicating the value of measured pressure to the interface connected directly to a PC computer, where the results were recorded in text files.

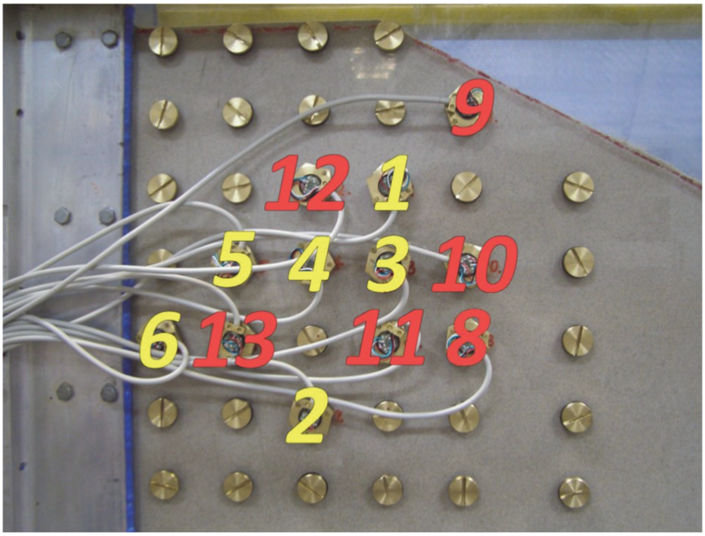

Fig. 4. Position of air and water sensors in the measuring box

3. The results of observations of physical model

The geometry of a model (physical model) corresponding to the landward or riverward (Fig. 2) part of the flood embankment was used in the first part of the research. One advantage of such a shape of the model was the ability to increase its height to 1 m; its disadvantage being the introduction of an impermeable border inside the body – which did not correspond to the factual working conditions of the most frequently observed flood embankment types. The physical model met the conditions described in the literature on geotechnical modeling (Wood 2004).

In some of the tests, when the level of water in the flood embankment model was changed, the air entrapment was observed in some zones, which remained dry for some time, despite being surrounded by saturated soil (Bogacz et. al. 2008, 2017, Kaczmarek et. al. 2010, 2011). The further evolution of these areas resulted in the appearance of open discontinuities, which evolved into variously shaped fissures filled with air. In some tests (e.g. test no 17 – overflow of water through the crown of the flood embankment with the output q ~ 9.25 ml/s), discontinuities occurred in the immediate vicinity of the pressure sensors, which enabled us to record changes in pressure, which were sometimes very abrupt. In most cases, changes in recorded pressures can be associated with the occurrence of a discontinuity in the soil structure, which had been previously described as a macropore (Bogacz 2017).

The diagram shown in Fig. 5 reveals a sudden increase in the air pressure at 58 minute. The peak in the pressure diagram appeared approximately at the moment of taking photo 0433, in which the opening of a macropore denoted with the number 1 can be seen (Fig. 7).

The subsequent increase in pressure is probably caused by the appearance of a zone supplying the discontinuity – a macropore which formed in the immediate vicinity of a sensor (Fig. 7).

Values recorded in the diagram representing water pressures – sensor 11 – Fig. 6 – indicate an increase, caused by the occurrence of the discontinuity mentioned above.

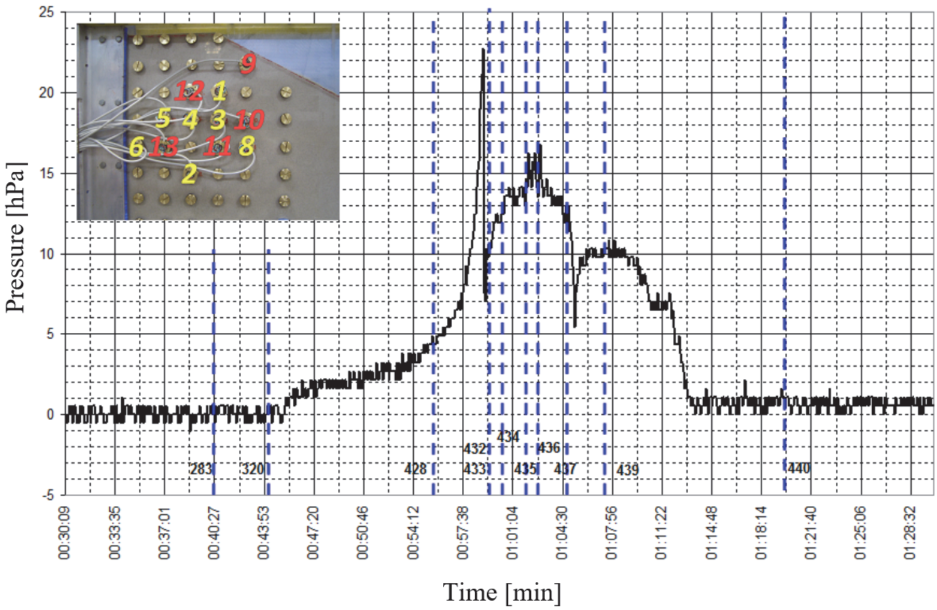

Fig. 5. Diagram of pressures – air sensor no 6 – test 17

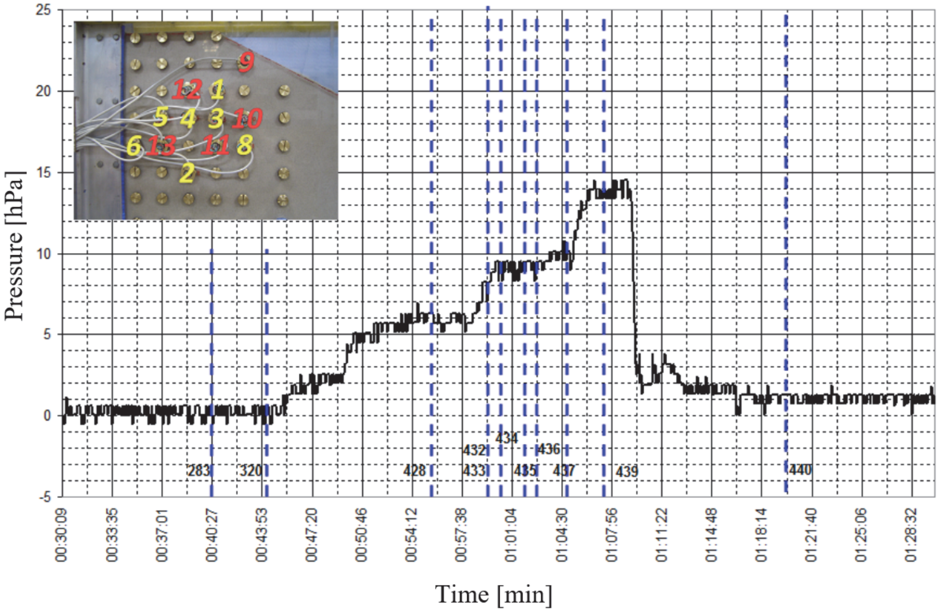

Fig. 6. Diagram of pressures – water pressure sensor no 11 – test 17

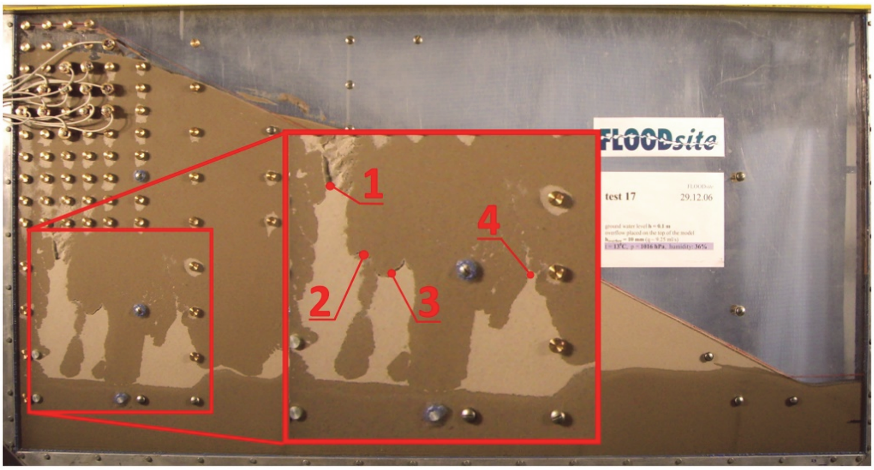

Fig. 7. Test 17 – a photo taken at the moment of a rapid increase in the pressure (Fig. 5), no of photo: 0433.
A – an area where discontinuity (a macropore) appeared

4. Conclusions

Numerous physical phenomena were observed during the research. One of them was a change in the pore pressure values recorded by the sensors. Observations of changes occurring in the model (appearance of macropores, discontinuities of the soil center) in association with the pressure graphs show that air transport is carried out within the shaft model. It is variable. The repetitive part of most tests was the appearance of the macropores mentioned, which were powered by the transported air. The appearance of macropores can depend on the method and the rate of irrigation of the model. The observations show that the main cause of soil discontinuity is the increase in pore pressure.

The phenomena related to the air flow in the opposite direction to the pore water flow, the influence of the settlement of the soil loaded with water and the effect of the model walls on its behavior cannot be ruled out.

The connection of the maximum recorded pressure of 22.5 hPa with the observation of the model's behavior allows us to state that a sudden increase in pore pressure initiates the formation of air spaces inside the model. The evolution of discontinuities became the initiator of the observed phenomenon of the destruction of the flood embankment model.

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Abstract

This paper contains results of measurements of the pore water pressures in a model flood embankment exposed to different water saturation levels. The pressure of air and water was measured, and the recorded values were referred to the atmospheric pressure value. Correlation of the variables corresponding to the recorded pressures was observed, with the appearance of discontinuous in the soil structure of the model.

Keywords:
flood embankment, pore pressure, variable water saturation

Wyniki pomiarów ciśnień w badaniach modelowych wału przeciwpowodziowego w zmiennych warunkach nawodnienia

Streszczenie

W pracy przedstawiono wyniki pomiarów wartości ciśnień porowych w modelu wału przeciwpowodziowego w zmiennych warunkach nawodnienia. Dokonano pomiaru ciśnień powietrza i wody, a zarejestrowane wartości odniesiono do wartości ciśnienia atmosferycznego. Zaobserwowano zbieżność zmienności zarejestrowanych wartości ciśnień z powstawaniem nieciągłości w strukturze gruntowej modelu.

Słowa kluczowe:
wał przeciwpowodziowy, ciśnienie porowe, zmienne warunki nawodnienia

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Selected Aspects of Heating System Design in an Energy-Balanced Floating House

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1. Introduction

Directives of the European Parliament and other international provisions aiming at de-signing energy-friendly facilities (environmentally friendly) are over time implemented in Polish legislation, (Directive 2009/28/EC, Ordinance of the Minister of Economy of 4 April 2014). They should meet the criteria for the limited use of energy from conventional sources. Preference is given to solutions that use systems powered by energy from renewable sources (RES), especially from the areas of distributed energy in small- and micro-scale facilities. The listed issues also include facilities operating in broadly understood branches of tourism and recreation. Due to the current limitations of international tourism caused, among others, by the coronavirus pandemic, the local form of rest and recreation is becoming the most recommended way of implementation. The proposed offer in this regard can be, for example, a floating house, founded on a float and moored to the marina (wharf) of the local water reservoir (e.g. lakes).

The subject of design and operational considerations contained in this article are select-ed issues related to the implementation of the required thermal energy demand for the so-called "Water House" hereinafter referred to as WH. The concept of "house on water (WH)" was already known in the 1950s (and even earlier), concerning facilities intended for seasonal or year-round residence on the surface of the water body (rivers, lakes, canal, etc.). The 70s and 90s of this century was a period of dynamic development of the construction of houses on the water, not only on a European scale but and globally. WH's construction pre-cursors include Dutch companies and those operating in the Scandinavian countries. In the Netherlands, 20-30% of the area is covered by water reservoirs, WH constructions in very different varieties developed, including residential buildings placed on barges and boats moored to canal quays (some Dutch cities are covered with a significant number of channels). The importance of the living in WH problem is demonstrated, among others, by the fact that in Amsterdam, at Prinsengracht 296 is the only Museum of Housing Boats in the world. Living in WH is very popular in many European cities, not only in Amsterdam but also in Copenhagen, London, Lower Saxony, Germany, etc. WH floating objects are also popular in the United States, Canada, and other countries of the world (e.g. in New Zealand). In recent years, WH-type construction has also appeared in some Polish cities in which companies producing such facilities are located. Among them are such locations as Koszalin, Warsaw, Wrocław, Gdańsk, etc. There are already many companies dealing with these problems.

There is a clear lack of available information in the literature in the form of studies covering the principles of designing and operating houses on the water (WH), as well as applicable legal provisions related to this. Most fragmentary information is obtained primarily from web portals (to a minimum extent from articles published in professional journals), while most of them are not at a sufficiently high engineering level.

2. WH object classification

There are currently a very large number of construction variants and methods for founding WH facilities. The following classification of WH facilities is proposed, depending on the used criterion. Due to the location of residential buildings, WH facilities can be classified as built:

- on the barge,
- on boats,
- on float platforms,
- other specialized solutions;

a) because of the possibility of WH movement, there are:
  - mobile floating houses - with or without drive (using other floating objects to move),
  - stationary ("quasi-stationary") floating houses - without self-drive, in principle attached to specific waterfront elements (platforms and other anchor systems);

b) due to the size of the WH object:
  - small tourist and recreational object,
  - medium-sized one-story residential buildings, corresponding to the dimensions of the average dimensions of an apartment located in a land building,
  - large, multi-story and multi-apartment WH floating objects (e.g. hotels, conference centers, etc.);

c) due to the duration of WH use:

- seasonal,
- all year round;

d) due to the nature of energy supply sources:
- powered by conventional sources,
- powered by renewable energy sources,
- conventional, with a partial share of renewable energy;

e) WH objects are distinguished by the way of energy supply:
- in which energy is supplied to the object only from external sources,
- with partial use of own energy sources,
- "self-sufficient" energy (under normal operating conditions) in emergency cases, they should have connections enabling the use of external power sources.

The proposed classifications of WH facilities do not take into account other criteria, including economic ones. In the case of water-based tourist and recreational houses, special requirements should be met, both during seasonal and year-round operation, which are beneficial for the owners and renters of the houses. For persons renting a WH type facility, two problems are of significant importance.
1. Ensuring high comfort during stay (this is also associated with an appropriately high standard of equipment).
2. Minimizing the costs associated with the stay.

From the WH owner's perspective, the two most important issues are:
1. Maximization of profits (while maintaining market rights – this means in practice the possibility of obtaining a high price from renters, in cases of ensuring high comfort of stay and appropriate advertising.
2. Minimization of costs, including minimum operating costs of installations in WH and energy acquisition.

Participation in this research project should indirectly contribute to meeting the expectations of the renter – the principal of this project.

3. WH object design Assumption

The current proposals of WH producers, both Polish and foreign, are based on the supply of electricity and heat from external power sources (from the quay). Also, they usually have devices in which energy comes from conventional sources and is initiated in the process of burning fuels (e.g. liquid gas heaters, fireplaces, etc.).

Fig. 1. Example overwiew of water house (WH) moored to the bridge at the lake quay – view from the entrance to the building (own materials)

A significant design assumption is that recreational WH shall have limited use of coastal power sources. At the same time, it is to be a low-energy facility with access to sources of electricity and heat from renewable energy sources (RES). Such systems can work both in monovalent mode and in hybrid combination. These types of systems include heat pump, photovoltaic panels, low power wind turbines (especially with vertical axis), etc. Limiting the supply of energy from renewable sources means that a recreational floating house is an ecological object. Compared with conventional sources, there is a significant reduction (or elimination) of greenhouse gas emissions such as CO_2, CO, SO_2 or NO_x. Such a facility is friendly for recreation, renters can rest in healthy conditions during certain stays.

Fig. 1 shows, for example, a view of the WH object anchored to a bridge founded at the lake quay in the Central Pomeranian region. The basic structural elements are float and a residential superstructure. The float acts as a "floating foundation" ensuring the stability of the object. It also allows for dynamic interaction on changes in wind pressure, atmospheric precipitation, changes in water level in the body, etc. In the case of a residential superstructure, it should function as a proper house. At the same time, the structure of the superstructure should have a small mass and adequate rigidity. Usually, the structure of the residential superstructure is made in truss technology. WH houses built in the USA are based in part on the superstructure on the Canadian truss frame. Highly effective thermal insulation limits the values of exchanged heat flux. The external walls of the superstructure are used to install solar panels. Inside the superstructure and partly inside the insulated float, there are installations of central heating, hot utility water, a plumbing system with a water and sewage system, electrical installation, elements of an intelligent control system, etc.

Fig. 2 presents an example of the layout of rooms in the residential WH object set on a rectangular float with dimensions 3.5x8x1 m. The operational depth of immersion approx. 30-40 cm above the surface of the water in the lake.

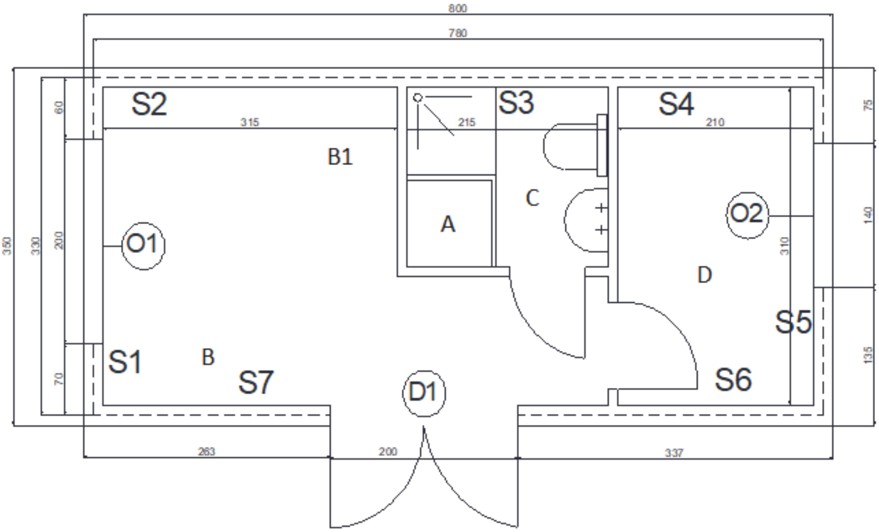

Fig. 2. An exemplary scheme of the layout residential WH object rooms mounted on the float 3.5 x 8 m; A – technical room for the heat pump, B – livingroom, B1 – kitchenette, C – bathroom and toilet, D – bedroom

In the version shown in Figs. 1 and 2, the WH object is intended for a seasonal stay in the recreational form for four people.

4. Designing calculations of heating and hot water installation in WH object

Calculations allowing the selection of installation elements in the scope of systems were made for the assumed design conditions:

- heating and domestic hot water system,
- photovoltaic system,
- wind turbine system,
- intelligent object control system.

This study presents the results of design calculations for a central heating (CH) system and domestic hot water (DHW). The basis for the selection of the heating system elements was the energy balance of the WH object. The foundation of the WH house structure on a float, partly submerged in the waters of the reservoir (lake) located in the Baltic Sea coastal zone creates additional circumstances for qualifying the object as non-standard. The technical literature lacks guidelines that take this type of object into account. The assumptions for the energy balance of the facility were as follows:

- the foundation of the object in the first climatic zone of Poland, which allows adapting the level of computational average outdoor air temperature at $t_{z,obl}$ = -16°C, and the design relative humidity of this air $\varphi_{z,obl}$ = 80%,
- having regard to the successive increase in temperature in the summer season (observed for the last few years), the value of the calculated average outside air temperature in this season was adopted as + 35°C, and relative humidity 60%,
- the calculated air temperature inside the rooms of the residential WH $t_{w,obl}$ = +20°C in the living room and bedroom, and +24°C in the bathroom,
- taking into account the results of measurements of water temperature in the lake basin in recent years, the calculated average water temperature value +5°C, and in the summer season up to +20°C,
- network water temperature supplied from the coastal installation +10°C.

The energy balance calculations were compiled for the heating season and the summer season. Among the balance components were heat fluxes: from heat exchange through glazed and unglazed partitions, from solar radiation, from ventilation and infiltration through leaks, from people staying indoors, etc.

An important item of the heat balance was the heat flux from heat transfer through transparent and opaque partitions. The calculations took into account the construction of individual structural partitions made in the form of a wooden structure with the use of wooden poles with a cross-section of 0.12x0.12 m, wooden paths, and cladding panels with a thickness of 0.025 m. In the construction of external walls, 0.12 m thick styrofoam insulation was used. The floor construction in the residential part consisted of floor panels 0.008 m, OSB board 0.022 m, wooden beams 0.06 m, and a layer of styrofoam 0.17 m. Inter-layer air spaces contained in the external wall elements were filled with polyurethane foam of the PIR type, with a conductivity λ = 0.014 W/(mK).

After considering the possibility of storm conditions in the coastal belt in the energy balance, the required heat flow demand in the heating season for central heating purposes was obtained: $Q_{c.o.}$ = 2500 W, and heat gains in the summer season: Q = 1600 W (e.g. for calculating the efficiency of an air conditioning system).

From the energy balance in terms of heat demand for domestic hot water were obtained $Q_{c.w.u.}$ = 1200 W. The calculations concerned for a family of 4 with the necessity of heating water from + 10°C to + 55°C. The summary states that the required power of the heat source (heat pump) in the calculated heating season should be max. 3.7 kW (for the most unfavourable operating conditions), which will meet the heating and domestic hot water needs.

5. Selection of heating source for WH

5.1. Legal and technical difficulties

The results of the energy balance for an example of a floating house were the basis for the analysis of the possibility of using modernized solutions for the supply of heat to the object. So far, the solutions proposed in the literature in the field of heat obtained for WH type houses relate in most cases to connecting them to the power supply from the external power grid or the use of local heating using fuel combustion. To meet the development trends of modern distributed energy, initiated in the European Union, it was necessary to consider the possibility of reducing the use of conventional energy systems in favour of an increase in the share of energy from renewable sources. In this way, a significant reduction in the consumption of primary fuels and their combustion products are obtained.

Based on the analysis made in the selection of the heating source, attention was paid to the possibility of using a heat pump. A very important problem is that, in the Polish legislation, the heat pump is not directly qualified as a renewable energy source. Unfortunately, neither the Energy Law Act (The Energy Law of April 10, 1997) and the Energy Efficiency Act (The Energy Efficiency Act of March 4, 2011), much less the Act on Renewable Energy Sources of 2015 and (The Act on renewable energy sources of February 20, 2015) do not take this fact into account. However, taking into account Directive 2009/28 / EC of the European Parliament and the Council (Directive 2009/28 / EC) and the Decision of the European Commission of 1 March 2013 (Decision of the European Commission of 1 March 2013) and its Annex (Annex VIII, 2009) can be determined indirectly when a cooperative heat pump is recognized from RES. These conditions were also provided in the Regulation of the Minister of Economy of 4 April 2014 (Regulation of the Minister of Economy of 4 April 2014).

5.2. Choosing the concept of a technical solution

The compressor heat pump belongs to the group of working heat machines in which, according to the second law of thermodynamics, obtaining a useful effect (heat for WH) re-choirs the supply of driving energy from the environment (in the compressor pump energy is supplied through work) (Rubik 1999). The heat pump is connected between the lower and upper heat sources. Proper selection of the type and parameters of sources allows achieving high values of energy efficiency indicators. Fig. 3 presents a schematic diagram of the compressor heat pump's cooperation with sources in the aspect of its use for the heat supply of the WH house.

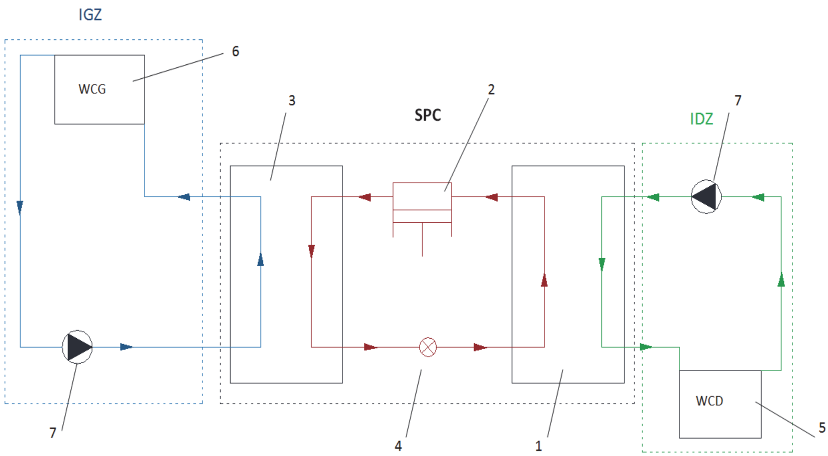

Fig. 3. Schematic diagram of the WH compressor heat pump cooperation with the lower and upper heat sources: 1 – evaporator, 2 – compressor, 3 – condenser, 4 – expansion valve, 5 – lower heat exchanger (WCD), 6 – upper exchanger heat sources (WCG), 7 – brine pumps, SPC – compressor heat pump, IDZ – installation of lower heat source, IGZ – installation of upper heat source

5.2.1. Lower source of heat pump

The lower heat source should have the following characteristics: high heat capacity, high and constant temperature value, no pollution, easy access to the source, and low cost of obtaining low-potential heat. Among the lower sources can be listed: outdoor air, soil, solar radiation, groundwater, surface water. In the conditions of the WH house in question: external air and surface water are available. In both cases, environmental conditions affect thermal stability – Fig. 4.

It was assumed that thelower source of the heat pump in project will be surface water contained in the lake. Surface water is one of the cheapest, generally available lower heat sources that can be used in heat pump systems. Extracting heat from such sources practically does not disturb the equilibrium of the environment. An important disadvantage of this type of source is the extremely large temperature variability depending on the season and depth. Fig. 5 presents fluctuations in surface water temperature both in the winter (heating season) and summer.

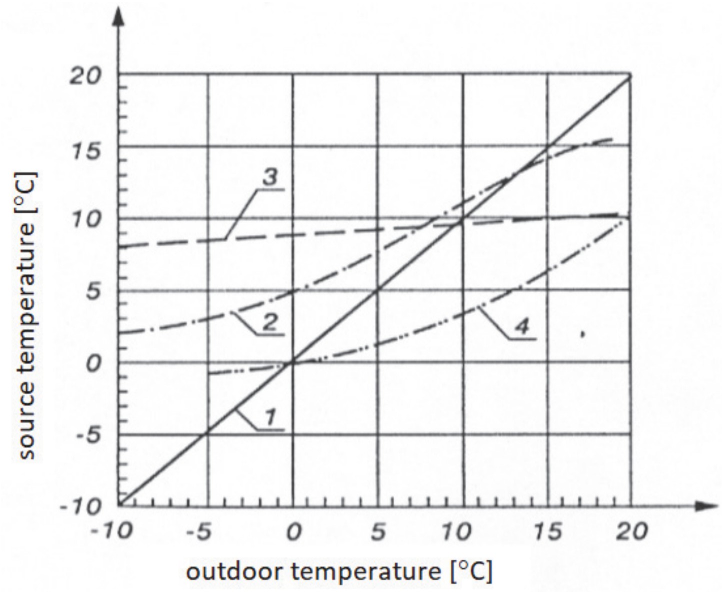

Fig. 4. Comparison of the impact of ambient temperature on the lower heat source temperature: 1 – outside air, 2 – surface water, 3 – ground water, 4 – ground

Fig. 5 shows that stable surface water temperature conditions can be provided from a depth of about 3 m. In winter, with an ice layer on the water surface, water at 4°C has the highest density and is significantly below the water mirror, while the water on the surface has a temperature of 0-3°C. In the temperate climate zone, the thermocline occurs at a depth of about 6-8 m and shifts to 1-2 m in spring.

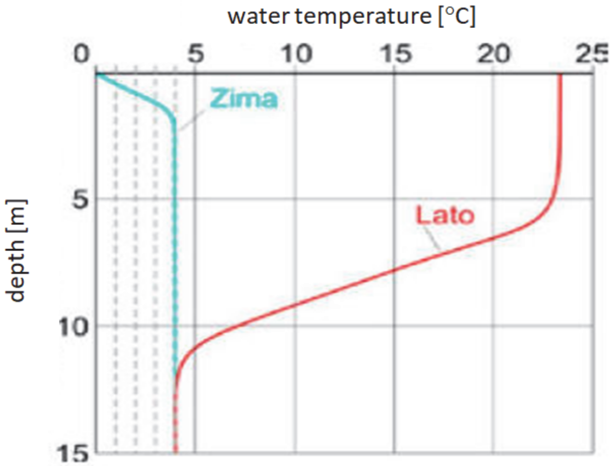

Fig. 5. Changes in surface water temperature depending on depth in winter and summer season (www.solis.pl)

5.2.2. Upper source of heat pump

The left-hand thermodynamic cycle is implemented in the compressor heat pump installation (the heat pump is included in the group of classic working heat machines). The thermodynamic factor is a properly selected refrigerant that meets the currently applicable criteria (Bohdal 2015). The Q_o heat flux taken from the lower source (fed to the heat pump's evaporator) is transported in the refrigerant circuit and is transferred in quantity Q to the upper source. Heat transfer of Q is realized in the heat pump condenser. This flux is transported using an intermediary factor, which is usually water, air or brine. Heat in the amount of Q = 3.7 kW received in the condenser can be used for heating. In the WH water floor heating system was used in the rooms of the residential part of building.

5.2.3. The example solution of the designed heat pump

Among the many options analyzed for WH heat pump installation, the solution shown in Fig. 6 has been proposed.

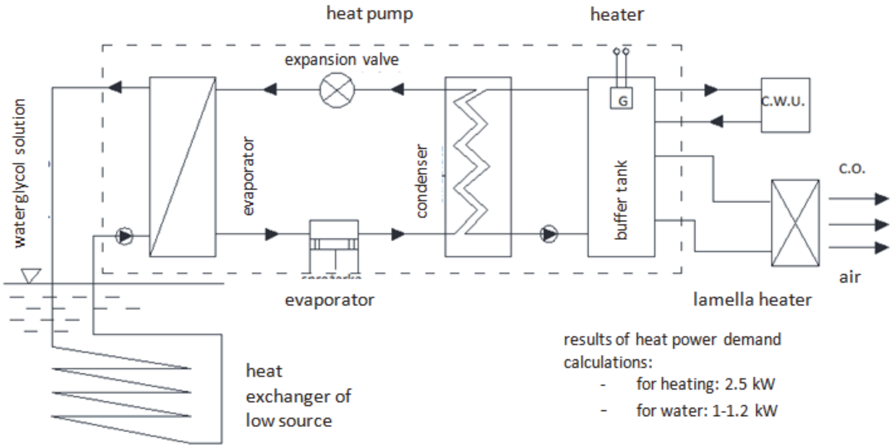

Fig. 6. Diagram of the example solution for the installation of a heat pump in the application of air heating and domestic hot water installation in the WH

For the implementation of the heat pump installation according to the scheme shown in Fig. 6, the SIW 6TES compact heat pump B/W (brine/water) was selected from the Dimplex catalogue (www.dimplex.de/pl/downloads). The refrigerant in the left-hand circuit of the heat pump is R410A, the intermediate medium of the lower source – aqueous mono-ethylene glycol solution (brine), and the intermediate medium of the upper source – heating water supplied to the floor heating system of the residential WH. According to the catalogue characteristics of this pump, it ensures correct thermal parameters in operating conditions, especially for the variable temperature of the brine.

Taking into account the standard, normative parameters of the selected heat pump, given in PN-EN-14511 (PN-EN 14 511), were adopted for further calculations for conditions B0 / W45: $Q_{g.pc} = 5$ kW, at which the catalogue value of the pump heat efficiency coefficient is COP = 3.6. The power of the electric motor P_{el} used to drive the refrigeration compressor results from the equation defining COP:

$$COP = \frac{Q_{g.pc}}{P_{el}} . \tag{1}$$

Using equation (1) and equation (1) of the heat pump's energy balance in the form:

$$Q_o = Q_{g.pc} - P_{el}, \tag{2}$$

the heat efficiency of the lower heat exchanger Q_o located in the surface water of the lake was calculated.

6. Some problems of the heat pump's lower heat exchanger designing

A very important problem in the calculation of the unconventional heat pump lower heat exchanger is the correct assumption of the average calculated value of the surface water temperature. The results of the surface water temperature tests in the lake from the last 4 years recorded by the meteorological station were taken into account. The analysis shows that it is reasonable to assume a calculated, average water temperature of + 5°C, taking into account that the selected heat pump has a slightly overestimated heating power. This heat pump will operate at a temperature below + 5°C with reduced energy efficiency.

In the design calculations, it was assumed that the mass concentration in the heat pump evaporator was an aqueous solution of ethylene glycol with a mass concentration $\xi = 27.4\%$, for which the freezing temperature $t_{zam} = -15°C$, density at + 15°C is $\rho = 1035$ kg/m^3, other solution parameters according to (PN-EN 14 511). The design calculations also adopted: glycol temperature overgrowth in the flow in the lower heat exchanger $\Delta t = 2\text{-}4$ K, and the average solution speed $w_{gl} = 0.4\text{-}0.7$ m/s. For technical and operational reasons, it has been assumed that the lower exchanger will be made of polyethylene pipes with a wall thickness of 2 mm ($\lambda = 0.45$ W/(mK)).

For the assumed thermal power of the lower heat exchanger, the energy balance equation was calculated in the form:

$$Q_o = m_{gl} \cdot c_{p,gl} \cdot \left(T_{gl,wy} - T_{gl,do}\right), \tag{3}$$

the mass flow rate of the glycol solution $m_{gl} \approx 1300$ kg/h, and hence, taking into account the average velocity of its glycol flow, was determined from the equation of mass conservation by the internal diameter of the polyethylene pipe d = 25.7 mm.

Assuming that the process of heat exchange between surface water in a lake and a glycol solution in the flow in a polyethylene pipe is carried out under fixed conditions, the value of the heat transfer coefficient was calculated, after introducing the calculation model shown in Fig. 7.

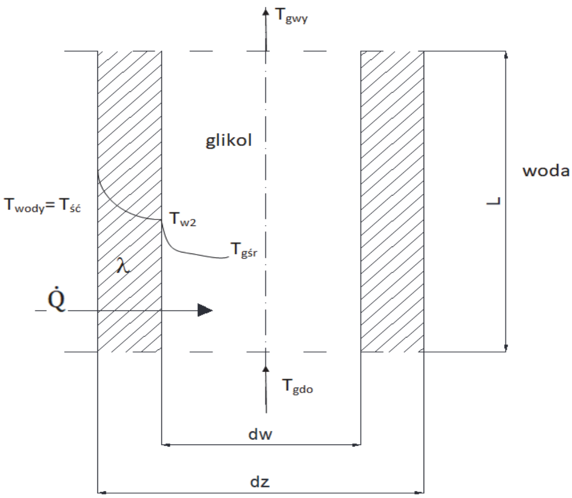

Fig. 7. Calculation model of heat exchange between surface water and an ethylene glycol water solution in a compressor heat pump lower heat exchanger

A simplifying assumption was introduced. First, the average temperature of the outer wall surface of the polyethylene pipe is approximately equal to the value of the average water temperature in the lake $T_{śc} = T_{wody} = 5°C$. In steady-state, the heat flux Q through a single-layer cylindrical wall is described by the relationship:

$$Q = \frac{2 \cdot \pi \cdot \lambda \cdot L \cdot \left(T_{wody} - T_{w2}\right)}{\ln \frac{d_z}{d_w}}, \tag{4}$$

$$Q = \pi \cdot d \cdot L \cdot \left(T_{w2} - T_{gl,śr}\right) = k_l \cdot L \cdot \Delta T_{\log} \tag{5}$$

where k_l is the linear coefficient of heat transfer through the cylindrical wall, L – the length of the lower heat exchanger pipe, ΔT_{log} – the average logarithmic temperature difference. The mean logarithmic temperature difference is, for small values, approximately equal to the arithmetic mean temperature difference, i.e. $(T_{wody} – T_{gl,śr})$. The linear heat transfer coefficient k_l can be written as:

$$k_l = \frac{1}{\frac{1}{\pi \cdot \alpha_w \cdot d} + \frac{1}{2 \cdot \lambda \cdot \pi} \cdot \ln \frac{d_z}{d}} \tag{6}$$

Based on the relationship (4)-(6), the required length L of the lower heat exchanger pipe can be calculated, after calculating the value of the heat transfer coefficient α_w from the inner wall of the pipe to the water solution of ethylene glycol. The nature of glycol movement inside the exchanger tube was determined by calculating the Reynolds number from the equation:

$$\mathrm{Re} = \frac{w_{gl} \cdot d}{\nu}, \tag{7}$$

which is Re = 63840, which means turbulent flow a formula describing the dimension-less Nusselt number was proposed in the form (Bohdal 2013):

$$Nu = \frac{\alpha_w \cdot d}{\lambda_{gl}} = 0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.4} \tag{8}$$

where from data substitution the following value was obtained:

$$\alpha_w = \frac{Nu \cdot \lambda_{gl}}{d} \cong 4100 \quad \mathrm{W/(m^2 \cdot K)}.$$

After the transformation of formulas (4)-(6), the relationship describing the required length of the lower heat exchanger pipe was obtained:

$$L = \frac{Q \cdot \left(\frac{1}{\pi \cdot \alpha_w \cdot d} + \frac{1}{2 \cdot \lambda \cdot \pi} \cdot \ln \frac{d_z}{d} \right)}{T_{wody} - T_{gl,śr}}. \tag{9}$$

Based on the calculations, the value of the linear heat transfer coefficient k_l = 12-14 W/(mK) and the minimum total length of the polyethylene pipe of the lower heat exchange L = 72 m were determined. Hydraulic calculations have shown that the frictional resistance to ethylene glycol flow is about Δp = 13,000 Pa in design conditions.

In the installation version, it was proposed to make the lower heat exchanger in the form of two coils consisting of 6 sections with a length of 6 m, connected using pipe elbows. Sections of straight pipe and elbow pipes made from polyethylene pipe with a diameter of 32/25.7 mm. Both coils were mounted on both sides of the float, with their supply and return connected by collectors, obtaining parallel operation of both parts of the exchanger coils.

7. Summary

1. An example of a house on the water (WH) with the dimensions of a residential object 8 x 3.5 m is intended as a house for recreational purposes, moored at the waterfront of the lake. The house can be used for 4 people. The calculated heating power demand for central heating (floor water system) is approx. 2.5 kW, and for domestic hot water approx. 1.2 kW.
2. A compressor heat pump was proposed as the heat source for heating. It works with the lower heat exchanger located in the surface water of the lake and supplies the central heating and hot water systems.
3. The methodology of calculating the nonstandard lower heat exchanger was presented. The bottom exchanger will be made in the form of two coils (consisting of straight sections of polyethylene pipe connected by elbows) located on both sides of the WH float.

The present study was performed under in accordance with the application for funding by the National Centre for Research and Development No. POIR.01.01.01-00-0466/17 for the implementation of the project entitled "Construction of energy balanced floating leisure house" with Ekosun Paweł Czupajło company, based in Koszalin at 4 Boh. Warszawy Street, 75-211 Koszalin

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Abstract

Recreational houses (WH) of a recreational nature may constitute an offer for the development of non-standard forms of recreation proposed by the domestic tourist industry. The paper presents some selected design problems of heating an exemplary WH house. For central heating (central heating) and domestic hot water (domestic hot water), it is proposed to use a compressor heat pump. It works with the central heating installation (water underfloor heating) and hot water, and with a lower source in the form of surface water in the lake. The heat exchanger for the brine is immersed in the lake water. The methodology for calculating the dimensions of the lower heat exchanger was presented. It was proposed that it will be made in the form of two coils made of polyethylene pipes and WH float sides placed on both sides. The design solution presented in the paper meets the conditions for qualifying as using renewable energy sources (RES).

It should be noted that covering the demand for electricity for the WH house, including to drive the heat pump motor and for other living purposes in a residential superstructure, is also made using a hybrid system in the form of cooperation between wind turbines and photovoltaic panels. Problems regarding the WH hybrid electricity supply system will be the subject of a separate study.

Keywords:
floating house, renewable energy sources, designing, heat pump

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Evaluation of Selected Physicochemical Indicators of the Waters of Rudnickie Wielkie Lake after Reclamation

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1. Introduction

Eutrophication manifests itself in many adverse phenomena for the natural environment and for the husbandry of phenomenon. The factors accelerating the process of eutrophication in the lakes affect numerous changes which are causing an increase of nutrition salts, mainly mineral form of nitrogen and phosphorus, which contributes greatly to the more intensified development of aquatic plants. The excess of organic substance falls to the bottom and creates organic deposits (Jezierska-Madziar & Pińskwar 2008). In aerobic conditions sediment works like a "phosphate trap", while in anaerobic conditions it becomes the most important source of phosphorus for the developing algae (Siwek et al. 2009). The organic substance logged at the bottom is disposed by aerobic bacteria which are using significant amount of oxygen to deplete it. Oxygen deficits in the bottom layers of the water are causing degradation of the organic compounds accumulated at the bottom as a result of anaerobic bacteria action. Incomplete degradation is leading to the release of hydrogen sulphide and methane. Mineral phosphorus (under aerobic conditions bound to the bottom with iron and aluminium compounds) in anaerobic conditions is excreted into the water causing further intense growth of algae (internal enrichment of water in phosphorus) and consequently blooms (Jezierska-Madziar & Pińskwar 2008).

The consequence of the progressing eutrophication is its poor quality, which is one of the most serious threats to water (Soszka 2009). This problem is often and widely discussed in the European Union's water policy.

Many EU directives contain a requirement to assess this phenomenon and give a range of protective measures which can limit its intensity (Soszka 2009).

Nowadays, both its causes and effects are well known and they are comprehensively described in the limnological literature.

Eutrophication is defined in the Act of "Water Law" as “enrichment of water with biogens, in particular compounds of nitrogen or phosphorus, which are causing accelerated growth of algae and higher forms of plant life, and as a result activating undesirable disturbances of biological relations in the water environment and deterioration of these waters” (Dz.U. 2017, poz. 1566). In natural conditions, eutrophication occurs over the period of almost thousand years causing intensive growth of algae and cyanobacteria in the water reservoirs, especially in spring and autumn. It leads to the cloudiness of water and finally to the loss of biological life (Kowalik et al. 2014).

Small kettels are mostly endangered by it opposite to the ribbon lakes, which are resisting best. This natural process has been significantly accelerated since the mid-18th century as a result of changes in the catchment management, forest burning and cutting, and arable areas increase. Another source of acceleration can be linked to the usage of artificial fertilizers, the transition from breeding to large-scale farming and land drainage. Intensification was also caused by the urbanization, which resulted in the flowage of sewage into the lake (Sondergaard & Jeppsen 2007, Lossow & Gawrońska 2000).

The intensity of eutrophication is determined by the phosphorus, which in comparison with other elements usually occurs in small amounts. The concentration of just about 20-30 $\mu g\ P \cdot dm^{-3}$ can cause water blooming. In addition to phosphorus, nitrogen is another factor contributing to the process of eutrophication. It’s compounds dissolved in both surface and underground water are reflecting quality of the natural environment. Therefore, it is very important to analyse and control the concentration of nitrogen in the water, especially in the era of the more and more intensive development of agriculture in Poland (Jekatierynczuk-Rudczyk et al. 1997).

Location of the lakes in the low-lying area makes them natural settlers, in which suspension sediments and compounds dissolved from the catchment or formed in the lake inflow. This process can be observed in all types of lakes, and depends on the age and individual morphometric characteristics of the reservoir. As a result, the lake disappears due to filling the bowl with crumbly and organogenic deposits (Choiński 1995).

In environmental protection methods of preserving lakes are not identical with the methods of their reclamation. The protection depends on good organization and rational water and sewage management in the catchment of the reservoir. Reclamation on the other hand, happens when there are treatments carried out within reservoir’s bowl to improve the cleanliness of both the water and reservoir’s bowl itself. The purpose of reclamation is to undo, stop or slow down the lake eutrophication processes, and sometimes even to remove its negative consequences.

The purpose of this study was to assess the effectiveness of the reclamation of the Lake Rudnickie Wielkie on the basis of analysis of selected physical and chemical indicators of water quality.

2. Material and methods

2.1. Description of the object

The object of the research was the Rudnickie Wielkie lake located in the Grudziądzka Basin, in the Vistula River basin, in the Kuyavian-Pomeranian Voivodeship, about 3km south from the city of Grudziądz. Rudnickie Wielkie lake, because of origination of it's bowl, is classified as a kettle. It is a flow-through lake, that stores on an average $6.7 \cdot 10^6$ m^3 of water. It has a tributary, the Marusza river in the eastern part, and an outflow, the Rudniczanka river in the south-western part. The Rudnickie Wielki lake catchment is a typical agricultural area (Table 1) (WIOŚ Bydgoszcz, 2001).

Table. 1. Morphometric data of the Rudnickie Wielkie Lake

Parameters	Value
Area (ha)	160.9
Maximum depth (m)	11.9
Average depth (m)	4.4
Shoreline length (m)	6585
Schindler's coefficient	18.4
Volume (10^6 m^3)	6.7
Catchment area (km^2)	127.6

In the studied lake since 1982 there were 2 pipelines exploited (1 more was added in 1991), which are pumping out extremely fertile deep water from two depths, instead of spontaneous outflow of surface waters. This treatment is much easier and cheaper than removal of bottom sediments, and can be use in flow lakes. Thanks to the use of the "Olszewski siphon", water from the hypolimnion, instead of surface water, is flowing out of the lake (Żbikowski & Żelazo 1993). Before proceeding, it is necessary to calculate how much water will be drained and how will the concentration of nutrients change, after what time the entire hypolimnion will be replaced, considering continuous though decreasing inflow of bottom sediments in the outflow. The only disadvantage of this method is the pollution of the watercourse flowing out of the lake (in the watercourse these pollutants are to some extent subject to the self-cleaning processes) by high concentrations of phosphorus and nitrogen, usually also hydrogen sulphide and other substances accumulated in deep water. This method can be used only in specific situations where such contamination is acceptable. In the process of the deep water removal, which is in chemical balance with the bottom sediments, they also diminish themselves and become less and less threatening to the secondary pollution of the reservoir. This process can take many years. Relatively low cost and ease of this treatment, including automatic runoff which does not require energy inputs, encourage its usage wherever possible (Mientki 1994).

2.2. Research methodology

Water was collected once a month from October to April 2018, from three points at the depth of 20 cm (Fig. 1) to sterile 0.5-litre bottles. The containers were filled completely with water, sealed, protected from light and cooled to a temperature of 4°C. After this, they were transported to the laboratory where the tests were carried out. The time from sampling water to the mark up did not exceed 24 hours.

The temperature and pH were measured *in situ* on the day of sampling.

The examination of the concentration of total phosphorus, phosphates, nitrates (III), nitrates (V) and ammonium nitrogen was carried out by the spectrophotometric method using the NOVA 400 spectrophotometer, while total nitrogen in mineralized samples was measured by using the Kjeldahl method in accordance with PN 73 / C-04576.12. Merck sets were used to mark the indicators.

Orthophosphate ions in the solution acidified with sulphuric acid react with molybdenum ions to form the molybdicphosphoric acid.

The resulting acid is reduced with ascorbic acid using phosphomolybdic blue (PMB), which is determined photometrically. The filtered sample was removed from the refrigerator early enough to reach a temperature in the range of 10-35 before analysis was performed °C. 5 ml of the sample was transferred to a beaker, to which 5 drops of P-1A reagent were added, after this solution was mixed. Next, 1 micro-peptide of reagent P-2A was poured. Solution prepared was mixed until reagent dissolved. After 5 minutes, the prepared sample was transferred to a 10 mm cuvette and marked in a spectrophotometer.

Total phosphorus. A solution of water (100 cm^3) and concentrated HCl (15 cm^3) was evaporated to dryness, then the sample with the addition of concentrated H_2SO_4 was mineralized. For discolouration 2 cm^3 of concentrated H_2O_2 was added. After the mineralization process, the sample was transferred to a 100 cm^3 graduated flask and topped up by the distilled water. In the mineralized samples, the total phosphorus was determined by using the colorimetric method (PN-91-C/04537.09).

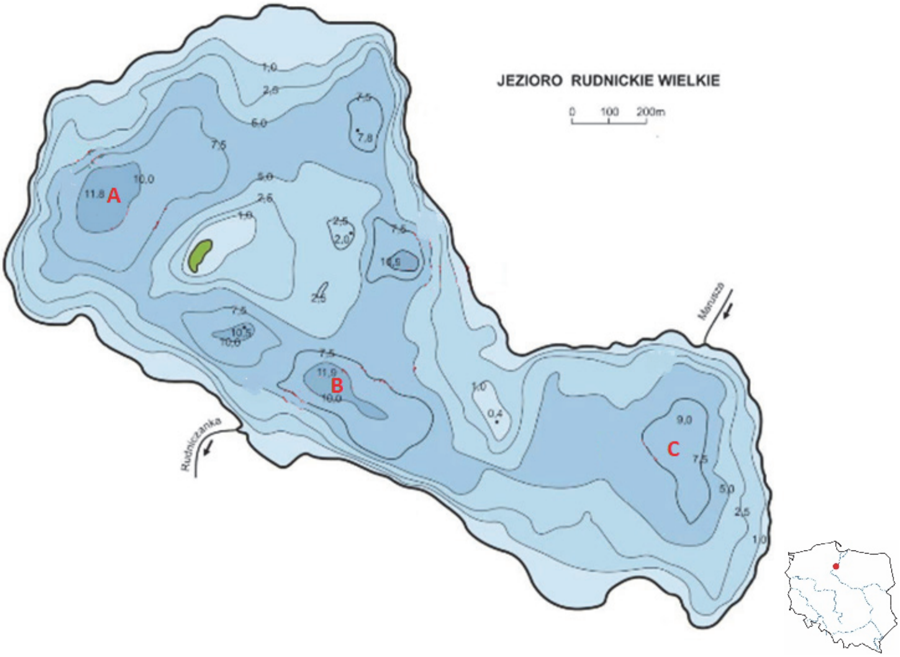

Fig. 1. Water sampling points

Nitrates (III). In a solution acidified with sulphuric acid and phosphoric acid, they react with 2.6-dimethylphenol to form an orange coloured solution of 4-nitro 2.6-dimethylphenol. Preparation of the sample for measurement included the introduction into the flask 4 ml of NO_3-1 reagent, then test water at 20°C was added. The next step was the introduction of 0.5 ml of NO_3-2 reagent and thorough mixing of the sample. After 10 minutes, it was measured using the 10 mm cuvette and the wavelength of 338 nm.

Nitrates (V). The nitrite ions in the acid solution reacted with the sulphanilic acid to form a diazonium salt that reacted with N-(1-naphthyl) ethylenediamine dihydrochloride to form a red-purple azo dye. The procedure consisted of introducing 5 ml of the test sample at 20°C, and then adding the NO_2-AN reagent and thorough mixing until the reagent was completely dissolved. After 10 minutes, it was measured using the 10mm cuvette and the wavelength of 338 nm.

Ammonium nitrogen. It occurs partly in the form of ammonium ions and partly as ammonia. There is a pH-dependent equilibrium between the two forms. In the highly alkaline solutions, ammonium nitrogen occurs mainly as ammonia, which reacts with the chlorinating agent to form monochloramine. This reacts with thymol to form a blue-coloured derivative of indophenol, which is determined photometrically. 5 ml of water were successively added to the test tube, 0.6 ml of NH_4-1 reagent was added and mixed. A flat teaspoon of NH_4-2 reagent was then introduced and vigorously shaken until complete dissolution of the reagent. After 5 minutes, 4 drops of NH_4-3 reagent were added and mixed. The process was then paused for another 5 minutes.

3. Results and Discussion

The results of the conducted own research, similarly as in the case of other reclaimed lakes, indicate the low efficiency of the chosen method in relation to the analysed basin.

The level of total phosphorus ranged from 0.074 to 0.495 mg·dm^{-3}. Its highest content was marked in March and April at all sampling points. The average for the entire study period was 0.2 mg·dm^{-3} (Table 2).

Gałczyński's (2008) research showed that the limit value for phosphorus, where extreme fertile of the reservoir can be concluded, is determined at the level above 0.1 mg·dm^{-3}. According to Maehl (2000), adequate transparency of water in shallow lakes guarantees the content of phosphorus from 0.05 to 0.15 mg·dm^{-3}. Its level in relation to the others occurring in the surface waters is lower, although it is one of the most necessary in organism's lifespan. A study of water in the recultivated Głęboczek lake conducted by Szatten (2010) showed that the concentration from 0.07 mg·dm^{-3} (in spring) to 0.08 mg·dm^{-3} (in summer) is satisfactory. At the same time, the amount of total phosphorus in the studied lake reached the maximum value (1.01 mg·dm^{-3}) in late spring – as in our own research, when the content of the analysed element reached its maximum value, classifying lake waters below the good state. In his own study for 2005, Konieczny (2014) states that the water resources of Rudnickie Wielkie lake in phosphorus amounted to an average of 0.188 mg·dm^{-3}.

The higher content of phosphates indicates a significant intensity of release of phosphorus compounds from the bottom sediments into water, which is the effect of processes associated with the degradation of organic forms of phosphorus and thus their rapid availability for primary production (Egemose et al. 2010). The content of organic phosphorus compounds in the research period ranged from 0.15 to 0.25 mg·dm^{-3} (average 0.2 mg·dm^{-3}). According to Goszczyński (2000) the sources of a slight increase in phosphate concentration in the early spring period should be seen in the depletion of oxygen in bottom sediments. The same author's research, conducted in the spring at Głęboczek lake, determined the content of phosphates in the range of 0.042-0.111 mg·dm^{-3}, whose concentrations were lower than those obtained in own research, yet exceeded the norms specified for the lowest class III purity. Similar average concentration (0.089 mg·dm^{-3}) is noted by Konieczny (2014) in the waters of the reclaimed

Rudnickie Wielkie lake. Many years of research on the phosphate content in Głęboczek lake was conducted by Lossow et al (2004). In the spring of 2002 and 2003, orthophosphates were not detected by them, which may indicate that the reclamation procedures have been carried out correctly. The proper selection of the reclamation method, and what is related to its effectiveness, is also supported by the results of research on phosphate content in the lakes of Mąkolno (0.014 mg/dm^3) and Powidzkie (0.0013 mg·dm^{-3}), which compared to both lakes reclaimed are only slightly exposed to external influences. Thus, these values were much lower than in the Rudnickie lake (average 0.2 mg·dm^{-3}), and especially Powidzkie lake, which is considered as one of the cleanest ones in Wielkopolska (26, 27).

Nitrogen, which is a biofilm, undergoes cyclic circulation in nature, during which a series of biochemical processes takes place in waters Gonzales et al. 2005). Its content in the water, along with phosphorus, determines their productivity.

Mineral nitrogen compounds in the surface waters are ammonium nitrogen, nitrates (III) and nitrates (V), while the latter are found in lake waters in small amounts in their transitional form. Of the total nitrogen in lake waters about 50% falls on organic compounds, the content of which varies depending on the intensification of processes in the tank, as well as the content of mineral nitrogen, which depends primarily on the season of the year (Kudelska et al. 1994).

Analysis of the waters of the Rudnickie Wielkie lake showed that the highest concentrations of total nitrogen (16.9 mg·dm^{-3}) were recorded in October, and the lowest (8.3 mg/dm^3) in April. Its average, the concentration was 13.56 mg·dm^{-3}. Gawrońska et al. 2004) in the research conducted in the waters of Głęboczek lake, a few years after its reclamation, recorded the presence of total nitrogen in the range of 0.075-0.125 mg·dm^{-3}. The same authors Gawrońska et al. 2005) also found a high concentration of total nitrogen in Długie lake in Olsztyn, which before reclamation in 1972 in surface layers ranged from 3.5 to 12.5 mg·dm^{-3}. Two years later, after the sewage system in the catchment was regulated, the waters were subjected to further analyses, which recorded total nitrogen at the level of: 2.6-21.5 mg·dm^{-3} in 1974, 1.9-12.6 mg·dm^{-3} in 1975 and 2.1-18.2 mg·dm^{-3} in 1976. After subsequent reclamation treatments, nitrogen concentration overall did not exceed 2.0 mg·dm^{-3}. The lower maximum level of total nitrogen content was characteristic for the Durowskie lake, in the waters of which Gołdyn et al. (2010) recorded it at the level of 2.18 mg·dm^{-3} to 5.25 mg·dm^{-3}. The maximum values were recorded in the summer months, when according to Dojlido (1995) they should be lower.

Table 2. Development of selected physiochemical variables of waters of the Rudnickie Wielkie Lake

Moonth of sam-pling	Place of collection	Temperature °C	pH	P_t $mg \cdot dm^{-3}$	PO_4 $mg \cdot dm^{-3}$	N_T $mg \cdot dm^{-3}$	$N\text{-}NO_3$ $mg \cdot dm^{-3}$	$N\text{-}NO_2$ $mg \cdot dm^{-3}$	$N\text{-}NH_4$ $mg \cdot dm^{-3}$
October	A	4.1	7.15	0.098	0.24	16.9	8.9	0.21	0.09
	B	4.1	7.22	0.115	0.21	16.9	8.8	0.23	0.08
	C	4.0	7.17	0.083	0.19	16.6	8.9	0.22	0.10
November	A	4.6	7.31	0.129	0.18	16.5	9.1	0.21	0.11
	B	4.4	7.19	0.148	0.18	16.6	9.0	0.19	0.09
	C	4.4	7.21	0.137	0.21	16.7	9.2	0.18	0.10
December	A	4.9	7.45	0.151	0.20	14.8	9.2	0.20	0.08
	B	4.8	7.51	0.129	0.17	14.3	9.0	0.17	0.07
	C	4.9	7.58	0.134	0.18	14.5	9.1	0.22	0.11
January	A	6.1	7.63	0.089	0.17	14.4	8.7	0.19	0.12
	B	6.2	7.71	0.132	0.15	14.3	9.2	0.18	0.11
	C	6.2	7.68	0.112	0.15	14.4	9.2	0.18	0.13

Table 2. cont.

Moonth of sam-pling	Place of collection	Temperature °C	pH	P_t $mg \cdot dm^{-3}$	PO_4 $mg \cdot dm^{-3}$	N_T $mg \cdot dm^{-3}$	N-NO_3 $mg \cdot dm^{-3}$	N-NO_2 $mg \cdot dm^{-3}$	N-NH_4 $mg \cdot dm^{-3}$
February	A	7.8	7.71	0.096	0.23	12.1	8.9	0.19	0.12
	B	8.1	7.68	0.088	0.18	12.5	8.9	0.21	0.12
	C	8.0	7.65	0.074	0.21	12.6	8.7	0.22	0.17
March	A	11.1	7.81	0.324	0.22	12.1	9.4	0.20	0,16
	B	11.3	7.88	0.377	0.19	12.1	9.5	0.21	0,18
	C	10.9	7.87	0.401	0.25	11.0	9.1	0.23	0.15
April	A	13.3	7.52	0.456	0.22	8.3	8.7	0.19	0.14
	B	13.1	7.69	0.433	0.23	8.5	9.1	0.18	0.16
	C	12.9	7.71	0.495	0.22	8.7	8.4	0.21	0.16
average		7.39	7.54	0.200	0.20	13.56	9.0	0.20	0.12
min-max		4-13.3	7.15-7.88	0.074-0.495	0.15-0.25	8.3-16.9	8.4-9.5	0.17-0.23	0.07-0.18
Sd		3.34	0.24	0.140	0.03	2.8	0.26	0.02	0.03

Sd – standard deviation

The content of nitrates (III) and other impurities accumulated in surface waters is subject to considerable fluctuations throughout the year. In the nitrogen cycle in surface waters, the nitrate nitrogen has a transitional form, which in addition to affecting the productivity of aquatic ecosystems also dissolves very well in water. The concentration of various forms of nitrogen depends on the degree of washing them out from the soil, and the size of their losses is related to the soil bonitation class, vegetation cover and purpose. On light soils, up to 98% of nitrogen and 7.7% of phosphorus can be washed out (Szpakowska et al. 2003).

In the waters of the Rudnickie Wielkie lake the content of nitrates (III) ranged from 8.4 to 9.5 mg·dm^{-3}, with the average for the whole period of 9.00 mg·dm^{-3}. A much smaller number of them, in the period from March to May (0.12-0.71 mg·dm^{-3}) were noted by Lossow et al. (2002) in the waters of the the reclaimed lake Głęboczek, similar to Rudnickie Wielkie lake Konieczny (2014) determined the value of this indicator at the level of 0.15 mg·dm^{-3}. The results obtained in comparison with the effects of reclamation of other lakes put a great question mark on the selection of the method of reclamation of the Rudnickie Wielkie lake, and it's efficiency. The presence of nitrates (III) in lake waters is considered as a factor accelerating their eutrophication. Views on the concentration of nitrates (III) causing eutrophication of waters are divergent and range from hundredth to tenths of parts mg/dm^3 (Zioła et al. 2003).

The transitional products of nitrogen compounds in surface waters are characterized by low durability nitrates (V), which are quickly reduced to ammonia, and under aerobic condition oxidize to nitrates (III) (Kułakowski & Biernacka 2007). Their presence indicates a fresh inflow of anthropogenic pollution. During the tests, this parameter remained at a similar level in the range of 0.17 to 0.23 mg·dm^{-3}. Much better results and, therefore, a higher efficiency of the reclamation were obtained in the Głeboczek lake, where the concentration was maintained in the range from 0.016 to 0.013 mg·dm^{-3} (Lossow et al. 2004) and in the Rudnickie Wielkie lake in (average 0.012 mg·dm^{-3}) (Konieczny 2014). These results classify the Głęboczek lake in the 3rd class of purity, whereas in the Rudnickie Wielkie lake waters cannot be classified using this parameter.

The unsatisfactory effects of reclamation are also demonstrated by the comparison of the results obtained with the waters of the lakes of Powidzkie and Mąkolskie, where the average content of nitrates (V) was 0.00045 mg·dm^{-3} and 0.0081 mg·dm^{-3}, respectively (WIOŚ Poznań 2009; WIOŚ Poznań 2008).

The presence of ammonium nitrogen in surface waters, which additionally mixed with the oxygen stimulates development of nitrifying bacteria, may indicate water pollution with the domestic and industrial sewage. In the study, this form of nitrogen was present in the amount from 0.07 to 0.18 mg·dm^{-3} – an average of 0.12 mg·dm^{-3}. The analysis of waters of the same lake, carried out by

Mientki (2000), showed a higher content of nitrogen (from 1.1 mg·dm^{-3} to 12.3 mg·dm^{-3}). According to this author, the reasons for this state should be found in the sudden delivery of sewage from a nearby sugar factory. n equally high average level (0.713 mg·dm^{-3}) was noted by Konieczny (2014) in the Rudnickie Wielkie lake. It might be worrying that pollution occurred in the second stage of reclamation, in other words theoretically after organizing properly water and sewage management in the catchment. Before the inflow of impurities, the amount of ammonium nitrogen ranged from 2.1 to 4.2 mg·dm^{-3}. Slightly higher results than those obtained in the own research were noted by Gołdyn and Messyasz (2008) who, when examining the Durawskie lake water which was prepared for reclamation, confirmed the presence of this form of nitrogen compounds at the level of 0.23 mg·dm^{-3} in October 2005 by 0.57 mg·dm^{-3} in November to 1.2 mg·dm^{-3} in January 2006. In their opinion, this increase can be explained by the supply of surface water floating towards the surface with hypolimnion waters (mixes) characterized by a high content of ammonium nitrogen and the presence of an ice cover that prevents waving and simultaneous oxygenation of water. The ammonium nitrogen content has been gradually decreasing since March.

4. Summary

Many years of research of the waters of the Rudnickie Wielkie lake indicate that it is constantly under strong anthropopressure. The oxygen deficit in the bottom zone, which was documented by many authors indicates an extremely high degree of degradation. This phenomenon is visible despite the declared limitation of the inflow of sewage and other pollutants to the reservoir. Therefore, it is assumed that the restriction itself, or at best he cutoff of nutrients is insufficient to obtain a specific water state, which encourages the continuation and simultaneous modernization of reclamation methods. The temperature and pH of water analysed in the course of the study were characteristic for the examined seasons and did not have a significant impact on the content of the determined chemical indicators. The level of biogenic elements and their compounds, determined a few years after reclamation, is higher than the results obtained in 2001 (immediately after reclamation), which may indicate improper sewage and agricultural management in the lake's catchment.

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Abstract

The research carried out was aimed at determining the effectiveness of reclamation of the Rudnickie Wielkie lake. Samples were taken 7-fold in 3 places during the period from October to April. In the tested water was determined by the colorimetric method PO_4^{-3}ions, total P and N, nitrate(V), nitrite(III) and NH_4 -N. Additionally, the pH and temperature.

The temperature and pH of water analyzed in the course of the study were at the level characteristic for the seasons under study and did not have a significant impact on the content of the determined chemical indicators. The level of biogenic elements and their compounds, determined a few years after reclamation, is higher than the results obtained in 2001 (immediately after reclamation), which may indicate improper sewage and agricultural management in the lake's basin.

Keywords:
reclamation, lake, physicochemical indicators

Ocena wybranych wskaźników fizyko-chemicznych wód jeziora Rudnickiego Wielkiego po rekultywacji

Streszczenia

Przeprowadzone badania miały na celu określenie skuteczności rekultywacji jeziora Rudnickiego Wielkiego. Próbki pobierano 7-krotnie w 3 miejscach w okresie od października do kwietnia. W badanej wodzie oznaczono metodą kolorymetryczną PO_4^{-3}ions, całkowitą P i N, azotan (V), azotyn (III) i NH_4 -N. Dodatkowo pH i temperatura. Temperatura i pH wody analizowanej w trakcie badania były na poziomie charakterystycznym dla badanych sezonów i nie miały istotnego wpływu na zawartość określonych wskaźników chemicznych. Poziom pierwiastków biogennych i ich związków, określony kilka lat po rekultywacji, jest wyższy niż wyniki uzyskane w 2001 r. (Bezpośrednio po rekultywacji), co może wskazywać na niewłaściwe gospodarowanie ściekami i rolnictwem w dorzeczu jeziora.

Słowa kluczowe:
rekultywacja, jezioro, wskaźniki fizykochemiczne

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The State of the Air Quality in Poland

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1. Introduction

The causes of climate change and the loss of biodiversity are global and transgenic and largely depend on air quality. The European Union (Poland has been in the EU since 2004) wants to achieve a European Green Deal by 2050. The main elements of the transformation of the EU economy with a view to a sustainable future which will lead to the Green Deal in Europe (Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the committee of the Regions) are as follows:

- achieving climate targets by 2030 – reduction of emissions of harmful substances by 2050 – achieving climate neutrality,
- providing clean, affordable and secure energy,
- mobilising the industrial sector for a clean, circular economy,
- building and renovating in a way that saves energy and resources,
- zero emissions to achieve a non-toxic environment,
- conservation and restoration of ecosystems and biodiversity,
- from field to table, a fair, healthy and environmentally friendly food system,
- accelerating the transition to sustainable and smart mobility.

The Green Deal is possible, inter alia, by achieving zero emissions. Directive 2016/2284 on the "Commitment for a National Reduction in Emissions" is the main legislative instrument for achieving the "Clean Air for Europe" target by 2030, (Directive 2016/2284). A fully implemented directive would reduce the negative health effects of air pollution by almost 50% and bring environmental and climate benefits. The Directive includes national emission reduction commitments for the period 2020-2029 and commitments from 2030 onwards, for five substances that contribute significantly to air pollution (Table 1). Compliance with the 2020 emission reduction commitments will be tested in 2022, when the 2020 emission balances will be available.

Table 1. Polish obligations to reduce emission (Directive 2016/2284)

Substance	Reduction compared to 2005	
	Each year from 2020 by 2029	Each year from 2030
Reduction of SO_2 compared to 2005	59%	70%
NO_x reduction compared to 2005	30%	39%
NMLZO reduction compared to 2005	25%	26%
NH_3 reduction compared to 2005	1%	17%
Reduction of PM2.5 compared to 2005	16%	58%

2. Air quality standards in force in Poland

By decree of the Minister of the Environment, of 8 June 2018, on the evaluation of the levels of substances in the air, are determined which substances should be included in the assessment of the state of air quality in Poland (Legal Journal of 2018 item 1119). This takes into account 12 substances which have been categorised as meeting the criteria laid down in order to protect human health (SO_2 sulphur dioxide, NO_2 nitrogen dioxide, CO carbon monoxide, benzene C_6H_6, ozone O_3, PM10 dust, PM2.5 dust, PB lead in PM10, arsenic As in PM10, cadmium Cd in PM10, nickel in PM10, benzo(a)pyrene B(a)P in PM10) and for compliance with plant protection requirements (sulphur dioxide SO_2, nitrogen oxides NOx, ozone O_3). The Regulation of the Minister of the Environment (Legal Journal of 2012 pos. 1031, Legal Journal 2019 pos. 1931) on the levels of certain substances in the air, specifies the amount of emissions and other parameters that determine the status of air quality. Table 2 shows the exposure concentration ceiling, the period for which the measurement results are averaged and the time limit for reaching the exposure concentration ceiling. Table 3 shows the limit and target levels for substances in the air, the periods for which measurement results and the permitted frequencies for exceeding those levels, are averaged. Table 4 lists the alert levels and information levels for certain substances in the air and the periods for which their measurement results are averaged.

Table 2. Exposure concentration ceiling, the period for which the measurement results are averaged and the time limit for reaching the exposure concentration ceiling (Legal Journal of 2012 pos. 1031)

Substance	Period wherein the measurements are averaged	Exposure concentration ceiling in μg/m^3
particulate matter PM2.5	three calendar years	20

Table 3. The limit and target levels for substances in the air, the periods for which the measurement results are averaged and the permitted frequencies for exceeding those levels (Legal Journal of 2012 pos. 1031)

Substance	Period wherein the measurements are averaged	Limit/target level of the substance	Frequency with which it is permissible to exceed levels per calendar year
benzene	calendar year	5 μg/m^3	–
nitrogen dioxide	one hour	200 μg/m^3	18 times
	calendar year	40 μg/m^3	–
nitrogen oxides	calendar year	30 μg/m^3	–
sulphur dioxide	one hour	350 μg/m^3	24 times
	24 hours	125 μg/m^3	3 times
	calendar year and period from 1.10 to 31.03	20 μg/m^3 (plant protection)	–
lead	calendar year	0.5 μg/m^3	–
particulate matter PM2.5	calendar year	25 μg/m^3	–
		20 μg/m^3 (plant protection)	–
PM10 suspended dust	24 hours	50 μg/m^3	35 times
	calendar year	40 μg/m^3	–
carbon monoxide	eight hours	10,000 μg/m^3	–
arsenic	calendar year	6 ng/m^3	–

Table 3. cont.

Substance	Period wherein the measurements are averaged	Limit/target level of the substance	Frequency with which it is permissible to exceed levels per calendar year
benzo(a)pyrene	calendar year	1 ng/m^3	–
cadmium	calendar year	5 ng/m^3	–
nickel	calendar year	20 ng/m^3	–
ozone	eight hours	120 $\mu g/m^3$	25 days
	growing season (1 V – 31 VII)	18,000 $\mu g/m^3 \cdot h$	–
	growing season (1 V – 31 VII)	6,000 $\mu g/m^3 \cdot h$	–

Table 4. Alert levels and Information levels for certain substances in the air and the periods for which the measurement results are averaged (Legal Journal of 2012 pos. 1031, Legal Journal 2019 pos. 1931)

Substance	Period wherein the measurements are averaged	Level	
nitrogen dioxide	one hour	400[1)] $\mu g/m^3$	emergency
sulphur dioxide	one hour	500[1)] $\mu g/m^3$	
ozone	one hour	240[1)] $\mu g/m^3$	
PM10 suspended dust	24 hours	150 $\mu g/m^3$	
ozone	one hour	180 $\mu g/m^3$	informed
PM10 suspended dust	24 ours	100 $\mu g/m^3$	

[1)] The value for three consecutive hours at measurement points representing air quality in an area of at least 100 km^2 or within a zone, whichever is smaller

3. Sources of PM10, PM2.5 and PAHs in Poland

National emissions of individual air pollutants are reported on the basis of the current structure of the source of emissions, in the NFR Classification System (Nomenclature for Reporting). The main source of PM10 emissions in Poland are stationary combustion processes. The volume of PM10 emissions in 2018 remains at levels similar to those of 2017. The primary source of PM2.5 particulate matter emissions are those of the energy (fuel combustion) category, which accounts for 85% of the total emissions of this pollutant. Particulate emissions are mainly associated with the burning of hard coal and wood in households. PM2.5 dust is a pollutant covered by the emission limit laid down in Directive 2016/2284 (Directive 2016/2284), currently in force. According to this directive, Poland should achieve a 16% reduction in this pollution, by 2020, compared to 2005. Data on PM10 and PM2.5 dust emissions and their sources are presented in Table 5 and Table 6.

Table 5. Sources and volume of PM10 dust emissions in Poland in the years selected. (National balance of emissions of SO_2, NO_X, CO, NH_3, NMLZO, particulate matter, heavy metals and TZO for the period 1990-2018)

Sources of emission according to NFR categories /Nomenclature of Reporting/	1990	2005	2010	2017	2018
	Gg				
Total	**315.0**	**278.27**	**273.54**	**242.79**	**242.76**
Energy	231.88	219.49	212.30	177.47	174.28
Industrial processes	39.74	24.56	30.37	32.37	34.29
Agriculture	40.21	30.38	26.81	28.45	29.48
Waste	3.28	3.84	4.07	4.50	4.71

Table 6. Sources and volume of PM2.5 dust emissions in Poland in the years selected. (National balance of emissions of SO_2, NO_X, CO, NH_3, NMLZO, particulate matter, heavy metals and TZO in the period 1990-2018)

Sources of emission according to NFR categories /Nomenclature of Reporting/	1990	2005	2010	2017	2018
	Gg				
Total	**154.64**	**153.63**	**152.53**	**137.85**	**136.73**
Energy	133.35	138.28	136.29	120.21	118.13
Industrial processes	12.73	8.30	9.31	10.08	10.70
Agriculture	5.38	3.30	2.96	3.16	3.31
Waste	1.12	1.06	1.17	1.29	1.36

The emission of PAHs into the air is estimated by assessing the emissions of four indicator compounds: benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)-fluoranthene, and indeno (1,2,3-cd) pyrene. A crucial part of PAH emissions (91%) comes from the energy category. The main part of these emissions is from households – as much as 96%. About 4% of the estimated domestic emissions of PAH come from the industrial processes sector – mainly from steel smelting in electric furnaces and sinter production (National balance of emissions of SO_2,

NO_X, CO, NH_3, NMLZO, particulate matter, heavy metals and TZO in the period 1990-2018). The structure of PAH emissions is presented in Table 7.

Table 7. PAH emissions (polycyclic aromatic hydrocarbons) in selected years in Poland (National balance of emissions of SO_2, NO_X, CO, NH_3, NMLZO, particulate matter, heavy metals and TZO in the period 1990-2018)

Sources of emission according to NFR categories /Nomenclature of Reporting/	1990	2005	2010	2017	2018
	Mg				
Total	**305.75**	**289.00**	**309.19**	**235.37**	**231.14**
Energy	295.35	277.31	297.18	223.06	218.33
Industrial processes	7.98	8.43	8.46	8.42	8.70
Agriculture	0.05	0.07	0.02	0.02	0.02
Waste	3.37	3.20	3.53	3.87	4.09

Even so, over about the last 30 years, there has been a trend towards a significant reduction in PAH emissions in the energy category and a gentle growth in the category of industrial processes. The first is mainly influenced by changes in lifestyle and habits as well as the technologically and economically justified modernisation of households in terms of the extraction and processing of heating fuels. In the second category, despite an increase in production and the dynamic development of transport (both rolling stock and the transport network), it is the technology and modern management that keeps PAH emissions at a similar level. It should be assumed that the implementation of the Lean Method in production (Sąsiadek 2016) and the optimisation and reduction of transport (Woźniak et al. 2015, 2016) in the industrial processes category, will be consistent with the reduction of PAHs emissions in Poland. It is also important to take into account the high recycling potential to reduce the emission of pollutants into the atmosphere (Wędrychowicz et al. 2019).

4. The state of the air quality in Poland

Poland is at the forefront of European Union countries in terms of exposure of urban population to air, polluted by PM2.5 and PM10 dust. The highest values for both types of particulate matter were recorded in 2017 in central Europe (Poland, Bulgaria, Croatia, Slovenia, Romania and Hungary) and Italy and Cyprus. Table 8 lists the emissions of PM10 and PM2.5 particulate matter in the years selected in the countries of the European Union.

Table 8. Urban population exposure to air pollution by particulate matter PM10, PM2.5 in the countries of the European Union (Environment 2019)

Countries	PM10				PM2.5			
	2010	2015	2016	2017	2010	2015	2016	2017
	micrograms per m^3							
Poland	**39.7**	**33.1**	**31.2**	**32.2**	**30.5**	**23.8**	**23.0**	**23.8**
EU – 28	26.3	22.7	21.2	21.6	18.1	14.6	13.8	14.1
Bulgaria	48.4	36.2	37.9	37.3	31.1	25.0	20.2	23.8
Hungary	31.3	26.9	25.3	26.5	22.3	–	–	20.9
Romania	34.9	27.7	23.4	26.6	19.1	17.1	17.2	20.4
Slovenia	28.2	27.7	25.6	24.8	21.8	21.6	21.6	19.7
Italy	30.5	30.5	27.5	29.2	23.4	21.6	19.3	19.4
Croatia	–	33.1	34.7	35.1	–	20.8	20.6	19.0
Czech Republic	29.9	24.3	22.6	23.9	22.8	17.4	18.1	18.4
Slovakia	29.6	23.9	20.7	24.2	22.8	19.0	14.7	17.5
Cyprus	48.0	35.2	27.3	29.2	22.2	17.3	14.6	14.7
Austria	26.9	20.8	18.4	19.2	19.9	14.4	13.1	13.8
Latvia	24.4	19.9	19.0	17.2	–	15.9	15.4	13.6
Belgium	27.0	21.4	20.9	20.4	17.7	13.5	13.3	12.9
Germany	22.9	18.9	17.7	17.5	17.4	13.3	12.8	12.7
Spain	23.9	23.4	20.7	21.9	12.4	13.0	11.3	12.1
France	25.0	20.5	19.2	19.1	18.3	13.5	12.7	12.0
Portugal	25.4	19.9	18.0	18.3	8.8	10.3	10.1	12.0
The Netherlands	24.7	19.7	19.0	19.2	17.1	12.7	11.2	11.3
Luxembourg	17.0	21.4	20.5	20.3	16.0	11.7	13.4	11.2
United Kingdom	17.8	16.4	17.4	15.6	13.6	9.9	10.1	10.0
Denmark	12.1	18.3	15.1	15.5	11.0	11.3	10.0	9.2
Ireland	15.6	13.2	12.5	11.5	10.9	7.9	8.5	7.7
Sweden	14.0	13.0	12.3	11.8	7.4	5.8	5.6	5.4
Estonia	13.9	13.0	12.1	10.5	7.6	6.7	5.4	5.3
Finland	13.4	11.3	12.2	10.0	8.4	6.0	5.7	4.9
Malta	–	–	–	–	–	–	–	–
Lithuania	26.9	21.7	24.1	22.8	–	–	–	–
Greece	33.4	26.5	29.0	–	–	16.4	14.7	–

The summary reports on the emissions of various substances to the atmosphere in Poland are provided in the form of Excel sheets by the General Inspectorate of Environmental Protection (GIOŚ).

4.1. PM10 and PM2.5 dust emissions

PM10 suspended particles are all particles smaller than 10 μm, while PM2.5 is less than 2.5 μm. Particulate pollutants can come in different sizes and shapes. Moreover, they have the ability to adsorb on their surface other very harmful impurities (dioxins and furans, heavy metals, polycyclic aromatic hydrocarbons, such as benzo(a)pyrene). Particulate matter is primarily emitted from fires, rising dust from buildings, roads, and combustion processes.

Particulate matter, suspended in the air due to its size, can easily enter the lungs, causing poisoning, upper respiratory tract inflammation, dust, lung cancers, allergic diseases and asthma. PM2.5 dust is particularly dangerous. It has the ability to penetrate deep into the lung-alveoli, causing permanent damage to them and can then enter the blood stream (Jędrak et al. 2017, Pope III et al. 2006, Kampa & Elias 2008, Clifford et al. 2016, Sówka et al. 2020).

Table 9 summarises the emissions of PM10 dust between the years 2015-2019 and the volume of PM2.5 emissions in 2019 in selected cities in Poland. In 2015, the level of PM10 dust emissions in Poland was measured at 159 points. At 28 points, dust emissions exceeded more than 40 μg/m^3. The highest emission of PM10 dust was in the city of Opoczno – 56 μg/m^3, a calendar average. The lowest calendar average was in the Borecka Forest and was 17 μg/m^3.

In 2016, PM10 emissions were measured at 161 points. At 19 points, the emissions standard was exceeded. The largest emission was in the city of Kraków – 56.7 μg/m^3, the lowest emission was in Bory Tucholskie – 15.57 μg/m^3.

In 2017 there were 166 measurement points of PM10 emission in Poland. PM10 emissions were exceeded at 21 measurement points. The highest emission was in Katowice – 52.03 μg/m^3, the lowest emission was in the Puszcza Borecka – 15.22 μg/m^3.

In 2018 there were 169 measurement points of PM10 emission in Poland. PM10 emissions were exceeded at 24 points. The highest emission was in the city of Kraków – 49.46 μg/m^3, the lowest emission was in the Puszcza Borecka – 15.22 μg/m^3.

In 2019, there were 179 PM10 emission points. PM10 emissions were exceeded at 5 measurement points. The highest emission of 49.59 μg/m^3 was measured in the city of Kraków, and the lowest emission of 15.40 μg/m^3 was in Bory Tucholskie.

In 2019 there were 64 measuring stations in Poland which measured a level of PM2.5 in the air. Four points recorded an average above the limit of

25 μg/m^3 in a given calendar year. But as many as 21 measurement points recorded annual averages above 20 μg/m^3. The lowest calendar average was recorded at the measurement point in Bory Tucholskie (9.64 μg/m^3), the highest annual average was recorded in Godów 30.61 μg/m^3.

Table 9. PM10 dust emissions in Poland in 2015-2019 and PM2.5 dust emissions in 2019 (Selected cities) (Data of the Main Inspectorate of Environmental Protection)

Town	PM10 Limit value = 40 μg/m^3					PM2. 5 Limit value: for humans = 25 μg/m^3, for plants = 20 μg/m^3
	Annual average [μg/m^3]					
	2015	2016	2017	2018	2019	2019
Kraków (communication station)	52	56.7	44.99	49.46	49.59	24.70
Pszczyna	52	50.9	55.59	54.89	44.29	no data
Rybnik	47	47.5	46.52	50.80	42.97	no data
Katowice (communication station)	46	46.9	52.03	47.30	40.55	27.69
Myszków	48	47.8	46.20	49.11	40.26	no data
…						
Nowa Ruda	46	45.5	48.35	42.78	39.73	no data
Zabrze	44	42.82	39.23	44.89	38.70	no data
Opoczno	56	52.2	37.08	35.14	30.54	no data
Ożarów	29	19.9	24.07	24.74	23.75	no data
Szczecin	26	22	21.98	24.49	20.31	13.69
Suwałki	24	19.2	21.04	24.05	19.77	no data
Białystok	25	19.8	20.99	23.98	19.2	no data
Osieczów	19	19.62	19.59	22.10	18.38	13.10
Słupsk	24	19.2	20.93	22.70	18	11.24
Gdynia	22	20.7	19.77	26.80	17.16	no data
Puszcza Borecka	17	15.69	15.52	16.79	16.07	11.10
Bory Tucholskie	18	15.57	16.03	19.86	15.40	9.64

In addition to emissions, an important parameter in determining the state of air quality is the number of days with PM10 concentrations higher than 50 μg/m^3, as summarised in Table 10.

In 2015, at as many as 118 measuring points, the number of days with PM10 concentrations levels higher than 50 μg/m^3 was exceeded (35 days).

In 2016, the number of days with PM10 concentrations higher than 50 μg/m^3 (35 days) was exceeded at 89 measuring points out of 161 measuring points.

In 2019, 33 of the 179 measuring points were exceeded, over the number of days with concentrations of PMP10 higher than 50 μg/m^3 – i.e. 35 days.

Table 10. Cities with the highest and lowest number of days with PM10 concentration (Data from the Chief Environmental Inspectorate)

Location	Number of days with concentrations above 50 μg/m^3 Permissible number of days = 35		
	2015	2016	2019
Kraków (communication station)	219	164	178
Pszczyna	119	102	107
Rybnik	103	101	88
Nowa Ruda	114	108	79
Myszków	93	109	63
Zduńska Wola	95	102	63
Opoczno	152	150	51
Nakło nad Notecią	111	107	50
…			
Gdańsk	39	14	12
Elbląg	30	14	10
Gdynia	24	13	7
Olsztyn	24	11	7
Gdynia	24	9	7
Suwałki	26	3	7
Koszalin	21	7	6
Szczecin	23	18	3
Słupsk	19	6	3
Puszcza Borecka	8	5	3
Białystok	26	2	3
Bory Tucholskie	10	3	2

To assess the state of air quality in terms of PM10 particulate emissions, in a given location, three parameters should be analysed simultaneously:

- average annual dust emissions,
- the number of days with concentrations above the limit, and
- dust emissions in individual months, not just the average calendar year.

In 2019, the city of Opoczno reached the permissible annual concentration of PM10 particulate emissions. However, there were as many as 51 days in this city where the emissions limit was exceeded. The breakdown of excess emissions is shown in Fig. 1.

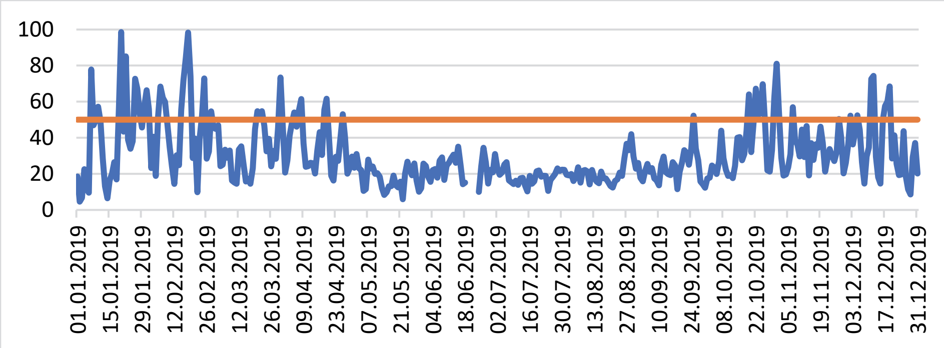

Fig. 1. PM10 dust emissions in the city of Opoczno in 2019

Let us consider a city that meets both the condition of the average annual concentration of dust and the number of days with a permissible concentration of dust, such a city, among others, is the city of Bielsko Biała. In this city the average annual emissions of PM10 particulate matter is 27.54 μg/m^3 (the limit value = 40 μg/m^3), the number of days with concentrations above 50 μg/m^3 is 30, so the condition for exceeding the limit per calendar year is met. However, by analysing data from Fig. 2, it can be seen that standards are exceeded significantly in the colder months; this is a characteristic of almost all cities in Poland.

Benzo(a)pyrene belongs to the group of polycyclic aromatic hydrocarbons (PAHs). It is persistent in the environment, with low volatility and water solubility. It can be adsorbed on dust surfaces (e.g. PM10 and PM2.5), which poses a greater risk to human health due to its ability to enter the lungs directly through the breathing process. Natural sources of emissions include forest fires, volcanic eruptions and grass burning. Anthropogenic sources of emissions include the burning of fossil fuels and waste, as well as industrial activities. It is present in car exhaust fumes and cigarette smoke. Benzo(a)pyrene can be formed in food by prolonged heat treatment (grilling, frying, smoking). This compound has strong carcinogenic, mutagenic or teratogenic effects which negatively affects foetal development. It can be bio-accumulated and can be accumulated in tissues for longer periods of time and metabolised to even more reactive derivatives (Brook et al. 2010, Kunzli et al. 2010, Kelly & Fussell 2011, Genc et al. 2012, Wojdat et al. 2016, Krzyżanowski 2016).

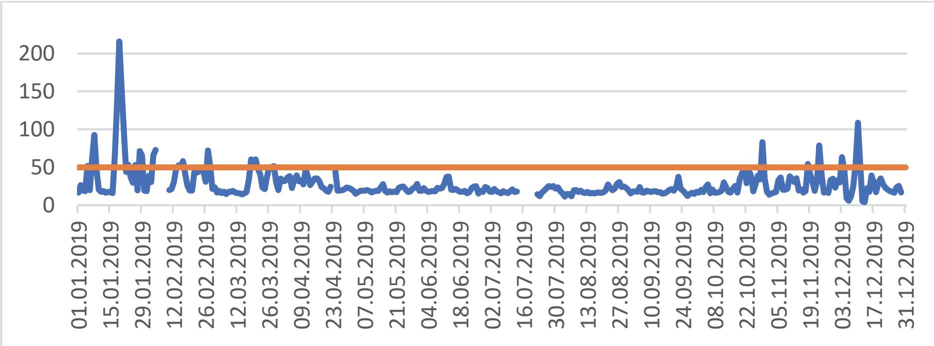

Fig. 2. PM10 dust emissions in Bielsko Biała in 2019.

4.2. Benzo(a)pyrene

Table 11 lists the emissions of benzo(a)pyrene in selected cities in Poland, in 2016 and 2019. In 2016, benzo(a)pyrene emissions were measured at 129 points, only two measurement points recorded levels of carcinogenic benzo(a)pyrene below 1 ng/m^3. The level of benzo(a)pyrene was exceeded more than ten times at eight measurement points.

Table 11. Carcinogen benzo (a)pyrene-emissions in selected cities in 2016 and 2019 (Data from the Chief Environmental Inspectorate)

Location	Annual average [ng/m^3] Target level = 1	
	2016	2019
Nowy Targ	no data	17.17
Rybnik	13.4	13.16
Nowa Ruda	16.86	8.13
Pszczyna	10.9	6.92
Radomsko	9.76	4.89
Opoczno	17.06	4.04
Tomaszów Mazowiecki	14.85	3.43
Białystok	1.1	0.94
Olsztyn	1.3	0.91
Koszalin	1.5	0.7
Bory Tucholski	0.8	0.55
Puszcza Borecka	0.7	0.53

In 2019, emissions of benzo(a)pyrene were measured at 159 points. Emissions below 1 ng/m^3 were recorded at 10 measurement points. The level of benzo(a)pyrene was exceeded more than ten times at 3 measurement points.

The emissions target for benzo(a)pyrene needs to be 1 ng/m^3. In Nowy Targ, from 16 to 22.12.2019, emissions amounted to 95 ng/m^3 every day (Fig. 3).

Even in the city of Kalisz, where the emission level of benzo(a)pyrene meets the requirements of the emissions target below 1 ng/m^3, this level is exceeded in the winter months (Fig. 4).

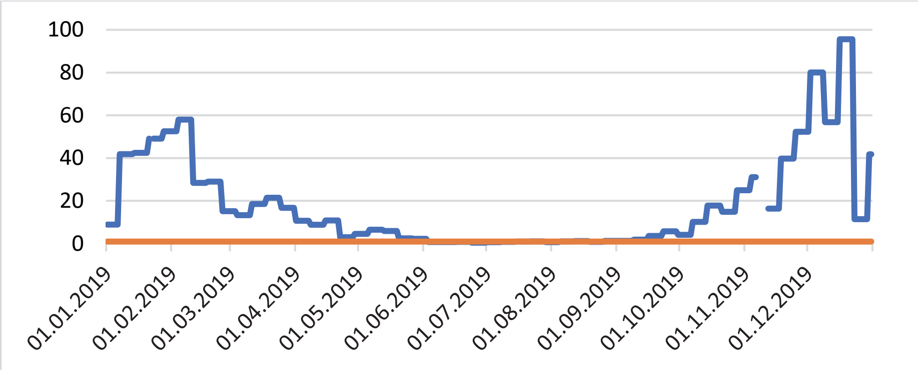

Fig. 3. Emissions of benzo(a)pyrene in Nowy Targ in 2019 (own study based on Table 11)

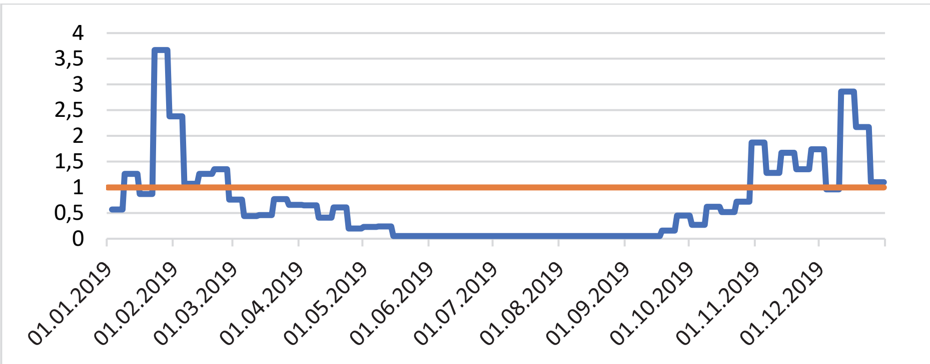

Fig. 4. Emissions of benzo(a)pyrene in Kalisz in 2019 (own study based on Table 11)

5. Summary

All air, water and soil pollution impair human health, affects life expectancy and well-being. The greatest impact of pollution on human and animal health is observed in industrial and urbanised areas. The size of the city is not as important as the structure of energy consumption which is at its highest during the cold season for heating purposes. Polluted air also has a negative impact on the health of ecosystems and the destruction of materials where there is the accelerated corrosion of metals, the erosion of buildings and the ever-changing conditions of production processes.

Despite the systematic improvement in air quality in Poland, concentrations of PM10 and PM2.5 particulate matter and benzo(a)pyrene remain a major problem during the winter season.

The effect of fine particles (PM10 dust) and very fine particles (PM2.5 dust) on health depends on the number of particles retained in different areas of the respiratory system. At the same time, PM2.5 dust has the ability to penetrate into the deepest parts of the lungs, where it accumulates and/or dissolves in biological fluids.

The main cause of the emission of gases and dust into the atmosphere is the lack of significant changes in the structure of energy consumption in Poland. Coal remains the primary energy carrier in the national economy, accounting for 51% of non-renewable energy.

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Abstract

This article analysed the state of air quality in Poland on the basis of data from the main Inspectorate of Environmental Protection. The emission limit values for PM10 and PM2.5 particulate matter were analysed along with the number of days in which their emission was exceeded. In addition to particulate emissions, target levels for benzo(a)pyrene, which is highly carcinogenic, have been assessed.

Keywords:
PM10 dust, PM2,5 dust, benzo(a)pyrene

Stan jakości powietrza w Polsce

Streszczenie

W artykule przeanalizowano stan jakości powietrza w Polsce na podstawie danych pochodzących z Głównego Inspektoratu Ochrony Środowiska. Przeanalizowano poziomy dopuszczalne emisji pyłów PM10 i PM2,5 wraz z ilością dni w których jest przekroczona wielkość ich emisji. Oprócz emisji pyłów oceniono poziomy docelowe dla benzo(a)pirenu, który ma silne działanie rakotwórcze.

Słowa kluczowe:
pył PM10, pył PM2,5, benzo(a)piren

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Economic and Climate Efficiency of Agriculture in the EU

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1. Introduction

Earth's climate is warming up - the average global temperature compared to the period 1850-1900 increased by almost 1°C (274.15K) (WMO, 2017). The problem, which became apparent to most people in recent years, has already been the subject of scientific research. Their results are unequivocal - observed global temperature rise caused by the greenhouse effect. It is caused by the increase in greenhouse gas emissions from anthropogenic sources since the beginning of the industrial revolution. The use of fossil fuels and other human activities led to a situation where the CO_2 concentration is 143% in comparison to the level before the industrial revolution (254% for CH_4 and 121% for N_2O, respectively). The most recognized international organization in the field of climate change research – Intergovernmental Panel on Climate Change (IPCC) stated that "it is extremely likely that more than half of the observed increase in global average surface temperature is due to human-related greenhouse gas concentrations" (IPCC 2013). An increase in temperature is not the only and worst effect of climate change. This process also leads to an increase in the level of water in the oceans and an increase in the frequency of extreme weather phenomena (drought, floods, tornadoes) and many other destructive effects on life on earth.

The article aimed to determine the level of greenhouse gas emissions in agriculture and the economic and climate effectiveness of agriculture in EU countries in comparison to other sectors of the economy.

The following research questions were adopted:
What changes in greenhouse gas (GHG) emissions in agriculture have occurred in recent years?
Which countries in the EU have agriculture with the highest economic and environmental efficiency?

2. Research basis

2.1. Climate change and greenhouse gas emissions

The year 2019 was the warmest in the history of measurements in Europe, and the temperature anomaly calculated to the reference period 1980-2010 was 2°C (275.15K).

Climate change will have a major impact on natural ecosystems, which may have the ability to adapt to climate change, but not as rapidly as it is today. Climate change may also harm agricultural development, including (Sulewski & Czekaj 2015):

- plant growth and crop yields,
- changes in the frequency of atmospheric phenomena with catastrophic effects (heat, drought, floods),
- shifts of the vegetation zone of plants by 300-800 km to the north and 500 m up in the mountains,
- increased risk of fungal diseases and weeds for crops,
- increasing the area of crops requiring irrigation,
- increasing water salinity,
- fall in yields in Africa, Central America, India and Southeast Asia,
- increase in the number of people exposed to hunger by 400 million,
- increasing the frequency of forest fires,
- the disappearance of some species of animals living in the coastal zone,
- the loss of many marine mammals living in Arctic and Antarctic waters.

Given these issues, reducing greenhouse gas emissions is becoming an increasingly important problem. According to scientists' warnings, the world has less and less time to take appropriate actions. Therefore, after long negotiations, on December 12, 2015, during the Paris climate conference, nearly 200 countries adopted an agreement aimed at halting global warming. The most important provisions of the agreement are included in art. 2 Convention (United Nations 2015). It assumes maintaining a temperature rise below the 2°C limit compared to pre-industrial times and making efforts to limit the increase to 1.5°C. In art. 4 of the Convention stipulates that to achieve these objectives, countries undertake to reduce current greenhouse gas emissions as soon as possible until a balance is reached between anthropogenic emissions and the uptake of these gases. This balance is to be achieved in the second half of the 21st century. However, attempts to withdraw from some agreements and question their legitimacy are very worrying.

2.2. Agriculture and greenhouse gas emissions

Agriculture is responsible for almost one third of anthropogenic emissions that cause climate change, including about 50% of methane (CH_4) emissions and 70% of N_2O emissions – mainly from the fermentation of ruminants, excrements, rice cultivation and nitrogen fertilizers (McIntyre et al. 2009). Methane is largely a by-product of agriculture (rearing of ruminants, rice cultivation), while nitrogen oxides are formed during wood burning, fossil fuels, and the use of nitrogen fertilizers. Industrial agriculture plays a shameful role in this respect (Gołębiewska & Pajewski 2016), being responsible for the excessive use of pesticides, including dichlorodiphenyltrichloroethane (DDT), poisoning of soils and waters with nitrogen compounds and the use of problematic genetically modified organisms (GMOs). It should be remembered that thanks to it the problem of food scarcity was solved (at least in developed countries).

Assuming that current trends are maintained, the reduction of greenhouse gases in agriculture by 2050 compared to 1990 is to amount to almost 50% (see Table 1) (European Commission 2011). One should bear in mind that some of the sectors as e.g. transport is one of the most important factors for development of the regions (in particular sustainable development), which enables the creation of new businesses or supports contacts with other regions (Gnap et al. 2019), nevertheless this sector is obliged for changes in greenhouse gas emission as well (Jacyna et al. 2018). Modelling of GHG gases diffusion is also an important aspect to consider, allowing to predict the spread and possibly impact of sources of GHG on the environment (Piekarski & Kowalska 2017).

Table 1. The planned reduction of greenhouse gas emissions by sector in EU countries in 2030-2050 compared to 1990

Reduction of greenhouse gas emissions compared to 1990	Gas reduction level (%)	
	2030	2050
Whole	-40 to -44	-79 to -82
By sector		
Energetics	-54 to -68	-93 to -99
Industry	-34 to -40	-83 to -87
Transport	+20 to -9	-54 to -67
Residential and commercial buildings	-37 to -53	-88 to -91
Agriculture	-36 to -37	-42 to -49
Gases other than CO_2	-72 to -73	-70 to -78

Source: European Commission 2011, 6.

Agriculture plays an important role in the fight for climate and world stability. As a branch of the global economy, it stood at the crossroads associated with the paradigms on which its functioning is to be based.

The industrial model began to run out, as it consumed increasing expenditure, both financial and non-renewable resources, and caused more and more negative externalities. Fotyma & Krasowicz (2007) recognize the year 1992 (ecological summit in Rio de Janeiro) and the first major reform of the Common Agricultural Policy (CAP), introducing the obligation to set aside some land and to protect the environment, as the symbolic end of the era of industrial agriculture. Further actions within the EU have deepened the pro-environmental attitude of agriculture. Subsequently, agriculture was included in the climate policy, both in terms of reducing greenhouse gas emissions and their absorption (sequestration).

There are two main development paths that post-industrial agriculture can follow.

Intensive agriculture, but subjected to ecological restrictions. It is to be both competitive in terms of food prices and meet basic environmental standards (cross-compliance, animal welfare standards introduced by CAP mechanisms). It is a kind of balancing the interests of farmers, consumers and environmental issues, which do not lead to rapid changes in the modern model of agriculture.

Sustainable agriculture (Zegar 2012), which is the expression of a broader paradigm of the functioning of the world economy based on sustainable development. This approach can be used in almost all fields and departments of agriculture. However, it is very important to choose the right direction of production, adapted to natural conditions, and the correct location and scale of production. These are the basic factors differentiating sustainability and contributing to improving production efficiency, and thus achieving the objectives of sustainable agriculture (Mańko et al. 2007).

Given these assumptions, agriculture must be actively involved in the fight against climate change. It is necessary to identify the current position of agriculture and the efficiency of using traditional factors of production and greenhouse gas emissions.

3. Materials and methods

3.1. Sources for materials

The research was based on materials and secondary data from EUROSTAT. To determine the economic and climate efficiency of agriculture in European countries in 2016 the Data Envelopment Analysis (DEA) method was used.

3.2. Data Envelopment Analysis

The Data Envelopment Analysis method is classified as nonparametric methods for testing the effectiveness of objects. In 1978, the authors of the DEA method (Charnes et al. 1978), based on the concept of productivity formulated by Debreu and Farell, defining the measure of productivity as a quotient of a single effect and single effort, applied it to a multidimensional situation, in which there are more than one effort and more than one effect (Charnes et al. 1978). Mathematically, the DEA model can be presented in the following way (Charnes et al. 1978):

objective function:

$$\max_{u,v} \frac{\sum_{r=1}^{s} \mu_r y_{ro}}{\sum_{i=1}^{m} v_i x_{io}} \tag{1}$$

under the following limiting conditions:

$$\frac{\sum_{r=1}^{s} \mu_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \quad (j = 0,1,\ldots,n) \qquad \mu_r, v_i \geq 0 \tag{2}$$

$$\frac{\mu_r}{\sum_{i=1}^{m} v_i x_{io}} \geq \varepsilon \quad for \quad r = 0,1,\ldots,s \tag{3}$$

$$\frac{v_i}{\sum_{i=1}^{m} v_i x_{io}} \geq \varepsilon \quad for \quad i = 0,1,\ldots,m \tag{4}$$

where:
s – number of effects,
m – number of inputs,
μ_r – weights determining the importance of individual effects,
v_i – weights determining the importance of individual inputs,
y_{rj} – the size of the r-th effect (r = 1, …, s) in the j-th object,
x_{ij} – the size of the i-th type (n = 1, …, N) in the j-th object; (j =1, …, n).

The DEA method allows the study of the relationship between the level of many inputs and many effects. In the DEA model m inputs and s different effects boil down to single sizes of "synthetic" input and "synthetic" effect, which are then used in calculating the object efficiency index (Roll & Hayuth 1993).

The effectiveness of the object is measured relative to other objects from the studied group and takes values from the interval (0,1). In the DEA method, the objects of analysis are Decision Making Units (DMU), which can be companies, sectors, countries (Charnes et al. 1994) (see Figure 1). The subject of the analysis is the effectiveness with which a given DMU transforms its inputs into results.

Nonparametric methods, including the DEA method, are used to analyse the effectiveness of various objects. The DEA method was most commonly used to investigate the effectiveness of banks (Berger & Humphrey 1997, Brockett et al.

1997), insurance institutions (Fukuyama & Weber 2001), educational institutions (Hu & Kao 2007, Saunders 2003), hospitals (Jacobs et al. 2006, O'Neil & Dexter 2005), farms (Galanopoulos et al. 2006), as well as industries of various types.

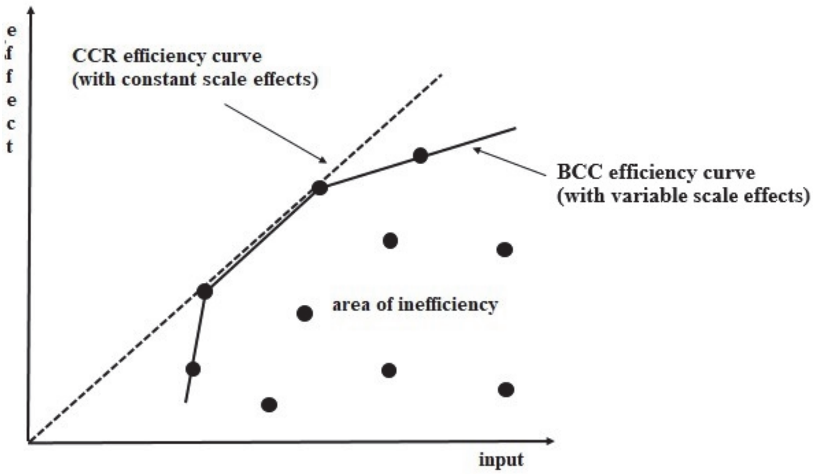

Fig. 1. CCR (Charnes, Cooper and Rhodes) efficiency curve (with constant scale effects) and BCC (Banker, Charnes and Cooper) efficiency curve (with variable scale effects), model with 1 effect and 1 input
Source: Charnes et al. (1994)

DEA models are increasingly used in economic and environmental analyses. This approach was presented in research, among others Ramanathan (2005), Zhou et al. (2007), Bian & Yang (2010) and Song & Wang (2014).

4. Results and discussion

Greenhouse gas emissions from agriculture in the entire EU in 2016 were estimated at 436 million tons of CO_2 per year, representing a decrease of almost 23% compared to 1990. This decline was particularly evident in the last decade of the last century, but it slowed down later. This was caused by a decrease in the use of nitrogen fertilizers, a decrease in the head of livestock and the implementation of EU environmental policy (Felman 2015). The introduction of the Nitrates Directive, which aimed to reduce water pollution by nitrogen compounds from agricultural production, also played an important role. The directive introduced quantitative and quantitative limits for the use of organic fertilizers. Also milk production quotas, limiting the size of cow population had a direct impact on stabilizing greenhouse gas emissions in agriculture (Syp 2017).

The absolute decline in emissions in agriculture is comparable to other sectors (-24% – energy, -28% – industry, -34% – waste management). The share of agriculture in total EU emissions throughout the period considered remains at the same level of 10% (see Figure 2). In the individual Member States, the changes were more diverse. In the EU, the largest greenhouse gas emitters in agriculture were France – 87 million tons and Germany – 72 million tons.

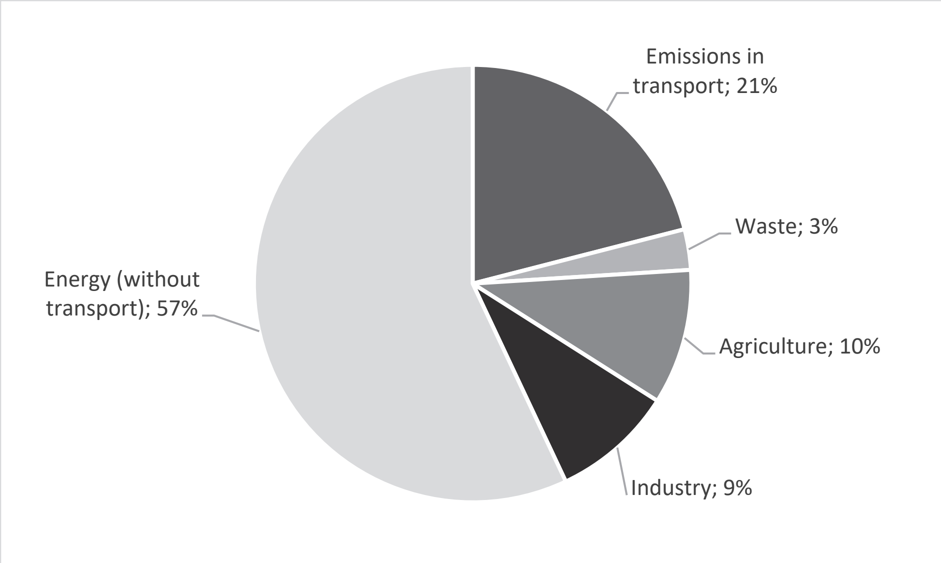

Fig. 2. Share of greenhouse gas emission sources in the EU in 2016
Source: Own study based on Eurostat

Except for Spain, each of the Member States reduced agricultural greenhouse gas emissions in 1990-2016 (see Figure 3). The largest absolute decrease was recorded in Germany (-18 million tons of CO_2), Romania (-17 million tons of CO_2) and Poland (-15 million tons of CO_2).

To assess individual elements of the EU economy, taking into account not only greenhouse gas emissions but also other variables, the DEA method was used and an attempt was made to determine the effectiveness of individual sectors of the EU economy by NACE2 category[1]. A model focused on maximizing the

[1]Statistical Classification of EconomicActivities in the EuropeanCommunity, Rev. 2 (NACE Rev. 2) (Nomenclaturestatistique des activitéséconomiquesdans la Communautéeuropéenne), the revisedclassification was adoptedat the end of 2006 – the firstreferenceyear for NACE Rev 2 statisticsis 2008.

CCR (Charnes, Cooper and Rhodes) output was adopted. Greenhouse gas emissions have been treated as an input in connection with the idea of a carbon budget. According to it, there is a limited amount of greenhouse gases that can be emitted by humanity to limit the temperature rise to a certain level [1.5-2.0°C (274.65-275.15K)] according to the Paris Agreements. With this approach, greenhouse gas emissions are a resource whose use affects the efficiency of a given sector of the economy. The following variables were used in the CCR DEA profile:

- output y – gross value added (euro),
- input x_1 – number of employees,
- input x_2 – greenhouse gas emissions (tons of CO_2 equivalent).

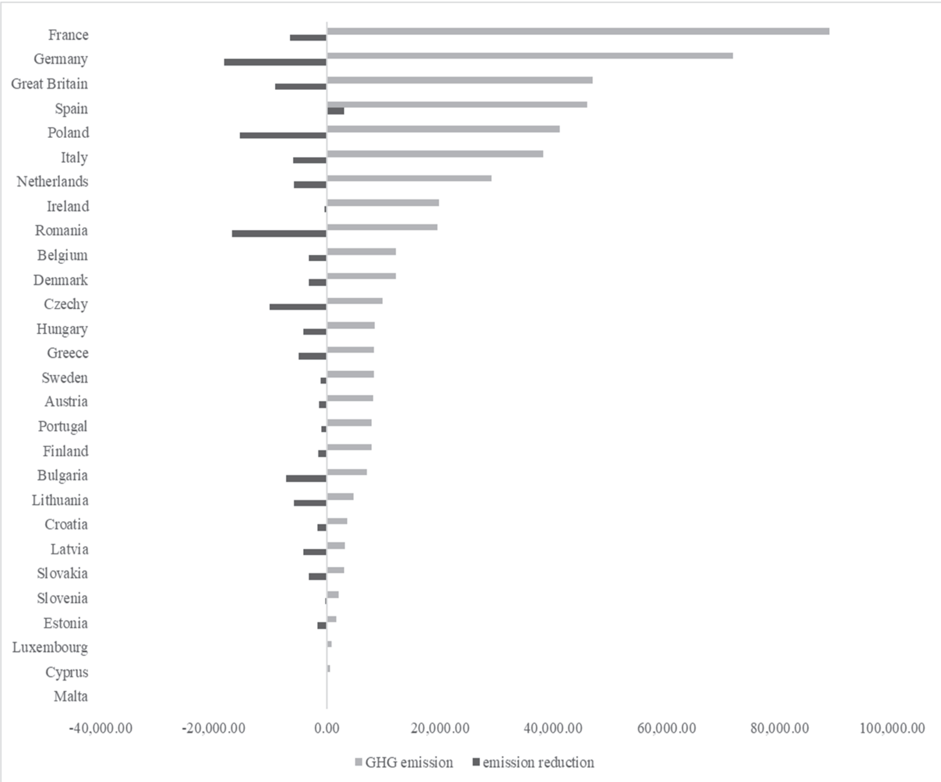

Fig. 3. Emissions in 2016 and changes in agricultural emissions of the Member States in 1990-2016; Source: Own study based on Eurostat

Comparing individual sectors of the economy, it should be noted that there are very large differences in their efficiency (see Figure 4). It was examined that in agriculture economic and climate efficiency was only at the level of 0.034, which is dramatically low compared to the fully effective sector. Very low efficiency was also recorded in construction (0.076) or wholesale and retail trade (0.077).

The next stage of the research was determining the level of agricultural efficiency in individual EU countries. In the initial phase of calculations, Malta and Luxembourg were eliminated, which due to their very specific structure of agriculture disturbed the obtained results. As part of the CCR DEA profile based on literature studies (Bórawski et al. 2019), the following variables were adopted:

- output y – gross value added (euro),
- input x_1 – UAA (ha),
- input x_2 – number of employees,
- input x_3 – greenhouse gas emissions in agriculture (tons of CO_2 equivalent).

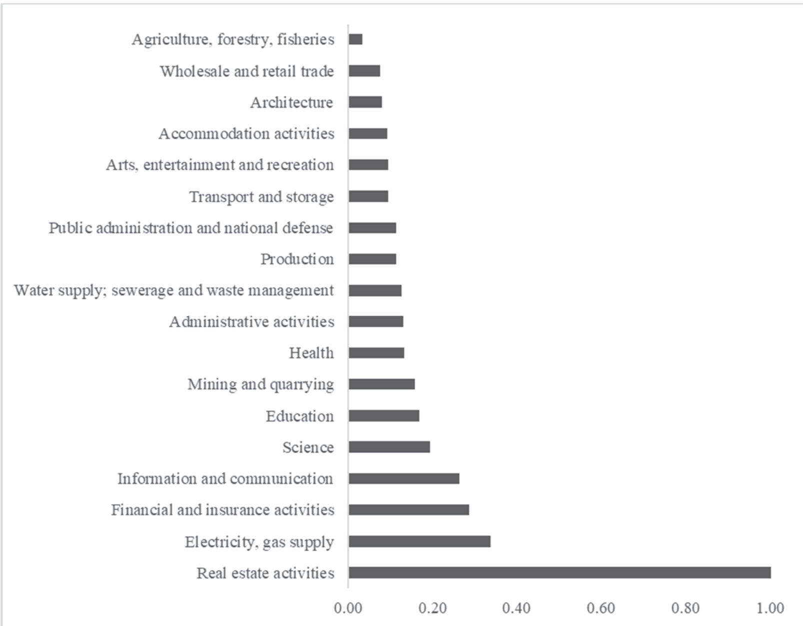

Fig. 4. Economic and climate efficiency of sectors of the economy in the EU (DEA)
Source: Own study based on Eurostat.

The calculations used data from the Eurostat database. The results of the calculations are presented in Figure 5. A ranking of countries was created starting from those with the least efficiency.

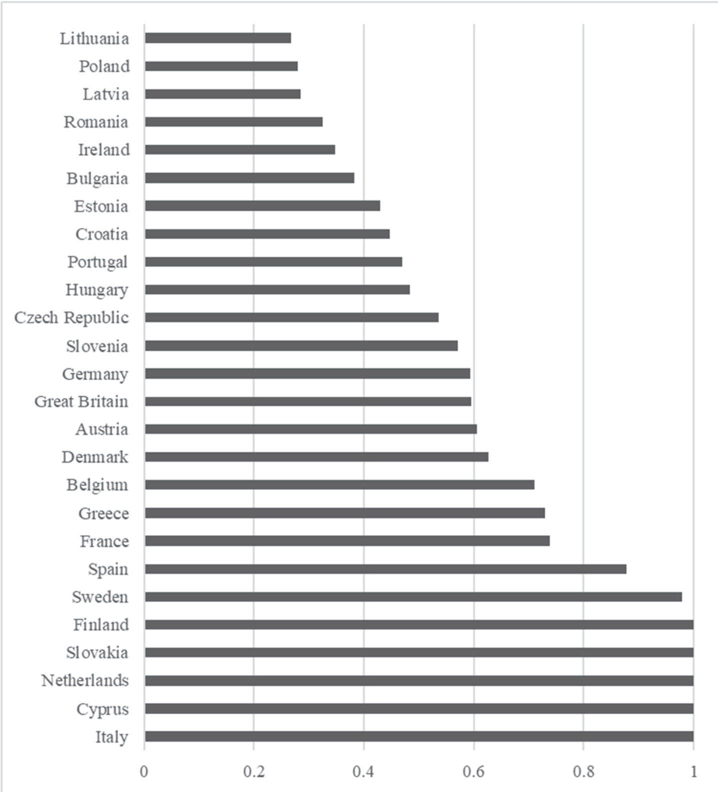

Fig. 5. Economic and climatic efficiency of agriculture in EU countries (DEA)
Source: Own study based on Eurostat.

The average agricultural efficiency of the studied countries was at a high level of -0.626. Considering the inputs and outputs applied, agriculture in five countries: Italy, Cyprus, the Netherlands, Slovakia and Finland should be considered as fully effective (benchmark). Polish agriculture, with an efficiency of 0.28, next to Lithuanian 0.267, was at the end of the ranking. The best countries achieve the same results as Poland, using only 28% of resources.

For future research mathematical, numerical or simulation model for the described research may be elaborated according to the structure presented in literature (e.g. Kostrzewski 2020, Kostrzewski 2017, Chamier-Gliszczyński 2017). However, it will be huge scale research which needs various types of data elaboration.

5. Conclusions

Climate change is a phenomenon that will affect all sectors of the European economy. Surprisingly, EU level regulations aimed at reducing GHG emissions may have a major impact on these changes. In connection with the above, it is important to determine what path agriculture has taken over the background of other departments and what is its climatic efficiency when using resources. The conducted research allowed us to accept the following conclusions:

1. In 1990-2016, agriculture accounted for around 10% of EU greenhouse gas emissions, despite the reduction of emissions by around 23% over the period considered. The constant share of agriculture resulted from a similar level of decline in emissions in other sectors of the economy.
2. During the period considered, each of the Member States, except for Spain, reduced its greenhouse gas emissions in agriculture. The largest absolute decrease was recorded in Germany (-18 million tons of CO_2), Romania (-17 million tons of CO_2) and Poland (-15 million tons of CO_2).
3. Agriculture has the lowest economic and climate efficiency of all sectors of the economy in the EU studied.
4. Comparing the agriculture of individual countries, it was observed that the highest economic and climate efficiency was achieved in such countries as Italy, Cyprus, the Netherlands, Slovakia and Finland. Poland, apart from Lithuania and Latvia, was among the three countries with the lowest efficiency.

The climatic efficiency of agriculture is at the lowest level among other sectors of the economy. However, it should be born in mind that it provides the most important products necessary for the functioning of society – food. All kinds of activities contributing to reducing GHG emissions in agriculture must take this into account, as well as the fact that since 1990 significant reductions have been made.

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Abstract

The article in the theoretical part draws attention to the phenomenon of climate change and two-way relations between these changes and agriculture. Agriculture as an economic sector is extremely sensitive to any climatic disturbances. However, as a greenhouse gas (GHG) emitter, it contributes to this process. In the era of significant reductions in GHG emissions, it is becoming increasingly important to obtain the highest economic effects with the smallest external effects (e.g. GHG). The purpose of the article is therefore to determine the level of GHG emissions in agriculture and the economic and climate efficiency of agriculture in EU countries and comparison to other sectors of the economy. The DEA method was used in the study. Calculations were made based on Eurostat data.

It was found that the share of GHG emissions of agriculture in the EU represents 10-11% of all emissions in the European Union. Agriculture is the least economically and climatically effective sector of the EU economy. Comparing the agriculture of individual countries, the highest efficiency was achieved by Italy, Cyprus, the Netherlands, Slovakia and Finland, the lowest – Lithuania, Poland and Latvia.

Keywords:
efficiency, climate, economy, GHG, agriculture, Europe

Efektywność ekonomiczno-klimatyczna rolnictwa w UE i Polsce

Streszczenie

W artykule w części teoretycznej zwrócono uwagę na zjawisko zmian klimatycznych oraz dwukierunkowych relacji pomiędzy tymi zmianami a rolnictwem. Rolnictwo jako sektor gospodarki jest niezwykle wrażliwy na wszelkie zaburzenia klimatyczne. Z drugiej strony jako emitent gazów cieplarnianych (GHG) m swój udział w tym procesie. W dobie znaczących redukcji emisji GHG coraz istotniejszą kwestią jest otrzymywanie jak najwyższych efektów ekonomicznych przy jak najmniejszych efektach zewnętrznych (np. GHG). Celem artykułu jest zatem określenie poziomu emisji GC w rolnictwie oraz efektywności ekonomiczno-klimatycznej rolnictwa w krajach UE oraz w porównaniu do innych działów gospodarki. W opracowaniu wykorzystano metodę DEA. Obliczeń dokonano na podstawie danych Eurostatu. Stwierdzono, że udział emisji GC rolnictwa w UE stanowi 10-11% wszystkich emisji we Wspólnocie. Rolnictwo jest najmniej ekonomiczno-klimatycznie efektywnym sektorem gospodarki UE. Porównując natomiast rolnictwo poszczególnych krajów, najwyższą efektywność osiągnęły Włochy, Cypr, Holandia, Słowacja i Finlandia, najniższą Litwa Polska i Łotwa.

Słowa kluczowe:
efektywność, klimat, ekonomia, emisja gazów cieplarnianych, rolnictwo, Europa

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Assessment of Concentrations of Selected Metals in the Groundwater in the Wielkopolska National Park

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1. Introduction

Contamination of groundwater may become a major problem reducing availability of water (Gu et al. 2020, Luczaj 2016, Umar et al. 2009). Increasing pollution of these waters also decreases in the groundwater resources, constituting not only the source of potable water, but also water used in agriculture, while also affecting the condition of vegetation and welfare of animals in areas covered by nature protection measures (Vitale et al. 2017, Aniszewski 2020).

Groundwater quality is determined by many factors, primarily human activity, the distribution of precipitation, the impact of surface waters and subsurface geochemical processes. Both natural hydrological processes and anthropogenic factors may lead to periodical changes in groundwater quality (Luczaj & Masarik 2015, Vasnthavigar et al. 2010). Groundwater susceptibility to contamination may be defined as sensitivity of such waters to an introduced pollutant load, resulting from specific properties of the aquifer (Van Duijvenbooden & Waegningh 1987). The actual groundwater susceptibility, difficult to determine using quantitative standardised methods, needs to include properties of the hydrogeological system, in which the water cycle takes place both in the unsaturated zone and in the aquifer. Thus it needs to consider the potential release of contaminants to groundwater (Wachniew et al. 2016, Krogulec 2016). Groundwater susceptibility to pollution may be assessed using methods based on the Geographic Information Systems (GIS), the process approach and statistical methods (Duarte et al. 2019, Kong et al. 2019, Mozejko 2012, Wachniew et al. 2016).

The process of cations mobility in the soils depend on various parametres such as rain pH and soil properties. The significant leaching of potassium, sodium, calcium and magnesium from the plant root zone could couse groundwater pollution and on nutrient imbalance (Małecki et al. 2017, Nawaz et al. 2012, Walna et al. 2000). The investigations of the chemical characteristics of the precipitation in the Wielkopolski National Park has shown its high acidity, which can drop below pH 3.0. Effect of such rains was washing out of large amounts of Ca and Mg from sandy and naturally very acid soils (Walna & Siepak 2012).

A frequently stressed aspect is connected with the advantageous effect of afforestation on the improvement of groundwater quality (Allen & Chapman 2001, He et al. 2019, Lowrance et al. 1997). In forested areas a considerable role in the circulation of contaminants is played by forest management measures, resulting among other things in leaching of nitrates and heavy metals from clear-cutting areas (Buttle 2011, Mannerkoski et al. 2005, McHale et al. 2007, Rusanen et al. 2004).

2. Materials and methods

This study is based on data concerning metal concentrations in groundwater, provided by the Wielkopolska National Park. Water samples were collected in February, May, August and November 2017 from 15 wells located in the Park (Fig. 1) varying in their position in the relief, as presented in the hill-shading map below (Fig. 2).

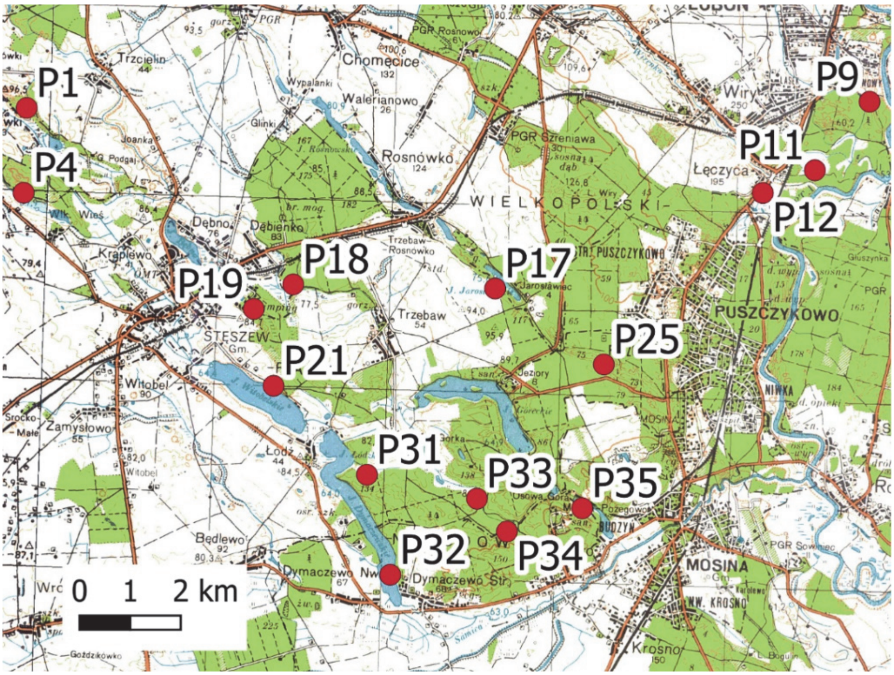

Fig. 1. Location of groundwater sampling sites

The Wielkopolska National Park is situated 15 km south of Poznań (western Poland) an covers area of 76 km^2. The soils originated from loamy and sandy postglacial material of the last glaciation. The dominating soils are grey brown podzolic (47%) and brown podzolic soils (30%), while the other soils are podzols (7%), proper brown soils (6%), alluvial soils (3%), deluvial soils (2%) and anthropogenic soils, arenosols, muck soils, turf soils, brown acid soils (Nowak 1999). The average annual sum of precipitation is 550 mm and does not show significant changes during long period (Miler 2018).

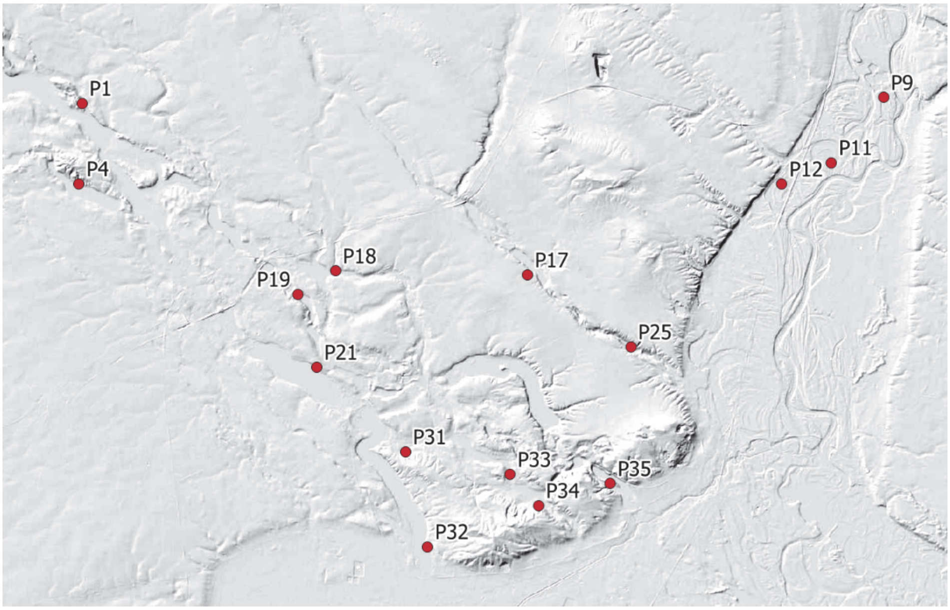

Fig. 2. Hillshading map of analyzed area

Groundwater was sampled after at least three exchanges of the water column in a borehole, using a suction-and-force combustion pump. Earlier, the water level in the piezometer and water temperature were measured. Analyzed elements were barium, boron, calcium, iron, potassium, magnesium, manganese, sodium and zinc. The concentrations of dissolved elements (B, Ba, Ca, Fe, K, Mg, Mn, Na, Zn) in the water samples were determined using the technique of atomic absorption spectrometry, according to method W-METAXFL1.

Variability of investigated parameters was assessed using the analysis of variance (ANOVA). Values outside 1.5·IQR (Inter Quartile Range) were considered to be outliers. The outliers were replaced by the values calculated according to the following equations:

$$Up = Q_3 + 1.5IQR \quad (1)$$
$$Low = Q_1 - 1.5IQR \quad (2)$$

where:
Up – concentrations for values outside the 75-th quartile (Q_3),
Low – concentrations for values below the 25-th quartile (Q_1).

In order to determine whether different metals exhibit a similar variability, respective analyses were conducted for the relationships using Pearson's correlation coefficients. The Principal Component Analysis (PCA) and cluster analysis made it possible to include various factors influencing variance. A factorial analysis applying normalised varimax rotation was performed in order to reduce related environmental variables and identify a small set of variables clearly explaining a considerable proportion of variance for the variables. Cluster analysis was conducted applying Ward's method, assuming Euclidean distances as a measure of similarity between clusters. Prior to PCA the Kaiser-Meyer-Olkin (KMO) tests and Bartlett's tests of sphericity were performed to assess applicability of original data. KMO<0.5 was assumed as a condition satisfying Bartlett's test of sphericity. Data which failed to meet the conditions for the normal distribution were transformed using logarithms. The number of clusters was determined applying the silhouette method.

In the case of metal concentrations in groundwater below the limit of detection, values corresponding to the limit for a given element were assumed for the analyses.

All statistical analyses and graphs were made using the R 3.6.2 statistical software package. Spatial data are presented with the use of the QGIS 3.12 programme.

3. Results and discussion

Characteristic concentrations of analysed metals (B, Ba, Ca, Fe, K, Mg, Mn, Na and Zn) in groundwater samples collected from 15 wells located in the Wielkopolska National Park are presented in Table 1 and in Fig. 1.

Concentrations of these metals showed high variability. Levels of the analysed metals in 2017 fell within the following ranges: B from 0.05 to 0.156 $mg·dm^{-3}$, Ba from 0.022 to 0.150 $mg·dm^{-3}$, Ca from 52.6 to 260 $mg·dm^{-3}$, Fe from 0.001 to 5.40 $mg·dm^{-3}$, K from 0.664 to 13.1 $mg·dm^{-3}$, Mg from 7.95 to 38.1 $mg·dm^{-3}$, Mn from 0.002 to 1.61 $mg·dm^{-3}$, Na from 7.02 to 97.4 $mg·dm^{-3}$ and Zn from 0.001 to 0.009 $mg·dm^{-3}$. Mean concentrations of tested metals fell within the order: Ca (127 $mg·dm^{-3}$) > Na (27.8 $mg·dm^{-3}$) > Mg (16.9 $mg·dm^{-3}$) > K (3.52 $mg·dm^{-3}$) > Fe (0.464 $mg·dm^{-3}$) > Mn (0.298 $mg·dm^{-3}$) > Ba (0.073 $mg·dm^{-3}$) > B (0.044 $mg·dm^{-3}$) > Zn (0.002 $mg·dm^{-3}$).

The comparison of metal concentrations presented by Walna & Siepak (2012) and Walna (2013) shows decrease of concentration of zinc, calcium and magnesium. Present average content of Zn is 0.004 mg·dm^{-3}, whreas in 2010 year was 0.007 mg·dm^{-3} and in 1994 0.040 mg·dm^{-3}. Average concentrations of Mg decreased from 31.4 mg·dm^{-3} in 2010 year to 16.9 mg·dm^{-3} in 2017 and average calcium concentration decreased in the same period from 198 mg·dm^{-3} to 127 mg·dm^{-3}. Concentrations of K and Na are at similar level as measured in 2010 (Walna 2013).

Median values of concentrations for most parameters correspond to quality class I in relation to boundary values for the physico-chemical condition of groundwater (Rozporządzenie 2015). Only the median of Mn concentrations corresponds to quality class 2, while that of Ca – to quality class 3. However, these values fall within the ranges for the geochemical background (Table 1). Low levels of heavy metal contamination for forested areas were also confirmed by Chrzan et al. (2013).

As shown in Table 1 and Fig. 3, the distribution of groundwater concentrations of analysed metals to a considerable extent deviates from normal distribution for most analysed elements. Figure 3 also presents a considerable number of outliers, particularly for higher concentration values.

The highest Ba concentrations in groundwater were observed in profiles P34, P35 and P9 throughout the entire year of 2017 (Fig. 4) and they were over 2-fold greater than in the other wells. Elevated Ba concentrations were recorded in well P12, Ca in P18, Fe in P11 and P33, K in P19, Mg in P19, Mn in P35, while Na – in wells P34 and P9. No significant variation in concentrations was observed in the successive measurement periods (Fig. 4).

Correlations in metal concentrations may indicate that contamination originates from the same source, and that they have the same circulation routes (Ke et al. 2017). On the other hand, a lack of significant relationships means that metals may originate from various sources and may be influenced by various factors (Xu et al. 2018). The matrix of correlations for Pearson's coefficients for the concentrations of analysed metals is presented in Table 2. A significant correlation was found between concentrations of the following metals at $p < 0.01$: B-Mn (r = 0.46), B-Na (r = 0.57), Ba-Mg (r = 0.47), Ba-Mn (r = 0.35), Ba-Na (r = 0.49), Ca-K (r = 0.39), Ca-Mg (r = 0.67), K-Mg (r = 0.58), Mg-Na (r = 0.49) and additionally at $p < 0.05$ for B-Zn, Ba-K, Ca-Na, Fe-Mn and K-Na. As can be seen here, elements showing the lowest correlation of concentrations with the other metals include Zn (only with B) and Fe (with Ba and Mn), whereas Ba shows correlation with the highest number of metals (Fe, Mg, Mn, Na and K).

Table 1. Concentrations of selected metals in groundwater, limits for water classes and geochemical background f or soils of analyzed area

Me-tal	Samples	Median	Mean	Min	Max	Std. deviation	Skew	Kurtosis	Limits for water class[1]			Geochemical background[2]
									1	2	3	
	No	mg·dm^{-3}										mg·kg^{-1}
B	60	0.027	0.044	0.005	0.156	0.043	1.243	0.169	0.5	1	1	0.01-0.06
Ba	60	0.072	0.073	0.022	0.150	0.028	0.464	-0.336	0.3	0.5	0.7	4-39
Ca	60	121.5	126.8	52.6	260	47.9	0.818	0.615	50	100	200	40-130
Fe	60	0.007	0.464	0.001	5.40	0.957	10.063	0.124	0.2	1	5	90-620
K	60	2.50	3.518	0.664	13.1	2.898	2.978	0.374	10	10	15	0.1-26
Mg	60	16.65	16.88	7.95	38.1	6.639	0.970	0.857	30	50	100	10-90
Mn	60	0.153	0.298	0.002	1.61	0.379	3.331	0.049	0.4	1	1	5-271
Na	60	23.15	27.80	7.02	97.4	19.5	2.467	2.515	60	200	200	0.5-39
Zn	45	0.001	0.002	0.001	0.009	0.002	1.582	1.484	0.5	1	2	7-67

[1] – Rozporządzenie … (2015)
[2] – Lis & Pasieczna (2005)

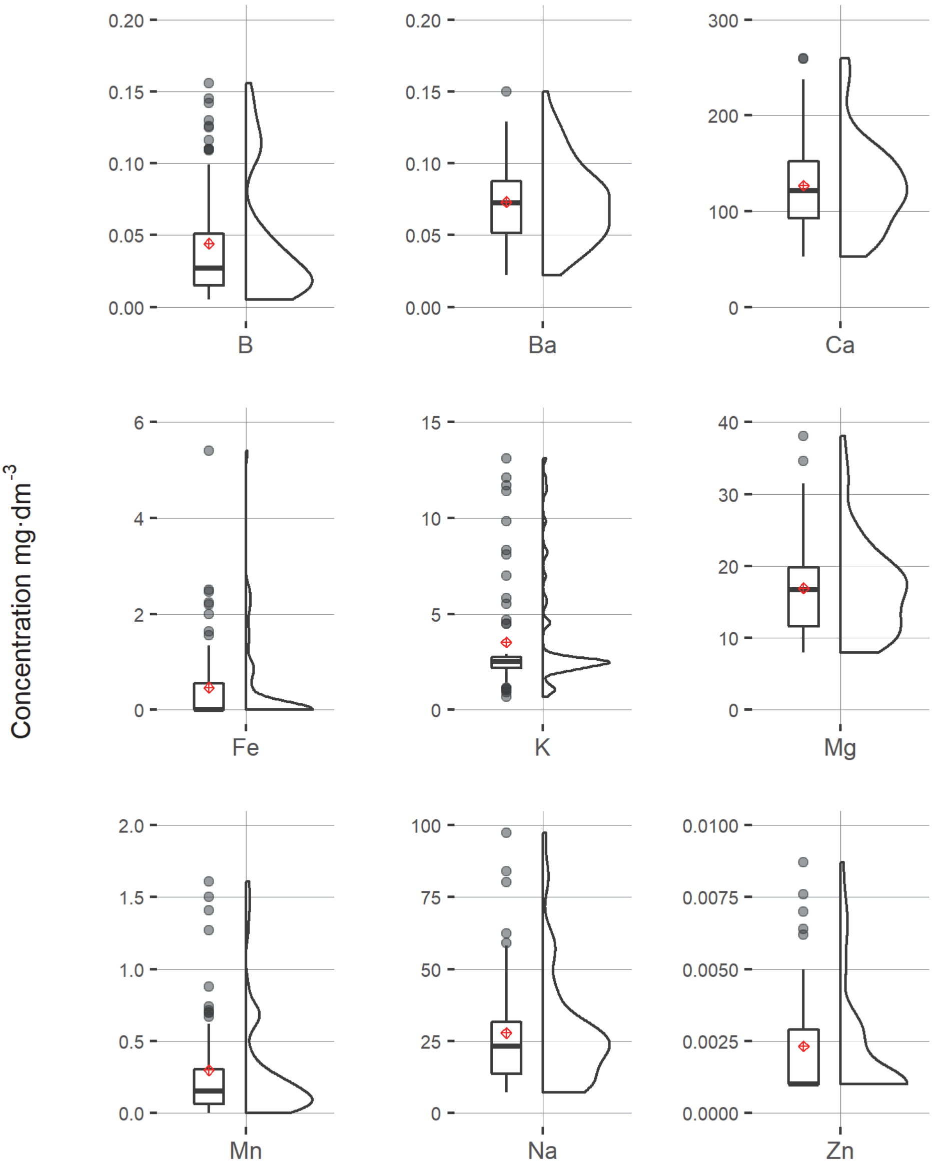

Fig. 3. Characteristic values, distribution and outliers of analysed metal concentrations in groundwater of the Wielkopolska National Park

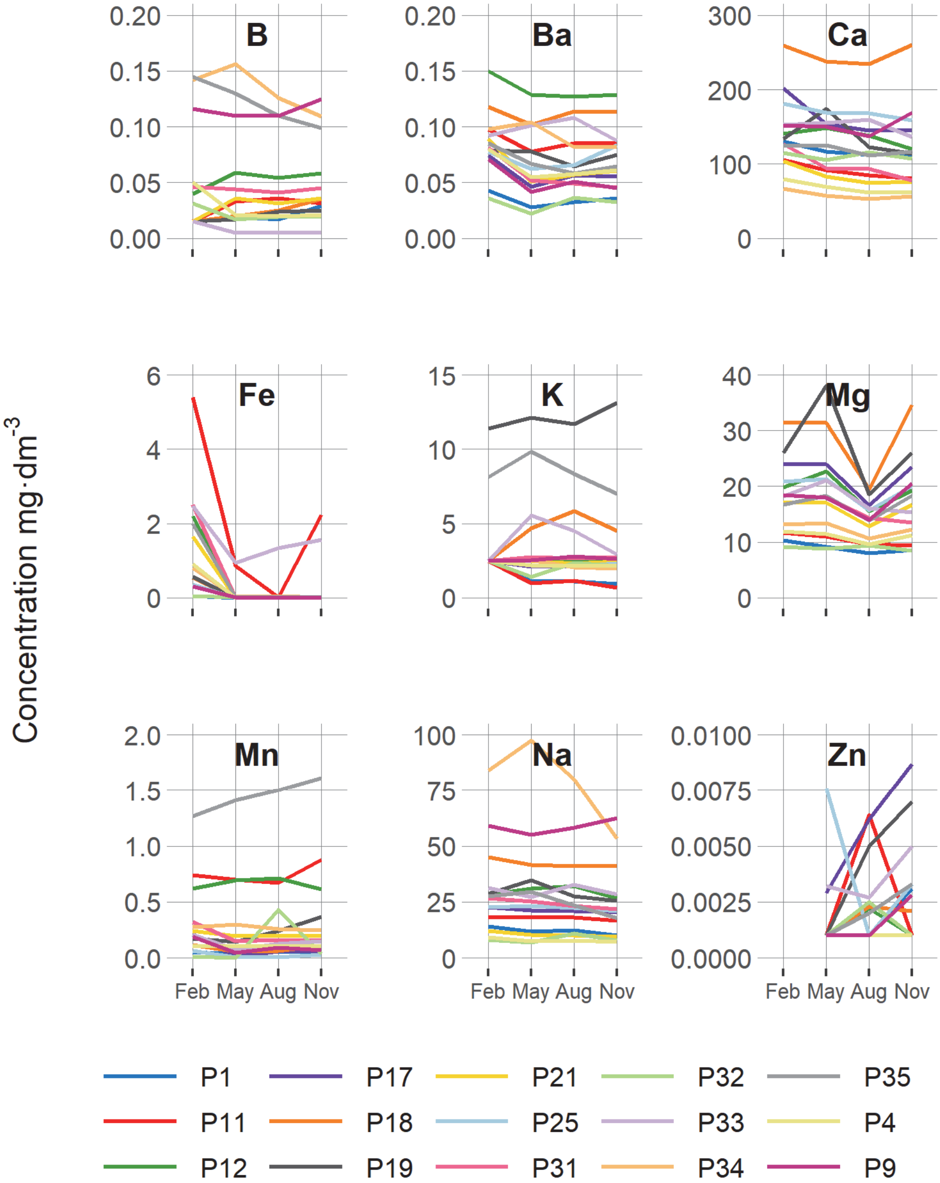

Fig. 4. Concentrations of metals in groundwater from sampling sites in the Wielkopolska National Park for the year 2017

Table 2. Correlation coefficient matrix for the analyzed elements and depth of groundwater (GWD)

	B	Ba	Ca	Fe	K	Mg	Mn	Na	Zn
Ba	0.04								
Ca	-0.28	0.25							
Fe	-0.10	0.44	0.07						
K	0.12	0.30	0.39	0.01					
Mg	-0.07	0.47	0.67	0.04	0.58				
Mn	0.42	0.35	-0.18	0.31	0.24	-0.05			
Na	0.57	0.49	0.27	0.08	0.31	0.49	0.09		
Zn	-0.31	0.04	0.29	0.05	0.13	0.25	-0.05	0.04	
GWD	-0.17	-0.26	0.08	-0.17	-0.17	0.17	-0.32	-0.04	0.40

– $p < 0.01$. – $p < 0.05$

Concentration of dissolved elements could be correlated with depth from ground surface to groundwater (GWD). For 2017 year average depth of groundwater surface was from 0,74 m in site P33 to 17,86 m in site P17 (Table 3). The groundwater table fluctuations during the investigations were greatest in site P1 and equal 0.67 m, while average GWD for this site was 1.08 m. The smallest variation of GWD were observed in the site P18 and were only 0.03 m. There was no significant correlation of metal concentration between depth of groundwater (GWD) and B, Ca, Fe, K, Mg and Na (Table 2). A significant correlation was found between GWD and Zn ($p < 0.01$), Mn and Ba (both $p < 0.05$).

Table 4 presents the matrix of principal components and variance of analysed heavy metal concentrations in groundwater identified at eigenvalues >1. These data for two principal components were additionally shown in Fig. 5. Three principal components given in Table 3 explain jointly 68.2% total variance, which does not meet the recommendation that principal components should explain min. 75% total variance (Loska & Wiechuła 2003). Principal component 1, responsible for the total load of metals in groundwater explains 31.6% variance and is correlated mainly with concentrations of Mg, Ba, Na, K and Ca. Principal components 2 and 3 explain 21.6% and 15.0% total variance, respectively. PC 2 is correlated mainly with B and Mn. In turn, PC 3 is correlated with Fe. The loading plot (Fig. 5) confirmed the results of the correlation analysis.

Table 3. Depth of groundwater at sampling sites (m)

Site	February	May	August	November
P1	2.97	2.86	2.88	2.74
P4	2.58	2.54	2.53	2.37
P9	4.78	4.60	4.86	4.49
P11	1.03	1.33	1.31	0.66
P12	1.27	0.98	1.13	0.72
P17	17.84	17.86	17.87	17.87
P18	0.82	0.90	0.85	0.49
P19	3.46	3.37	3.49	3.29
P21	7.27	7.17	7.75	7.32
P25	5.75	5.56	5.65	5.50
P31	2.24	2.21	2.21	2.02
P32	1.99	1.93	1.82	1.62
P33	0.81	0.63	0.75	0.78
P34	4.39	4.31	4.34	4.25
P35	0.80	0.78	0.84	0.68

Table 4. The first three principal components (PCs) obtained by PCA and percentage cumulative variance explained.

Metal	PC 1	PC 2	PC 3
B	0.02	0.66	0.21
Ba	0.53	0.05	0.15
Ca	0.42	0.31	0.00
Fe	0.08	0.04	0.65
K	0.48	0.00	0.03
Mg	0.71	0.10	0.03
Mn	0.06	0.46	0.12
Na	0.49	0.12	0.13
Zn	0.06	0.21	0.03
Eigenvalues	2.84	1.95	1.35
Cumulative explained variance	31.6	53.2	68.2

Performed correlation and PCA analysis identified two groups of elements. First group comprises Ba, Ca, K, Mg and Na. This group include elements that have high concentration levels and have natural sources. The second group is composed of B, Fe, Mn and Zn which usually are connected with anthropogenic sources. Additionally iron and manganese are widely found in soils and aquifers, which have similar geochemical behavior (Zhang 2020).

Cluster analysis also identified groups of sampling locations showing a similar variation in metal concentration in groundwater (Fig. 6). Three groups of sampling locations were identified. One includes wells P1, P4, P21, P1 and P32. This group represents sites located in the neighbourhood of open water bodies and there is possible temporary influence of lake or river water on groundwater in analysed sites. Sites P4, P21 and P32 are located nearby lakes and site P11 close to the Warta River (Fig. 1 and 2). The second one comprises wells P19, P18, P33 and P35 which are located in the lowest parts of area relief and are supplied by flows from surrounding areas. The third group is composed of wells P9, P12, P17, P25, P31 and P34 located on middle and upper parts of slope.

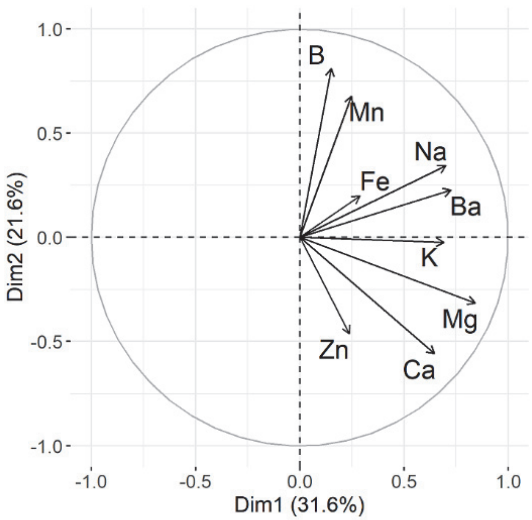

Fig. 5. Plot of loading of the first two principle components

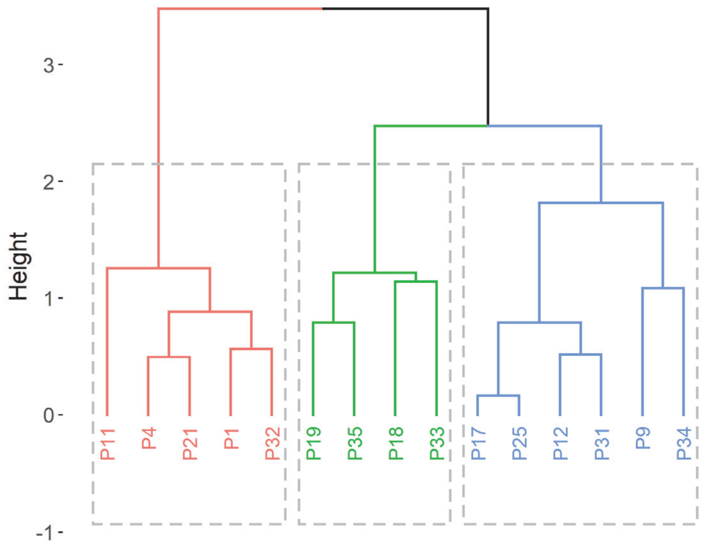

Fig. 6. Dendrogram of division of sampling sites

4. Conclusions

Heavy metals are some of the most hazardous contaminants of groundwater. This hazard is of particular importance in protected areas of nature value located near large industrial and urban centres. The impact of anthropopressure needs to be assessed on an on-going basis to ensure the earliest possible detection of threats.

Results of conducted studies indicate a relatively good condition of groundwater in the analysed area. Values of medians for concentrations in the case of most indexes correspond to quality class I in view of boundary values for physico-chemical parameters of groundwater. Only the median for Mn concentrations corresponded to quality class 2 and Ca for quality class 3. However, to ensure adequate assessment of water status it is necessary to determine proper values of the geochemical background under local conditions.

Performed statistical analyses identified two groups of elements. First group comprises Ba, Ca, K, Mg and Na. The second group is composed of B, Fe, Mn and Zn which usually are connected with anthropogenic sources.

The spatial analysis of variation in metal concentrations in groundwater may be facilitated by the application of cluster methods, combining areas with a similar variation in water quality parameters. Three groups of sampling locations showing a similar variation in metal concentration in groundwater were distinguished. The first one is located nearby open water bodies, the second in the lowest parts of relief and the third in the upper and middle parts of slopes.

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Abstract

This paper presents a statistical analysis of concentrations for selected metals in groundwater samples collected from 15 sites located in the Wielkopolska National Park in four periods of 2017. Concentrations of such metals as B, Ba, Ca, Fe, K, Mg, Mn, Na and Zn were analysed. Statistical analysis identified two groups of metals in terms of similarity in their concentrations in groundwater. One group is composed of Ba, Ca, K, Mg and Na, while the other comprises B, Fe, Mn and Zn. The analyses showed also considerable variation of investigated elements between various well locations. Three types of location were distinguished: situated nearby open water bodies, situated in the lowest parts of relief and located in the upper and middle parts of slopes.

Keywords:
groundwater quality, heavy metal, protected areas, Wielkopolska National Park

Ocena stężeń wybranych metali w wodzie gruntowej na terenie Wielkopolskiego Parku Narodowego

Streszczenie

W pracy przedstawiono statystyczną analizę stężeń wybranych metali w próbkach wody gruntowej pobieranych w roku 2017 w 15 miejscach na terenie Wielkopolskiego Parku Narodowego. Analizie poddano stężenia następujących metali: B, Ba, Ca, Fe, Mg, Mn, Na i Zn. Obliczenia statystyczne pozwoliły wydzielić dwie grupy pierwiastków wykazujące podobną zmienność stężeń. Do pierwszej zaliczono Ba, Ca, K, Mg i Na, podczas gdy do drugiej zaliczono B, Fe, Mn i Zn. Analizy wykazały również znaczącą zmienność stężeń badanych metali wynikającą z położenia miejsca poboru próbki w rzeźbie terenu. Wydzielone trzy typy lokalizacji to: położone w bezpośrednim sąsiedztwie wód powierzchniowych, położone w najniższych partiach terenu oraz położone w górnych i środkowych partiach zboczy.

Słowa kluczowe:
jakość wody gruntowej, metale ciężkie, obszary chronione,
Wielkopolski Park Narodowy

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Changes in Selected Water Quality Indicators of the Warta River Due to the Jeziorsko Dam Reservoir

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1. Introduction

Assessing and interpreting of data on the quality of water in reservoirs and their impact on the quality of river water flowing through such reservoirs is a complex problem due to numerous factors and determinants. Regrettably, existing literature on the subject offers many examples limited to very simplistic approaches (Pytka et al. 2013, Pęczuła & Suchora 2011).

Reservoirs, according to flow characteristic, have features more or less similar to a very dynamic lakes (Wetzel 1990). Physical, chemical and biological characteristics allows to distingue three regions (zones): initial zone, transition zone and lentic region (Soares et al. 2008). Similar reservoir division into the zones described Straskraba (1999), noticing that even the whole reservoir can be treated as river-like or lake zone, depending on the water retention time and that the retention time influences both the longitudinal and the vertical patterns. Accordingly to these zones identification, it is valuable to note, that the first zone can occur as separate reservoir, named pre-dam, which can contribute to over 50% of nitrogen and phosphorus elimination (Czamara et al. 2008).

Damming rivers involves several important features and conditions, e.g. related to reservoir volume – water temperature and thermal stratification, residence time, turbidity, primary production and related to the construction – oxygen and nutrient balance or organic carbon cycle (Teodoru & Wehrli 2005, Friedl & Wüest 2002) and related also to watershed and catchment features (Soares et al. 2008).

There are contradict results of studies related to reservoirs impact on the matter and pollutants being transported by the river, e.g. Czamara et al. (2008) reported that large reservoirs can temporarily sink 90% of the total load of inflowing matter and biogenic substances, what corresponds to other authors remarks (Liu et al. 2019, Teodoru and Wehrli 2005). However Teodoru and Wehrli (2005) indicated a slight increase in nutrient loads before the dam (18% of total nitrogen and 13% of total phosphorus) and reported only 1% of nutrient retention in the Iron Gate Reservoir.

Liu et al. (2019) indicated basic processes of removal nutrients in reservoirs: temporary storage in biomass, denitrification and burial of sediment. Recirculation of elements and substances from the sludge to the water depth depends on: sediment bioturbation (Parsons et al. 2017) water body morphology (average depth) (Waters & Curran 2015), meteorological conditions, advection, speed and thermal stratification, dissolved oxygen concentration and red-ox potential (Lee et al. 2019).

Nitrogen compounds can be realized or absorbed at different time scales and its daily retention is influenced by flow velocity and water level (Liu et al. 2019).

There are a few processes and phenomena related to the amount of phosphorus in water, e.g. dependency on the external and internal load from the sediments. The amount of phosphorus released in the sediment depends on the duration and surface extent of anoxia and the rate at which phosphorus is released from the anaerobic surface of the sediment (Lee et al. 2019).

A reliable assessment of changes in the quality of water along the watercourse, taking into account the reservoirs through which it flows, requires a balance of inflow and outflow loads, data on real retention times and flow rate velocities as well as identification of potential and ongoing processes (Pawełek & Grenda 2010, Wiatkowski 2011). If the (transformation) time of a particular substance or related demand for it (identified by a specific pollution indicator) does not change significantly, the existing relationship is simpler to interpret.

The process of self-cleaning is a fundamental issue related to water quality in watercourses and yet, a very complex one, with intensity depending on numerous factors. The observed as well as future increase in water temperature will modify current processes occurring in the river, referring to among others water quality, composition of ichthyofauna, or hydrological conditions. A fairly common approach to this process (Starmach et al. 1976) includes, among others: the section length where the process is analysed, the self-cleaning rate per unit of time, the biologically active surface and the activity of organisms present in a given ecosystem. There are also known approaches based on the use of specific self-cleaning factors (indicators). The most commonly considered indicators in the context of water self-cleaning capacity are dissolved oxygen in water (DO) and biochemical oxygen demand over five days (BOD_5). Depending on the conditions, other indicators – nitrogen and phosphorus – are also included (Jaskuła et al. 2019). A decrease in the concentration of ammonium ions is considered a fairly representative indicator of water self-cleaning capacity, which proves good oxygenation of water as well as a proper run of nitrification and biological assimilation processes.

One of the important hydrological parameters to be analysed in this context is the actual water retention time in the reservoir, which, in turn, is crucial for possible processes requiring a specific time. As a result, time intervals for determining these indicators should be adapted to the duration of specific processes and the actual water retention time in the reservoir (Soares et al. 2008).

Despite a fairly wide scope of standard analyses performed for surface waters, their usefulness often raises significant doubts, except for identifying variations and trends of changes over time, meeting or failing some formal criteria and evaluating the process of eutrophication. Therefore, it seems reasonable to ask whether the data provide information on other important processes.

Numerous works and studies to date, even if they show differences between water quality at the inflow and outflow from the reservoir, supported with statistical analysis, (Wiatkowski 2010, Kanclerz et al. 2014, Bogdał et al. 2015), very rarely (Przybyła et al. 2014) give reasons for this state of affairs or identify processes leading to it.

The objective of the study was to evaluate, on the example of the Jeziorsko reservoir, the applicability of standard physical and chemical analyses of water (performed by the Institute of Environmental Protection and Water Management) in order to assess changes in selected water quality indicators of the Warta River under the impact of the Jeziorsko dam reservoir.

2. Methodology

The undertaken analyses concern the impact of the Jeziorsko reservoir on the quality of water in the Warta river. The reservoir was created as a result of partitioning the valley with a front dam. It is located on the border of the Wielkopolskie and Łódź voivodships in the middle course of the Warta River. Its usable capacity is 113.91 million m^3, and the total capacity equals 202 million m^3.

Since there is no hydrological data for smaller watercourses forming the catchment of the Jeziorsko reservoir (Fig. 1), the authors, in order to compare the amount of water flowing into the reservoir from the Warta river and the amount of water supplied from other inflows, compared the catchment surfaces. Based on Atlas Podziału Hydrograficznego Polski (the Atlas of the Hydrographic Division of Poland) (Czarnecka 2005), the Jeziorsko catchment area is 625.6 km^2, and the Warta catchment area is 9012.64 km^2. Direct inflows to the reservoir constitute 6.94% of the total area of the Warta river area at the front dam cross-section.

In view of their low share, apart from the Warta river, they were omitted as part of the analysis, assuming their impact as negligible or insignificant.

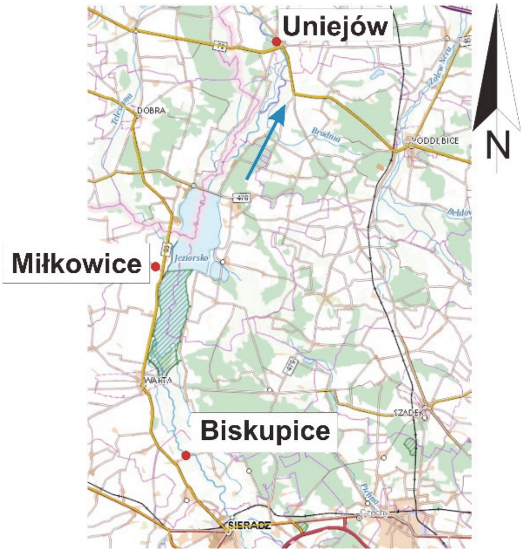

Fig. 1. Location of water sampling points

Water quality tests were carried out by the Voivodeship Inspectorate for Environmental Protection in Łódź, the Sieradz Inspectorate in the selected points: above in Biskupice, Miłkowice, below the Jeziorsko reservoir in Uniejów, no more than once a month and at least six times a year. The samples were taken in 2006, 2008, 2011, 2014. The following parameters belonging to the physical-chemical elements (supporting biological elements – thermal conditions, oxygenation conditions, organic pollutants, acidification state and biogenic conditions): temperature, pH, biochemical oxygen demand over five days (BOD_5), total phosphorus (P_{tot}), total organic carbon (TOC) and total nitrogen (N_{tot}) were used for analysing. All the analyses of water samples as well as assessments of water quality were carried out in accordance with applicable standards set out in the Regulation of the Minister of the Environment of July 21, 2016 on the classification of the state of surface water bodies and environmental quality standards for priority substances (Regulation Journal of Laws, item 1187 2016), Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions to be met when discharging wastewater into waters or soil, as well as when discharging rainwater or meltwater into waters or into aquatic devices (Regulation Journal of Laws, item 1311 2019). For the purpose of this paper, as a representative of the impact of the reservoir on river water quality, there were arranged water sampling points near Biskupice (at 511.8 km of the Warta river) and below the dam in Uniejów (at 468.8 km of the Warta river). According to the JCWP, the Warta River is assigned to type 19, i.e. a sandy-clay lowland river. The R software was used for statistical computing. The statistical test was applied to assess the average differences in water quality indicators (pH, temperature, BOD_5, TOC, N_{tot}, P_{tot}) between the sampling point in Biskupice and the sampling point Uniejów through comparing the value of each indicator in individual months of the year. The Shapiro-Wilk test was used to examine normal distribution of samples in the first stage. In order to identify significant differences in water quality between the sampling point located in Biskupice and the sampling point Uniejów, the paired t-test was used for samples with normal distribution, and the Wilcoxon test for tied pairs – for distribution other than normal, at a substantial level of significance $p < 0.05$.

3. Results and discussion

A classic approach to qualitative analyses of reservoir waters requires a balance of direct inflows (from direct and indirect catchment areas) and outflows of pollution loads, particularly of biogenic nature (eutrophic – Galicka et al. 2007, Kanclerz 2011). However, for indicators with a statistically significant difference found between the sampling points, there was no data on loads introduced to the reservoir from the direct catchment: from point, spatial and scattered sources. Due to the fact that statistically significant differences occurred mainly for 2014 data, it seems that they had no decisive impact. In the analyses examining biogens, these sources accounted for up to 10% of the loads flowing into the Jeziorsko reservoir (Galicka et al. 2007).

The value of BOD_5 in the months in 2006 in Biskupice was on average 1.7 mg $O_2 \cdot dm^{-3}$, and Uniejów -2.2 mg $O_2 \cdot dm^{-3}$. In 2014, the average value was 2.15 mg $O_2 \cdot dm^{-3}$ in Biskupice and 2.81 mg $O_2 \cdot dm^{-3}$ in Uniejów (Fig. 2). The values of BOD_5 in Miłkowice in 2008 were between 1.26 and 5.26 mg $O_2 \cdot dm^{-3}$.

The results of statistical analysis showed that the average differences in BOD_5 between the sampling point in Biskupice and the sampling point located below the main dam (Uniejów) in 2006, 2011 and 2014 were -0.50, -0.32 and -0.66 mg $O_2 \cdot dm^{-3}$, respectively. The analysis of data indicated that BOD_5 samples taken in Biskupice and Uniejów in 2006 and 2011 showed normal distribution (the Wilcoxon test, $p > 0,05$). The results of the t-par test showed that there was no statistically significant difference at the level of significance $p < 0.05$ in 2006 and 2011, while in 2014 a statistically significant difference was observed between the samples taken in Biskupice and Uniejów.

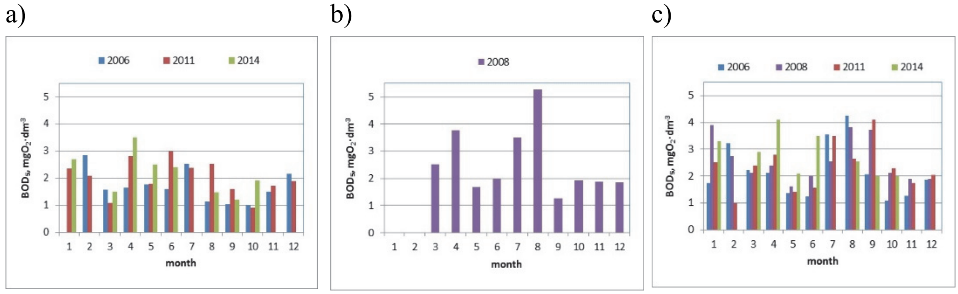

Fig. 2. Changes in the value of BOD_5 a) in Biskupice, b) in Miłkowice c) in Uniejów (below the main dam)

The results presented in Fig. 3 showed that in Biskupice the values of the analysed indicator were higher than in Uniejów. The values of pH in Miłkowice in 2008 were between 7.8 and 8.7.

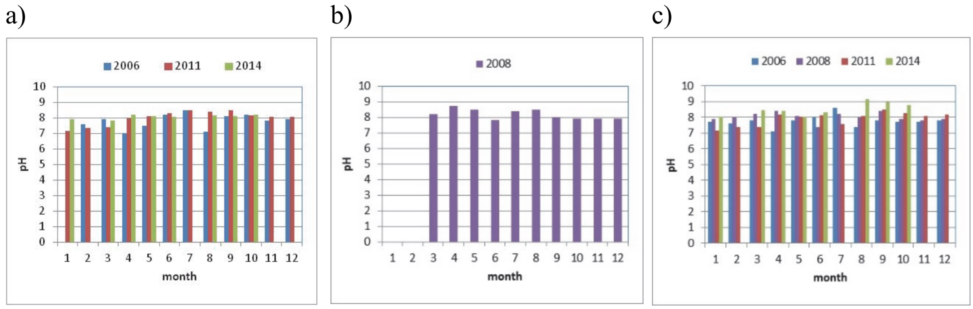

Fig. 3. Changes in the value of pH a) in Biskupice, b) in Miłkowice c) in Uniejów

Comparing the values of average water temperatures in 2006, 2011 and 2014, it was found that differences in temperature between the sampling points were -0.4°C, -0.5°C and 1.2°C, respectively.

When analysing Fig. 4, it can be stated that in most months the temperature was higher below the main dam than at the sampling point in Biskupice. The statistical analyses performed showed that the difference in temperature was not statistically significant in 2006 and 2011, and the paired t-test demonstrated that the difference in temperature in 2014 was statistically significant at the level of significance $p < 0.05$.

The average value of TOC in Biskupice in 2006, 2011 and 2014 was 5.68 $mg{\cdot}dm^{-3}$, 7.29 $mg{\cdot}dm^{-3}$ and 6.91 $mg{\cdot}dm^{-3}$, respectively, and at the sampling point Uniejów -6.26 $mg{\cdot}dm^{-3}$, 8.53 $mg{\cdot}dm^{-3}$ and 7.27 $mg{\cdot}dm^{-3}$ (Fig. 5). The statistical analysis for 2006 was carried out using the Wilcoxon test for samples with abnormal distribution. Average differences between the sampling points located above and below the main dam were in 2006, 2011 and 2014 -0.58 mg·dm^{-3}, -1.25 mg·dm^{-3} and -0.35 mg·dm^{-3}, respectively. This indicates that the values of TOC were higher in Uniejów than in Biskupice. Based on statistical computing, no significant difference was found between the values of sampling points at the level of significance $p < 0.05$. The values of TOC in Miłkowice in 2008 were highly differentiated – between 3.4 and 20.6 mg·dm^{-3}.

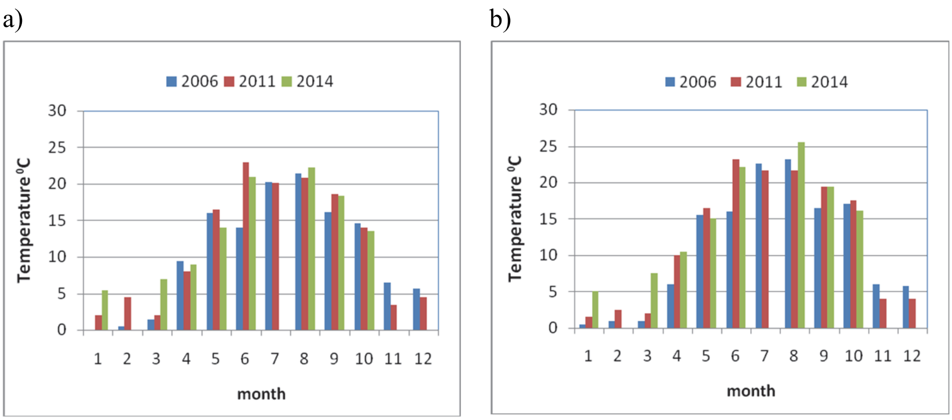

Fig. 4. Changes in the value of water temperature a) in Biskupice, b) in Uniejów

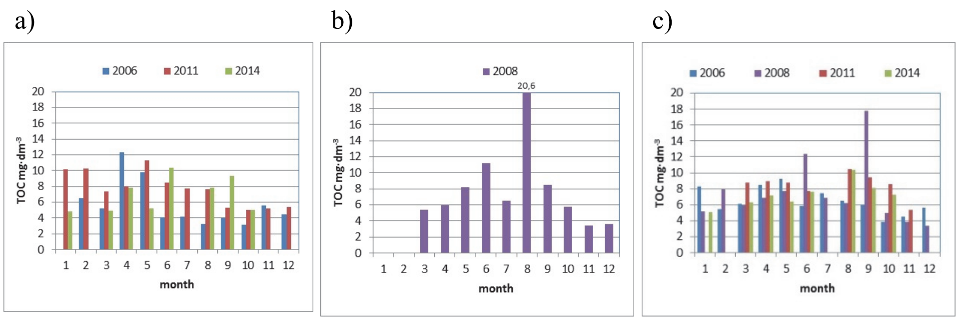

Fig. 5. Changes in the value of TOC a) in Biskupice, b) in Miłkowice, c) in Uniejów

Differences in average values between total phosphorus concentrations in 2006, 2011 and 2014 were -0.017 mg·dm^{-3}, 0.015 mg·dm^{-3} and 0.03 mg·dm^{-3}, respectively (Fig. 6). The difference in average values for total phosphorus between the sampling point in Biskupice and the sampling point located in Uniejów was not statistically significant at the level of significance $p < 0.05$ in individual years of the study. The values of P_{tot} in Miłkowice in 2008 were between 0.05 and 0.19 mg·dm^{-3}.

The results of statistical analysis for total nitrogen in 2006, 2011 and 2014 showed that differences in average values between the sampling point in Biskupice and the sampling point located in Uniejów were 2.97, 0.27 and 0.8 mg·dm^{-3}, respectively (Fig. 7). The values of N_{tot} in Miłkowice in 2008 were higly changeable – between 0.85 and 4.48 mg·dm^{-3}.

a) b) c)

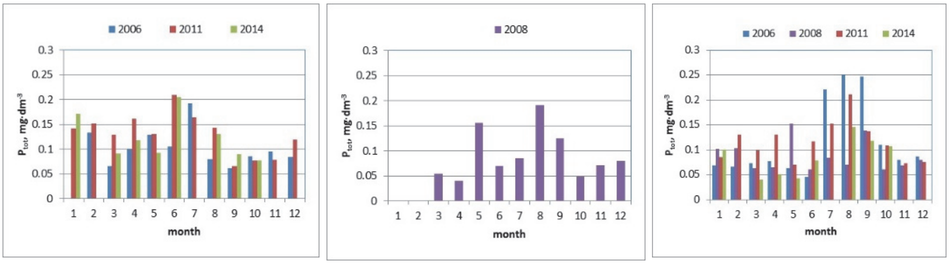

Fig. 6. Changes in the value of P_{tot} a) in Biskupice, b) in Miłkowice, c) in Uniejów

a) b) c)

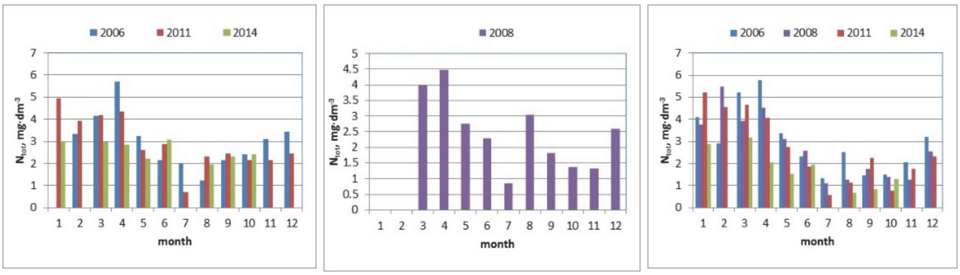

Fig. 7. Changes in the value of N_{tot} a) in Biskupice, b) in Miłkowice, c) in Uniejów

The results of statistical analysis showed that there was no statistically significant difference in the average index of total nitrogen between the sampling point in Biskupice and the sampling point below the main dam (Uniejów) in 2011 ($p > 0.05$).

The average content of N_{tot} in 2006, 2008, 2011 and 2014 in samples taken from the sampling point in Uniejów was 2.88 mg·dm^{-3}, 2.35 mg·dm^{-3}, 2.66 mg·dm^{-3} and 1.80 mg·dm^{-3}, respectively, and in samples taken in Biskupice in those years -3.00 mg·dm^{-3}, 2.45 mg·dm^{-3}, 2.93 mg·dm^{-3}, respectively.

The result of average differences in the analysis of water quality in 2006, 2011 and 2014 between the sampling point in Biskupice and the sampling point located in Uniejów showed that the concentration of N_{tot} in all years was higher in Biskupice than at the point located in Uniejów. The decrease between Biskupice and Uniejów could result from nitrogen utilisation by live biomass in the reservoir. The values of following indicators: temperature, BOD_5, TOC in all analysed years were higher in Uniejów than in Biskupicewas higher in Biskupice and lower in Uniejów, while in 2014 it was the opposite. The variability analysis of P_{tot} indicator showed that in 2006 it was higher below the dam, and in 2011 and 2014 it took higher values at the sampling point located in Biskupice. The differentiated P_{tot} concentrations at Biskupice and Uniejów sampling taken points and its opposite trends (comparing 2006 and 2011/2014 years) was the result of phosphorus compounds release or absorption by bottom sediments at changeable oxic/anoxic conditions (Lee et al. 2019).

For most indicators, slightly higher average values were found below the dam (Uniejów) compared to the sampling point above the dam in Biskupice. In the analysed years, the average N_{tot} index was higher above the dam. In most cases the difference was very small.

Among a few indicators analyzed for Miłkowice and Uniejów sample taken point only TSS and N_{tot} showed some decrease (TSS) or increase (N_{tot}). Very little decrease was observed in case of TOC. Although none of these differences was statistically significant (95% confidence interval for matched pairs data).

Table 1. The average value of differences and statistical significance of the analysed water quality indicators between Biskupice and Uniejów in 2006, 2011, 2014, Miłkowice and Uniejów in 2008

Indicator	2006		2008		2011		2014	
	Average differences	p	Average differences	p	Average differences	p	Average differences	p
Temperatura (°C)	-0.40	0.46	–	–	-0.53	0.20*	-1.29	0.02
BOD_5 (mg $O_2 \cdot dm^{-3}$)	-0.50	0.13	-0.15	0.47	-0.32	0.33	-0.66	0.02
TOC ($mg \cdot dm^{-3}$)	-0.58	0.32*	-0.32	0.56	-1.25	0.16	-0.39	0.57
N_{tot} ($mg \cdot dm^{-3}$)	2.97	<0.01	-0.10	0.62	0.27	0.17	0.80	0.01
P_{tot} ($mg \cdot dm^{-3}$)	-0.02	0.89*	-0.01	0.81	0.02	0.30	0.04	0.11

* Wilcoxon test for tied pairs – for distribution other than normal
(-)values below the dam (Uniejów) higher than for the point in Biskupice

The analysis of these determinations has shown that they are sufficient for assessing the status of water, also in terms of its eutrophication, however, they do not provide too many opportunities to analyse processes, phenomena, trends and variations, particularly their causes.

Additionally, the quality of water flowing out of the reservoir is affected by the frequency and time of discharges and their method from hydroelectric power plant or overflow.

In 2006, the largest water inflows to the reservoir occurred in the second half of February and from the third decade of March to mid-May. In contrast, water outflows larger than the designed water flow rate of the power plant were observed from early April to mid-May, counting for 51 days. The average daily water retention time in the reservoir in 2006 was 26 days (minimum 8 and maximum 85 days). The longest average daily retention time was recorded from the beginning of June to the end of the first decade of September.

The largest water inflows and outflows from the Jeziorsko reservoir in 2011 occurred from the beginning of January to the beginning of April. Water outflows larger than the designed water flow rate of the power plant lasted for 63 days from the beginning of the year. The average annual inflow and outflow of water from the reservoir were 55.5 $m^3 \cdot s^{-1}$ and 58 $m^3 \cdot s^{-1}$, respectively. In 2011, the average daily water retention time in the reservoir was 28 days. Retention times ranged from 8 to 65 days, and the longest times were observed from the end of March to mid-July and from mid-August to the end of the first decade of September.

Water inflows to the Jeziorsko reservoir in 2014 were more compensated than in 2006 and 2011, because the maximum values in these years were 212 $m^3 \cdot s^{-1}$ and 226 $m^3 \cdot s^{-1}$, respectively, while in 2014 it was only 70 $m^3 \cdot s^{-1}$. Water outflows larger than the designed water flow rate of turbines lasted a total of 16 days. These outflows occurred in May (7 days) and December (7 days), and the remaining two days – in other months of this analysed year. The average annual inflow and outflow of water was 40 $m^3 \cdot s^{-1}$. During 2014, the average daily water retention time in the Jeziorsko reservoir was 32 days (minimum 7 and maximum 73 days). The longest retention times were recorded from mid-March to mid-May and from mid-June to mid-September.

The actual water retention time in reservoirs is sometimes much longer or shorter than the interval between sampling times, which can make interpretation of the results difficult (if the substance concentration has changed over time, then the dilution or concentration will increase due to the retention time). When the concentration of a substance in the inflow increases for a moment, and in the absence of its decomposition, there is a simple relationship of "delay" between the peak and the actual retention time. However, such situations, independent of other factors, are quite rare in practice. It is also important to remember, what has already been mentioned, that constant concentration does not necessarily mean that there is no change in a particular substance, since it can be the result of balancing its increase and decomposition rates.

Due to numerous factors and determinants, as well as the lack of data continuity, it is challenging and fallible to interpret the state of water quality in reservoirs in the context of their impact on the quality of watercourses (rivers). This difficulty is related to i.e. the actual water retention time in the reservoir (problematic to determine), lack of data on the periods between measurements (periods of occurrence of specific concentrations of pollutants and nutrients, associated with the introduced load). Yang et al. (2012) stated the degradation of water quality associated with excess levels of nitrogen and phosphorus impacted by interactions among agriculture and urban factors. For the interpretation of water quality, it is also important to know the local flow rates that have a decisive effect on the sedimentation rate of suspensions. In the context of suspensions, it is equally necessary to have a methodology to determine them, particularly the minimum particle size. Additionally, for suspensions, but also for compounds accumulated in sediments and debris, sediment thickness and flow velocity in their immediate vicinity may be of key importance.

4. Conclusions

Despite certain dependencies or trends in particular cases, few measurements and their high variability do not allow for drawing cause and effect conclusions. A larger number of measurements would definitely help demonstrate the statistical significance of differences. The analysed data, despite pointing to a certain "tendency" for the majority of pollution indicators (water quality) do not confirm these relationships due to significant variations in the values of indicators. Most indicators were characterised with the significance of differences for the study carried out in 2014. It is known that often in such situations more data is required to demonstrate statistical significance. Compilation of data in an appropriate range and a sufficient amount, at least in some cases, may allow for estimating the actual retention time in the reservoir without using data related to the work of individual elements of the water barrage. The following conclusions can be drawn based on this study:

1. The study did not show a statistically significant difference between the average differences in parameters between the sampling point in Biskupice and the sampling point below the dam in 2006 and 2011 (in the 95% confidence interval).

2. However, a statistically significant difference was found in the average values for most parameters measured in 2014, except for TOC and P_{tot} (in the 95% confidence interval).
3. Among a few indicators analyzed for Miłkowice and Uniejów sample taken point only TSS and N_{tot} showed some decrease or increase, however none of these differences was statistically significant.
4. Routine tests of surface water quality are difficult to analyse in terms of the impact of the dam reservoir on the quality of river waters.

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Rozporządzenie Ministra Środowiska z dnia 21 lipca 2016 r. w sprawie sposobu klasyfikacji stanu jednolitych części wód powierzchniowych oraz środowiskowych norm jakości dla substancji priorytetowych (Dz. U. poz. 1187)

Rozporządzenie Ministra Gospodarki Morskiej i Żeglugi Śródlądowej z dnia 12 lipca 2019 r. w sprawie substancji szczególnie szkodliwych dla środowiska wodnego oraz warunków, jakie należy spełnić przy wprowadzaniu do wód lub do ziemi ścieków, a także przy odprowadzaniu wód opadowych lub roztopowych do wód lub do urządzeń wodnych (Dz. U. poz. 1311)

Abstract

Many factors affect the quality of water in rivers, including: types of pollution sources, the shape of the catchment, the type of land use, the amount of pollution flowing in. The construction of a retention reservoir is one of the factors affecting changes in the river valley related to the landscape, the environment, and water flow hydraulics. Reducing the velocity of water flow on the section of the reservoir causes changes in the characteristics of the movement of pollutants, some of them are deposited in the reservoir. The article analyzes water quality parameters at intake points located below (Uniejów) and above (Biskupice) of the Jeziorsko dam on the Warta River. The variability of such parameters as BOD_5, TOC, pH, temperature, N_{tot}, P_{tot} was analyzed. The research also analyzed the dynamics of water inflow and outflow from the reservoir. The actual water retention time in the reservoir, which makes interpretation of the results difficult. The most indicators were characterized by the significance of differences for research in 2014.

Keywords:
water quality, reservoir, Warta river, pollutant, nutrient

Zmiany wybranych wskaźników jakości wody rzeki Warty pod wpływem zbiornika zaporowego Jeziorsko

Streszczenie

Na jakość wody w rzekach wpływa wiele czynników do których należą: rodzaje źródeł zanieczyszczeń, ukształtowanie zlewni, rodzaj użytkowania terenu, ilość dopływających zanieczyszczeń. Budowa zbiornika retencyjnego jest jednym z czynników wpływających na zmiany w dolinie rzecznej związane z krajobrazem, środowiskiem, hydrauliką przepływu wody. Zmniejszenie prędkości przepływu wody na odcinku zbiornika powoduje zmiany w charakterystyce przemieszczania się zanieczyszczeń, część z nich osadza się w zbiorniku. W artykule przeanalizowano parametry jakości wody w punktach poboru zlokalizowanych poniżej (Uniejów) i powyżej (Biskupice) zapory zbiornika Jeziorsko na rzece Warcie. Analizie poddano zmienność takich parametrów jak BZT_5, OWO, pH, temperatura, N_{og}, F_{og}. W badaniach przeanalizowano również dynamikę dopływu i odpływu wody ze zbiornika. Rzeczywisty czas retencji wody w zbiorniku jest różny co utrudnia interpretację wyników. Najwięcej wskaźników charakteryzowało się istotnością różnic dla badań w 2014 roku.

Słowa kluczowe:
jakość wody, zbiornik retencyjny, rzeka Warta, zanieczyszczenie, biogen

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Impact of Road Transport on Air Pollution in EU Countries

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1. Introduction

As a result of transport activities, external effects are created. They can be defined as the various effects of transport processes, the recipients of which are third parties not involved in these transports (Verhoef 1994, Celbis et al. 2014). External effects are the result of imperfections in the market mechanism and lead to discrepancies between private costs and benefits arising from a given business or other activity and social costs and benefits (Fiedor 2002, Rokicki 2016, 2017, Vlahinić Lenz et al. 2018). Transport can have a positive and negative impact on the environment (Dodgson 1973, Rothengatter 1994). The positive impact of transport in historical terms was manifested in the technological and economic development of the world (Gwilliam & Geerlings 1994, Del Bo & Florio 2012, Yu et al. 2013, Jiang et al. 2016). In turn, negative externalities were noticed later (Button 1994).

Nowadays, attention is paid to limiting the unfavorable aspects of transport functioning, such as accidents, environmental pollution, noise, congestion, destruction of nature and landscape (Himanen et al. 2005). The aspect of counteracting the adverse effects of human activity has been particularly important since the beginning of the 21st century. People want to live in a friendly environment and reduce negative externalities (Stetjuha 2017).

Transport is an activity that is usually closely related to economic parameters (Hu & Liu 2010, Alvarez et al. 2016). However, the level of socio-economic development of individual countries may determine the scale of negative externalities of transport. The use of modern vehicles with lower emissions, lower noise levels as well as better road infrastructure contribute to reducing the external effects of transport (Konečný et al. 2016, Mostert & Limbourg 2016). Road transport dominated in most EU countries. It was also a mode of transport generating the most negative externalities (Mostert et al. 2017).

2. Literature review

Air pollutants can be classified as primary or secondary. Road transport mainly emits primary pollution, i.e. going directly to the atmosphere. The main primary air pollutants include particulate matter (PM), black carbon (BC), sulfur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_3), carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOC). The most important secondary air pollutants are PM, ozone (O_3) and nitrogen dioxide (NO_2) formed in the atmosphere (Peters & Jouvanis 1979, Builtjes & Paine 2003, Daly & Zannetti 2007, Al-Dhurafi et al. 2018, Sówka et al. 2020, Kamińska & Turek 2020).

Total emission of pollutants in the European Union in the years 2000-2017 decreased in relation to the concentration of PM, O_3 and NO_2 in the air, as well as arsenic (As), cadmium (Cd), nickel (Ni), lead (Pb), mercury (Hg). The largest reduction was achieved for SO_x (by 77%), and for NH_3 (9%) (EEA 2019a). Road transport is a major sector contributing to emissions of air pollutants in Europe. The research is based on transport work performed during the transport of people and goods, using cars, motorbikes, buses and coaches (EEA 2018, European Commission 2018). In 2017, road transport in the EU accounted for 39% of emission of NO_x, 18% BC, 19% NH_3, 11% of $PM_{2.5}$ and PM_{10} particles (EEA 2019b, 2019c).

In the road transport sector, emissions of key pollutants (e.g. NO_x) have decreased significantly, despite a gradual increase in the volume of passengers and freight transported. The reason was the initiation of actions at EU level to counteract air pollution from transport, which at the same time enabled the development of the transport sector. An example is regulating emissions by setting emission standards (e.g. Euro 1-6) or setting fuel quality requirements (Dore et al. 2003, Fameli & Assimakopoulos 2015, Dzikuc et al. 2017, Grange et al. 2017, Dzikuc & Dzikuc 2018).

In the years 2000-2017 emissions of air pollutants showed a significant separation from economic activity measured by the value of GDP, which was desirable due to environmental protection and increased productivity. Every euro of GDP generated was associated with ever lower emissions of air pollutants in subsequent years. Success in this area was the result of increased policy regulation and implementation, fuel type swapping, technology improvements and process efficiency, and increased consumption of goods produced in industries outside the EU (Brand 2016, Crippa et al. 2016, Guevara 2016, Rokicki et al. 2018, EEA 2019a, Koszela et al., 2019). EU countries were diverse across the EU in terms of GDP volume, specialization of production, socio-economic characteristics and innovation (Chapman & Meliciani 2017). According to the Kuznets environmental curve, economic development causes an increase in environmental pollution up to a certain point. Later, this impact decreases with economic development, as environmental pressure rises faster than income at early stages of the country's development and slows down relative to GDP growth at higher income levels (Stern et al. 1996, Ansuategi et al. 1998, Andreoni & Levinson 2001) . The dependence presented has been confirmed by the example of economically developed countries (e.g. Apergis & Ozturk 2015, Jebli et al. 2016, Lau et al. 2018), but not fully confirmed in developing countries (e.g. Al-Mulali et al. 2015, Dasgupta et al. 2002, Harbaugh et al. 2002, Cole 2003, Dinda 2004). In developing countries, environmental protection depends on economic liberalization, legal regulations and the use of low-carbon technologies. Developing countries often follow the example of developed countries, adopting their environmental solutions with a short delay (Stern 2004).

Many studies have found a significant relationship between transport infrastructure and economic growth. At the same time, more extensive road infrastructure and urbanization contribute to greater emissions of pollutants into the environment. The level of economic development of the country is also of great importance in this aspect (Achour & Belloumi 2016, Saidi & Hammami 2017, Baloch 2018, Gherghina et al. 2018).

3. Aim, materials and methods

The main purpose of the work is to show the level of air pollution emitted by road transport and its relationship with economic development and transport infrastructure in European Union countries. The specific objectives are: to present the diversity of pollutant emissions from road transport in countries, to show the dynamics of changes in this area, to determine the relationships and regularities between the level of economic development, road infrastructure equipment and air pollution emissions in EU countries. The paper presents a hypothesis according to which in the EU countries in 2006-2017, the regularities between the level of economic development and the emission of pollutants from road transport were confirmed in accordance with the Kuznets environmental curve. All EU Member States were selected for research as of December 31, 2017 (28 countries). The research period concerned the years 2006-2017. The sources of materials were EUROSTAT data, literature on the subject. In the paper, one of the methods of multidimensional data analysis was used to build a ranking of EU countries in terms of emissions of harmful substances into the air. As part of this method, a synthetic indicator constructed based on normalized variables by the method of zeroed unitarisation was used. The determination of this indicator allowed the creation of an appropriate ranking and was the basis for the division of facilities (in this case EU countries) into classes (Kukuła 2014).

The following 14 diagnostic variables treated as stimulants were taken into account in the study (average for the years 2014-2017 for 28 countries):
X_1 – length of roads in km per km^2 of the country,
X_2 – number of vehicles in units per population,
X_3 – NH_3 emissions in tons per road length in km,
X_4 – NH_3 emissions in tons per number of vehicles,
X_5 – NMVOC emissions in tons per road length in km,
X_6 – NMVOC emissions in tons per number of vehicles,
X_7 – $PM_{2.5}$ emissions in tons per road length in km,
X_8 – $PM_{2.5}$ emission in tons per number of vehicles,
X_9 – PM_{10} emission in tons per road length in km,
X_{10} – PM_{10} emission in tons per number of vehicles,
X_{11} – SO emission in tons per road length in km,
X_{12} – SO emission in tons per number of vehicles,
X_{13} – NO emission in tons per road length in km,
X_{14} – NO emission in tons per number of vehicles.

These variables were normalized by the method of zeroed unitarisation. This normalization of variables is very often used in multidimensional data analysis. A detailed description of this method can be found eg. in the paper of K. Kukuła (Kukuła 2014). It's unquestionable advantage is that the normalized variables always take values from the interval [0, 1] and the ranges of variability always have the same width. Then a synthetic index Q was created, being the arithmetic mean of normalized variables. Based on the size of this indicator, a ranking was created of countries that least or poison the environment through road transport, and a division of these countries into 3 groups was made using the parameter k. It was decided to use the parameters k, because this method shows the natural division of variability– in this case, the synthetic variable Q. So taking into account the number of objects and the convenient interpretation of the obtained results, it was set to create 3 groups. Therefore, the range of the Q index in determining the k parameter was divided into 3 according to the formula:

$$k = \frac{R(Q)}{3} \qquad \text{where R(Q) is a range} \tag{1}$$

$$Q_i \in [\max_i Q_i - k, \max_i Q_i] \text{ – Group 1}$$

$$Q_i \in \left[\max_i Q_i - 2k, \max_i Q_i - k\right] \text{ – Group 2}$$

$$Q_i \in [\max_i Q_i - 3k, \max_i Q_i - 2k] \text{ – Group 3}$$

4. Research results

The emission of harmful compounds into the atmosphere and the diversity of its level in the EU countries is associated with various aspects of transport – the number of transporting cars, but also length and quality of roads used by vehicles. Figures 1 and 2 graphically illustrate the average annual rate of change in pollutant emissions (of four compounds: NMVOC, NH_3, $PM_{2.5}$ and PM_{10}) for road transport in the years 2006-2017.

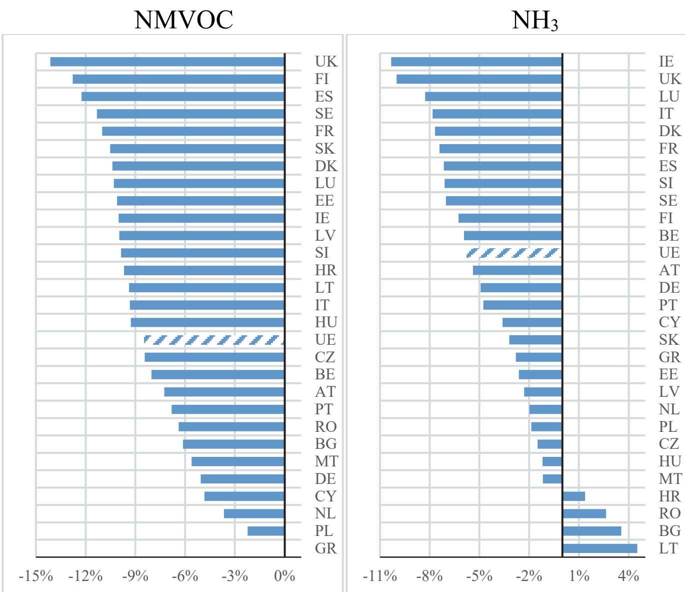

Fig. 1. The average annual rate of change in NMVOC and NH_3 emissions in the European Union countries in the years 2006-2017. Source: author's elaboration based upon EUROSTAT

The average for the entire European Union is marked with a striped bar, the countries with the highest emission reductions of these substances are at the top of the chart, while at the bottom are the countries that have reduced the emission the least or even increased it. For example: the largest NMVOC emitters in the European Union in 2017 were Italy (19.5%), Germany (16.40%), Poland (14.97%) and the rest countries (49.07%), the lowest emissions were recorded in Malta, Luxembourg and Estonia (EUROSTAT). The emission of NMVOC is reduced the fastest by United Kingdom and the Scandinavian countries and Northern Europe (Finland, Estonia, Sweden), while in Poland the pace of change is the slowest (the zero value for NMVOC in Greece is probably due to the lack of data in the Eurostat report). The largest NH_3 emitters in Europe in 2017 were Germany (22.36%), Italy (10.59%), United Kingdom (9.42%), Poland (9.08%), Netherlands (7.96%) (EUROSTAT), although EU directives force EU countries to reduce emissions. Ireland, the United Kingdom and Luxembourg are the countries that lower NH_3 emissions the fastest, while Lithuania, Bulgaria, Romania and Croatia have increased them in the long term. The high average growth rate of NH_3 emissions in Lithuania is caused by a very high relative increase in emissions in 2011 compared to 2010 (91.53%), which influenced the overall assessment of the rate of change in emissions for the whole 12 years, but Lithuania is one of the countries with the lowest emission of this compound.

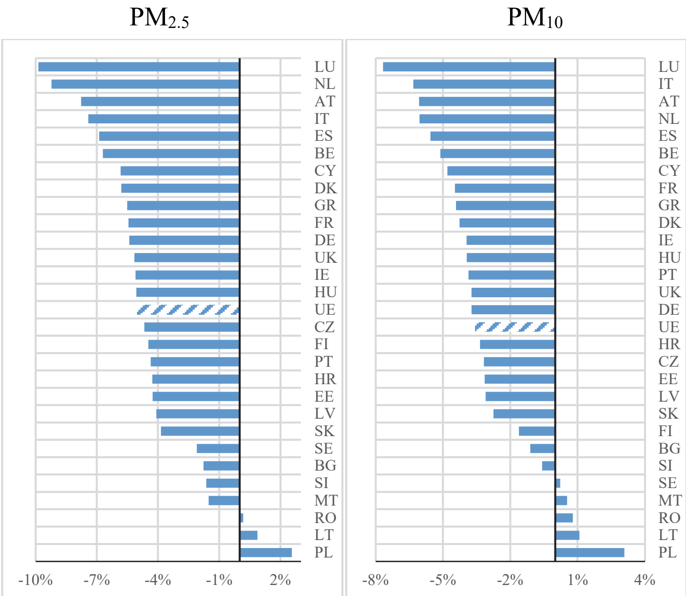

Fig. 2. The average annual rate of change in $PM_{2.5}$ and PM_{10} emissions in European Union countries in 2006-2017. Source: author's elaboration based upon EUROSTAT

The largest emitters of $PM_{2.5}$ in 2017 are: France (17.16%), Germany (13.04%), Italy (11.44%), Poland (10.51%), while of PM_{10} France (13.48%), Germany (12.27%), Italy (9.40%), United Kingdom (8.93%), Poland (8.25%) (EUROSTAT). The average annual increase in dust emissions of $PM_{2.5}$ and PM_{10} type for Poland, Lithuania and Romania is noteworthy, while in the remaining "28" countries a rather downward trend can be observed. In the case of PM_{10} emissions, the average growth rate still applies to Malta and Sweden, but these countries have some of the lowest levels of dust emissions across the Union.

Other pollutants from transport are sulfur oxides and nitrogen oxides for which the highest emissions are recorded by the United Kingdom (21.67%), France (14.20%), Germany (14.12%), Poland (9.18%) – sulfur oxide and the same countries were leaders in nitrogen oxides emissions – gaining total together 63.06% (EUROSTAT). These infamous statements show that Poland is one of the largest transport "polluters" of the environment, and in terms of the rate of change in emissions of both oxides, it is on the last place in the ranking (Fig. 3).

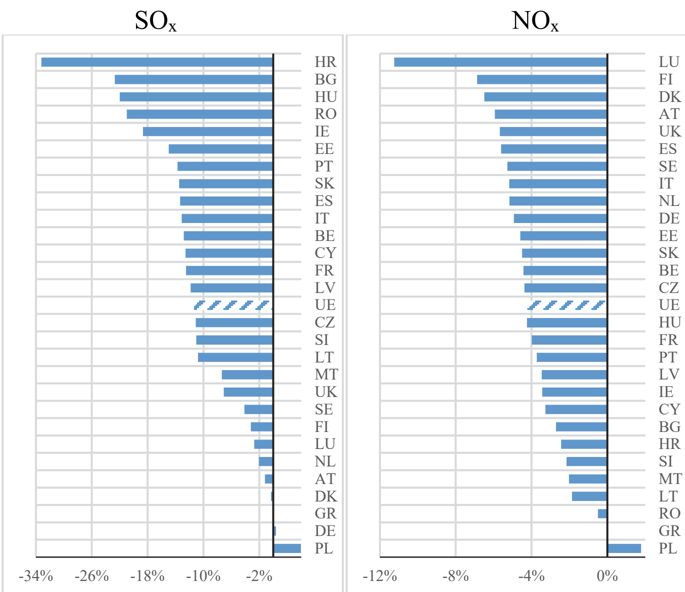

Fig. 3. The average annual rate of changes in sulfur and nitrogen oxides emissions in the European Union in the years 2006-2017. Source: author's elaboration based upon EUROSTAT

The development of road infrastructure and increasing number of vehicles adversely affect the emission of harmful substances. Table 1 summarizes the correlation coefficients for the data from three 4-year time subperiods of the 12-year period studied. The data for which the correlation coefficients were calculated are arithmetic averages for 28 EU countries from 4 years for each of the subperiods. Their high values (from 0.47 to even 0.96-0.98 in the case of $PM_{2.5}$ and PM_{10} and the number of cars and NO_x and the number of cars) confirm this relationship.

Table 1. Correlation coefficients between the average road length and the number of cars and the emission of air pollutants. Source: author's elaboration based upon EUROSTAT

	2014-2017		2010-2013		2006-2009	
	AVH	*LOR*	*AVH*	*LOR*	*AVH*	*LOR*
NH_3	0.90	0.47	0.92	0.52	0.94	0.55
NMLZO	0.89	0.53	0.90	0.60	0.92	0.66
$PM_{2.5}$	0.96	0.83	0.96	0.84	0.96	0.80
PM_{10}	0.94	0.79	0.95	0.82	0.96	0.79
SO_x	0.88	0.71	0.81	0.66	0.59	0.63
NO_x	0.98	0.77	0.98	0.77	0.98	0.75

Legend: LOR – Lenght of the roads – mean value, AVH – All vehicles (except trailers and motorcycles) – the mean value

Figure 4 presents the average rate of change of gross domestic product over the 12 years studied. A certain relationship can be observed here between the average GDP growth rate and the growth rate of pollutant emissions for relatively new EU members such as Poland, Lithuania, Romania and Bulgaria. This conclusion is confirmed by the analysis of the relationship between the average rate of change in consumer spending per capita and the rate of emission of harmful substances – the results are very similar. This correlation lies in the fact that the high growth rate of these two economic indicators is accompanied by a higher growth rate of pollutant emissions.

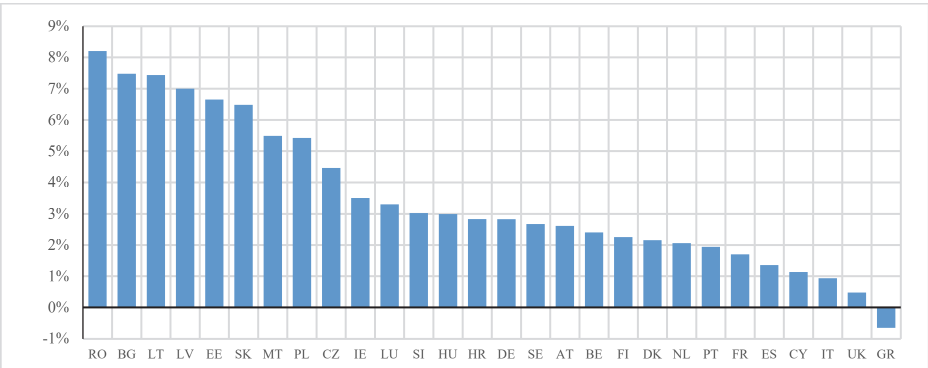

Fig. 4. The average rate of change of Gross Domestic Product in the European Union in the years 2006-2017. Source: author's elaboration based upon EUROSTAT

In this case, it should be noted that the high position of Ireland is largely the result of a large increase in GDP in 2015 compared to 2014. This anomaly was caused by a large injection of foreign capital, which positively affected Ireland's GDP.

Figures 5 and 6 show the relationship between average GDP and average consumption expenditure and the average annual rate of change in emissions of harmful substances into the air in the period 2006-2017. The drawings illustrate the hypothesis of an increase in emissions of transport-related pollution along with the increasing rate of growth of economic development indicators such as GDP or FCE. The graphs in Figures 4 and 5 also clearly show that the increase in emissions depends on the level of economic development. It is easy to notice that countries with a high level of GDP or FCE were characterized by declines in emissions of harmful substances, in contrast to countries that are at a much lower economic level. The bend representing the average rate of change in emissions of harmful substances maintains a clear upward trend along with the decreasing GDP or FCE level, which confirms compliance with Kuznets's environmental theory. The results are somewhat disturbing for NMVOC emissions Greece due to the lack of data on emissions of this dust.

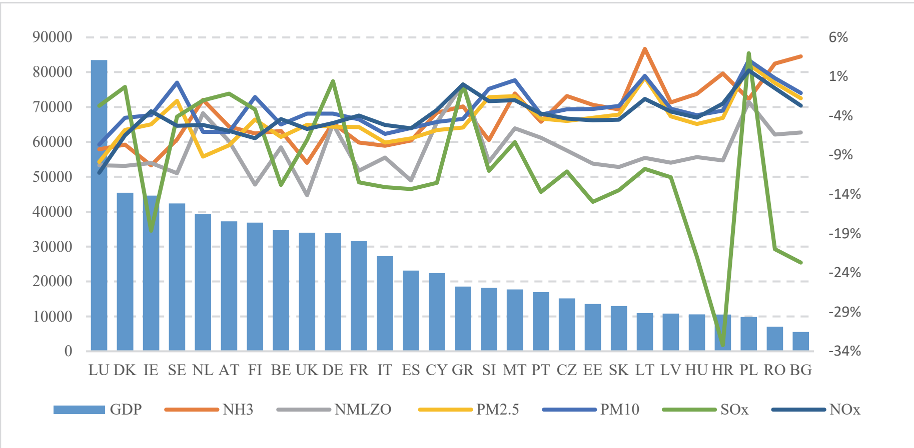

Fig. 5. The average rate of change in Gross Domestic Product and the average annual rate of change in emissions of selected pollutants in the European Union in 2006-2017. Source: author's elaboration based upon EUROSTAT

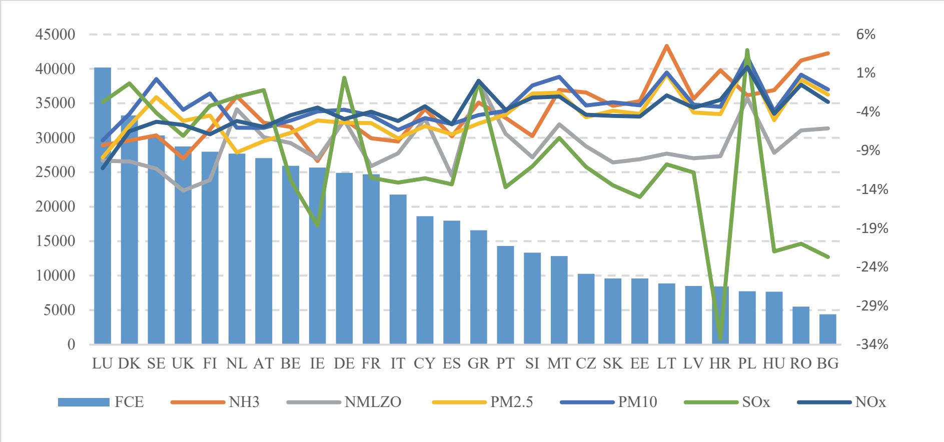

Fig. 6. The average rate of change in consumer spending and the average annual rate of change in emissions of selected pollutants in the European Union in the years 2006-2017. Source: author's elaboration based upon EUROSTAT

One of the aims of the paper was to rank the EU countries in such a way that the emission values of harmful substances from transport were calculated in proportion to the quality of road infrastructure, the area of the country and the number of cars. Table 2 shows the ranking obtained by means of multidimensional data analysis methods, the values of the syn-thetic variable Q and the groups formed.

Table 2. Ranking and grouping of EU countries in terms of the amount of pollutant emissions from transport. Source: author's elaboration based upon EUROSTAT

	2006-2009		2014-2017				2006-2009		2014-2017		
Country	Q	R1	Q	R2	Gr	Country	Q	R1	Q	R2	Gr
GR	0.1056	1	0.1524	1	1	IE	0.2443	20	0.2626	15	1
UK	0.1838	9	0.1581	2	1	DK	0.2462	21	0.2702	16	1
ES	0.1907	13	0.1607	3	1	IT	0.2602	25	0.2908	17	1
SK	0.1882	12	0.1786	4	1	FI	0.2476	22	0.2929	18	1
EE	0.1609	5	0.1794	5	1	HR	0.3630	26	0.2954	19	1
FR	0.1733	8	0.1829	6	1	LT	0.1578	3	0.3013	20	1
CZ	0.1719	7	0.1944	7	1	NL	0.2138	16	0.3054	21	1
RO	0.1590	4	0.2067	8	1	DE	0.2267	17	0.3088	22	1
BE	0.1928	14	0.2092	9	1	SE	0.2527	23	0.3436	23	2
AT	0.1875	11	0.2142	10	1	CY	0.2591	24	0.3521	24	2
LV	0.1412	2	0.2305	11	1	MT	0.2394	18	0.3571	25	2
PL	0.1633	6	0.2467	12	1	BG	0.2427	19	0.3738	26	2
HU	0.1848	10	0.2494	13	1	LU	0.6806	28	0.5816	27	3
SI	0.2126	15	0.2592	14	1	PT	0.5396	27	0.6262	28	3

Table 2 contains the Q indicators and positions that individual countries occupied in the ranking created on the basis of data on diagnostic variables from 2006-2009. The higher the country is in the ranking, the lower the emissions of harmful substances per country, road length and number of cars. You can see the changes that have occurred in terms of the Q factor in the above two 4-year periods. For some countries, these values decreased, e.g. for United Kingdom, Spain, Italy, Denmark, and in some increased (e.g. Lithuania, Latvia, Poland, Bulgaria). The high position of Greece is unreliable in this case due to zero NMVOC emission values. Luxembourg's low position, in turn, does not contradict previous analyzes. The Q index significantly decreased, which means a significant improvement, but still its high value did not allow this country to take a higher place in the ranking, which was built based on relative data. It is a small country with a relatively high population density, dense, as for the area occupied, network of good quality roads and a great geographical location when it comes to the communication route in Western Europe, hence, in terms of the country's surface or road infrastructure, the emission of pollution placed this country in group 3, together with Portugal, with the worst emission parameters.

5. Conclusions

The paper aimed at analyzing emissions of harmful substances from transport that have an adverse effect on the environment in the European Union in the years 2006-2017. Reports and summaries in this regard provide the total annual value of emissions, while the paper attempts to look at the issue of emissions in a way that takes into account other factors related to transport. It is logical that a smaller and non-transit country (such as the island of Malta or Cyprus) will see lower emissions, and large-scale countries with well-developed road infrastructure are not able to have such low emission rates, despite attempts to reduce them. Taking into account the length of roads, the country's area and the number of cars, the dynamics of emission changes (i.e. its reduction in time), the countries can be divided into groups of the largest and smallest emitters, and the results more comprehensively reflect the reality. Thanks to the use of multidimensional data analysis methods and a multifaceted view, the results of calculations better reflect the capabilities of countries in reducing emissions of major harmful substances over the years and allow a different view on the problem of the state of pollution caused by the branch of economy which is transport. It turns out that this approach gives quite surprising results, which in no way undermine other considerations on the dynamics of changes in emitted harmful substances. The example of Luxembourg and its situation, where large emission of harmful substances in a small area is not only the result of a lack of pro-ecological actions on the part of the government, but geopolitical conditions. The ranking created in this way also presents Poland – the main emitter of the harmful substances under study in a more favorable light, although at the same time the country in the 12-year period fell by 6 positions. The ranking pointed to Portugal and Luxembourg as countries with relatively high emissions (group 3), countries with moderate emissions are Bulgaria, Malta, Cyprus and Sweden (group 2).

Analysis of data on the rate of changes in emissions and the volume of GDP in EU countries also indicates compliance with the Kuznets environmental curve – countries with lower economic levels have poorer indicators regarding environmental protection.

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Abstract

The main purpose of the work is to show the level of air pollution emitted by road transport and its relationship with economic development and transport infrastructure in European Union countries. The study presents the diversity in emissions of road transport by countries, shows the dynamics of changes in this area, determines the relationships between the level of economic development, equipping with road infrastructure and emissions of air pollution in EU countries. The research period concerned the years 2006-2017. The sources of data was EUROSTAT database. The ranking built by means of multidimensional data analysis tools indicated Portugal and Luxembourg as countries with relatively high emissions of air pollutants (group 3), countries with moderate emissions are Bulgaria, Malta, Cyprus and Sweden (group 2).

Analysis of data on the rate of change in emissions and the volume of GDP in EU countries also indicates compliance with the Kuznets environmental curve.

Keywords:
road transport, transport infrastructure, air pollution, EU, environmental Kuznets curve, multidimensional data analysis

Wpływ transportu drogowego na zanieczyszczenie powietrza w krajach UE

Streszczenie

Celem głównym pracy było porównanie poziomu zanieczyszczenia powietrza emitowanego przez transport drogowy i jego związku z rozwojem gospodarczym i infrastrukturą transportową w krajach Unii Europejskiej w latach 2006-2017. W pracy przedstawiono zróżnicowanie w emisji zanieczyszczeń przez transport drogowy w krajach UE, ukazano dynamikę zmian w tym zakresie, określono związki i między poziomem rozwoju gospodarczego, wyposażeniem w infrastrukturę drogową, a emisją zanieczyszczeń powietrza. Dane pochodziły z baz i raportów EUROSTAT. Zbudowany za pomocą metod wielowymiarowej analizy danych ranking szeregujący Państwa pod względem emisji związków do atmosfery pochodzących z transportu i uwzględniając infrastrukturę drogową oraz powierzchnię kraju, wskazał na Portugalię i Luksemburg jako kraje o stosunkowo dużej emisji (grupa 3), kraje o umiarkowanej emisji to Bułgaria, Malta, Cypr oraz Szwecja (grupa 2).

Analiza tempa zmian emisji zanieczyszczeń do powietrza oraz wielkości PKB w krajach Unii wskazuje także na zgodność ze środowiskową krzywą Kuznetsa.

Słowa kluczowe:
transport drogowy, infrastruktura transportowa, zanieczyszczenie powietrza, UE, środowiskowa krzywa Kuznetsa, wielowymiarowa analiza danych

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Utilization of Process Wastewater Heat

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1. Introduction

The requirements of sustainable development of the economy cause that in the energy policy of industrial plants more and more attention is paid to the possibility of heat recovery from various types of process waste, including industrial wastewater. This is mainly due to increasing costs of energy for production purposes, as well as for heating and ventilation of production halls. In the case of wastewater at elevated temperature, heat utilization makes it possible to achieve greater economic effect. For comparison, the temperature of municipal wastewater is within the range of 10-20ºC, whereas in the case of industrial wastewater it can be above 40ºC. It is worth noting that lowering the temperature by 1ºC makes it possible to obtain 1.16 kW of heat from 1 m^3/h of wastewater (Górski & Matuszewska 2013, Kosieradzki 2009, Noch et al. 2018). In some branches of industry it is possible to recover heat even up to 60% of the plant's heat balance (Wodołażski 2015).

In the case of industrial wastewater disposal to a biological treatment plant, heat recovery becomes a key and necessary element. The decrease of wastewater temperature accompanying recovery allows for more effective removal of colloidal and suspended matter from it, and thus - for further decrease of treatment costs at the treatment plant. In addition, industrial wastewater at elevated temperature can constitute a significant threat to the natural environment from an ecological point of view. Therefore, utilization of wastewater heat in industrial plants is not only economically but also ecologically justified, as it reduces its potentially negative impact on the environment.

In those places where wastewater is generated continuously and in large quantities, heat utilization is economically justified. On the market there are ready-made devices for heat utilization. The most commonly used are heat exchangers and heat pumps, which are used to recover heat from wastewater from various technological processes (Górski & Matuszewska 2013). However, it should be emphasized that wastewater as an energy source is a resource with limited thermal potential and variable characteristics. It depends on the process in which it came from and on the amount of water consumed. The variable physicochemical composition of wastewater and its unspecified quantity very often makes it difficult to use ready-made technical solutions available on the market.

2. Object, target and research methodology

The Homanit company was selected to be the object of research and the said company is located in the town of Karlino in the West Pomeranian Province of Poland. The plant produces thin, highly refined medium and high density fiberboards (MDF and HDF). Among many production cycles, a steam thermal treatment of wood cycle was selected, which produces around 8.3 m^3/h of wastewater per day at an average temperature of 80ºC. This wastewater contains a number of chemical pollutants. The main ones are sugars that occur in the form of disaccharides. These carbohydrates include mannose, arabinose, galactose, xylose and glucose, cellulose and hemicellulose. Organic acids, such as formic and acetic, are also present, and in trace amounts – propionic acid. In addition, there are contaminants from mechanical wood processing: sand and a fine fraction of wood fiber with average dimension of approx. 1 mm. The wastewater shows acidic reaction within the range of pH = 5.0-5.5.

Wastewater, due to its composition, tends to coagulate and stick to the pipeline walls. For this reason, as well as to reduce the costs associated with wastewater treatment in a station located in Kołobrzeg, the wastewater is pre-treated at the plant. For this purpose, a centrifuge is used; its efficiency is greatly reduced due to high temperature of wastewater. The centrifugation technology is based on the assumption that temperature of the centrifuged medium should not exceed 40ºC. To lower the temperature, two mechanical draft cooling facilities are currently used. Their efficiency is not always sufficient to cool the peak wastewater stream to the required temperature. Furthermore, wastewater heat is not utilized.

The purpose of this research work was to develop a concept for reliable cooling of variable-flow wastewater with heat recovery for heating or production purposes. The research methodology consisted mainly of theoretical computation based on the initially obtained technological information and partly on the measurements made.

3. Computation results

3.1. Shell-and-tube heat exchanger for heating purposes

Water heating for the purposes of heating the production building was considered as the first variant of wastewater heat utilization. The concept of a shell-and-tube heat exchanger was developed, which consists of a cylindrical shell and a bundle of straight, thin-walled tubes. The heat exchange surface is the surface of the tubes along which the heat exchange takes place between cooling water flowing inside these tubes and wastewater flowing around them. The decision to use such an exchanger design, which is nowadays considered obsolete, is based on facilitating the cleaning of the area around the tubes to which wastewater is channeled.

Structural computation of the shell-and-tube heat exchanger were made based on the following initial assumptions for the medium streams:

- hourly wastewater flow: V_1 = 8.3 m^3/h,
- initial wastewater temperature: t_1' = 90ºC,
- expected wastewater temperature after cooling: t_1'' = 40ºC,
- initial temperature of cooling water: t_2' = 20ºC,
- expected temperature after cooling: t_2''= 80ºC.

The physical properties of the wastewater were adopted as for water at an average temperature of $t_1^{av.}$ = 65ºC: specific heat c_p = 4183 kJ/(kg·K); density ρ = 980.5 kg/m^3. The above data shows that the recovered heat flux is:

$$Q_1 = \frac{V_1}{3600}\rho c_p\left(t_1' - t_1''\right) = \frac{8.3}{3600}980.5\cdot 4.183\left(90-40\right) = 472.8 \text{ kW}.$$

From the enthalpy balance under the above assumptions, mass flow rates of the mediums were determined: for wastewater M_1 = 2.26 kg/s; for water M_2 = 1.89 kg/s.

The exchanger shell is expected to be made of steel seamed pipe 114×2.5 mm with an internal diameter of 109 mm, while the tube bundle will consist of seamless steel tubes 12×1 mm with internal diameter of 10 mm. The recommended flow rate of mediums for such exchanger design was adopted (Piotrowski 1973): for the inter-tube area (cooled wastewater) - 0.45 m/s; for a tube bundle area (cooling water to be used as a heating medium) - 0.65 m/s.

Fig. 1 shows the exchanger cross-section obtained as a result of the design on the condition that the inter-tube area is optimally filled. The number of tubes in the bundle was 37. For such a design, the actual flow rates of mediums were: for inter-tube space w_1 = 0.45 m/s; for tube bundle area w_2 = 0.66 m/s.

The following physical properties of mediums were applied in further thermal computation (Szkarowski et al. 2017):

- For wastewater at average temperature $t_1^{av.}$ = 65ºC:
  - Prandtl number: Pr_1 = 2.765,
  - specific heat: c_{p1} = 4.183 kJ/(kg·K),
  - kinematic viscosity coefficient: $\nu_1 = 0.447 \cdot 10^{-6}$ m²/s,
  - thermal conductivity coefficient: $\lambda_1 = 66.35 \cdot 10^{-2}$ W/(m·K),
  - density ρ_1 = 980.5 kg/m³,
- for cooling water at average temperature $t_2^{av.}$ = 50ºC:
  - Prandtl number: Pr_2 = 3.54,
  - specific heat: c_{p2} = 4.174 kJ/(kg·K),
  - kinematic viscosity coefficient: $\nu_2 = 0.556 \cdot 10^{-6}$ m²/s,
  - thermal conductivity coefficient: $\lambda_2 = 64.8 \cdot 10^{-2}$ W/(m·K),
  - density ρ_2 = 988.1 kg/m³.

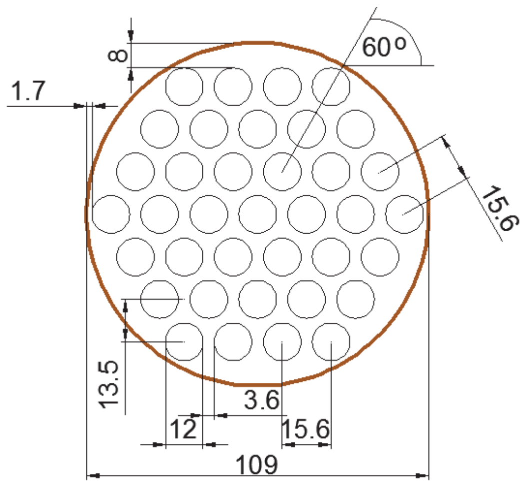


Fig. 1. Cross-section of the wastewater-water heat exchanger

Based on the above values of physical properties and velocity of mediums, the value of Reynolds number was determined for the adopted exchanger design:

- for wastewater in inter-tube area: Re_1 = 12100,
- for water in pipes: Re_2 = 11870,

which proves the developed turbulent movement of both mediums. This gives an opportunity to determine the Nusselt number, which characterizes heat transfer on the surface of the tube bundle, from the universal formula (Szkarowski et al. 2017): for wastewater on the outer surface of tubes $Nu_1 = 61.23$; for water on the internal surface of tubes $Nu_2 = 67.06$.

The above premises were used to determine the value of the heat transfer coefficient, which for the wastewater side is $\alpha_1 = 3385$ W/(m^2·K), and on the water side $\alpha_2 = 4295$ W/(m^2·K). The value of the heat transfer coefficient, taking into account the material and wall thickness of the tubes, is 1681 W/(m^2·K).

The nature of the variation of temperature of the mediums along the heat exchange surface allows the active temperature difference to be taken as the arithmetic mean (Orłowska 2018), which amounts to $\Delta t = 15$°C. The required surface of the tube bundle with the above heat exchange characteristics was about 18.52 m^2, and the length of the tubes in the bundle was 13.28 m. In order to shorten the heat exchanger length, the series connection of three sections of 4.5 m long each was suggested.

Hydraulic computation were also performed to determine fluid pressure loss during flow through the exchanger. The required power to drive the wastewater pump was approximately 260 W, while the power required for the water pump – approximately 540 W.

Dimensions and basic characteristics of the designed heat exchanger are shown in Fig. 2. Inspection hatches are provided for cleaning the space between the tubes. An annular collector is provided at each wastewater inlet and outlet. Its dimensions were chosen so that the medium velocity in the connector, in the annular channel and in the inter-tube area be similar.

It should be emphasized that several Polish companies manufacturing heat exchangers would propose ready-made solutions for the obtained preliminary results. However, a certain problem would be the need to periodically quickly clean the inter-tube area.

3.2. Ventilation heater

An air heater was developed as a second way to cool the wastewater and recover its heat. Currently, an oil heater is used to heat the outside air for ventilation of the factory boiler room. Most of this air is used to burn fuel in boilers.

A two-row tube type "wastewater-air" exchanger with cross flow of mediums and cross-section of 5×5 m was chosen. The vertical ribbed tubes constitute the heat exchange surface. Heat exchange takes place between wastewater flowing inside these tubes and air flowing across them - horizontally. Due to the large stream of heated air and expected expansion of the plant, a decision was made to calculate the maximum daily wastewater flow.

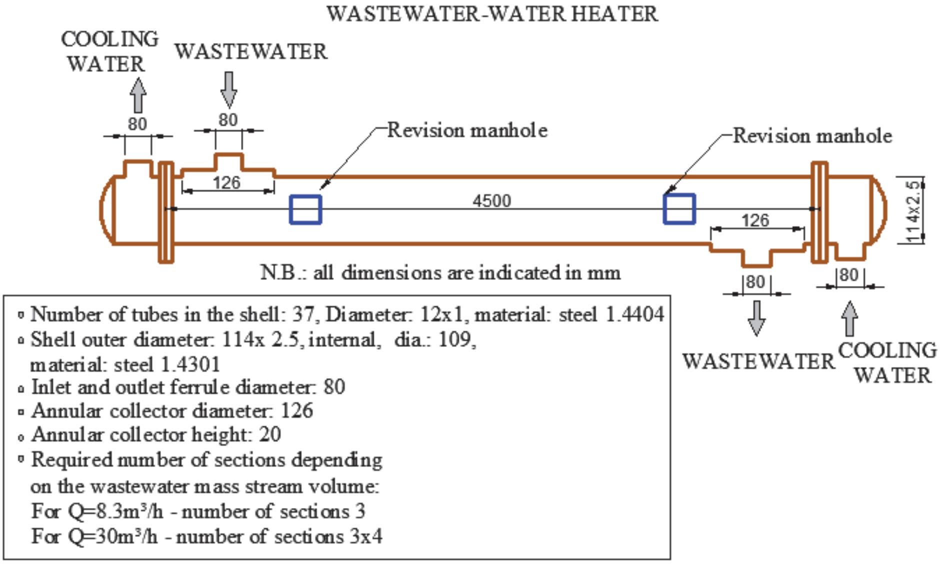


Fig. 2. Basic characteristics of one section of the wastewater-water heat exchanger

Design-verification computation of the cross-flow exchanger was made based on the following initial assumptions for the mediums streams:

- initial wastewater temperature: $t_1' = 90°C$,
- expected waster water temperature after cooling: $t_1'' = 40°C$,
- hourly wastewater flow: $V_1 = 30$ m^3/h,
- hourly air flow: $V_2 = 485{,}000$ m^3/h,
- initial external air temperature $t_2' = -10°C$.

Physical properties of wastewater were assumed initially as for water at arithmetic average temperature $t_1^{av.} = 65°C$ C: specific heat $c_p = 4183$ kJ/(kg·K); $\rho = 980.5$ kg/m^3. The above data shows that the recovered heat flux is:

$$Q_1 = \frac{V_1}{3600}\rho c_p\left(t_1' - t_1''\right) = \frac{8.3}{3600} 980.5 \cdot 4.183(90 - 40) = 1702 \text{ kW}.$$

This allowed for the determination of the final air temperature: $t_2'' = 0°C$. The nature of mediums temperature variation along the heat exchange surface requires the use of active temperature difference as the logarithmic mean

(Orłowska 2018), which was $\Delta \boldsymbol{t} = 68.12\,^{\circ}\mathrm{C}$. In this conditions the average wastewater temperature is:

$$\boldsymbol{t}_1^{av.} = \boldsymbol{t}_2^{av.} + \Delta \boldsymbol{t} = \frac{-10+0}{2} + 68.12 = 63.12\,^{\circ}\mathrm{C}.$$

For this temperature we have the following properties of wastewater: $\boldsymbol{c}_p$ = 4181 kJ/(kg·K); density ρ = 981.5 kg/m^3, which needs slight correction of the recovered heat flux:

$$\boldsymbol{Q}_1 = \frac{8.3}{3600} 981.5 \cdot 4.181 (90 - 40) = 1703\ \mathrm{kW}.$$

From the enthalpy balance under the above assumptions, mass flow rates of mediums were determined: for wastewater $\boldsymbol{M}_1$ = 4.52 kg/s; for air $\boldsymbol{M}_2$ = 33.8 kg/s.

The design of the double-row "wastewater-air" heater obtained as a result of computation is shown in Fig. 3. For the selected diameter of vertical tubes 33.7×2.0 mm, dimensions of the square ribs are 7.4×7.4 cm. Thickness of the metal plate is 1 mm, and the distance between the rib axes is 3 mm.

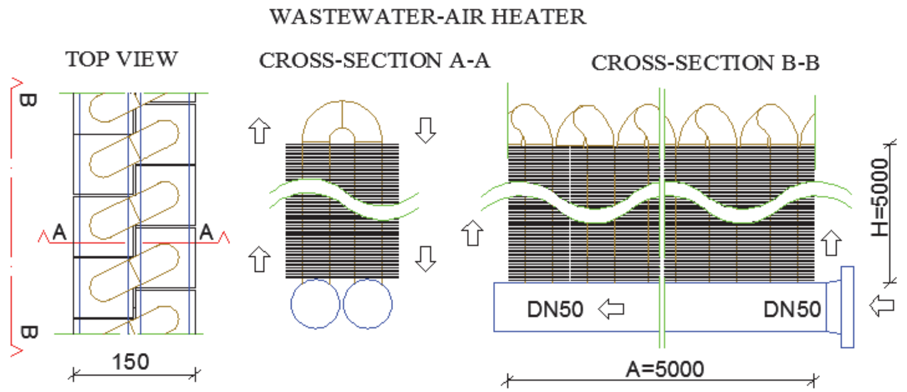
The assumed wastewater velocity in the tubes was 0.45 m/s, while real air velocity in the inter-tube area was 14.2 m/s.

The following physical properties of mediums were adopted for further thermal computation (Szkarowski et al. 2017):

- For wastewater at average temperature $\boldsymbol{t}_1^{av.}$ = 63.12ºC:
  - Prandtl number: Pr_1 = 2.846,
  - specific heat: c_{p1} = 4.181 kJ/(kg·K),
  - kinematic viscosity coefficient: $\nu_1 = 0.458 \cdot 10^{-6}$ m^2/s,
  - thermal conductivity coefficient: $\lambda_1 = 66.18 \cdot 10^{-2}$ W/(m·K),
  - density ρ_1 = 981.5 kg/m^3,
- for cooling air at average temperature $\boldsymbol{t}_2^{av.} = -5\,^{\circ}\mathrm{C}$:
  - Prandtl number: Pr_2 = 0.71,
  - specific heat: c_{p2} = 1.007 kJ/(kg·K),
  - kinematic viscosity coefficient: $\nu_2 = 12.855 \cdot 10^{-6}$ m^2/s,
  - thermal conductivity coefficient: $\lambda_2 = 2.4 \cdot 10^{-2}$ W/(m·K),
  - density ρ_2 = 1.318 kg/m^3.

Based on the above values of physical properties and velocity of mediums, the value of Reynolds number was determined for the adopted exchanger design:

- for wastewater in tubes in the inter-tube area: $Re_1 = 32424$,
- for air in the inter-tube area: $Re_2 = 170000$.



CHARACTERISTIC:	
• Heater width: 5m	• Number of tubes in the second row: 65
• Heater height: 5m	• Vertical tubes diameter: DN25: DN25 (33.7x2mm)
• Number of tubes in one row: 66	• Collector diameter: DN50 (60.3x2.9mm)

Fig. 3. Cross-section of the designed "wastewater-air" heater

The above allowed for the opportunity to determine the Nusselt number from appropriate formulas (Szkarowski et al. 2017): for wastewater on the inner surface of tubes: $Nu_1 = 189.22$; for air on the outer surface of ribbed tubes: $Nu_2 = 368.2$.

From the above premises, the value of the heat transfer coefficient was determined, which on the wastewater side is $\alpha_1 = 4216.4$ W/(m^2·K) and on the water side $\alpha_2 = 50.3$ W/(m^2·K). The value of the heat transfer coefficient, taking into account the material and wall thickness of the tubes, is 15.64 W/(m^2·K).

The required ribbed surface at this heat exchange intensity is about 1374 m^2, with an area of one row equal to 1023 m^2. Such design of the exchanger in the assumed computation conditions will provide air temperature behind the heater of about 0°C, which will reduce the strain on heaters generating heat for the boiler by up to 50%. As the outside temperature increases, the designed exchanger will be able to provide more heat and even cover 100% of the demand for ventilation purposes.

4. Summary

The possibility of process wastewater heat recovery was estimated at Homanit plant located in Karlino, Poland. To determine the volume of heat recovered, a steam thermal treatment of wood cycle was selected, which currently generates about 8.3 m^3/h of wastewater at average temperature of 80ºC. The need to cool down wastewater in order to improve the efficiency of wastewater pretreatment by centrifugation provided an additional motive.

A shell-and-tube heat exchanger was developed, the purpose of which is both cooling wastewater to the desired temperature and heating water, which will then serve as a heating medium for heating a production building. The heat exchange surface consisting of straight, thin-walled tubes is approximately 18 m^2. The recovered heat flux with an average daily wastewater flow is 473 kW.

A cross-flow heater was developed, the purpose of which is to cool wastewater and heat outside air for ventilation of the boiler room. The heat exchange surface of vertical ribbed tubes is approx. 1532 m^2. The theoretical thermal power recovered from the wastewater stream with a maximum daily flow is 1703 kW.

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Abstract

This papers presents the results of computation of two heat exchangers used for heat utilization of industrial wastewater generated in a refined fiberboard production plant. The basic task was to cool wastewater to a temperature of approximately 40ºC enabling efficient centrifugation of suspended matter at the stage of wastewater pretreatment. A shell-and-tube heat exchanger with the power of 473 kW for water heating was developed for heating the production hall. A cross-flow exchanger was also developed for heating ventilation air in the boiler room building, power of which is 1703 kW.

Thermal and hydraulic computation was performed, the required heat exchange surface was selected, the main structural characteristics of both exchangers were determined.

Keywords:
process wastewater, heat recovery, shell-and-tube heat exchanger, cross-flow heat exchanger

Utylizacja ciepła ścieków poprodukcyjnych

Streszczenie

W niniejszym artykule przedstawiono wyniki obliczeń dwóch wymienników ciepła typu służących do utylizacji ciepła ścieków przemysłowych powstających w zakładzie do produkcji uszlachetnionych płyt pilśniowych. Zadaniem podstawowym było schładzanie ścieków do temperatury ok. 40ºC umożliwiającej sprawne odwirowanie zawieszonych substancji na etapie wstępnego podczyszczania ścieków. Opracowano wymiennik płaszczowo-rurowy podgrzewający wodę na cele ogrzewania hali produkcyjnej o mocy 473 kW. Opracowano również wymiennik krzyżowy na cele podgrzania powietrza wentylacyjnego w budynku kotłowni, którego moc wynosi 1703 kW. Wykonano obliczenia cieplne i hydrauliczne, dobrano wymaganą powierzchnię wymiany ciepła, określono główne charakterystyki konstrukcyjne obu wymienników.

Słowa kluczowe:
ścieki produkcyjne, odzysk ciepła, wymiennik płaszczowo-rurowy, wymiennik krzyżowy

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Computation of Filtration Bed Porosity Based on Selected Filtration Coefficient Equations by Application of Numerical Methods

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1. Introduction

Gravitational filtration is a process of solid and liquid phase separation. Wastewater suspension conveyed to a porous bed makes a single-phase solution or is a mixture of solid impurities contained in liquid phase (Piecuch 1984, Piekarski 2004, Skoczko 2019). Stopping of such impurities is based on mechanical action of a filtration bed mostly through wedging of the solid phase in its pores (Rup 2006). However, the relationship between size of the solid phase fraction contained in wastewater and size of grains of the filtration bed is important because it determines the type of the process as gravitational filtration may proceed, among other things, on a porous bed, in the very porous bed, simultaneously on and in the porous bed, in the porous bed with a colmatation barrier and accumulated sediment layer etc. (Piecuch et al. 2013, Palica et al. 2001, Piekarski 2009).

Analysing a filtration process, based on the general balance equation, which assumes in simplified form that the suspension solid phase inflowing in volume Q_{SN} was stopped in the filtration bed pores and created a colmatation barrier in the filtration bed pores as well as developed a sediment on the bed and got into filtrate in amount of Q_{SF}, one can generally put it as follows (Piekarski 2009, Piekarski 2019):

$$\int_0^{Q_{SN}} dQ_{SN} - \int_0^{Q_{SF}} dQ_{SF} = A \cdot \rho_S \cdot \sum_i^n (L_i \cdot \int d\varepsilon_i) \tag{1}$$

Having put in equation (1) particular layers:

$$\beta_N \int_0^{V_N} dV_N - \beta_F \int_0^{V_F} dV_F = A \cdot \rho_S \cdot \left[L_Z \int_{\varepsilon_Z}^{\varepsilon_{Z0}} d\varepsilon_Z + L_K \int_{\varepsilon_K}^{\varepsilon_Z} d\varepsilon_K + L_O \int_{\varepsilon_O}^{1} d\varepsilon_O \right] \tag{2}$$

Hence equation (2) takes the following form:

$$\beta_N \cdot V_N - \beta_F \cdot V_F = A \cdot \rho_S \cdot \left[L_Z \cdot (\varepsilon_{Z0} - \varepsilon_Z) + L_K \cdot (\varepsilon_Z - \varepsilon_K) + L_O \cdot (1 - \varepsilon_O) \right] \quad (3)$$

It can be stated, based on equations (1) (2) (3), that the gravitational filtration process is a complex phenomenon and to provide possibly accurate characteristic of such process it is necessary to perform experiments within possibly broad range of parameters variability. Mathematical description of the gravitational filtration process requires determination of values of a number of parameters (Skoczko et al. 2016). This pertains to the presentation of the filtration barrier through determination (based on the grain size analysis) of sizes of characteristic diameters as well as the characteristic of medium flow through the filtration bed computing e.g. filtration or permeability coefficient values. The filtration coefficient is a feature specific for given bed and it depends on its porosity, grain size and flowing medium temperature. In practice, the filtration coefficient is being computed through application of laboratory methods, measurements performed in real terms or using any indirect methods based on empirical formulas. Of course, the methods based on physical medium flow through the bed take into account, in the most accurate way, impact of grain geometry and, in effect, impact of porosity on the filtration coefficient value. Some researches suggest that the difficulty in putting bed microstructure in analytical and empirical mathematical formulas results in unreliability of the results originating from it. However, it is a well known fact that bed microstructure has impact on the size and shape of the porous space determining its capability to retain bound and contact waters therein. Presence of such waters reduces volume of pores through which water could flow freely, therefore, it determines the effective porosity size (Parylak et al. 2013).

To compute values of the described gravitational filtration characteristic parameters my own computer software FILTRA was used (Piekarski 2011). This application is composed of a number of modules being separate subroutines. The first module for the so-called grain size analysis performs, based on initial data, computation of the grain size distribution curve and characteristic diameters. In the next step of this application operation the results of computation can be exported to a module associated with computation of the filtration coefficient and bed permeability. Consequently, the values computed in this module, i.e. filtration coefficient and bed permeability coefficient as well as values computed in the grain size analysis module i.e. characteristic diameters, can be exported to a subsequent module responsible for computation of medium flow through the porous layer or exported to a module associated with gravitational filtration process computation.

In this paper an interesting combination of a direct laboratory method and computational indirect method based on Slichter's analytical and empirical mathematical formula in order to determine variations in filtration bed porosity values has been presented using FILTRA application.

2. Methodology of research

One of the methods of measurement of filtration coefficient value K_L [m/s] is the direct laboratory method called the variable pressure method.

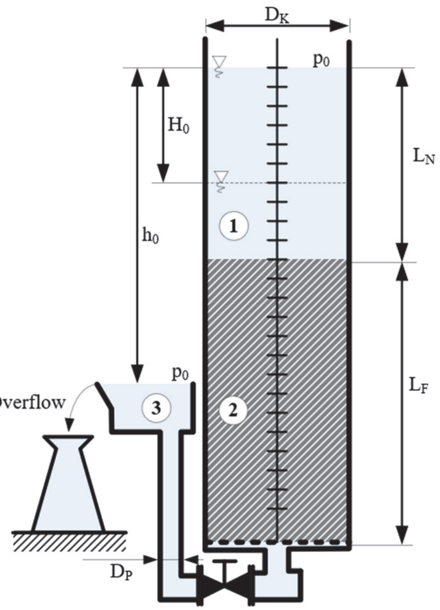

Fig. 1. Diagram of laboratory experimental stand for determination of filtration coefficient using method of variable pressure of medium (1 – medium; 2 – filtration bed; 3 – overflow tank)

This method takes into account height of filtration layer L_F [m], the distance between the upper medium level in the filtration column and the level in the overflow tank h_0 [m], downgrade of medium level H_0 [m] after time t_K [s] and filtration column diameter D_K [m] as well as the diameter of the pipe connecting it with the overflow tank D_P [m] (Piekarski 2009):

$$K_L = -t_K^{-1} \cdot D_P^2 \cdot D_K^{-2} \cdot L_F \cdot Ln\left(1 - H_0 \cdot h_0^{-1}\right) \text{ [m/s]} \quad (4)$$

Indirect methods using empirical formulas can be divided, in terms of the input data type essential for filtration coefficient computation, into three groups, which take into account solely characteristic grain diameters (group I), characteristic grain diameters and bed porosity (group II), grain size distribution, bed porosity and physical properties of the flowing medium (group III). Slichter's formula, which belongs to group III is used to determine the filtration coefficient K_{SL} [m/d] of sand and gravel featuring diameter of $d_{10} \in <0.01$ mm-5.00 mm>:

$$K_{SL} = 88{,}3 \cdot m_{SL} \cdot \mu_{SL}^{-1} \cdot d_{10}^{2} \text{ [m/d]} \tag{5}$$

where:
μ_{SL} – coefficient of dynamic viscosity in CGS system, [P],
m_{SL} – analytical coefficient, [-].

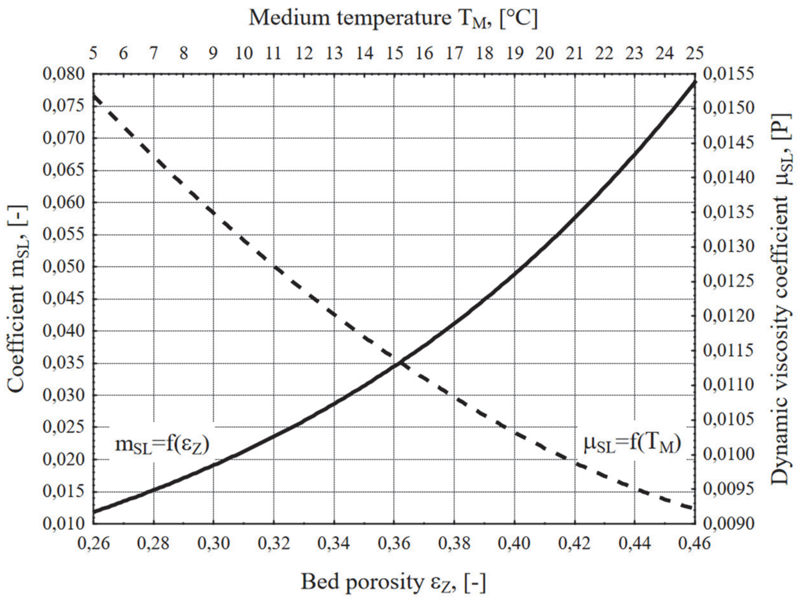

Fig. 2. Change of value of m_{SL} [-] coefficient against bed porosity ε_Z [-] and dynamic viscosity coefficient μ_{SL} [P] against medium temperature T_M [ºC]

Value of coefficient m_{SL} [-] in formula (5) pertaining to bed porosity $\varepsilon_{SL} \in <0.26-0.46>$ can be calculated from the following equation (Figure 1):

$$m_{SL} = 2.108 \cdot \varepsilon_{SL}^{3} - 1.199 \cdot \varepsilon_{SL}^{2} + 0.357 \cdot \varepsilon_{SL} - 0.037 \text{ [-]} \tag{6}$$

where:
ε_{SL} – bed porosity in the Slichter's formula, [-].

However, dynamic viscosity coefficient value μ_{SL} [P] in formula (5) pertaining to water temperature $T_M \in$ <5-25ºC> can be calculated from the following equation (Figure 1):

$$\mu_{SL} = 2.72E\text{-}8 \cdot T_M^3 + 6.79E\text{-}6 \cdot T_M^2 - 5.24E\text{-}4 \cdot T_M + 1.76E\text{-}2 \text{ [P]} \tag{7}$$

where:
T_M – water temperature [ºC].

Transformation of formula (5) into a form making possible computation of bed porosity results in its excessive complexity. In order to avoid use of artificial neural networks (Wartalska 2020, Dawidowicz 2018, Dawidowicz et al 2018) the best method for solving of such computational problem is application of the iteration method. Therefore, assuming that value of the filtration coefficient computed from application of the variable pressure laboratory method (4) is equal to the value obtained from Slichter's empirical formula (5) i.e. $K_L = K_{SL}$ the value of filtration bed porosity ε_{SL} can be computed. A fragment of source code entered into FILTRA application algorithm (Piekarski 2011), making possible computation of porosity value ε_Z using Slichter's empirical formula (5), is presented in the below source code:

```
...
εi : =  0.26; εSL: = 0.26; i : =  0.0001;
Repeat
  εi: = εi+i;
  PSlichter(d10, εi, Tm, vmi0, mSL, KSL);
  if (KSL > =  KL) and (KSL>0) then εSL: = εi;
Until εi > =  0.46;
...
```

Due to formula (5) the initial value of bed porosity is $\varepsilon_i = 0.26$. Operation of filtration bed porosity value ε_i increase was repeated by the so-called counter, value of which reflected accuracy of computation (i = 0.0001). Lower value of the counter resulted in reduction of application speed but provided more accurate results. Then, using PSlichter's procedure filtration coefficient value was being computed based on the Slichter's formula (5)(6)(7). Computation was performed until the final condition i.e. getting of such bed porosity value ε_i, at which filtration coefficient value K_{SL} computed from formula (5) would be equal to or slightly higher (considering counter value) than the filtration coefficient value computed based on the variable pressure method K_L (4), was effected. The top iteration limit was the maximum value of applicability of formula (5), i.e. $\varepsilon_i = 0.46$.

During the laboratory tests filtration material featuring total mass of 1000g was prepared; it was then subjected to the grain size analysis, computing values of characteristic diameters i.e.: d_{10}, d_{20}, d_{60}, reliable d_M and modal d_{MO} as well as medial d_{ME}. The filtration bed was each time flushed/rinsed and put in a water filled column featuring diameter of $D_K = 5$ cm up to height of $L_F = 30$ cm. A cut-off valve was located in the bottom part of the filtration column on a pipe featuring diameter $D_P = 1.6$ cm, which connected the bed with the overflow tank (Fig.1). Water featuring temperature of $T_W = 21°C$ was fed in portions to the column at the medium-table height $L_N = 17$ cm above the filtration bed. The difference between the initial water-table height in the column and in the overflow tank was $h_0 = 36$ cm. During the test time t_K [s] of water-table downgrade in the filtration column at height of $H_0 = 13$ cm for three different filtration bed fractions was measured. Figures obtained were put into FILTRA, which resulted in values of filtration coefficient obtained through application of the variable pressure method K_L [m/s] and also using various analytical and empirical mathematical formulas, among other those proposed by Slichter K_{SL} [m/s].

3. Test results and interpretation

Filtration beds used in porosity testing were made of silica sand used for water purification in a way presented in Table 1.

Table 1. Filtration beds grain size characteristic

Pos.	Diameter d [mm]		Class weight, g_i [g]		
	min	max	Z_I	Z_{II}	Z_{III}
1	0.00	0.40	150	150	150
2	0.40	0.50	200	180	160
3	0.50	0.63	300	200	150
4	0.63	0.80	150	250	350
5	0.80	1.00	100	150	120
6	1.00	1.25	50	50	50
7	1.25	2.00	50	20	20

The data presented in Table 1 was entered into FILTRA, which resulted in production of mass fraction graphs $f_N(d_i)$ and summary mass fraction $F_N(d_i)$ depending on substitute diameter d_i [mm] taking into account modal diameter d_{MO}, medial diameter d_{ME}, reliable diameter d_M and d_{10}, d_{20} and d_{60} (Fig. 3).

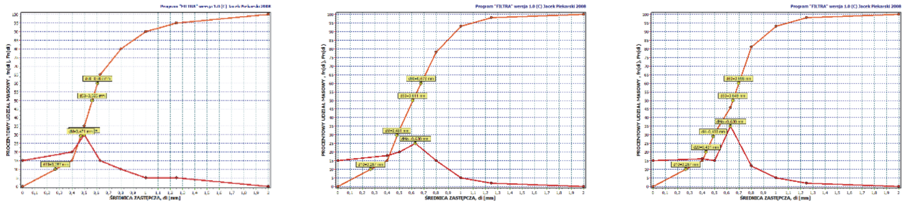

Fig. 3. Curves of mass fraction $f_N(d_i)$ and total mass fraction $F_N(d_i)$ depending on value of substitute diameter d_i [mm] taking into account modal diameter d_{MO}, medial d_{ME}, weighted particles diameter d_M, d_{10}, d_{20}, d_{60} Z_I, Z_{II} and Z_{III} filter beds

Based on the grain size analysis performed for the tested filtration beds (Figure 3) it can be stated that modal diameter (so-called dominant) d_{MO} reflecting the maximum of the mass fraction curve $f_N(d_i)$ is from 500 μm for bed Z_I and 630 μm for beds Z_{II} and Z_{III}. The medial diameter (so-called median) d_{ME} equal to 50% of the mass fraction varies from 565 μm (Z_I), through 611 μm (Z_{II}) to 649 μm (Z_{III}). Values of the grain reliable diameter d_M are 471 μm (Z_I), 481 μm (Z_{II}) and 488 μm (Z_{III}). The remaining characteristic values are for d_{20}: 425 μm (Z_I), 428 μm (Z_{II}) and 431 μm (Z_{III}) and for d_{60}: 608 μm (Z_I), 678 μm (Z_{II}) and 698 μm (Z_{III}) respectively. Due to applied formula (5) the most important is diameter d_{10}, value of which in the case of the tested filtration beds (Z_I, Z_{II}, Z_{III}) is 267 μm. The coefficient of grain size nonuniformity U [-] expressed as a quotient of diameters d_{60} and d_{10} respectively varies from 2.28 (Z_I), through 2.54 (Z_{II}) to 2.62 (Z_{III}). Based on temperature T = 21°C of water fed in portions and equation (7) the computed value of the dynamic viscosity coefficient is μ_{SL} = 9.88E-3 P, which in SI system is equivalent to μ_{SL} = 9.88E-4 Pa·s value.

Table 2. Test results for impact of variation in grain fractions size on porosity of three different filtration beds

Pos.	Bed	Water-table downgrade time	Filtration coefficient	Coefficient in equation (6)	Bed porosity
		t_K	$K_L = K_{SL}$	m_{SL}	ε_{SL}
		[s]	[m/s]	[-]	[%]
1	Z_I	54	2.55E-4	34.64E-3	36
2	Z_{II}	43	3.20E-4	43.39E-3	39
3	Z_{III}	38	3.62E-4	49.08E-3	40

Based on the results presented in Table 2 it can be stated that in the case of tested filtration beds Z_I, Z_{II} and Z_{III} during analysis of the filtration coefficient by application of the variable pressure laboratory method, the time of water-table downgrade t_K changes within the range from 38 s to 54 s. Based on formula (4) the computed value of filtration coefficient K_L varies from 3.62E-4 m/s to 2.55E-4 m/s. Change of values of the presented resultant variables is associated with differing grain size distribution of particular filtration beds (Table 1), which results, in particular, in variable porosity ε_{SL} within the range from 36 % to 40%.

As it appears from my research work, due to application of the first or second degree polynomial regression, equations determining the change of bed porosity value ε_{SL} can be obtained depending on the variation of the considered independent variables parameters such as, for example, characteristic diameter d_{60}, medial diameter d_{ME}, reliable diameter d_M or the coefficient of grain size non-uniformity U – see Figs 4 and 5. Quality of such approximation described by the correlation coefficient is close to 1, which confirms very good fitting of the obtained equations to the measurement points.

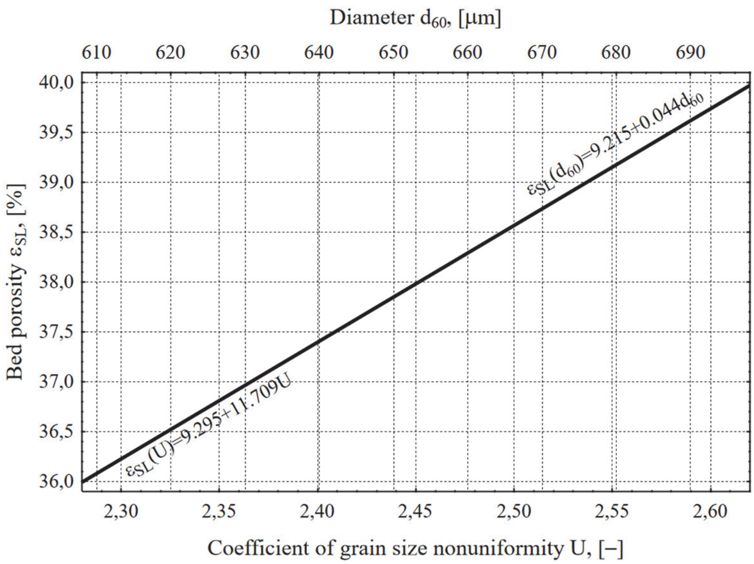

Fig. 4. Change of value of bed porosity ε_{SL} [%] depending on characteristic diameter value d_{60} [μm] and on coefficient of grain size nonuniformity U [-] of tested filtration beds Z_I, Z_{II} and Z_{III}

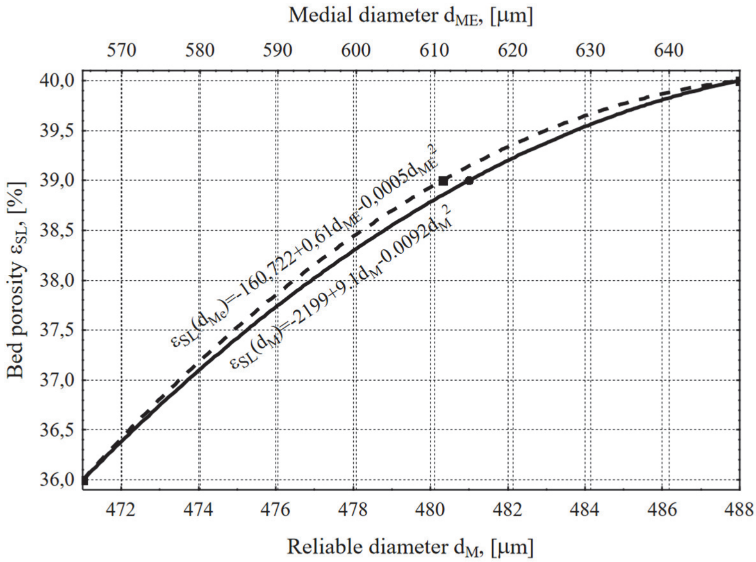

Fig. 5. Change of value of bed porosity ε_{SL} [%] depending on characteristic reliable diameter d_M [μm] and medial diameter d_{ME} [μm] values of tested filtration beds Z_I, Z_{II} and Z_{III}

The change of bed porosity value ε_{SL} [%] depending on the change of diameter value d_{60} [μm] within the range of 608 μm to 698 μm, can be put as $\varepsilon_{SL}(d_{60}) = 9.215+0.044 \cdot d_{60}$. Due to the coefficient of grain size nonuniformity U [-] the linear equation is defined within the range from 2.28 to 2.62 taking shape of: $\varepsilon_{SL}(U) = 9.252+11.709 \cdot U$. However, the change of bed porosity value ε_{SL} [%] in function of the reliable diameter value d_M [μm] within the range from 471 μm to 488 μm, is described by the following relationship:
$\varepsilon_{SL}(d_M) = -2199+9.1 \cdot d_M-0.0092 \cdot d_M^2$. Taking into account medial diameter value d_{ME} [μm] within the range from 565 μm to 649 μm, the resultant parameter can be presented in the following form: $\varepsilon_{SL}(d_{ME}) = -160.722+0.61 \cdot d_{ME}-0.0005 \cdot d_{ME}^2$.

4. Conclusions

Based on the test performed it can be stated that:

- Due to combination of the direct variable pressure laboratory method and indirect method based on a mathematical analytical and empirical formula e.g. Slichter's formula, applied for computation of the filtration coefficient, porosity of a filtration bed can be determined. Krüger's formula can also be used in such type computation.

- Application of any iteration methods allows for computation of bed porosity without any necessity to transform complex formulas. In such type iteration computation FILTRA software was particularly useful.
- Mathematical and empirical formulas for computation of filtration bed porosity can be created with sufficient accuracy using polynomial regression.
- Filtration bed porosity analysis experiments should be performed in possibly broad range of independent parameters variability (d_{20}, d_{60}, d_M, d_{Me}, U) and such experiments should pertain to the change of bed porosity values during filtration process when, for example, wastewater suspension is used (equation 3).

Key to symbols

t_K –time of water level downgrade at height H_0, [s],
ρ_S – mass density of solid phase, [kg/m^3],
Q_{SN} – initial mass of solid phase, [kg],
Q_{SF} – mass of solid phase in filtrate, [kg],
V_F – volume of filtrate, [m^3],
V_N – volume of medium, [m^3],
h_0 – distance between upper level of medium in column and level in overflow tank, [m],
ε_K – porosity of solid phase colmatated in bed, [-],
ε_{Z0} – porosity of bed without colmatation, [-],
ε_O –porosity of sediment layer, [-],
ε_Z – porosity of bed with colmatation, [-],
ε_{SL} –porosity of bed in Slichter's formula, [-],
A – surface of bed, [m^2],
D_K – filtration column diameter, [m],
d_{ME} – medial diameter, [mm],
d_{MO} – modal diameter, [mm],
D_P – diameter of pipe connecting filtration column with overflow tank, [m],
d_{10}, d_{20}, d_{60} – characteristic diameters, [mm],
T_M – temperature of water, [ºC],
K_L – filtration coefficient computed based on the variable pressure method, [m/s],
μ_{SL} – coefficient of dynamic viscosity in CGS system, [P],
U – coefficient of grain nonuniformity, [-],
m_{SL} – analytical coefficient, [-].
H_0 – downgrade of medium level after time t_K [m],
L_K – height of colmatated solids layer in bed, [m],
L_O – height of sediment layer, [m],
L_Z – height of porous bed, [m],
β_N – initial concentration of solids, [kg/m^3],
β_F – concentration of solids in filtrate, [kg/m^3].

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Abstract

Gravitational filtration is a process of solid and liquid phase separation. Wastewater suspension conveyed to a porous bed makes a single-phase solution or is a mixture of solid impurities contained in liquid phase. Stopping of such impurities is based on mechanical action of a filtration bed mostly through wedging of the solid phase in its pores. However, the relationship between size of the solid phase fraction contained in wastewater and size of grains of the filtration bed is important because it determines the type of the process as gravitational filtration may proceed, among other things, on a porous bed, in the very porous bed, simultaneously on and in the porous bed, in the porous bed with a colmatation barrier and accumulated sediment layer etc. Gravitational filtration process is a complex phenomenon and to provide possibly accurate characteristic of such process it is necessary to perform experiments within possibly broad range of parameters variability. Mathematical description of the gravitational filtration process requires determination of values of a number of parameters. This pertains to the presentation of the filtration barrier through determination (based on the grain size analysis) of sizes of characteristic diameters as well as the characteristic of medium flow through the filtration bed computing e.g. filtration or permeability coefficient values. The filtration coefficient is a feature specific for given bed and it depends on its porosity, grain size and flowing medium temperature. In this paper an interesting combination of a direct laboratory method and computational indirect method based on Slichter's analytical and empirical mathematical formula in order to determine variations in filtration bed porosity values has been presented using FILTRA application.

Keywords:
gravitational filtration, bed porosity, mathematical modelling

Obliczenia porowatości złoża filtracyjnego na podstawie wybranych równań współczynnika filtracji przy wykorzystaniu metod numerycznych

Streszczenie

Filtracja grawitacyjna to proces rozdziału fazy stałej od ciekłej. W warunkach rzeczywistych zawiesinowe ścieki kierowane na złoże porowate stanowią roztwór jednofazowy lub są mieszaniną zawartych w fazie ciekłej zanieczyszczeń stałych. Zatrzymywanie takich zanieczyszczeń polega na mechanicznym działaniu warstwy filtracyjnej przez najczęściej klinowanie w jej porach fazy stałej. Jednak stosunek wielkości frakcji fazy stałej zawartej w ściekach oraz wielkości uziarnienia złoża filtracyjnego jest na tyle istotny, gdyż determinuje rodzaj procesu, ponieważ filtracja grawitacyjna może zachodzić między innymi: na złożu porowatym, w samym złożu porowatym, jednocześnie na złożu i w złożu porowatym, w złożu porowatym z blokadą kolmatacyjną i przyrostem warstwy osadu, itd. Proces filtracji grawitacyjnej jest zjawiskiem złożonym i aby charakterystyka takiego procesu była możliwie dokładna, niezbędne są eksperymenty prowadzone w możliwie szerokim zakresie zmienności parametrów. Opis matematyczny procesu filtracji grawitacyjnej wymaga wyznaczenia wartości szeregu parametrów. Dotyczy to przedstawienia przegrody filtracyjnej, poprzez wyznaczenie na podstawie analizy granulometrycznej wielkości średnic charakterystycznych, jak również charakterystyki przepływu medium przez złoże filtracyjne obliczając np. wartości współczynników filtracji czy przepuszczalności. Współczynnik filtracji jest wielkością charakterystyczną dla danego złoża i zależy od jego porowatości, uziarnienia oraz temperatury przepływającego medium. W niniejszej publikacji korzystając z aplikacji FILTRA przedstawiono interesujące połączenie bezpośredniej metody laboratoryjnej oraz obliczeniowej metody pośredniej bazującej na formule matematycznej analityczno-empirycznej Slichtera w celu wyznaczenia zmian wartości porowatości złoża filtracyjnego.

Słowa kluczowe:
filtracja grawitacyjna, porowatość złoża, modelowanie matematyczne

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The Use of Chosen Biological Methods for Forest Soil Revitalization in Scots Pine Cultivation

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1. Introduction

The devastated and degraded land requiring reclamation (revitalization, remediation) cover in Poland approximately 64 thousand hectares (CSO 2017). The size of this area has changed only slightly over the last few years. Since 2005, only an area of between 1,222 and 1,861 hectares per year has been reclaimed, of which only 581 to 1,132 hectares were restored to cultivation.

Devastated and degraded soils are usually devoid of the humus layer that protects the soil against drying and creates a favorable environment for the development of soil microflora and microfauna. The lack of an organic matter layer on the soil surface also inhibits the process of natural succession and has a negative impact, mainly during warm and dry summer months, on the population size of soil mesofauna, such as moss mites (Oribatida) (Lindberg & Bengtsson 2005).

The restoration of the forest biocenosis – which is the most natural and biodiverse land biocenosis in our climate zone – is considered as the best wayfor revitalization of degraded land. Nowadays, in Poland, forest resources are steadily increasing through the implementation of a program of afforestation of economically inefficient land (Koreleski 2003). These areas usually have poor soil, so they are most often forested by Scots pine (*Pinus sylvestris* L.). In Poland, Scots pine is the dominant forest-forming species that covers 52% of the forest area in our country (Skolud 2006).

The aim of this study was to specify the most effective method of revitalizing degraded forest area. The different modifications of wood chips were used as a substitute for humus layer. The mites (Acari), as well moss mites as the bio-indicators of succession changes occurring in the reconstructed forest soil, were used. The study began 2 years after planting of Scots pine seedlings on the land devastated by military activity, at the former military training ground in Bydgoszcz-Jachcice.

2. Material and methods

2.1. Description of the experiment

The experiment was conducted at the former military training ground in Bydgoszcz-Jachcice, which is currently managed by the Żołędowo Forest District (Forestry Jagodowo, branch 222c, GPS: 53.156943N, 17.986440E). Before renewal, this area was a post-agricultural land overgrown with a rare and degraded Scots pine tree stand, which in 2010 has a fire. According to the Tree Stand Data Sheet of the Żołędowo Forest District, the soil on this area was in the type of rusty soils and subtype of the rusty algae soils. Before planting, the soil surface was tilled with a double-layer forest plow. For planting, Scots pine seedlings with a covered root system, from the Bielawa container nursery (Forest District Dobrzejewice), were used. Scots pine seedlings were planted in spring 2011, in a distance 1.5×0.8 m. After afforestation, this habitat was classified as "fresh boron", dominated by Scots pine with a 10% addition of silver birch (*Betula pendula* Roth).

One-factor experiment was located in forest cultivation. The studied factor was soil mulching with the Scots pine wood chips, used in the following four treatments: 1. uncovered soil (without mulching) as the control (C), 2. soil mulched with wood chips (W), 3. soil mulched with wood chips with the addition of mycorrhizal preparation (WM), 4. soil mulched with wood chips with the addition of forest litter (WL). Three replicates of microplots arrangement was applied. Each microplot was 5 m long and covered 3 rows of Scots pine plants. The surface of one replication covers 10 rows of Scots pine plants. Mulching with wood chips was carried out on April 12, 2012. Wood chips were prepared from scrub Scots pine trees cut in the former military training ground. The Scots pine wood was shredded with the BRUKS 805 disk-chipper. On October 25, 2012, the wood chips on the WM microplots were inoculated with the mycorrhizal biopreparation (2.5% biopreparation with the mycelium of *Hebeloma crustuliniforme* (Bull.) Quél.). At the same time, on the WL microplots, a 10% addition of fresh forest litter from the ripe fresh coniferous forest in the Białe Błota Forestry was applied.

2.2. Pluvial and thermal conditions

The average air temperature in the growing season i.e. from April 1 to September 30, in the years 2012-2014 was 14.5°C that was 0.3°C higher than the long-term average temperature (Table 1). The warmest growing period with the temperature 15.4°C (0.9°C higher than the long-term average) was noted in 2014. The highest air temperature occurred in July 2014 (21.5°C that was 2.8°C, i.e. 15%, higher than the long-term average for this month).

During the considered three-year interval, the lowest precipitation sum 289.9 mm (51 mm below the long-term average) in the vegetation period occurs in the year 2014. The highest rainfalls during the vegetation period were observed in the first year of study (2012), when the sum of precipitation was 378.2 mm (37.3 mm above long-term average). Particularly high rainfalls occurred in June (133.8 mm) and July (115.6 mm) 2012, that is 252 and 133% of the long-term average, respectively.

Table 1. Meteorological conditions in the study years according to standard measurements at the Mochełek Research Station of the University of Science and Technology in Bydgoszcz

Specification	Months of growing season						
	IV	V	VI	VII	VIII	IX	IV-IX
Air temperature (°C)							
2012	8.4	14.5	15.2	18.8	17.6	13.3	14.6
2013	7.0	14.2	17.4	18.9	18.1	10.7	14.4
2014	9.9	13.3	16.0	21.5	17.2	14.4	15.4
2012-2014	8.4	14.0	16.2	19.7	17.6	12.8	14.8
Long-term average	8.1	13.2	16.3	18.7	17.8	13.0	14.5
Difference (+/-)	+0.3	+0.8	-0.1	+1.0	-0.2	-0.2	+0.3
Precipitation (mm)							
2012	26.5	25.4	133.8	115.6	51.8	25.1	378.2
2013	13.6	91.7	49.3	79.0	56.6	64.1	354.3
2014	40.7	65.7	44.9	55.4	57.3	25.9	289.9
2012-2014	26.9	60.9	76.0	83.3	55.2	38.4	340.8
Long-term average	28.7	61.1	53.1	87.1	66.5	44.4	340.9
Difference (+/-)	-1.8	-0.2	+22.9	-3.8	-11.3	-6.0	-0.1

2.3. Scots pine growth and development measurement

At the end of 2012, 2013 and 2014, after the end of the growing season, a number of developmental features of young Scots pine trees were measured. The measurement was carried out: the height (cm), the root neck diameter (mm), the length of one-year increments in the last whorl (cm), the number of one-year increments of the last whorl (pcs) and the lengths of one-year increments of the last whorl (cm).

2.4. Acarological research

The samples for acarological tests were collected four times: June 25, 2013, October 15, 2013, June 3, 2014 and October 21, 2014. From each treatment of the experiment, at each sampling-time, 10 substrate samples were collected (3 or 4 samples from the microplot). In total, 40 samples with a volume of 50 cm^3 each were collected from each treatment. Mites extraction was carried out for 7 days in Tullgren apparatus. Then the mites were preserved in 70% ethyl alcohol. All mites were identified to the order, and moss mites to the species or genus, including juvenile stages. In total, 6,499 mites were identified, including 5,104 moss mites.

The average density (N) of mites was measured in 50 cm^3 of substrate. The dominance index (D) was estimated in %. The species richness and the diversity of moss mites was determined by the number of species (S), also the average number of species in the sample (s) and the Shannon general species diversity index (H) were calculated.

Before statistical analysis the measurement results were subjected to the logarithmic transformation – $\ln (x + 1)$ (Berthet & Gerard 1965). Statistical analysis was performed using the Statistica 13.3 software package. The Kolmogorov-Smirnov test was applied to evaluate the compliance of the distribution of measurable parameters with the normal distribution. However, due to the lack of normal distribution a non-parametric analysis of variance (Kruskal-Wallis test) was performed. In the case of the statistically significant differences ($p < 0.05$) the analysis was performed for each pair (Mann-Whitney *U* test) for selecting the significantly different means.

3. Results

3.1. Scots pine growth and development

The use of mulching treatments did not significantly affect the height of Scots pine plants during the first three years after planting (Table 2). The height of Scots pine trees ranged from 41.1 cm on the soil mulched with wood chips with addition of forest litter to 48.2 cm on the soil mulched only with wood chips.

On average, Scots pine plants cultivated on the control plots (without mulching) were by 4.9 cm higher comparing to the mulched plants. The mean value of studied feature ranged from 19.1 cm in 2012 to 71.5 cm in 2014. However, the differences between treatments were not statistically important.

Table 2. Effect of mulching with wood chips on Scots pine height (cm)

Treatment	Years			
	2012	2013	2014	2012-2014
C	20.4	45.9	78.3	48.2
W	19.1	45.5	66.2	43.6
WM	18.3	42.8	74.3	45.2
WL	18.6	37.7	67.1	41.1
Mean	19.1	43.0	71.5	44.5
$LSD_{0.05}$	ns	7.423	ns	ns

Explanations: C – control (uncovered soil – without mulching); W – soil mulched with wood chips; WM – soil mulched with wood chips with the addition of mycorrhizal preparation; WL – soil mulched with wood chips with the addition of forest litter; ns – not significant ($p < 0.05$).

The average diameter of the root neck of Scots pine plants grown in the years 2012-2014 on the plots mulched with wood chips (13.6 mm) was significantly lower than on the control plots (17.4 mm) (Table 3). However, there were no important differences in root neck diameter between individual mulching treatments. In each of the study years, the value of the observed characteristic of plants grown on the control plots were higher in comparison to the plants cultivated on mulched plots, but they were not statistically important.

Table 3. Effect of mulching with wood chips on the Scots pine root neck diameter (mm)

Treatment	Years			
	2012	2013	2014	2012-2014
C	7.2	16.7	28.1	17.4
W	5.8	13.1	22.0	13.6
WM	6.6	15.2	24.6	15.5
WH	6.2	13.8	24.3	14.8
Mean	6.5	14.7	24.7	15.3
$LSD_{0.05}$	ns	ns	ns	2.835

Explanations: see Table 2

There were no significant differences in the average length of one-year increments in the last whorl of Scots pine plants between the studied treatments (Table 4). The mean value of this feature ranged from 17.1 cm in 2012 to 20.8 cm in 2013. The lowest length of one-year increments (14.0 cm) was noted on the soil mulched with wood chips with the addition of forest litter and the highest (18.7 cm) on the soil mulched only with wood chips.

Table 4. Effect of mulching with wood chips on the average length of one-year increments in the last whorl (cm) of Scots pine

Treatment	Years			
	2012	2013	2014	2012-2014
C	17.8	21.0	19.4	17.8
W	18.7	19.5	19.1	18.7
WM	17.8	21.2	19.5	17.8
WL	14.0	21.3	17.7	14.0
Mean	17.1	20.8	18.9	17.1
$LSD_{0.05}$	ns	ns	ns	ns

Explanations: see Table 2

The number of one-year increments of the last whorl of Scots pine did not differ significantly among the tested treatments (Table 5). However, the highest value (6.2) of observed characteristic was noted in the case of control plants. The number of one-year increments of the last whorl was stable in the particular years of the study and ranging from 5.6 in 2012, and 2014 to 5.7 in 2013.

Table 5. Effect of mulching with wood chips on the number of one-year increments of the last whorl (pcs) of Scots pine

Treatments	Years			
	2012	2013	2014	2012-2014
C	6.2	6.5	6.4	6.2
W	5.4	4.7	5.1	5.4
WM	5.9	6.0	5.9	5.9
WL	4.8	5.7	5.2	4.8
Mean	5.6	5.7	5.6	5.6
$LSD_{0.05}$	ns	ns	ns	ns

Explanations: see Table 2

The sum of the lengths of one-year increments of the last whorl was not considerably modified by the performed mulching treatments (Table 6). The highest value of this trait (124.1 cm) was observes in the control plants, while the lowest on the plots mulched only with wood chips and on the plots mulched with wood chips with the addition of forest litter (95.4 cm). The sum of lengths of one-year increments of the last whorl varied between 96.7 cm in 2013 and 118.4 cm in 2014.

Table 6. Effect of mulching with wood chips on the sum of lengths of one-year increments of the last whorl (cm) of Scots pine

Treatments	Years		
	2013	2014	2012-2014
C	109.2	139.0	124.1
W	101.9	88.8	95.4
WM	104.7	127.0	115.9
WL	72.0	118.8	95.4
Mean	96.7	118.4	107.7
$LSD_{0.05}$	ns	ns	ns

Explanations: see Table 2

3.2. Analysis of mites number

Measurement of the number of mites carried out on the control plots revealed their low density, which was 4,020 individuals in 50 cm^3 of substrate (Table 7). Among the mites, Actinedida clearly dominated (88.6%). Another large group were moss mites which covered 9.2% of all mites. Therefore, the Oribatida to Actinedida ratio (Or : Ac) was extremely low (0.10). On the mulched plots, the density of mites was many times higher and ranged from 29,630 to 70,760 individuals in 50 cm^3 of substrate. Moreover, in contrast to the control plots, the mulched plots were dominated by moss mites, whose number ranged from 64.1 to 70.8% of all mites. On the mulched plots, Actinedida was the second large group, and Mesostigmata was the third largest group (on the plots WM and WL). The Oribatida to Actinedida ratio, on the mulched plots, was high and varied from 2.6 to 6.94. Acaridida and Tarsonemida were the least numerous mite groups in this study.

The most numerous population of moss mites was on the plots mulched only with wood chips (60,440 individuals in 50 cm^3 of substrate) (Table 7). In addition, the differences in the number of moss mites between the plots mulched only with wood chips and other mulching treatments were statistically significant. However, there was no important difference in the number of moss mites between the plots mulched with wood chips with the addition of mycorrhizal preparation and the plots mulched wood chips with the addition of forest litter. Compared to the control plots, the size of the Actinedida population on the mulched plots increased significantly, but the differences between the individual mulching treatments were not visible. The population size of Mesostigmata on the control plots and on the plots mulched only with wood chips was clearly lower than on the plots mulched with wood chips with the addition of mycorrhizal preparation, as well forest litter. Acaridida and Tarsonemida mites were found only on the plots mulched with wood chips with the addition of mycorrhizal preparation and on the plots mulched with wood chips with the addition of forest litter.

3.3. Analysis of moss mites clusters

24 species of moss mite were noted in the present study (Fig. 1). Most of them (21) were found on the plots mulched with wood chips with the addition of forest litter and only 2 on the control plots. On the plots mulched only with wood chips and on the plots mulched with wood chips with the addition of mycorrhizal preparation, 11 and 6 species of moss mites, respectively, were observed.

The analysis of the average number of species in the sample (s) presented the visible differences in the mite species abundance between the control plots and the plots mulched only with wood chips (Table 7). The highest value of this index (s = 3.7) was recorded on the plots mulched with wood chips with the addition of forest litter. The lowest Shannon's species diversity index (H) was noted on the control plots (H = 0.22) and the highest value of this index (H = 1.52) was found on the plots mulched with wood chips with the addition of forest litter.

In the group of moss mites, *Tectocepheus velatus* clearly dominated in all treatments of the experiment (Fig. 1). The highest domination index (D) (94.6%) estimated for this species was noted on the control plots, and the lowest (62.1%) was detected on the plots mulched with wood chips with the addition of forest litter.

Table. 7. Density of mites and selected species of moss mites (N in thousand individuals in 50 cm^3 of substrate), the ratio of Oribatida to Actinedida (Or : Ac), the number of species (S), the average number of species (s) and the Shannon's species diversity index (H) of moss mites in the studied mulching treatments of Scots pine

Index – Taxon	Treatments				Kruskal-Wallis test	
	C	W	WM	WL	*H*	*p*
N – Acaridida	0	0	0.03^{a}	1.53^{b}	31.09	0.000
N – Actinedida	3.56^{a}	8.71^{b}	6.78^{b}	7.13^{b}	29.53	0.000
N – Mesostigmata	0.09^{a}	0.09^{a}	1.39^{b}	1.45^{b}	26.73	0.000
N – Oribatida	0.37^{a}	60.44^{b}	27.80^{c}	18.99^{c}	71.56	0.000
N – Tarsonemida	0	0	0.57^{a}	0.53^{a}	8.69	0.034
N – Acari (Total)	4.02^{a}	70.76^{b}	36.57^{c}	29.63^{c}	72.28	0.000
N – *Oppiella nova* (Oudemans)	0	0.36^{a}	1.25^{a}	1.32^{a}	12.88	0.005
N – *Pergalumna nervosa* (Berlese)	-	-	-	1.26	-	-
N – *Scutovertex sculptus* Michael	0	6.95^{a}	2.87^{ab}	0.83^{b}	34.90	0.000
N – *Tectocepheus velatus* (Michael)	0.35^{a}	52.48^{b}	23.45^{c}	11.79^{c}	66.43	0.000
Others Oribatida (*N* < 1.0)*	0.02	0.65	0.23	3.79	-	-
Or : Ac	0.10	6.94	4.10	2.66	-	-
S – Oribatida	2	11	6	21	-	-
s – Oribatida	0.23^{a}	1.98^{b}	1.58^{b}	3.70^{c}	89.47	0.000
H – Oribatida	0.22	0.47	0.56	1.52	-	-

Explanations: ^{a,b,c} – data with the same letter do not differ significantly ($p < 0.05$)
**Autogneta longilamellata* (Michael) – W, WL; *Banksinoma lanceolata* (Michael) – WL; *Brachychthonius* sp. Berlese – WL; *Camisia biurus* (C. L. Koch) – W; *C. horrida* (Hermann) – WL; *C. segnis* (Hermann) – WM; *Carabodes minusculus* Berlese – WL; *C. subarcticus* Tragardh – WL; *Chamobates schuetzi* (Oudemans) – WL; *Eremaeus oblongus* C. L. Koch – WL; *Liochthonius* spp. van der Hammen – W; *Metabelba pulverulenta* (C.L. Koch) – W, WM, WL; *Oppiella neerlandica* (Oudemans) – W; *Oppiella nova* (Oudemans) – W, WM, WL; *Oribatula tibialis* (Nicolet) – C, WL; *Pergalumna nervosa* (Berlese) – WL; *Punctoribates punctum* (C. L. Koch) – WL; *Scheloribates laevigatus* (C. L. Koch) – WL; *Scheloribates latipes* (C. L. Koch) – W, WL; *Suctobelba* spp. Paoli – W, WM, WL; *Trhypochthonius tectorum* (Berlese) – WL; *Trichoribates trimaculatus* (C. L. Koch) – W, WL

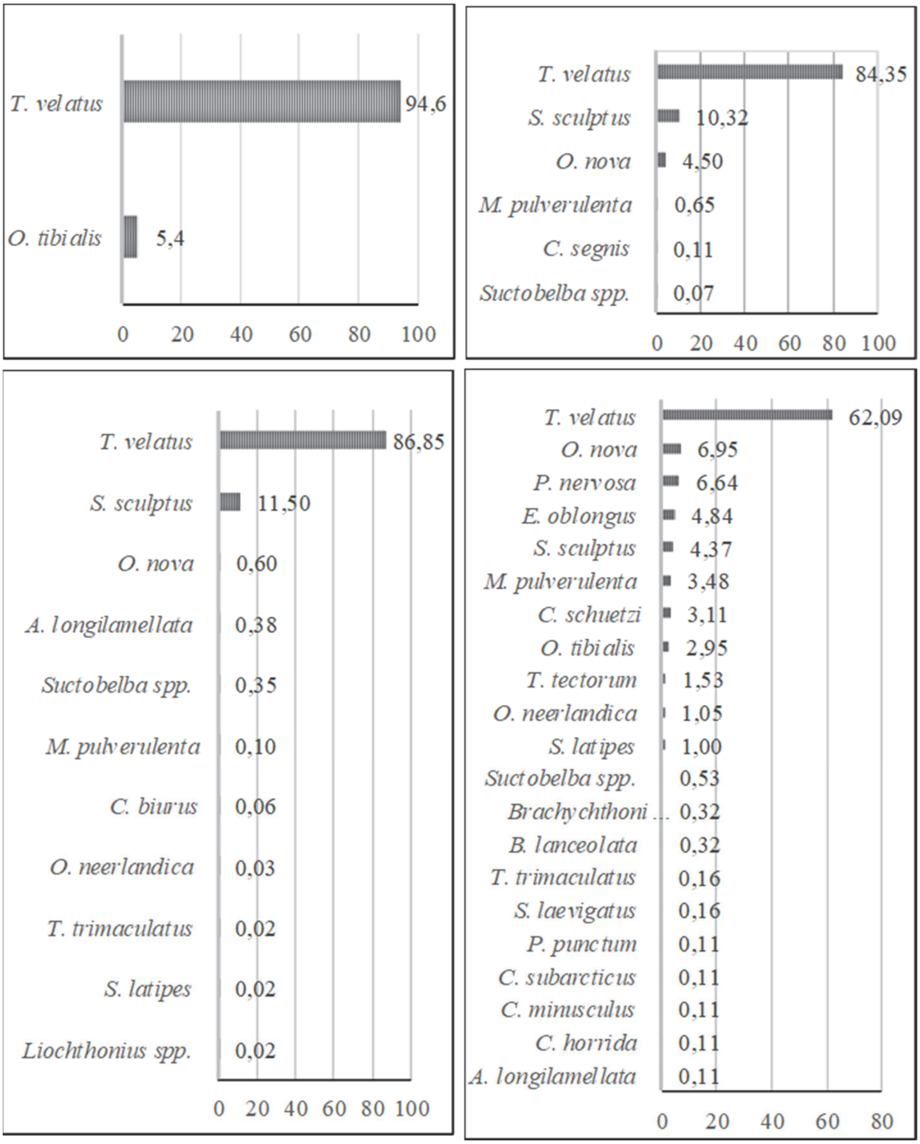

Fig. 1. Domination index (D) for the moss mites groups in the particular experiment treatments

3.4. Analysis of the occurrence of selected moss mites species

On the control plots the number of *Tectocepheus velatus* was only 350 individuals in 50 cm^3 (Table 7). The highest population of this species was observed in the case of mulching only with wood chips (522,480 individuals in 50 cm^3 of substrate). Much lower population of *Tectocepheus velatus* was noted on the plots mulched with wood chips with the addition of mycorrhizal preparation or forest litter. *Oribatula tibialis* also appeared on the control plots as the second species of mites (20 individuals in 50 cm^3 of substrate). On the plots mulched only with wood chips, the second most abundant species was *Scutovertex sculptus* (830-6,950 individuals in 50 cm^3 of substrate). *Oppiella nova* was also a large species of moss mites on the mulched plots (360-1,320 individuals in 50 cm^3 of substrate).

4. Discussion

The height and width of the trunk are the two most commonly measured features that determine the size of tree biomass (Orzeł 2007). In the present research, the height of Scots pine after the first growing season (measurement at the end of 2012) ranged from 18.3 to 20.4 cm (average 19.1 cm). For comparison, in the study reported by Klimek et al. (2009) the average height of Scots pine trees in the first year after planting on the former military training ground in Bydgoszcz-Jachcice (Żołędowo Forest District) was 36.2 cm. In the study presented by Klimek et al. (2009) the highest growth of the Scots pine was noted in the case of seedlings produced using mulching and fertilizing with compost mixed with sawdust, as well as grown on the plots, where lupine was not the forecrop. In the current study, the height of trees after the second growing period (measurement at the end of 2013) varied between 37.7 and 45.9 cm (average 43 cm). According to the research published by Klimek & Rolbiecki (2011), the height of Scots pine trees in the second year after planting on the former military training ground in Bydgoszcz-Jachcice (Żołędowo Forest District) was on average 57.7 cm. The plants grown on the former military training ground were higher (58.5 cm) than the plants grown on the control forest plots (51.7 cm). The different way of seedlings production is an important factor affecting plant growth after planting, as well biomass production (Klimek et al. 2008, 2009, 2011, 2013, Orzeł 2007). In the present experiment, for planting were used Scots pine seedlings with a covered root system production in a container nursery.

Compared to the results published by Klimek et al. (2009) as well Klimek & Rolbiecki (2011), in the current research lower growth and smaller diameter of the root neck of Scots pine plants in the first three years of cultivation on the plots mulched with wood chips with the addition of forest litter can be explained by the immobilization of nutrients occurring in this treatment. According to Prescott et al. (2000), the accumulation of organic matter on the soil surface can affect the forest ecosystem by immobilizing nutrients, which does not allow plants to absorb them. Generally, the physical and environmental conditions can hinder the growth and survival rate of tree seedlings. Szabla (2007), considering the development of selected growth parameters of Scots pine (the height, the diameter of root neck and the sum of length of the lateral shoots of the last whorl) in the different crop groups and on the different types of soil, the highest height increases observed successively for the seedlings mycorrhized and non-mycorrhized: in the crops on the former agricultural lands, next on the grounds after cutting down of forest or fire, on the forest areas degraded by industrial emissions and on the lands reclaimed after sand exploitation. At the same time, the author reports that in the first three years of cultivation the increase of height and diameter of the root neck of mycorrhized Scots pine seedlings was significantly greater (often 2-3 times) than in the case of non-mycorrhized seedlings. In each subsequent year, the differences in the height between mycorrhized and non-mycorrhized seedlings decreased.

A number of studies confirm the usefulness of the wood chips, especially Scots pine chips, as the mulching material that create a good conditions for the development of soil mesofauna (Klimek & Chachaj 2015, 2018, Klimek et al. 2017a, b). Therefore, in the current experiment this material was selected for mulching degraded forest soil for its revitalization. At the first stage of seedlings growth (forest succession), this treatment can replace the layer of forest litter, which naturally occurs on the forest soil of the renewed forests after cutting down the mature trees.

The size of the mites population on the control plots noted in the present experiment was low and similar to the number of mites recorded in the years 2008 and 2009 by Klimek et al. (2009) and Klimek & Rolbiecki (2011). Both in the above research and in the current study, a clear numerical superiority of Actinedida over Oribatida was observed. After mulching with wood chips, the total number of mites increased many times, and moss mites began to dominate in these group. The Oribatida to Actinedida ratio (Or : Ac) may indicate the environment quality, as well as the degree of its anthropogenisation (Werner & Dindal 1990, Gulvik 2007). According to Werner & Dindal (1990) the Oribatida to Actinedida ratio below 1.0 is recorded on arable land, while above 1.0 occurs in more stable ecosystems, e.g. semi-natural meadows and forests, i.e. on the soils with a significant share of the organic matter. In the present study, the high value of Or : Ac ratio noted after using the wood chip mulching on the degraded soil may indicate an increase in the biological balance of this habitat.

The former military training ground in Bydgoszcz-Jachcice, where the research was conducted, had a very small population of the soil mites and very low species diversity of moss mites. In 2008 and 2009, in another area of the same former military training ground, was conducted the research in which phytomelioration was carried out using lupine cultivation before forest planting (Klimek et al. 2009, Klimek & Rolbiecki 2011). The purpose of phytomelioration was to enrich the soil with nutrients to improve the physical properties and soil fertility. However, this treatment neither increased the population of soil fauna nor its diversity.

In the present study, mulching of soil with wood chips obviously increase the number, as well the species diversity of mites, especially moss mites. The largest increase in the moss mite population was observed in the wood chips without additives. However, the largest increase in the species diversity was recorded in wood chips with the addition of forest litter.

In the forest ecosystem, numerous micro-arthropods perform very important soil-forming functions, but one of the most important are moss mites. Unfortunately, these little animals have a limited adaptability to new habitats (Beckmann 1988, Wanner & Dunger 2002, Lehmitz et al. 2011). Haimi (2000) believes that the presence of mesofauna, which restores the soil biological activity, is important during the soil remediation operations. Therefore, the reclamation treatments can be supported by the addition of fresh forest litter, which contains a large amount of mesofauna and soil microorganisms such as fungi and bacteria. According to Klimek et al. (2008), Klimek (2010), Klimek & Rolbiecki (2011, 2014), Klimek at al. (2012, 2013) and Klimek & Chachaj (2015) for the effective inoculation of soil with forest mesoflora and mesofauna, 1 cm of the forest litter needs to be introduced into a suitable substrate, e.g. wood chips.

As Haimi (2000) reported that micro-arthropods can be used in the soil reclamation processes in two ways. First, micro-arthropods have a direct and indirect influence on the soil metabolism, as they feed on microorganisms, which stimulates their growth and reproduction. Secondly, micro-arthropods are bioindicators of the biological state of soils. Moss mites are considered as good bioindicators of the biological properties of soil (Behan-Pelletier 1999, 2003, Gulvik 2007). In addition, moss mites (as vectors) have a beneficial influence on the spread of bacteria and fungi, so they have an indirect effect on the development of mycorrhizae (Klironomos & Kenrick 1996, Behan-Pelletier 1999, Schneider et al. 2005, Remén et al. 2010).

Among the moss mites, *Tectocepheus velatus*, for which the dominance rate ranged from 62.9 to 94.6%, clearly dominated in all treatments of the present experiment (Fig. 1). *T. velatus* are a common soil moss mites that occurring in the different biotopes (Weigmann & Kratz 1981). *T. velatus* has a high reproduction rate and high ability to colonize new habitats. Generally, in the pine forests, this species most often dominates among moss mites, and is also a good bioindicator of the soil biological activity (Klimek 2000). In the current study, *Oppiella nova* was second (mulching with wood chips with the addition of forest litter) or third (mulching only with wood chips and mulching with wood chips with the addition of mycorrhizal preparation) group of moss mites species in terms of population size. Both of the above-mentioned moss mites species are the pioneer species; they produce a large number of offspring, they are parthenogenic and develop according to the life strategy of the "r" type, which is a genetically conditioned set of the individual traits enabling survive (Siepel 1994, Skubała & Gulvik 2005). In addition, these moss mites species may prey on ectomycorrhizae, thus contributing to their spread (Schneider et al. 2004, Remén et al. 2010).

Scutovertex sculptus also occupied an important place in the hierarchy of the moss mites dominance. This species clearly preferred the wood chips without additions. *S. sculptus* is a large moss mite with strong sclerotization of the cuticle, and thus it is well protected against drying out and adapted to the life in the initial soils in the conditions of high sunlight, e.g. on the fallow soils and industrial heaps (Klimek et al. 1991, Skubała 1999, Rolbiecki et al. 2006). In the present research, no *S. sculptus* was observed on the control plots, however, in earlier studies at the former military training ground in Bydgoszcz-Jachcice, this species was noticed, as did *Oppiella nova* and *Tectocepheus velatus* (Klimek & Rolbiecki 2011). Moss mites, which rarely appearing on the experimental surface before the start of the study, most likely found favorable conditions for development in the wood chips and gradually inhabited them.

On the plots mulched with wood chips with the addition of forest litter, the moss mites domination structure was more even than in the other study treatments. The average number of species and the species diversity index on the plots mulched with wood chips with the addition of forest litter were much higher than for other treatments. After using this treatment, the average number of species and the species diversity index of the substrate were most similar to the forest soils (Klimek & Seniczak 2002, Klimek 2004).

The research indicates the great usefulness of Scots pine wood chips for practical use in the regeneration of degenerated soils, on which a stable forest ecosystem will be created in the future. For this purpose, the wood chips can be used without additions, but then the succession of soil micro-arthropods will last much longer, and the time of stable and species-diverse soil formation will be extended. This process can be accelerated by adding the forest soil mesoflora and mesofauna to the wood chips with the litter coming from a mature forest. In the case of the addition of mycorrhizal preparation to the wood chips, no effect on the number and the species diversity of mites in the substrate was observed.

5. Conclusions

1. The use of soil mulching with the Scots pine wood chips did not significantly affect the growth and developmental characteristics of the Scots pine plants.
2. After mulching with wood chips, the total number of mites increased many times, and moss mites began to dominate among micro-arthropods.
3. Mulching treatments increased the number and the species diversity of moss mites in the substrate. The number of moss mites increased the most in wood chips without additives. The highest species diversity was observed in the wood chips with the addition of forest litter.
4. Among moss mites *Tectocepheus velatus* visibly dominated in all study treatments. *Oppiella nova* and *Scutovertex sculptus* also constituted numerous mites populations.
5. The study shows that the wood chips are very useful for use in the regeneration of the degenerated forest soils.
6. In general, the use of soil mulching with Scots pine wood chips did not affect the growth characteristics of the young Scots pine trees.

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Abstract

The purpose of this investigation was to indicate the most effective method of revitalizing degraded forest area. The different modifications of wood chips were used as a substitute for humus layer. The mites (Acari), and moss mites (Oribatida) as the bioindicators of soil succession changes were used. The study began 2 years after planting of Scots pine seedlings on the land devastated by military activity, at the former military training ground (GPS: 53.156943N, 17.986440E). The soil on this area was in the type of rusty soils and subtype of the rusty algae soils. Scots pine seedlings were planted in spring 2011, in a distance 1.5×0.8 m. In one-factor experiment four soil mulching treatments were tested: 1. uncovered soil – control (C), 2. soil mulched with wood chips (W), 3. W + mycorrhizal preparation (WM), 4. W + forest litter (WL). Three replicates of microplots arrangement was applied. Each microplot was 5 m long with 3 rows of Scots pine. Each replication covers 10 rows. Mulching with wood chips was carried out on April 12, 2012. On October 25, 2012, the wood chips on the WM microplots were inoculated with the mycorrhizal biopreparation, and on the WL microplots, a 10% addition of fresh forest litter from the ripe fresh coniferous forest was applied. After the end of the growing season of 2012, 2013 and 2014, the measurement of the plants was carried out (the height, the root neck diameter, the length of one-year increments in the last whorl, the number of one-year increments of the last whorl and the lengths of one-year increments of the last whorl). The samples for acarological tests were collected four times. In total, 40 substrate samples with a volume of 50 cm^3 each were collected from each treatment. Mites extraction was carried out for 7 days in Tullgren apparatus. Mites were identified to the order, and moss mites to the species or genus, including juvenile stages. Calculated: the average density of mites, the dominance index, the species richness, the diversity of moss mites, the average number of species, and the Shannon general species diversity index. The use of soil mulching with the Scots pine wood chips did not significantly affect the growth and developmental characteristics of the Scots pine plants. After mulching with wood chips, the total number of mites increased many times, and moss mites began to dominate among micro-arthropods. Mulching treatments increased the number and the species diversity of moss mites in the substrate. The number of moss mites increased the most in wood chips without additives. The highest species diversity was observed in the wood chips with the addition of forest litter. Among moss mites *Tectocepheus velatus* visibly dominated in all study treatments. *Oppiella nova* and *Scutovertex sculptus* also constituted numerous mites populations. The study shows that the wood chips are very useful for use in the regeneration of the devastated and degraded forest soils.

Keywords:
forest litter, mite, moss mite, mulching, mycorrhizal preparation, *Pinus sylvestris*

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Assessment of the Possibility of Introducing a Cogeneration System in the Biogas Development Process by the Example of the Wastewater Treatment Plant Located in Rybnik Orzepowice

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1. Introduction

Combined electricity and heat production systems are used in sewage treatment plants due to the possibility of using heat to warm up the sludge which has been introduced and circulates in separate fermentation chambers (Polish acronym: WKF) and the use of electricity for the plant's own purposes or for sale to external customers (Kołodziejak 2012). Biogas cogeneration systems are used to produce combined electricity and heat in wastewater treatment plants. Biogas is a product derived from the sludge fermentation process carried out in fermentation chambers. In accordance to Art.2 point 28 Directive (EU) 2018/2001 biogas means "gaseous fuels produced from biomass" (Directive 2018/2001).

Biogas consists mainly of methane: 55-70%, carbon dioxide: 32-37%, hydrogen: about 1%, nitrogen: 0.2-0.4% and other gases in trace amounts (e.g. Słupek 2020, Kisielewska 2020). In biogas, hydrogen sulphide is also found in trace amounts, which due to corrosive aggressiveness is removed from the tank prior to biogas storage in it (Oleszkiewicz 1998).

Table 1 summarizes the results of biogas testing from the Rybnik Orzepowice wastewater treatment plant carried out in the years 2015-2018.

Information in the scientific literature provided by many authors indicates that in very favourable conditions it is possible to obtain 200 m^3 of biogas from 1,000 m^3 flowing into municipal sewage treatment plants. However, when calculating the technical potential it is assumed that 100 m^3 of biogas can be obtained from 1000 m^3 of sewage flowing in (Kaltschmitt 2001).

According to (Kołodziejak 2012), on average, one cubic meter of biogas allows the production of:

- for a split system:
  - 2.1 kWh of electricity (assuming 33% system efficiency),
  - 5.4 kWh of thermal energy (assuming 85% system efficiency),
- for the combined system: 2.1 kWh of electricity and 2.9 kWh of heat.

Table 1. Results of biogas tests carried out from 2015-2018

Parameter	Unit	Date of the analysis				Arithmetic mean
		2015-02-13	2016-03-21	2017-03-24	2018-03-26	
Methane CH_4	% vol.	60.90	63.00	69.90	65.90	64.93
Carbon dioxide CO_2	% vol.	38.90	37.00	30.10	34.10	35.03
Oxygen O_2	% vol.	<0.1	<0.1	<0.1	<0.1	<0.1
Carbon monoxide CO	% vol.	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Nitrogen N_2	% vol.	<0.1	<0.1	<0.1	<0.1	<0.1
Hydrogen sulphide H_2S	ppm	9.0	41.0	35.0	6.0	22.75
Calorific value	kJ/m^3	21,860.0	22,600.0	25,100.0	23,655.0	23,303.8

Source: (Karwot et al. 2018)

Variable atmospheric conditions affecting fluctuations in the wastewater inflow, i.e. precipitation, drought, temperature affect the amount of biogas produced and the demand for heat and electricity in the wastewater treatment installation.

2. Research methodology

2.1. Research object

The Rybnik-Orzepowice wastewater treatment plant which operates in the Biodenipho® technology (Karwot et al. 2018) is located in Rybnik. It receives and treats wastewater from Rybnik agglomeration with a pollutant load expressed as Equivalent Number of Residents of about 92,000 PE (Person Equivalent). In addition to the mechanical-biological-chemical processes of wastewater treatment, the sewage treatment plant has a sludge processing node, including a part related to sewage sludge fermentation, biogas storage and processing.

The biogas storage and processing installation includes the following devices:

- biogas desulphurisation tank,
- condensate wells (2 pcs),
- biogas tank,
- biogas blower,
- biogas analyser,
- cogeneration unit,
- gas boilers,
- flare.

A cogeneration unit and gas boilers generate energy in the form of electricity and heat. Electricity from a cogeneration unit is used for the sewage plant's own needs or it is sold to an external recipient. The generated heat, however, produced on the cogeneration unit and in boilers is used to maintain the temperature of the sludge in the methane fermentation process, to heat buildings and to prepare domestic hot water.

The following has been installed in the system:

- two Viesman VITOPLEX 350 boilers with a rated heat output of 350 kW, each,
- PETRA 250C cogenerator with an electric rated power: 190/190 kVA/kWe, rated thermal power 231 kW, with electrical efficiency: 38.6%, thermal efficiency: 46.9%.

The cogenerator operates with a power of approx. 180 kWe (i.e. with an efficiency of approx. 94.7%), which allows obtaining around 4,320 kWh/d per day. With the maximum use of the power of a cogeneration unit, approx. 4,560 kWh/d of electricity can be obtained daily. Operation at maximum power is not recommended by the device manufacturer. During operation, oil change intervals occur (every 400 hours of operation) and the machine is serviced (every 1,600 hours of operation). Due to the synchronization of the electricity generated from the cogenerator, with the electricity from the external operator, there are also periodic breaks in the operation of the cogeneration system.

The total rated thermal power of the devices is 931 kW, including: 700 kW boiler power (two 350 kW boilers), 231 kW cogeneration power. The heat production system is not metered. Biogas is the main fuel used to produce electricity and heat, but it is possible to supply boilers with natural gas.

In summer, the sludge is heated mainly with the heat from the cogenerator. In winter, half of the heat required to heat the sludge comes from a cogenerator, while the rest from boilers. The heat from boilers is used in winter to heat the administrative buildings and workshop buildings. In the case of insufficient amount of biogas, boilers can also be supplied with natural gas.

2.2. Research methodology

Measurement data of the years 2013-2018 (daily, monthly data) held by the Water and Sewage Limited Liability Company [Przedsiębiorstwo Wodociągów i Kanalizacji Sp. z o.o.] in the scope of: the amount of inflowing sewage, the amount of biogas produced and consumed by the cogeneration unit, boilers and biogas sent to flaring, the amount of electricity generated from biogas, the total amount of electricity consumed by the Rybnik-Orzepowice sewage treatment plants.

The monthly amounts of wastewater flowing into the treatment plant were determined on the basis of measurements of the daily wastewater inflow. The amount of wastewater flowing through the Sewage Treatment Plant in Rybnik-Orzepowice is measured continuously with an ultrasonic level meter installed in a measuring chamber with a Parschall venturi, measuring 16.7x2.48 m, located behind the main pumping station. Table 2 presents the average daily sewage flow in the years 2013-2018 broken down by months. Table 3 presents the average daily amount of biogas produced in the years 2013-2018 divided into months.

Biogas flow is measured separately on each device, i.e. biogas flow directed to boilers: MZ 50 turbine flow meter manufactured by Itron (Q_{max} = 100 m^3/h, Q_{min} = 6 m^3/h, 1 ipuls = 0,1m^3), gas flow to the cogeneration unit: turbine flow meter MZ 80 manufactured by Itron (Q_{max} = 160 m^3/h, Q_{min} = 10 m^3/h, 1 ipuls = 1 m^3), biogas flow to the flare: MZ 100 turbine flow meter manufactured by Itron (Q_{max} = 400 m^3/h, Q_{min} = 16 m^3/h, 1 ipuls = 1 m^3).

The wastewater treatment plant in Rybnik is powered by two 20 kV cable lines at the ends of which there are 20/0.4 kV transformers. Each transformer supplies the main switchboard: RG1 and RG2 with a voltage of 0.4 kV, which work separately. A coupling was located between the RG1 and RG2 switching stations. The electricity produced in cogeneration is sent exclusively to the RG2 switching station and mostly used for own needs. The excess of electricity produced in cogeneration is sent to the power network. Based on the indications of the metering and billing system installed on the 20 kV line and the generator's gross production measurement system, the amount of electricity from cogeneration used for own needs is calculated.

Table 4 presents the average daily total demand for electricity by wastewater treatment plant Rybnik-Orzepowice (WWTP Rybnik-Orzepowice) in the years 2013-2018 broken down by months. Table 5 shows the average daily amount of electricity produced from biogas by WWTP Rybnik-Orzepowice in 2013-2018, broken down by month.

Table 2. Average daily sewage flow in 2013-2018 broken down by months [m^3/d]

Year	**Month**												**Annual mean**
	01	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	
2013	16,898	18,944	18,109	20,035	23,241	26,665	17,579	16,227	18,792	15,504	16,054	15,946	**18,666**
2014	15,557	16,324	16,773	15,981	17,907	19,067	17,965	19,746	21,794	18,271	18,017	17,403	**17,900**
2015	17,321	17,487	16,915	16,236	16,577	16,858	15,697	14,297	15,088	15,328	17,018	16,319	**16,262**
2016	16,680	18,494	16,872	17,930	15,912	17,274	19,219	18,541	16,109	18,234	16,605	18,187	**17,505**
2017	16,530	19,316	18,765	22,307	20,133	18,489	18,299	17,334	22,010	23,609	20,897	19,911	**19,800**
2018	17,702	17,356	18,706	17,174	19,227	19,592	17,766	16,097	16,300	16,608	15,322	17,866	**17,476**
Mean	***16,781***	***17,987***	***17,690***	***18,277***	***18,833***	***19,658***	***17,754***	***17,040***	***18,349***	***17,926***	***17,319***	***17,605***	***17,935***

Source: own elaboration

Table 3. Average daily biogas quantity of biogas produced in 2013-2018 broken down by month [m^3/d]

Year	**Month**												**Annual mean**
	01	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	
2013	3,150	2,990	3,003	3,311	3,591	3,430	2,914	2,546	2,755	2,933	2,796	3,144	**3,047**
2014	3,027	2,996	3,345	3,661	3,734	3,558	3,164	2,636	2,538	2,591	2,805	3,164	**3,102**
2015	3,317	3,204	3,069	3,260	3,166	2,485	2,609	2,238	2,049	2,328	2,688	3,051	**2,789**
2016	2,804	2,983	2,824	2,831	2,756	2,525	2,323	2,610	2,778	2,342	2,176	1,860	**2,568**
2017	1,907	2,822	2,968	2,863	2,906	2,420	2,098	1,907	2,062	2,297	2,855	2,746	**2,488**
2018	3,037	2,630	2,685	3,018	2,805	2,971	2,897	2,666	2,539	2,529	2,974	3,622	**2,864**
Mean	**2,874**	**2,938**	**2,982**	**3,157**	**3,160**	**2,898**	**2,668**	**2,434**	**2,454**	**2,503**	**2,716**	**2,931**	**2,809**

Source: own elaboration

Table 4. Average daily total electricity demand by the OS Rybnik-Orzepowice in 2013-2018 broken down by month [kWh/d]

Year	Month												Annual mean
	01	02	03	04	05	06	07	08	09	10	11	12	
2013	8,946	9,176	9,633	9,360	9,206	9,128	7,917	8,245	8,295	7,955	8,171	9,047	**8,757**
2014	8,727	9,271	8,905	8,438	7,964	7,929	7,834	8,126	8,885	8,650	9,015	9,217	**8,580**
2015	8,918	8,799	9,079	9,018	8,730	9,709	8,220	8,463	9,354	9,554	9,261	8,599	**8,975**
2016	8,993	8,534	8,810	8,716	8,354	8,178	8,005	7,867	7,621	7,788	8,143	8,776	**8,315**
2017	9,635	9,637	9,535	9,987	9,136	9,070	8,526	8,468	8,832	8,943	9,103	9,759	**9,219**
2018	9,483	9,626	10,667	10,178	9,235	8,896	8,311	8,388	8,383	8,886	8,990	9,686	**9,227**
Mean	**9,117**	**9,174**	**9,438**	**9,283**	**8,771**	**8,818**	**8,135**	**8,259**	**8,562**	**8,629**	**8,780**	**9,181**	**8,846**

Source: own elaboration

Table 5. Average daily amount of electricity produced from biogas by WWTP Rybnik-Orzepowice in 2013-2018 broken down by month [kWh/d]

Year	Month												Annual mean
	01	02	03	04	05	06	07	08	09	10	11	12	
2013	3,489	4,287	4,146	4,182	4,053	3,724	4,286	4,094	3,923	4,145	4,245	4,247	**4,068**
2014	4,005	4,253	4,123	3,832	4,013	3,454	4,059	3,996	4,044	4,110	3,997	3,970	**3,988**
2015	4,237	4,184	4,256	4,194	4,057	2,566	3,894	3,952	3,496	3,930	3,905	3,603	**3,856**
2016	3,890	3,573	3,855	3,653	3,788	4,146	4,158	4,202	4,149	2,657	2,447	2,512	**3,586**
2017	2,387	3,200	4,220	4,251	3,984	4,158	3,896	3,612	3,756	3,861	3,916	4,221	**3,788**
2018	3,489	4,287	4,146	4,182	4,053	3,724	4,286	4,094	3,923	4,145	4,245	4,247	**4,068**
Mean	**3,583**	**3,964**	**4,124**	**4,049**	**3,991**	**3,628**	**4,096**	**3,992**	**3,882**	**3,808**	**3,793**	**3,800**	**3,892**

Source: own elaboration

3. Results and their interpretation

Analysing the average value of sewage inflow for 2013-2018, it can be stated that it remains at the level of 17,935 m^3/d (dry periods: -20.2%; periods with precipitation: + 48.7%). Significant fluctuations in the amount of sewage inflow are associated with the extensive sewage network, which in some parts is combined sewage system. In the months May-June and September-November, increased sewage inflows to sewage treatment plants are observed, resulting from the occurrence of increased precipitation in these months. Daily variability of wastewater inflow is presented in Figure 1.

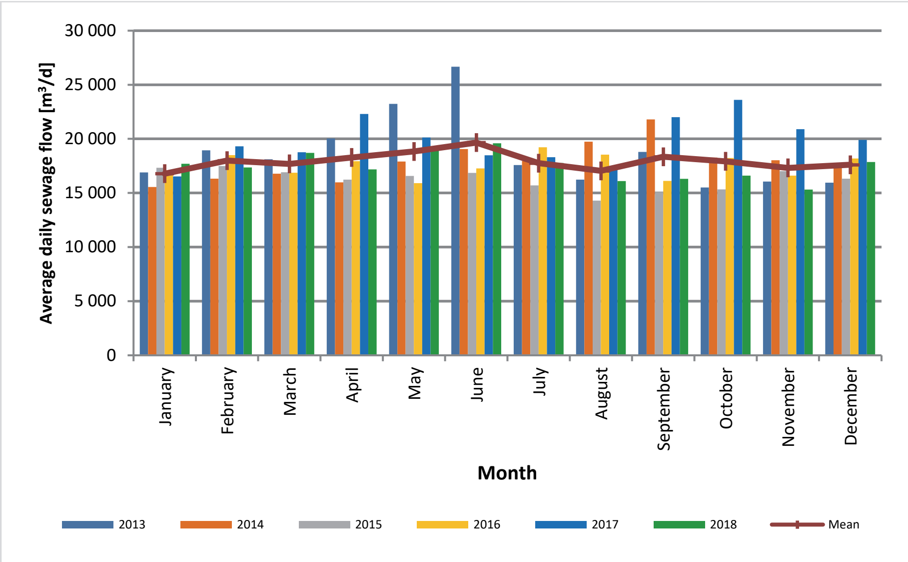

Fig. 1. Average daily sewage flow in 2013-2018 broken down by month [m^3/d]; Source: own elaboration

Analysing the average value of biogas production for 2013-2018, it can be stated that it remains at the level of 2,809 m^3/d (±33%). A decrease in biogas production is observed in the months June-October. The average daily amount of biogas produced in 2013-2018 is presented in Figure 2.

Analysing the average value of total electricity consumption for 2013-2018, it can be stated that it remains at the level of 8,846 kWh/d (-13.8%; +20.6%). Reduced demand for electricity occurs in the summer months (July-September), while in the autumn-winter-spring period there is a higher electricity consumption compared to the average. The average daily total demand for electricity is shown in Figure 3.

Analysing the average value of electricity generated from biogas for 2013-2018, it can be stated that it remains at the level of 3,892 kWh/d (-38.7%; +10.1%). Chart 4 presents the average daily amount of electricity produced from biogas by WWTP Rybnik-Orzepowice in 2013-2018 broken down by month.

Analysing long-term data on the amount of electricity produced from biogas in relation to the total demand for electricity by the treatment plant, it can be concluded that the energy produced from biogas allows us to cover the demand at the level of 44% (minimum 39%, maximum 50%). Chart 5 presents the share of electricity generated from biogas in relation to the total demand for electricity by the treatment plant.

Biogas consumption in 2013-2018 by individual facilities amounted to: cogeneration unit approx. 65%, boilers: 10%, flare: 25%. More than 75% of biogas is used to produce electricity and heat used for the sewage plant's own needs. Excess biogas, i.e. about 25% is burned in a flare.

Figure 6 shows the use of biogas in the system: cogeneration unit, boilers and a flare. The data shows the work of the above units in the years 2013-2018 and are average daily monthly values.

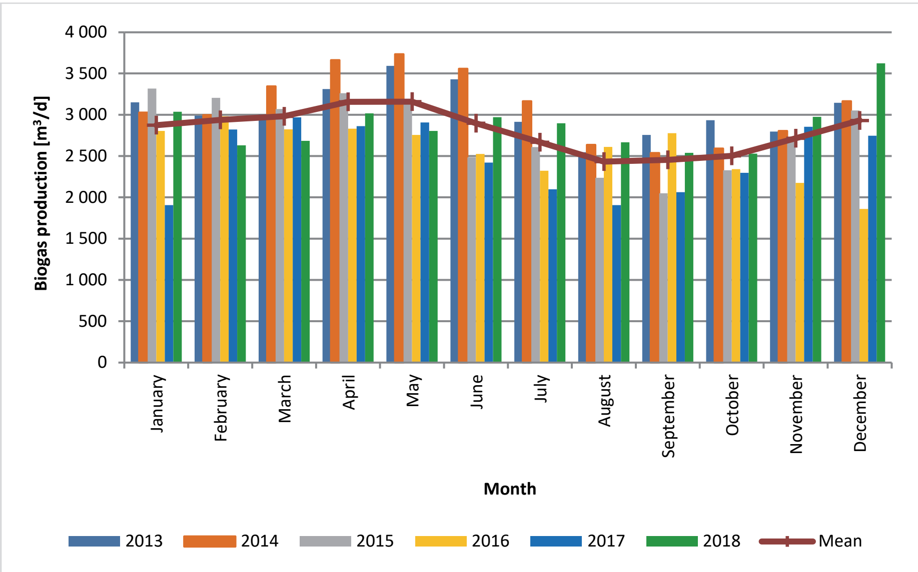

Fig. 2. Average daily biogas quantity of biogas produced in 2013-2018 broken down by month [m^3/d]; Source: own elaboration

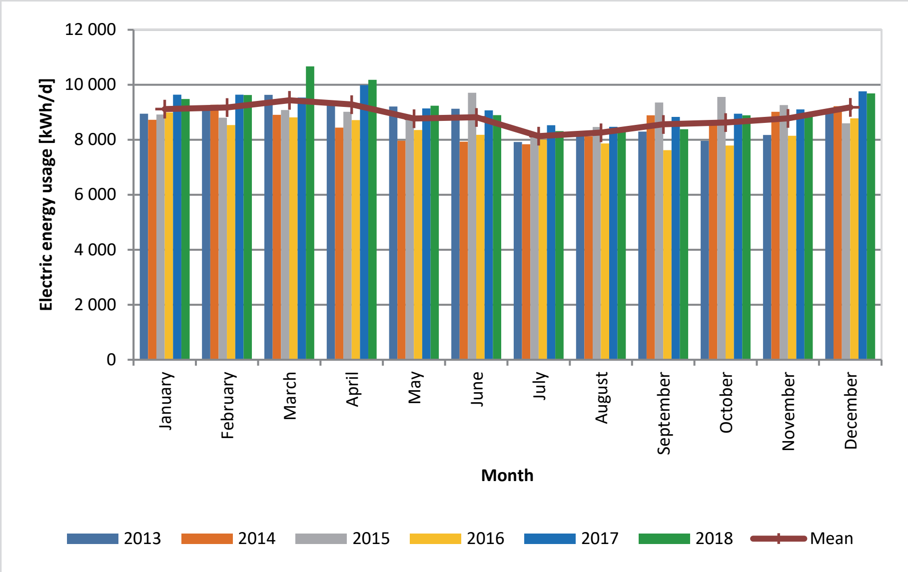

Fig. 3. Average daily total demand for electricity by WWTP Rybnik-Orzepowice in 2013-2018 broken down by month [kWh/d]; Source: own elaboration

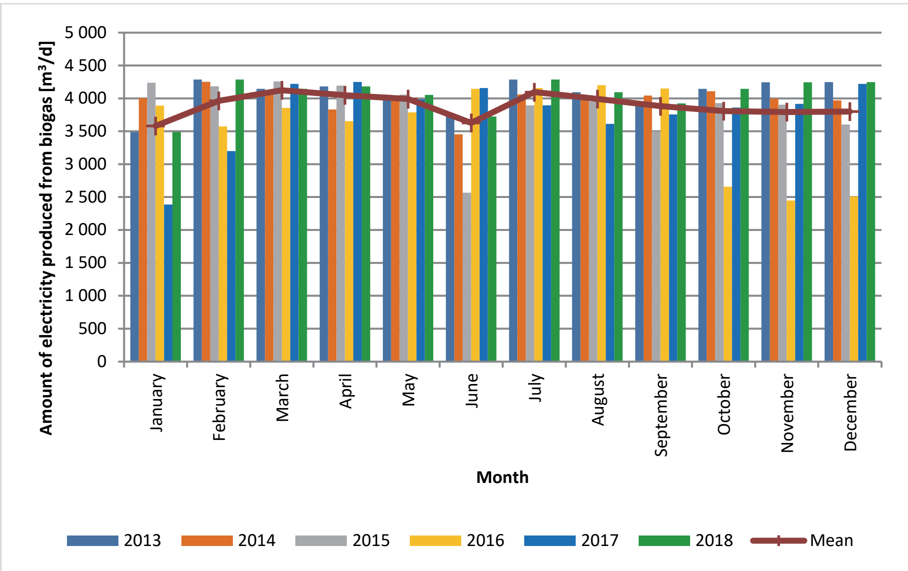

Fig. 4. Average daily amount of electricity produced from biogas by WWTP Rybnik-Orzepowice in 2013-2018 broken down by month [kWh/d]; Source: own elaboration

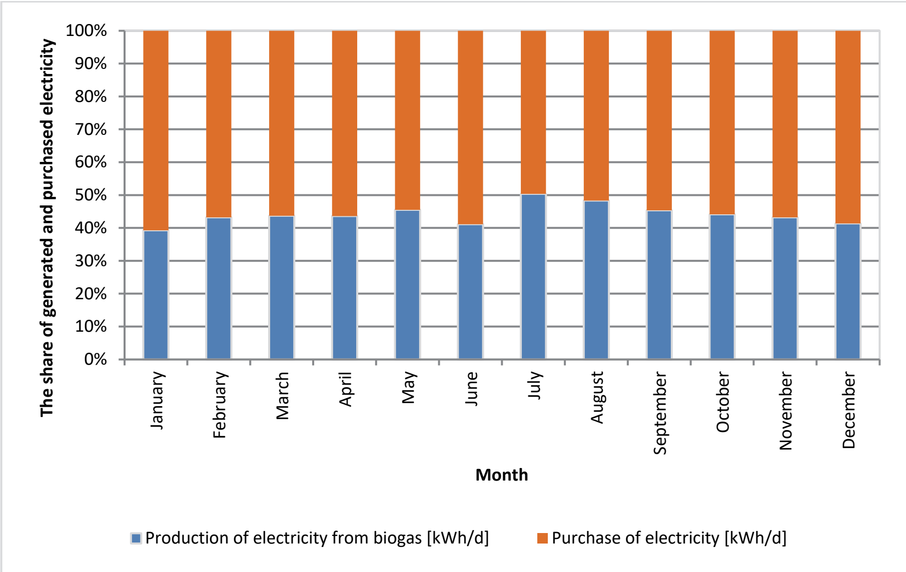

Fig. 5. The share of electricity generated from biogas in relation to the total demand for electricity by the treatment plant; Source: own elaboration

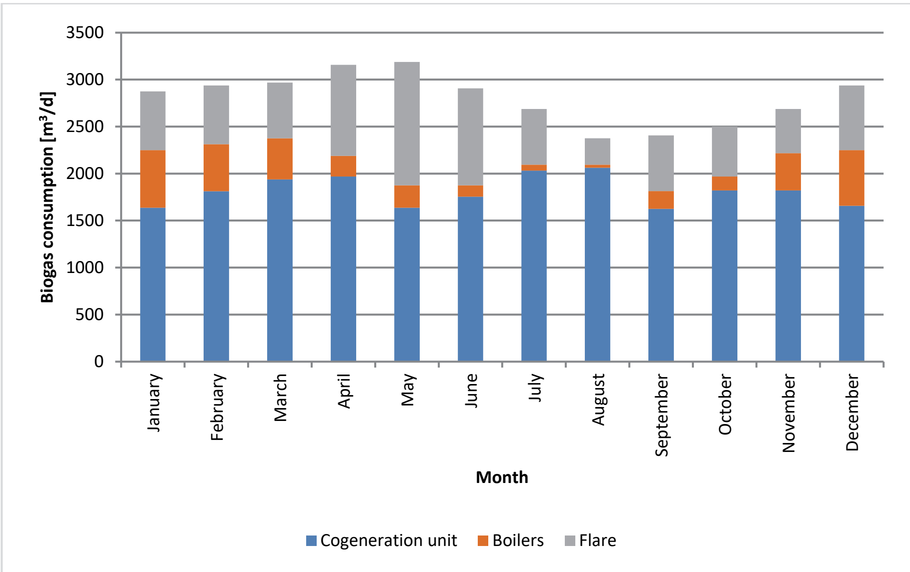

Fig. 6. The use of biogas in the system: cogeneration unit, boilers and flare; Source: own elaboration

In Kaltschmitt & Hartmann (2001) is presented assumptions for a cogeneration installation converting biogas into electricity and heat. The installation was planned for biogas combustion in the amount of 2115 m_n^3/d, with an estimated biogas extraction rate from sewage at the level of 0.101 m_n^3/m^3 (Energoprojekt Gliwice 2009). The monitoring of the daily amount of sewage inflow and the daily amount of biogas produced showed that during 6 years of operation of the installation, the average daily amount of biogas produced was 2809 m_n^3/d (min. 1806 m_n^3/d, max. 3102 m_n^3/d). In relation to the assumed amount (Energoprojekt Gliwice 2009, Smyk et al. 2017), in real operating conditions the amount of biogas increased by approx. 38.2%. The increase in the amount of biogas is closely related to the unit index of obtaining biogas from wastewater, whose average value from the years 2013-2018 amounted to 0.1584 m_n^3/m^3 (min. 0.0937 m_n^3/m^3, max.: 0.2291 m_n^3/m^3). The unit index of obtaining biogas from sewage calculated on the basis of data from six years of operation is by 56.8% higher than the adopted value (Energoprojekt Gliwice 2009, Smyk et al. 2017).

Figure 7 presents changes in the unit indicator of biogas extraction from sewage per month in the years 2013-2018.

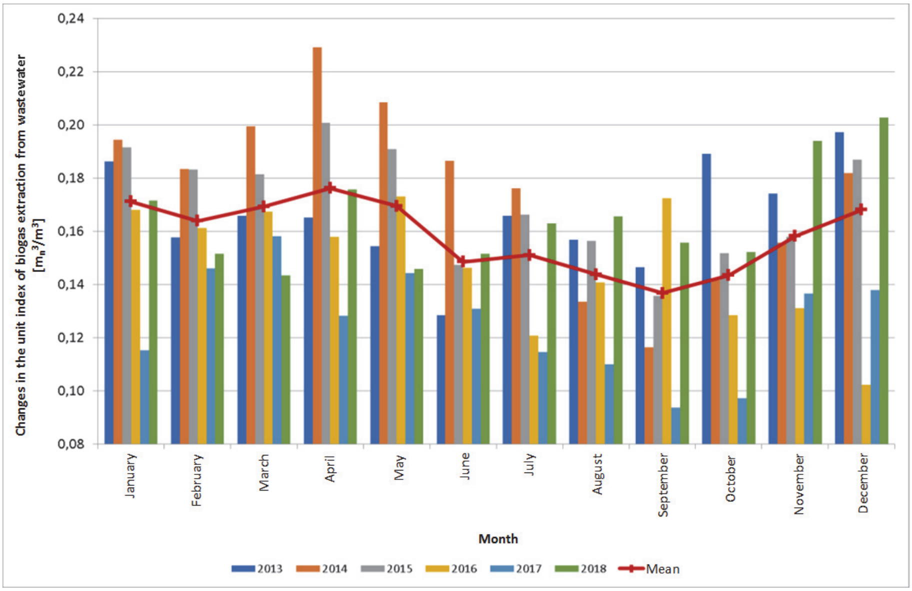

Fig. 7. Changes in the unit index of biogas extraction from wastewater per month in the years 2013-2018; Source: own elaboration

The lowest average annual value of the unit index of biogas extraction from wastewater was recorded in 2016 and it was 0.1475 m_n^3/m^3. It was lower than the average value from many years by about 7.3%. The highest value was recorded in 2014 and amounted to 0.1756 m_n^3/m^3. It was higher than the value from many years by about 10.8%.

The unit amount of biogas in relation to the COD (Chemical Oxygen Demand) load, according to research (Banks et al. 2011, Wilderer 2011) is estimated at 0.35 m^3 biogas/kg COD. Analysis of data from many years in the case of WWTP Rybnik-Orzepowice showed that on average 0.22 m^3 of biogas/kg COD can be obtained in the case of inflowing sewage.

Fig. 8 presents the unit amounts of biogas in relation to the pollution load expressed as COD, in the years 2013-2018, on a monthly, average daily basis.

The highest unit amount of biogas in relation to the COD load in the incoming sewage was 0.47 m^3 of biogas/kg COD, while the lowest was 0.09 m^3 of biogas/kg COD. Unit low values of the amount of biogas in relation to the COD load are recorded in months with increased sewage inflow to the treatment plant, while high – in months with medium and low flows.

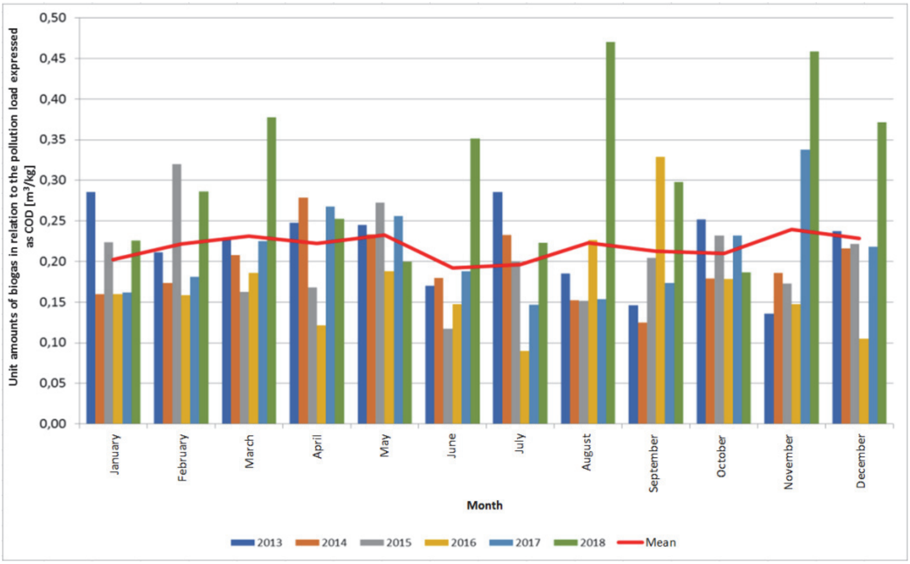

Fig. 8. Unit amounts of biogas in relation to the pollution load expressed as COD, in 2013-2018, on a monthy, average daily basis; Source: own elaboration

The unit amount of biogas in relation to the BZT_5 (Biochemical Oxygen Demand) load, according to research (Wilderer 2011) is estimated at 0.4-0.98 m^3 of biogas/kg BZT_5. The maximum amounts of biogas in relation to the BZT_5 load were obtained at the level of 1.46 m^3 biogas/kg BZT_5 at a ratio of pollutants BZT_5/COD = 0.5 (Wilderer 2011). Analysis of data from many years in the case of WWTP Rybnik-Orzepowice showed that on average 0.61 m^3 of biogas/kg BZT_5 can be obtained in the case of inflowing sewage.

The highest unit amount of biogas in relation to the BZT_5 load in the incoming sewage was 1.20 m^3 biogas/kg BZT_5, while the lowest was 0.28 m^3 biogas/kg BZT_5. Figure 9 presents the unit amounts of biogas in relation to the pollution load expressed as BZT_5, in the years 2013-2018, on a monthly, average daily basis.

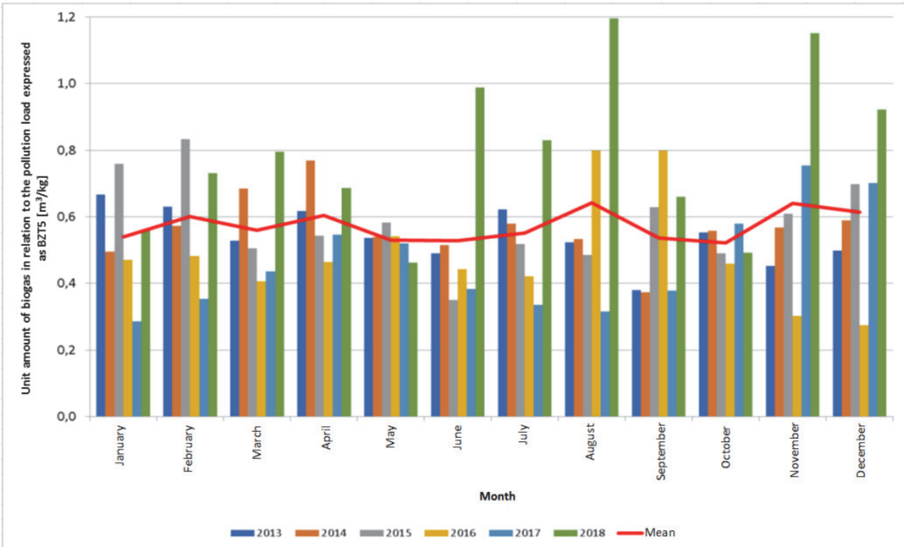

Fig. 9. Unit amount of biogas in relation to the pollution load expressed as BZT_5, in the years 2013-2018, on a monthly basis; Source: own elaboration

The unit amount of biogas obtained from the COD and BZT_5 load is closely correlated, from data from many years, the BZT_5/COD pollution ratio is 0.39, which indicates the inflow of sewage with hardly decomposable compounds (Smyk et al. 2017, Zdebik et al. 2010).

4. Conclusions

Based on the results of own research, obtained in operating conditions after the construction of the cogeneration system, i.e. in a 6-year period, it can be stated that:

- The value of the unit index of biogas extraction in relation to the amount of sewage, changes and depends on the inflow of sewage and the load of pollutants contained in it. The parameters and conditions of the fermentation process (e.g. temperature, amount of excess and initial sludge introduced, age of sludge in the fermentation chamber, etc.) are also significant,
- In the annual operation cycle of the sewage treatment plant, a reduction in biogas production is observed in the months June-October, which is influenced by the load of pollutants inflowing with sewage.
- In winter, biogas is 85% combusted in a cogeneration unit and boilers, and the heat obtained is used 100% to heat sludge and buildings. The generated electricity covers 44-47% of the total balance of the treatment plant. The remaining amount is burned in the flare.
- In summer, biogas is burned mainly in a cogeneration unit and in a flare. The heat obtained in the cogenerator is 100% sufficient to heat the sludge in the fermentation chamber system. In periods with lower temperature, the sludge is additionally heated with heat from biogas combustion in boilers.
- The electricity produced in the cogeneration unit in the summer covers 45-50% of the total electricity consumption of the treatment plant. The amount of biogas burned in the summer in the cogeneration unit is at the level of 75%, the remaining amount is burned in the flare. Increasing the amount of electricity from biogas combustion in the existing technological system will result in excess heat, which will be difficult to manage in summer.
- The maintenance of sludge concentration in biological chambers in summer and winter is directly related to the amount of excess sludge discharged into the methane fermentation chambers. This results in an increase or decrease in the amount of biogas produced.

The introduction of an additional cogeneration unit to the wastewater treatment system requires a detailed financial and economic analysis taking into account both capital expenditure, operating costs, as well as the balance of heat treatment plant demand in relation to the amount of fees incurred for burning biogas in a flare.

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Abstract

The paper presents and discusses the 6-year effects of the operation of a biogas-fired cogeneration system which operates at the Rybnik Orzepowice sewage treatment plant. The qualitative composition of biogas, average daily amount of biogas produced, total demand of the sewage treatment plant for electricity and the amount of electricity obtained from biogas were presented. Regarding the average daily biogas production for the years 2013–2018, it can be stated that it remains at the level of 2,809 m^3/d (±33%). The average daily total electricity consumption for 2013-2018 remains at 8,846 kWh/d (-13.8%; +20.6%). The average daily amount of electricity produced from biogas for the years 2013-2018 remains at the level of 3,892 kWh/d (-38.7%; +10.1%). Electricity generated from biogas allows us to cover the demand of the treatment plant at 44% (minimum 39%, maximum 50%). In the analysed period, biogas consumption by individual facilities was: cogeneration unit approx. 65%, boilers: 10%, flare: 25%. Based on the operational data, it was calculated that: the unit indicator for biogas extraction from sewage, on average is 0.1584 m_n^3/m^3 (min. 0.0937 m_n^3/m^3, max .: 0.2291 m_n^3/m^3), the unit indicator for biogas extraction in relation to for COD load an average of 0.22 m^3 of biogas/kg COD (min. 0.09 m3 of biogas/kg COD, max. 0.47 m^3 of biogas/kg COD), the unit ratio of biogas extraction in relation to the BZT_5 load was on average 0.61 m^3 biogas/kg BZT_5 (min. 0.28 m^3 biogas/kg BZT_5, max. 1.20 m^3biogas/kg BZT_5).

Keywords:
biogas, cogeneration, heat, electricity, COD load, BZT_5 load

Ocena możliwości wprowadzenia układu kogeneracji w procesie zagospodarowania biogazu na przykładzie oczyszczalni ścieków w Rybniku Orzepowicach

Streszczenie

W artykule przedstawiono i omówiono 6-cio letnie efekty pracy układu kogeneracyjnego zasilanego biogazem, który pracuje w Oczyszczalni Ścieków Rybnik Orzepowice. Zaprezentowano skład jakościowy biogazu, średniodobową ilość wytwarzanego biogazu, całkowite zapotrzebowanie oczyszczalni na energię elektryczną oraz ilość energii elektrycznej uzyskiwanej z biogazu. Średniodobowa produkcji biogazu, za lata 2013-2018 można stwierdzić, że utrzymuje się ona na poziomie 2,809 m^3/d (±33%). Średniodobowe całkowite zużycie energii elektrycznej za lata 2013–2018, utrzymuje się on poziomie 8,846 kWh/d (-13,8%; +20,6%). Średniodobowa ilość produkowanej energii energii elektrycznej z biogazu za lata 2013–2018 utrzymuje się on poziomie 3,892 kWh/d (-38,7%; +10,1%). Energia elektryczna wytwarzana z biogazu pozwala na pokrycie zapotrzebowania oczyszczalni na poziomie 44% (minimalnie 39%, maksymalnie 50%). W analizowanym okresie zużycie biogazu przez poszczególne obiekty wynosiło: jednostka kogeneracyjna ok. 65%, kotły: 10%, pochodnia: 25%. Na podstawie danych eksploatacyjnych obliczono, że: jednostkowy wskaźnik pozyskania biogazu ze ścieków, średnio wynosi 0,1584 m_n^3/m^3 (min. 0,0937 m_n^3/m^3, max.: 0,2291 m_n^3/m^3), jednostkowy wskaźnik pozyskania biogazu w odniesieniu do ładunku ChZT średnio wynosił 0,22 m^3 biogazu/kg ChZT (min. 0,09 m^3 biogazu/kg ChZT, max. 0,47 m^3 biogazu/kg ChZT), jednostkowy wskaźnik pozyskania biogazu w odniesieniu do ładunku BZT5 średnio wynosił 0,61 m^3 biogazu/kg BZT_5 (min. 0,28 m^3 biogazu/kg BZT_5 w, max. 1,20 m^3 biogazu/kg BZT_5).

Słowa kluczowe:
biogaz, kogeneracja, ciepło, energia elektryczna, ładunek ChZT, Ładunek BZT_5

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Threats to Wastewater Treatment Plant in Combined Sewer System – Analysis of Problems and Possible Solutions on the Example of Lodz

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1. Introduction

Municipal wastewater treatment plants (WWTP), due to the increasing requirements of environmental protection, have to meet more and more stringent requirements regarding both the quality of discharged sewage and operational reliability. This is sometimes difficult due to unforeseen situations, usually independent of the sewer network operator and sewage treatment plant. WWTPs are exposed not only to technical equipment failures, but also to an uncontrolled inflow of toxic substances that can inhibit biological treatment processes and, in extreme cases, lead to their breakdown. Such situations may be caused by intentional action (illegal discharge of wastewater into the sewage system), but also may be the effect of introduction of new substances and products, which in turn results in the introduction of new contaminants to a treatment plant, whose effects on living organisms is not fully recognized. In the case of combined sewage system, hydraulic overload resulting from stormwater inflow after prolonged and intense rainfall, is an additional threat, which may also worsen the effects of treatment. In both cases, not fully treated wastewater may be discharged to the receiver. Such situation causes a threat to the aquatic environment on the one hand, and on the other may result in financial penalties for treatment plants, resulting from non-compliance with the conditions for sewage disposal, as well as costs of removing the effects of failure (e.g. restoration population of microorganisms in activated sludge chambers).

According to the current legal status in Poland, the requirements for the quality of sewage discharged to the receiver increase with the size of the treatment plant, but they do not take into account the size and absorbency of the receiver, which is crucial for the possibility of maintaining its good condition or good ecological and chemical potential. The impact of discharged wastewater on the receiver depends primarily on the pollutant load and the dynamics of emissions, and of course depends on the size of the receiver as well as on type and form of pollution. Intense anthropogenic activities and rapid development of new industries may cause adverse impact on fragile river ecosystems and consequently human health, especially when discharged wastewater contains e.g. heavy metals, xenobiotics, estrogens, priority pollutants, micropollutants, oil and other petrochemical products, pesticides, pharmaceuticals, and emerging contaminants (Han & Currell 2017, Liu et al. 2020, Palli et al. 2019, Végsöová et al. 2019). Rapid changes in the level of pollutant emissions are dangerous especially for small receivers, which is why sewage treatment plants discharging sewage to them should be particularly well protected against the possibility of discharge of not fully treated sewage.

Significant sudden changes in the quality of inflow to WWTP, and primarily the presence of toxic substances, can affect the reduction of the biological treatment efficiency. In particular, nitrifying bacteria are sensitive to the effects of toxic factors such as increased heavy metal concentration, pH changes, reduced oxygen concentration and rapid changes in ammonium nitrogen concentration in the inflowing sewage (Black et al. 2014). Wastewater toxicity is more and more often the subject of research, however, generally used methods do not allow its simple and reliable on-line measurement. Attempts to establish a correlation between sewage toxicity and physicochemical parameters are not effective yet. Vasquez and Fatta-Kassinos (2013) have only established that two parameters: conductivity and ammonium nitrogen concentration are related to toxicity. Research conducted by Liwarska-Bizukojć et al. (2016) in the wastewater treatment plant in Zgierz (Poland) did not show any significant correlation between toxicity and basic parameters of wastewater (pH, BZT_5, COD, ammonium nitrogen, total nitrogen, total phosphorus), and their biodegradability BZT_5/COD). Only a weak correlation was found between the conductivity and toxicity of raw wastewater in the short-time summer campaign.

Rapid changes of inflow may cause difficulties in optimal control of municipal sewage treatment plants cooperating with the combined sewer system which is largely due to the unpredictability of precipitation. For this reason, attempts to forecast inflow to the treatment plant with sufficient time in advance are being made in the world. Based on rainfall data (currently occurring or forecast from radar data) and measurements of sewage depth and flow in the sewers, RTC (Real Time Control) systems are being created (Garcia et al. 2015, Schilling et al. 2010). Solutions for forecasting the WWTP inflow using artificial intelligence methods, such as neural networks, neural-fuzzy networks, etc. are also being developed (Seggelke et al. 2013, Szeląg et al. 2018, van Daal et al. 2017, Vezzaro et al. 2014, Zhou et al. 2019). Attempts to include into these systems tools that enable qualitative forecasting of inflows are being made (Langeveld et al. 2017). According to Vezzaro et al. (2014) controlling the sewage system based on the measurement of WWTP inflow quality allows to mitigate the effects of first flush pollution phenomenon.

However, there are currently no solutions enabling comprehensive forecasting of both the sewage inflow to the treatment plant and the concentration and loads of pollutants. Meanwhile, early warning of treatment plants about the possibility of hazards could enable, for example, storage of some wastewater not only to avoid hydraulic overloads, but also inflow of toxic substances or excessive loads of pollution to the biological part. This would create a chance for optimal control of treatment processes in all conditions and, as a consequence, better protection of the sewage receiver.

2. Studies aim and methods

The aim of the studies is to identify threats to the sewage treatment process in Group WWTP in Lodz. The variability of the wastewater inflow in terms of quantity and quality, which may have an impact on the treatment effects and creating hazards for the quality of receiving waters, will be analysed. Solutions that can minimize these risks will be presented.

3. Analysis of the current state

3.1. Characterisation of Lodz sewer system

Lodz is equipped with a hybrid sewage system. In the central part there is a combined sewer system with 4 main collectors running from the north-east to the south-west of the city towards the Group Wastewater Treatment Plant of the Lodz Agglomeration. There are 18 combined sewer overflows in the combined sewerage. Two sanitary sewers collecting sewage from northern and south-eastern regions of Lodz are included in this system. Two sewage collectors from Pabianice and Konstantynów Łódzki are connected to the system prior to WWTP. Total catchment area is inhabited by nearly 800 thousand people. The designed capacity of the treatment plant is 1.026.260 PE, while the actual load on the treatment plant, calculated on the basis of operational data from 2015-2017, is currently 934.700 PE. Maximum sewage inflow to the treatment plant during dry weather for a probability of 85% is 166,000 m^3 per day.

Wastewater flowing into WWTP is first subjected to mechanical treatment in the screens building, than wastewater flows into the grit chamber. The final facilities of mechanical wastewater treatment are rectangular preliminary settling tanks. Biological sewage treatment is carried out in activated sludge chambers operating in MUCT technology. In each technological line the anaerobic, anoxic, and aerobic zones are separated. The final treatment facilities are rectangular secondary settling tanks blocked with activated sludge chambers. The treatment plant scheme is presented in Fig. 1.

In dry weather, the sewage inflow to the treatment plant, in terms of both quantity and quality, is stable. Under these conditions, the characteristics of the inflow during the day or week are repeatable, and its changes are relatively small. It is different during wet weather, when the amount of inflowing sewage increases significantly, sometimes rapidly, and can cause WWTP overload, especially the biological part. Therefore, there are situations in which not all wastewater flowing into the WWTP is fully treated. Part of the wastewater after the primary settling tanks, and in extreme cases after the grit chambers, is directed to the bypass channel, which may contribute to increased emission of pollutants to the receiver compared to other periods.

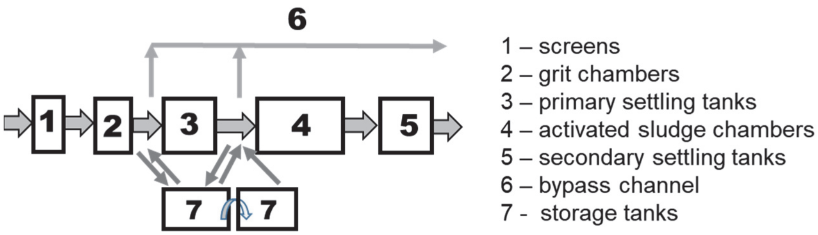

Fig. 1. Schematic of the Group Wastewater Treatment Plant of the Lodz Municipal Agglomeration

3.2. Wastewater inflow to WWTP

Although in recent years the annual rainfall in the city and the number of wet weather days do not show an upward trend, the occurring rainfall is characterized by a higher maximum intensity, which may cause a rapid increase in sewage inflow to WWTP (Fig. 2).

Measurements of sewage inflow to WWTP in Lodz indicate that for about half the days in a year the sewage treatment plant has to cope with increased inflows resulting from precipitation, and several or more times a year the volume of inflowing sewage exceeds twice the reliable maximum flow for the sewage treatment plant, which releases from the need to meet requirements contained in the water-legal permit regarding the composition of discharged wastewater (Table 1). In such cases, some of the wastewater is discharged through a bypass channel without biological treatment. Storage them could help avoid such situations.

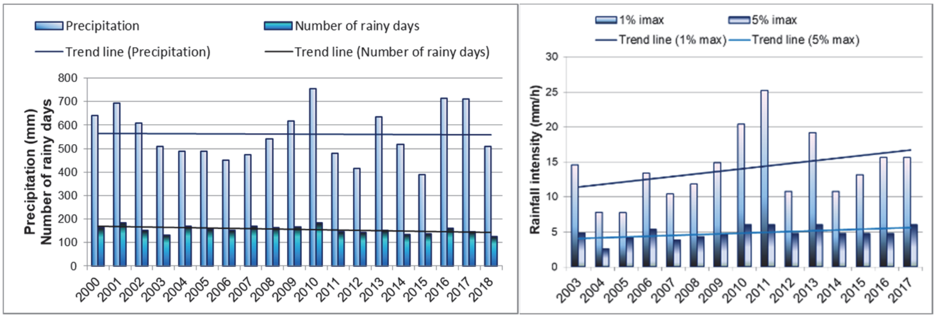

Fig. 2. Precipitation height and number of days with precipitation (a) and the intensity of precipitation with the highest intensity (mm/h) according to 5-minute records (data for 1% and 5% of highest values and trend lines) (b)

Table 1. Number of exceedances of the daily sewage inflow to WWTP jn Lodz Qd in relation to the maximum dry weather flow Q_m = 166.000 m^3/day

Year	$Qm < Q_d < 2Q_m$		$Q_d > 2Q_m$	
	monthly	per year	monthly	per year
2017	4-29	201	0-4	14
2018	1-25	143	0-2	5

The analyses carried out using the US EPA SWMM program have shown that an effective solution limiting sewage discharge to bypass channel is the construction of storage tanks (Sakson et al. 2018). The effectiveness of such tanks depending on their volume is shown in Fig. 3.

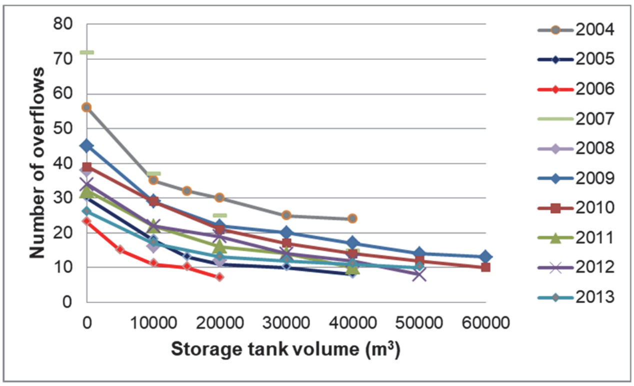

Fig. 3. Impact of separated storage tank volume on the reduction of biologically untreated sewage discharge by the bypass channel in Lodz WWTP (Sakson et al. 2018)

It is also possible to use in-sewer storage in large sewer Polesie XV prior the WWTP with the RTC system. The detention would be forced by 4 pairs of gates installed in the sewer. Exemplary effects of such a solution are presented in Fig. 4.

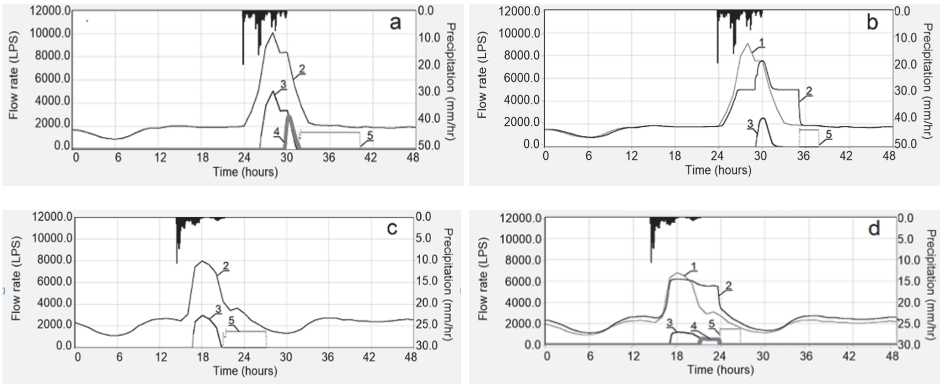

Fig. 4. Example of simulation of WWTP operation with the storage tanks, flow (l/s)
a, b – example of a rainfall with overflow in case of sewage storage in tanks (a) and without overflow in case of additional storage in the sewer Polesie XV (b);
c, d – example of a rainfall without overflow in case of sewage storage in tanks (c); and with overflow in case of additional storage in the sewer Polesie XV (d)
1 – inflow to the sewer Polesie XV; 2 – inflow to WWTP; 3 – inflow to storage tank;
4 – overflow from storage tank; 5 – storage tank emptying; right axis – precipitation (mm/hr)

3.3. Quality of wastewater in sewer system

Quality of wastewater flowing into WWTP may also change significantly during wet weather. Strormwater, which in this period may constitute the majority of the entire inflow volume (depending on precipitation parameters) may carry a significant amount of pollutants washed out from the catchment and leached from the sewer deposits, hindering the treatment process. In wet weather, as well as during snowmelt, inflows to WWTP are often characterized by the occurrence of the first flush phenomena. This means that in the beginning of precipitation in the mixture of municipal wastewater and stormwater much larger amount of pollutants may flows to WWTP than in the further runoff.

The inflow of a large amount of pollutants in very short time, even if there are no toxic substances among them, can cause significant difficulties in the treatment process. Changes in the quality and quantity of sewage flowing into WWTP are not repeatable, they depend primarily on rainfall characteristic and the length of the dry weather period before precipitation, which determines the amount of pollution built-up on the catchment and wash-off during rainfall. Even on the same catchment, in the case of different precipitation, the first flush phenomenon may not be observed, it may be pronounced or the so-called the last flush phenomenon may occur, moreover, the flow of pollutants may be different for basic quality parameters of sewage (Fig. 5).

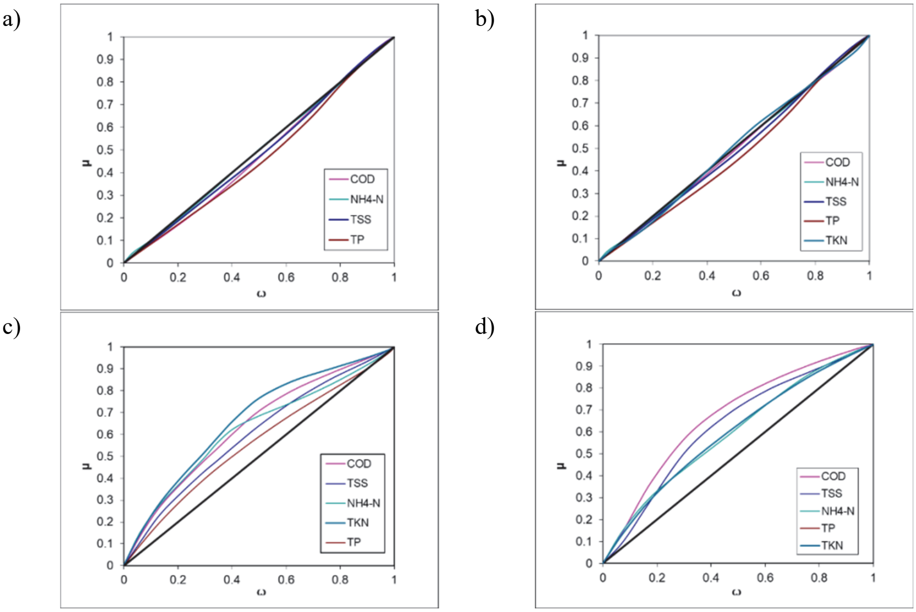

Fig. 5. Analysis of the first flush phenomena in inflow to GOŚ ŁAM: a) storm with a high intensity of precipitation; b) long rainfall of low intensity; c) long-lasting heavy rainfall; d) snowmelt combined with rainfall. COD – chemical oxygen demand; TSS – total suspended solids; NH_4-N – ammonium nitrogen; TKN – total Kjeldahl nitrogen; TP – total phosphorus; ω – cumulative wastewater volume; μ – cumulative load

An important threat to the WWTP is the inflow of toxic substances that can cause inhibition of biological treatment processes. Such situations took place in September 2011 and April 2019, when as a result of the inflow of unidentified substances to Lodz WWTP, inhibition of the nitrification process was found, which resulted in limiting the reduction of nitrogen concentration, a significant increase in the emission of nutrients to the environment, and the threat of non-compliance with legal requirements. The process collapse was associated with the destruction of the nitrifying bacterial population, which is most sensitive to the effects of toxic agents. Restoration of the relevant nitrification process parameters is possible after the termination of toxic substances inflow, and taking action to accelerate the recovery of the bacterial population. This can be done by inoculating the activated sludge with sludge from other treatment plants and dosing preparations containing nitrifying bacteria. Regardless of chosen solutions, the reconstruction can take up to several weeks. This time depends on many factors, including the parameters of treatment process and the nitrogen load in sewage inflowing to WWTP.

Research on wastewater quality in the Lodz sewage system conducted in recent years have shown considerable variability in its composition. Sudden increse in parameters such as BOD, COD, and suspended solids were sometimes observed, which may indicate illegal sewage discharge (Table 2, Fig. 6).

Table 2. Variability of wastewater composition in example points of the sewage system

Parameter	Unit	1. Sanitary sewer		2. Large sanitary sewer		3. Large combined sewer	
		range	CV	range	CV	range	CV
pH	(-)	7.12-8.65	0.04	7.1-7.62	0.02	7.13-8.5	0.04
Conductivity	(µS/cm)	257-4648	0.66	1582-2750	0.19	803-2915	0.19
Suspended solids	(mg/l)	296-11500	2.53	194-858	0.25	80-5004	1.36
BOD	(mg O_2/l)	200-9600	2.28	260-875	0.27	20-1450	0.56
COD	(mg O_2/l)	649-17955	2.16	459-1854	0.25	77-4041	0.68
NH_3	(mg/l)	26.9-76	0.26	28-56	0.16	18.1-99.1	0.26
H_2S	(mg/l)	<0.01-0.1	2.07	<0.1-0.4	0.58	<0.01-0.7	1.47

CV – coefficient of variation

4. Concept of the monitoring, early warning and sustainable management system

In order to improve WWTP functioning, two storage tanks of the volume 15,000 m^3 and 25,000 m^3. are being built in Lodz WWTP. Tanks volume was determined on the basis of many years of observation of inflows to the WWTP and computer simulations (Zawilski & Sakson 2008). The total useful capacity of the tanks (40,000 m^3) is to ensure the capture of most of the runoff after low and medium rainfall and the most polluted first flush of large runoff, exceeding the volume of the tanks.

Filling of tank I (Fig. 1) is foreseen after preliminary settling tanks – from the distribution channel to activated sludge chambers (ASC) or after grit chambers (GC), from the distribution channel to preliminary settling tanks (PST), through the designed channel valve. The maximum sewage inflow to the preliminary settling tanks was assumed to be about 30,000 m^3/h (above this inflow the excess sewage will be directed to tank I). It was assumed that the sewage inflow to ASC will not exceed the value of 18,200 m^3/h. Excess wastewater after PST, in the amount of approx. 12,000 m^3/h, will be directed through channel valves designed in the distribution channel on the ASC to the storage tank I. The tank chambers will be filled in cascade. After filling the first chambers, excess sewage will overflow to the common channel between tanks I and II, and then to tank II or to the bypass channel. Tank I will be emptied into PST distribution channel, while wastewater from tank II will be directed to distribution channel to ASC through a system of designed pump systems.

Optimal use of storage tanks requires information on quality and quantity of wastewater flowing into the WWTP and the forecast of their changes. If the excess volume of wastewater after rainfall is taken over by the tanks, it will be possible to fully clean it after the increased inflow stops. Also, if significant changes in sewage quality are identified that may affect their biological treatment, it will be possible to divert this type of inflow to tanks. Therefore, having information on the current composition of sewage in the sewer system and forecasting inflow to the treatment plant will facilitate optimal use of the technological possibilities of WWTP. The above premises, analysis of the current state of knowledge and technical capabilities, as well as experience in the field of monitoring and modelling of the Lodz sewage system constitute the basis for the development by Lodz University of Technology, Institute of Environmental Engineering and Building Installations, and Wastewater Treatment Plant of Lodz, Ltd. the prototype of monitoring, early warning and sustainable management system for WWTP in Lodz. The system will be based on measurement data from three main sources, these are:

- existing pluviometric system in the city, consisting of 18 raingauges, of which 5 are located on the combined catchment,
- flow measurement system in sewers next to 18 combined sewer overflows,
- newly constructed 4 stations (Fig. 6) for qualitative monitoring of wastewater in the sewage system with on-line sensors measuring min. 8 parameters on each station (pH, conductivity, organic substances, ammonium nitrogen, suspended solids/turbidity, chlorides, BTX, hydrogen sulphide). Research on sewage quality with on-line probes conducted on the J1 CSO since 2011, as well as previous tests on the inflow to WWTP (Brzezinska et al. 2016). showed that these types of stations can be successfully used for assessment of sewage quality and amount of pollutant emissions from the sewage system.

The system will enable receiving, well in advance, reliable information by sewage treatment plant employees on anticipated significant quantitative and qualitative changes in inflowing sewage and the possibility of a threat to biological treatment processes. This creates the opportunity to optimally control the treatment plant, both the parameters of the treatment process and flows. In a situation where there is a suspicion of the inflow of hazardous substances, part of the wastewater may be direct into the tanks, which will allow for their storage, collection of sewage samples and their analysis as well as determination of the way to proceed (referring to biological treatment or neutralization). Optimal use of storage tanks will allow reducing the bypass channel operation. According to the conducted analyses (Zawilski et al. 2017) limiting the operation of the bypass channel and the volume of discharges by 70% will allow reducing the emissions of basic pollutants by approx. 2.7-6.8% depending on the parameter (BOD_5, COD, TSS, TN, and TP).

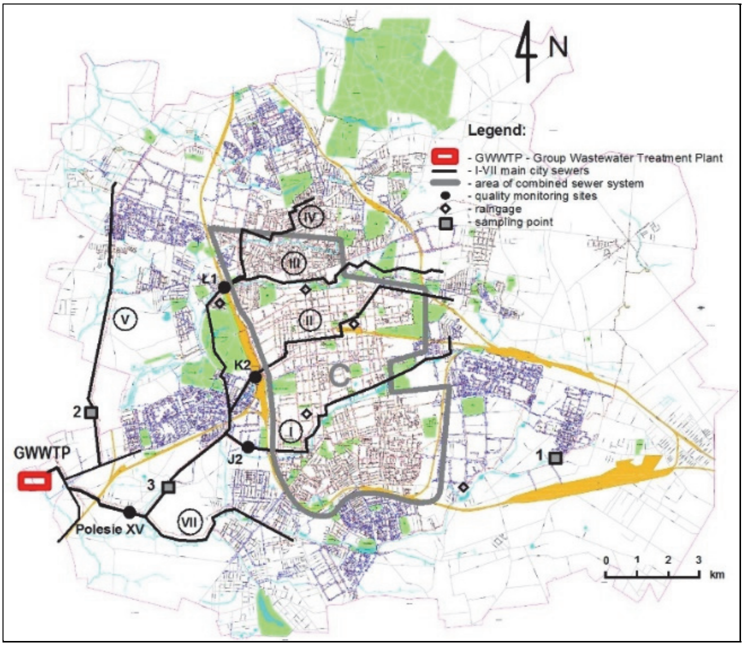

Fig. 6. Location of sewage quality monitoring stations in the Lodz sewage system

The system, based on only 4 stations for monitoring the quality of sewage, will not yet allow full control of the inflow to WWTP due to the existing sewer system layout in the city. Current research on sewage quality (including toxicity) in the entire sewer system should allow to determine the quality characteristics of sewage discharged from the whole catchment, which will allow more accurate inflow forecasting, but this will not take into account uncontrolled pollutant discharges into not monitored sewers. For this reason, the system will probably need to be expanded in the future. The use of quantitative and qualitative online monitoring of the sewage system is a very convenient and promising tool that facilitates solving many operational and modernization problems, however it creates many operational difficulties. There may be gaps in measurements or the measurement data is of poor quality. However, it can be assumed that the rapid progress in the development of on-line measurement methods and the expansion of experience in the field of operation of this type of equipment will contribute to the improvement of the efficiency and reliability of such solutions.

5. Conclusions

WWTP in Lodz is exposed to sudden changes in the inflow quantity, which now sometimes necessitates discharging part of sewage through a bypass channel without required biological treatment. The analysis of rainfall data shows that these phenomena may intensify. Significant changes in the composition of wastewater are also observed, and even the inflow of toxic substances inhibiting the biological treatment process. Research on wastewater composition in the sewer system shows that illegal discharges of concentrated sewage into the sewerage may occur. Introducing wastewater detention in WWTP can prevent the negative effects of rapid changes in inflow quality and quality. Optimal use of the storage tanks will be possible thanks to introducing the monitoring, early warning and sustainable management system for WWTP. The system will be based on data from raingauges, flowmeters and online quality sensors and will forecast the sewage inflow to the treatment plant and the concentration and loads of pollutants.

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Abstract

Municipal WWTP are exposed to the inflow of toxic substances, which may impede their proper functioning, especially of the biological part. In the case of combined or hybrid sewer systems, additionally, in wet weather, there may appear a rapid inflow of a mixture of domestic and industrial sewage, and stormwater in an amount exceeding the capacity of the devices, causing the need to discharge parts of not fully treated wastewater through the bypass channel. In such situations, the receivers are exposed to an inflow of increased amounts of pollutants. The article presents the concept of a monitoring, early warning and sustainable management system for the Lodz wastewater treatment plant, which will allow minimizing pollutant emissions to the aquatic environment.

Keywords:
sewer system, sewage treatment, water protection, predictive model, toxicity

Zagrożenia dla oczyszczalni ścieków w systemie ogólnospławnym – analiza problemów i możliwych rozwiązań na przykładzie Łodzi

Streszczenie

Miejskie oczyszczalnie ścieków są narażone na napływ substancji toksycznych, które mogą utrudniać ich prawidłowe funkcjonowanie, zwłaszcza części biologicznej. W przypadku ogólnospławnych lub mieszanych systemów kanalizacyjnych dodatkowo w czasie pogody mokrej może pojawić się gwałtowny dopływ mieszaniny ścieków bytowo-gospodarczych i przemysłowych oraz wód opadowych w ilości przekraczającej przepustowość urządzeń, powodując konieczność zrzutu części nie w pełni oczyszczonych ścieków przez kanał ominięcia. W takich sytuacjach odbiorniki są narażone na napływ zwiększonych ilości zanieczyszczeń. W artykule przedstawiono koncepcję systemu monitorowania, wczesnego ostrzegania i zrównoważonego zarządzania łódzką oczyszczalnią ścieków, który pozwoli zminimalizować emisję zanieczyszczeń do środowiska wodnego.

Słowa kluczowe:
kanalizacja, oczyszczanie ścieków, ochrona wód, model prognostyczny, toksyczność

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Environmental Corporate Social Responsibility as a Tool for Creating the Future of Environmental Protection

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1. The essence of environmental corporate social responsibility

The development of civilization and, in particular, among others, creation of a free market, spatial economy based on the growing needs and expectations of stakeholders, the development of entrepreneurship, modern production and service technologies, etc., pose an increasing threat of poisoning and pollution of the natural environment (Ison 2010), often resulting in irreversible environmental degradation (Berry 2006). In order to minimize and eliminate the threats, all pro-environmental measures should be consciously undertaken (Welchman 2012) and carried out both in the administrative (Mikkila & Toppinen 2008, Wolniak et al. 2019) and governmental spheres (Basu & Palazzo 2008).

Environmental security can be perceived and interpreted differently by individuals (Mathevet et al. 2018, Matheve et al. 2016), social groups and business entities, as it affects different spheres of life, including quality of life, becoming a determinant of development or competitive advantage (Rozzi et al. 2015, Wolniak & Jonek-Kowalska 2020). Creating awareness and responsibility for the reality around us fits into the concept of social responsibility.

The concept of the c*orporate social responsibility* (CSR) is a strategic approach to the actions desired by society and the created social values. In other words, it is a 'commitment' of business entities to create sustainable development with the participation of workers, their families, local communities and society as a whole, in order to improve the quality of life, with positive effects for both business (Bober et al. 2017) and social development (World Bank 2005, Payne 2006).

The analysis of the literature and the development of the concept of corporate social responsibility indicate the evaluation of the approach to the management and methods of integrating social and environmental problems

(Raymond et al. 2016) with everyday business activities and management systems (Wolniak & Sędek 2009) in favour of integrating environmental issues with regular management systems, such as ISO 14001 (Pacana et al. 2017, Pacana 2017) or ISO 50001 (Bober & Olkiewicz 2017). This results in comprehensive environmental, social, quality and health integration within the framework of the new standards created as SA8000 (Makuch 2011), ISO 2600:2010 based on codes of ethics or codes of conduct (Dobers 2009).

Attempts to describe, identify the idea of corporate social responsibility have been unified in the international standard ISO 26000, as the organization's responsibility for the impact of its decisions and actions on the society, environment and sustainable development of the organization through the adopted transparent and ethical behavior (ISO 2018). Process based approach to management/activity in the areas of: Community involvement and development; Human rights; Human resource management; Environment; Fair business practices and Consumer affairs are intended to enable an organization to achieve market success by recognizing, building appropriate stakeholder relations and enhancing the organization's value (Olkiewicz 2020). It should be noted that ISO 26000 is not a "strict" management standard, but a guideline to promote a commonly understood social responsibility, shaped by organizations' compliance with legal, environmental, cultural, social, organizational and economic requirements. Fig. 1 presents the idea of ISO 26000 and indicates the relations between individual elements of the standard including the methodology of its application.

The analysis of the mentioned respective literature shows that CSR is designed to:

- comply with the letter of the law and ethical standards,
- voluntary create activities for the benefit of the natural environment and stakeholders,
- identify and record CSR principles in strategic documents,
- improve management systems, in particular in the area of stakeholder relations, meeting and monitoring their needs, etc.,
- develop products from innocuous materials or with little harm to the environment,
- implement innovative, pro-ecological, economically and socially justified solutions,
- reduce the use of natural resources, energy,
- monitor, reduce or eliminate potential threats to: respect for human rights, compliance with labor standards, environmental protection and fight against corruption, by creating environmental activity reports.

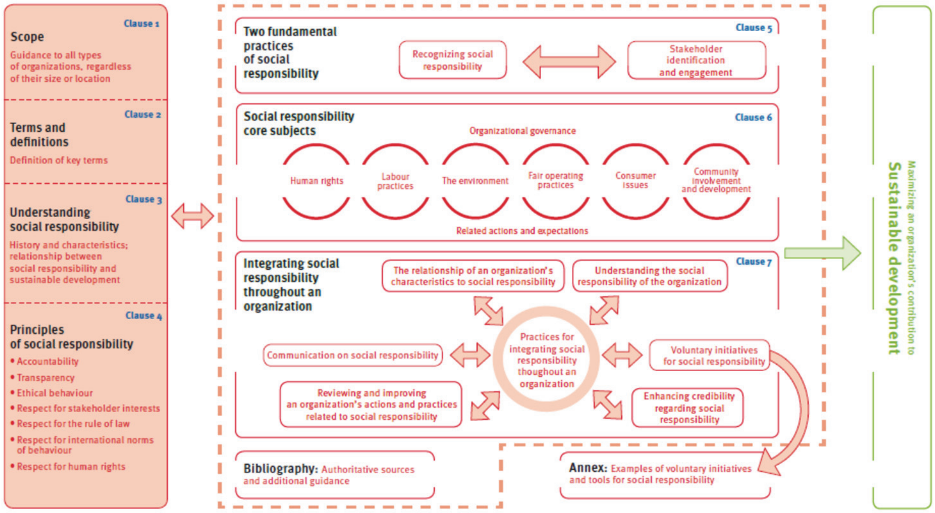

Fig.1. The idea of ISO 26000
Source: *Discovering ISO 26000 provides a basic Understanding of the voluntary International Standard ISO 26000:2010, Guidance on social responsibility*, 2018, International Organization for Standardization, Geneve, Switzerland

In practice, CSR (Lindgreen et al. 2009, Jamali & Mirshak 2007) is an area that is identified in different ways and is subject to scientific research, because the scope of activities and the extent of its impact are very broad, both in the set of instruments and in the areas of economy, including science (Rasche2009, Oskarsson & Malmborg 2005). It should be noted that CSR is an inspiring concept that offers many opportunities, freedoms of awareness-building and responsibility for actions taken, especially strategic ones (Chandler 2016, Rasche & Morsing 2017), which increase the credibility of a company both on business dimension and in non-business sphere. Popularization of the idea of corporate social responsibility, the creation of a "positive" image of the organization (Anderson et al. 2010), affects market stakeholders, which in turn allows entities to sustainable development by maximizing profits (Callan & Thomas 2009, Sivarama 2011), implementing innovations (Olkiewicz 2018), dominating the sector, improving the quality of products and services, optimizing manufacturing processes (Walker et al. 2014), etc., taking into account social and environmental issues (COEC 2001, Glachant 1994). Therefore, building awareness and an organizational culture of the company focused on meeting needs, as well as the growing threat of environmental degradation increases the need to identify and apply *environmental corporate social responsibility* (ECSR) (Farrow et al. 2017, Hynes & Wilson2016). In other words, it is an extension of the CSR concept to management development, where the main determinant, the reference, is environmental protection.

The reluctance to raise environmental awareness, to recognize threats to environmental safety and to take responsibility or share responsibility for the wider good is significant, both in society and in business. Therefore, continuous improvement of the implemented activities, intensive educational work and activities for the safety and protection of natural resources are required from all stakeholders (Horan et al. 2011, Golob et al. 2019, Caillaud et al. 2016). It was also recognized that activities aimed at environmental responsibility are of a long-term nature (Opoku 2004, Moon 2007), also in the area of creating and complying with laws (Olkiewicz & Olkiewicz 2020), implementing pro-environmental management systems, but the results achieved are always assessed in terms of the environmental effect (Chiarini&Vagnoni 2017, Ostrom 2009).

The concept of ECSR assumes that: (Jabłoński et al. 2010),

1. it is a concept of increasing the company's value through the dynamics of using ecological criteria to meet the needs of shareholders and other stakeholders,
2. it is a platform for building an effective business model based on ecological criteria,
3. it is a source of creating eco-innovation for the long-term development and growth of the company,
4. it creates activities connected with striving to balance business needs between shareholders and stakeholders, where the dialogue platform is related to treating environmental protection as a key success factor, considering critical processes in relation to their greening and the development of bio-ecological products,
5. it is a source of effective use of the combination of tangible resources and intangible factors of the company's functioning in the context of the adopted ecological criteria (pro-environmental raw materials, pro-environmental machines, devices and other material resources of the company, ecological knowledge, ecological competence),
6. it is a link between the internal and external environment (comparison of macro-environmental factors, e.g. regulatory, legal and political factors in relation to the company's environmental impact),
7. it guarantees effective reporting of standards of conduct for stakeholders with regard to the internal functioning of the company (human and natural rights, work and technology, working and environmental environment, health and environmental protection, etc.),
8. it provides a platform for an effective use of the company's intellectual capital (relational, organizational, innovative and human) in terms of increasing social capital between all stakeholders, and

9. it is a source of reduction of the company's business risk (improvement of creditworthiness, improvement of business credibility, reduction of process risk of the company's strategic resources).

The ECSR activities, as voluntary, taking into account the social, ecological, business and legal spheres, are possible to implement using the appropriate competences, knowledge and management skills, as well as technology, while ensuring sustainable pro-ecological development (Callan & Thomas 2009, Stern2000), consumer loyalty (Homburg & Giering 2001) and the company's reputation (Cuesta-Valiño et al. 2018, Bormane et al. 2017), and providing customers with an appropriate level of satisfaction and improving the quality of life.

2. Actions for environmental corporate social responsibility – Legislative requirements

The high and ever-growing awareness of the need for environmental protection measures resulted in the creation of a treaty in Kyoto in 1997 to support action against global warming. The Kyoto Protocol is a legally binding agreement under which industrialized countries have been committed to reducing their total greenhouse gas emissions by 5.2% by 2012 compared to 1990. This meant that all activities aimed at reducing gas emissions were directed at investments in new technologies, as part of renewable energies. An additional determinant of the need to implement modern solutions and change the perception and importance of the natural environment was the climate and energy package, adopted as a "green revolution" in 2008 by EU states. EU countries have declared that there will be a reduction in CO_2 emissions by 20%, an increase in the share of renewable energy to 20% and up to 20% energy savings until 2020. The term "3x20 objectives" is commonly used. Table 1 presents other normative acts determining the direction of pro-ecological activities.

Also Poland, under the ecological responsibility resulting from the ECSR, on 10. November 2009 adopted long-term measures aimed at the development of the energy sector, defining Poland's energy policy until 2030, taking into account pro-environmental aspects.

Table 1. Selected EU directives

Sing.	Directive	Objectives and main activities
1.	Directive 2002/91/WE on the energy performance of buildings	- establishment of minimum energy performance requirements for new and existing buildings, - housing energy certification, - inspection of boilers, air-conditioning and heating systems.
2.	Directive 2003/87/WE establishing a scheme for greenhouse gas emission allowance trading within the Community	- establishing a scheme for greenhouse gas emission allowance trading within the Community, - promoting reductions of greenhouse gas emissions in a cost-effective and economically efficient manner.
3.	Directive EC/2004/8 on the promotion of useful cogeneration	- increasing the share of combined production of electricity and heat (cogeneration), - increasing the efficiency of primary energy use and reducing greenhouse gas emissions, - promotion of highly efficient cogeneration and beneficial to the economic incentives (tariffs).
4.	Directive 2005/32/WE establishing a framework for the setting of eco-design requirements for energy-using products	- design and manufacture of the equipment and consumer electrical appliances with increased energy efficiency, - for establishing energy efficiency requirements based on the criterion of minimizing costs throughout the product life cycle (life cycle costs include the costs of acquiring, owning and decommissioning).
5.	Directive 2008/50/EC on air quality CAFE	- air quality objectives, - zones and agglomerations, - quality evaluation systems, - management and air quality plans.
6.	Directive 2009/28/WE on the promotion of the use of energy from renewable sources	- national action plans by 30 June 2010, - calculation of the RES shares, - joint projects of the EU-27, - joint support schemes.
7.	Directive 2010/31/WE On the Energy performance of buildings	- establishment of a minimum performance requirements for new and renovated buildings, - energy certification of buildings, - inspection of boilers, air-conditioning and heating systems.
8.	Directive 2012/32/WE on energy and energy services efficiency	- reduction from 2008 final energy consumption by 1%, achieving 9% in 2016, - obligation to establish and periodically update the National Action Plan for the improvement of energy efficiency.

Source: Olkiewicz & Bober 2017.

The assumptions of the Ministry of Economy include a fuel and energy demand forecast (by 2030 the demand for energy will increase by 29%, and in particular the demand for renewable energy will increase by 55%) and a programme of activities related to the development of renewable energy sources by 2012, which include, among others:

- an increase in the share of renewable energy sources in total energy consumption by at least 15% by 2020 and further increase in the following years (in 2009, the share was at the level of 8.6T i.e. 40 031 TJ) (GUS 2010),

- increase to 10% of the share of biofuels in the transport fuel market and increase of the use of second-generation biofuels,
- increase in the degree of diversification of supply sources by 2020 and creating optimal conditions for the development of dispersed energy generation based on locally available raw materials.

One of the most important points of the development strategy are restrictions on energy production using RES and the widespread use of green technologies by both producers and consumers, particularly in terms of legal conditions. The most frequently mentioned legal barriers include:

- problems with new power connections
- the lack of a clear definition of the division of costs related to the modernization and adaptation of the power grid between the investor and the operator,
- disproportionate differences in the determination of connection costs per 1 MW of capacity,
- difficult procedure under the scheme of applying for the issuance of connection conditions,
- interpretation of the definition of energy sources, such as waste,
- frequent changes in the amount of subsidies for the purchase of technology or connections.

The constantly changing legal conditions in the Polish and EU energy system cause that large investments in the implementation of pro-environmental measures are postponed because of the uneconomic calculation and the lack of local and regional support for this type of investments. Therefore, more and more often, business and local government entities are being forced to create distributed energy systems using local production sources and to create innovative technological solutions, in products as well as production processes, which minimize energy consumption and CO_2 emissions, which closely correlates with the concept of environmental corporate social responsibility.

3. Actions for environmental corporate social responsibility – Renewable energy sources

Growing expectations, awareness, responsibility, the need for action by many countries and global organizations in the field of environmental protection and the introduction of all restrictions, including CO_2 emissions, as well as increased consumption, make it necessary to implement new, innovative energy production technologies, e.g. from renewable sources (RES). By reducing CO_2 emissions, the economies of various countries have begun to implement production systems based mainly on traditional mine energy resources processed in power plants and refineries, as a result of the implementation of the ECSR.

Poland has also made efforts to minimize environmental destruction within the framework of ECSR activities. The highest demand for final energy from petroleum products (22.4 Mtoe) was determined, as well as for energy from coal (10.9), natural gas (9.5 Mtoe) and energy from renewable sources (4.6 Mtoe). Analyzing the existing demand, it is forecast that by 2030 the situation will change radically and the energy demand is to be met with a greater share of oil products (27.9 Mtoe), natural gas (12.9 Mtoe) and renewable energy (6.7 Mtoe). (Ministerstwo Gospodarki 2010).

These assumptions mean that investments will increasingly be directed towards activities promoting new energy sources, including low or zero-carbon renewable. Various technologies, such as biomass incinerators plants, biogas plants, wind farms, solar and photovoltaic systems, can be used for the main sources (providing green connection energy) of biomass, solar, wind and geothermal energy. Such a large possibility of using energy sources is of great importance, because there is still a growing demand trend for energy in Poland. This shows, for example, an increase of primary energy consumption per capita from 101.2 GJ in 2009 to 113.9 GJ in 2010, with the total primary energy consumption in Poland in 2010 amounting to 4351.8 PJ2 (GUS 2010a).

The need to increase the share of renewable energy sources in overall energy consumption is becoming more and more important due to the significantly increasing trend in energy demand. Changes in environmental measures that are in line with the ECSR and aim, inter alia, at reducing emissions of unwanted greenhouse gases and improving awareness among market participants and the general public are necessary. In order to increase the activation of investments aimed at the construction of ecological power plants, sewage treatment plants and other sensitive objects of the local self-governments and to make the local and regional area more attractive, an analysis of the investment attractiveness of renewable ecological activities has been created.

It should therefore be stressed that the national territorial potential, taking into account the factors of production (sun, wind, biomass, geothermal energy, etc.), is suitable for investing (as part of renewable energy sources) in modern, capital-intensive, innovative technological solutions, i.e. thermal power plants, biogas plants or agro-refineries. This means that ECSR activities can ensure a sustainable development of the country or its specific areas, while implementing pro-environmental measures. However, due to limited financial capacity, small or medium-sized installations are promoted in the country, most often located in rural or urban-rural areas. The assessment of the possibility of carrying out pro-environmental activities has shown the need for local and regional support for:

- creation of appropriate investment instruments (infrastructure, financing, qualified human resources, tax reliefs and exemptions, appropriate relations between local and regional authorities, etc.),
- knowledge transfer between science and entrepreneurship (economy),
- a right climate – an ecological culture of the region.

4. Actions for environmental corporate social responsibility – Improving quality in the field of environmental protection

Evolutionary changes in governance, the development of entrepreneurship, the growing needs of stakeholders, environmental degradation, global warming, etc. led to, among others:

- modern management of organizations,
- the need to take account of environmental protection elements in production and quality management processes,
- increased awareness of the need to care for and improve the environment,
- improvement of environmental performance processes.

Modern governance of organizations, including of local self-governments, is caused by a change in the way of thinking, creating policies and strategies of action from central (autocratic) to decentralized (participatory), focused on long-term social and economic development of regions. Such model (standardized) governance makes it possible to create quantitative, task-oriented and qualitative correlations, ensure security (including those related to environmental protection (PKN 2016) in the region, strengthen administrative units and focus on market shareholders(especially entrepreneurs and residents (O'Sullivan & Dooley 2009), which is closely linked to the idea of the concept of environmental corporate social responsibility.

It should be assumed that the optimization of activities aimed at creating an appropriate environmental policy determines the process approach based on management instruments, and quality management in particular (PKN 2015). The need for constant monitoring, improvement, identification of newly emerging threats, as well as chances and opportunities, e.g. for investment, increasing competitiveness, economic attractiveness and local and regional as well as social and economic potential provides an opportunity for responsible governance aimed at improving quality, pro-quality measures, within the framework of environmental protection.

The instruments of quality management used in modern environmental protection activities are to have a significant, long-lasting impact on the shape, effectiveness and efficiency of the adopted system solutions. Due to the importance and the need to conduct radical measures aimed at improving the environment, guaranteeing the achievement of the assumed parameters, the formal modern quality management instrument implemented according to standards (developed and improved over the years and adopted) allow to ensure the maximum level of quality, safety, satisfaction, development, etc. as part of the implemented (production) processes. Such management instruments include international management systems according to the ISO family of standards. In its general assumption, management systems can be classified as tools for long-term activities relating through: quality policy, hierarchization of goals, tasks, identified processes and parameterization, to all areas of the organization as well as relations created with market shareholders. Within the framework of management systems, the following can be distinguished:

- quality management and/or quality assurance systems (ISO 9001 – Quality Management System; ISO 13485 – Quality Management System for manufacturers of medical devices; ISO/ TS 16949 – Quality Management System for automotive manufacturers, etc.),
- strategic management systems (BS 25999/ ISO 22301 – Business Continuity Management System, ISO 26000 – Social Responsibility Management System, etc.),
- environmental management systems (ISO 14001 – Environmental Management System; EMAS – Eco-Management and Audit Scheme; ISO 50001 – Energy Management System, etc.),
- risk-based management systems,
- health and safety management systems,
- food safety systems,
- management system of the laboratory or inspection body,
- and others.

ISO 14001 is the most widely used management system, which incorporates the elementary basis of pro-environmental activity correlated with the idea of ECSR *Environmental Management Systems* according to the PN-EN ISO 14001:2015-9 standard, complements the organization's comprehensive management system that identifies existing and potential environmental threats, as well as indicates ways to reduce and prevent them. The environmental management system, due to its multidimensional and multi-faceted approach to potential threats, as well as meeting certain requirements, makes the costs of adjusting the organization and maintaining the system, ensuring the clients that the offered products and production process comply with all environmental requirements, very capital-intensive and time-consuming. Perhaps that is why this system is not very successful, as Table 2 presents in comparison with the enterprise management system from the Table 3.

Table 2. Number of entities certified under ISO 14001 for the period 2006-2017

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Total	128211	154572	188574	222974	239880	243393	260852	273861	296736	319496	346147	317941
Europe	55919	65097	78118	89237	103126	101177	111807	115764	119072	119754	120595	111133
Poland	837	1089	1544	1500	1793	1900	2014	2220	2208	2798	3184	2921

Source: own work on basis of data from: ISO Survey 2018

The environmental management system in accordance with the PN-EN ISO 14001 standard is therefore aimed at pro-environmental activities that increase environmental safety while maintaining quality, economy and process optimization. It is worth noting that the environmental management system can exist independently, focused on environmental quality and safety, or together with another system of the ISI family, e.g. ISO 9001, as an integrated management system. That is also due to the fact that ISO 9001 refers to an organization's management system and is therefore the most widespread (Table 3) and has a structure that complies with other ISO family standards.

Table 3. Number of entities certified under ISO 9001 for the period 2011-2017

Year	2011	2012	2013	2014	2015	2016	2017
Total	1009845	1017279	1022877	1036321	1034180	1105937	1055028
Europe	459367	469739	458814	453628	439477	451415	386009
Poland	10984	10105	10527	9574	10681	12152	11846

Source: own work on basis of data from: ISO Survey 2018

A broader analysis of a country's environmental certificate density ratio expressed in the number of certificates per million inhabitants and the GDP per capita rate for each country calculated in accordance with the purchasing power parity method is presented in the publication Implementation of ISO 14001 standard in the European Union countries (Olkiewicz et al. 2019).

Another significant management system within the framework of comprehensive environmental protection measures is the energy management system ISO 50001:2012 that replaced the BS EN 16001:2009 standard. The new standard had significant differences in approach to energy management, as BS EN 16001:2009 focused on the energy aspects of environmental protection (contained in ISO 14001) while ISO 50001:2012 focused exclusively on the use and consumption of energy.

The new management standard has been developed to meet emerging needs and market requirements in the provision of energy services, ensuring that energy performance is improved and energy efficiency is achieved through the definition of appropriate energy consumption and use indicators, leading to reductions in costs and greenhouse gas emissions. Due to its membership in the ISO series of standards, the system is integrated with other systems such as ISO 9001 or ISO 14001.

The management system in accordance with the ISO 50001:2012 standard applies to all types and sizes of organizations, regardless of the industry, geographical location, cultural and social conditions (it proves its flexibility and functionality). It is particularly important for organizations operating in energy-intensive industries, which also have to meet the requirements and regulations on greenhouse gas emissions. The analysis of the literature shows that the ISO 50001:2012 standard can significantly reduce energy consumption by up to 60% (Olkiewicz & Bober 2017), which is why it is becoming increasingly popular, as shown in the Table 4.

Table 4. Number of entities certified under ISO 50001 for the period 2011-2017

Year	2011	2012	2013	2014	2015	2016	2017
Total	459	2236	4826	6765	11985	20216	21501
Europe	364	1919	3993	5526	10152	17102	17655
Poland	2	12	22	38	74	112	173

Source: own work on basis of data from: ISO Survey 2018

Efficient energy management is one of the main determinants of development and environmental protection, creating regional energy policies in the process of efficient use of energy resources and regulation of greenhouse gas emissions, which is why it also forms part of the ECSR.

To sum up, through continuous monitoring and research of degradation phenomena, the use of formal environmental management systems allows for the identification of best pro-environmental activities (practices) that guarantee environmental improvement and increase environmental awareness among market shareholders. The best-suited concept for such activities is the Environmental Corporate Social Responsibility (ECSR) concept based on the ISO 26000 standard.

5. Conclusions

Environmental issues, and in particular its care for it, has become the main determinant of modern management of organizations, as evidenced by various publications in the literature. The increasing awareness of the importance of environmental issues in a given country, company or household results in greater activity in pro-ecological activities. The analysis carried out in this publication has shown that social and economic changes force organizations to implement or adopt pro-environmental solutions that are compatible with both international management systems (ISO 9001, ISO 14001, ISO 50001) and responsible practices as well as environmental corporate social responsibility (ECSR). In other words, compliance by business entities with pro-quality requirements or with recommendations and an appropriate, documented pro-quality policy.

It is worth noting that the idea of ECSR implemented by companies has a significant impact on the role and attitude of citizens towards environmental issues. There are also positive changes among ECSR users related to: building a stable development of the organization (pro-environmental organization, business success), reputation (building trust in the company or its products, loyalty, increased number of customers, etc.), easier ability to attract and retain employees (respecting employee rights, ethical behavior, etc.), better relations with market stakeholders (customers, suppliers, contractors, media, etc.) and quality of life. It should be kept in mind, however, that building a responsible environmental action strategy is a long-term process and requires appropriate resources, sometimes-innovative solutions that will bring the desired environmental and non-environmental effect in the future.

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Abstract

The level of environmental safety culture depends on many factors, including the influence of parents and the education system, the media and the quality of life. In the current Economy 4.0, globalization, increasing greenhouse effect, etc., it is the information and education system and the pro-environmental strategic actions undertaken by organizations that are beginning to play a significant role in building awareness and care for the environment. It is precisely the environmental corporate social responsibility, both of state institutions, the legislator, business entities and society (every citizen) that can significantly change the phenomenon of environmental degradation. The aim of the article is to present the essence of ecological corporate social responsibility and the activities undertaken by selected market stakeholders. The analysis carried out implies that ECSR is built through the implementation of pro-environmental stakeholder's actions, e.g. legislative changes, implementation of management systems according to ISO standards, use of renewable energy sources, etc. that aim at ensuring safety or improving the current state of the environment.

Keywords:
environmental management, social responsibility, ISO 14001, ISO 26000, environmental aspects, environmental corporate social responsibility

Ekologiczna społeczna odpowiedzialność biznesu narzędziem kreowania przyszłości ochrony środowiska

Streszczenie

Poziom kultury bezpieczeństwa ekologicznego uzależniony jest od wielu czynników między innymi wpływu rodziców i systemu edukacji, mediów, jakości życia. W obecnej gospodarce 4.0, globalizacji, zwiększającym się efekcie cieplarnianym itd., to system informacyjno-edukacyjny i podejmowane przez organizacje strategiczne działania pro środowiskowe zaczynają odgrywać znaczącą rolę w budowaniu świadomości oraz troski o środowisko naturalne. To właśnie ekologiczna społeczna odpowiedzialność biznesu, zarówno instytucji państwowych, ustawodawcy, podmiotów gospodarczych i społeczeństwa (każdego obywatela) może w znaczący sposób wpłynąć na zmianę zjawiska degradacji środowiska naturalnego. Celem artykułu jest przedstawienie istoty ekologicznej społecznej odpowiedzialności biznesu oraz działań podejmowanych przez wybranych interesariuszy rynku. Z przeprowadzonej analizy wynika, że ECSR budowane jest poprzez implementację działań pro środowiskowych interesariuszy np. zmian ustawowych, wdrożeń systemów zarządzania wg norm ISO, wykorzystywanie odnawialnych źródeł energii, itp. zmierzających do zapewnienia bezpieczeństwa lub poprawy obecnego stanu środowiska naturalnego.

Słowa kluczowe:
zarządzanie środowiskowe, odpowiedzialność społeczna, ISO 14001, ISO 26000, aspekty środowiskowe, ekologiczna społeczna odpowiedzialność biznesu.