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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.

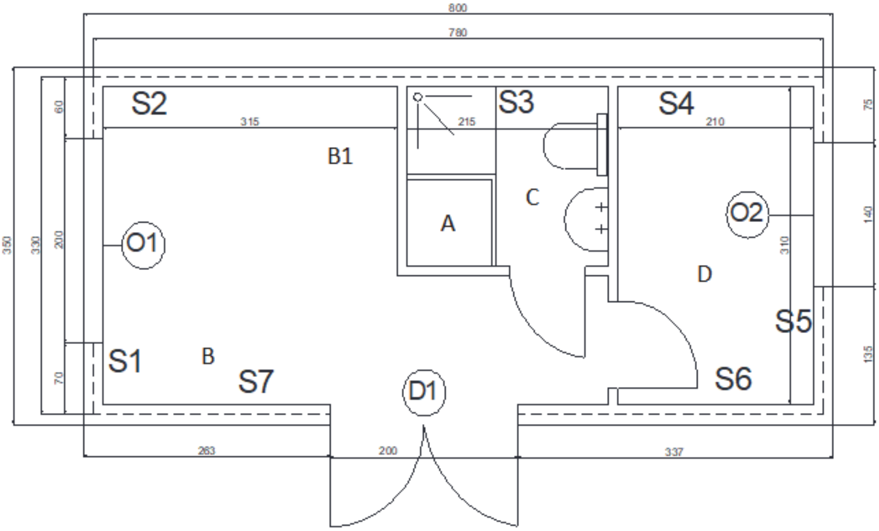

Fig. 2. An exemplary scheme of the layout residential WH object rooms mounted on the float 3.5 x 8 m; A – technical room for the heat pump, B – livingroom, B1 – kitchenette, C – bathroom and toilet, D – bedroom

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.

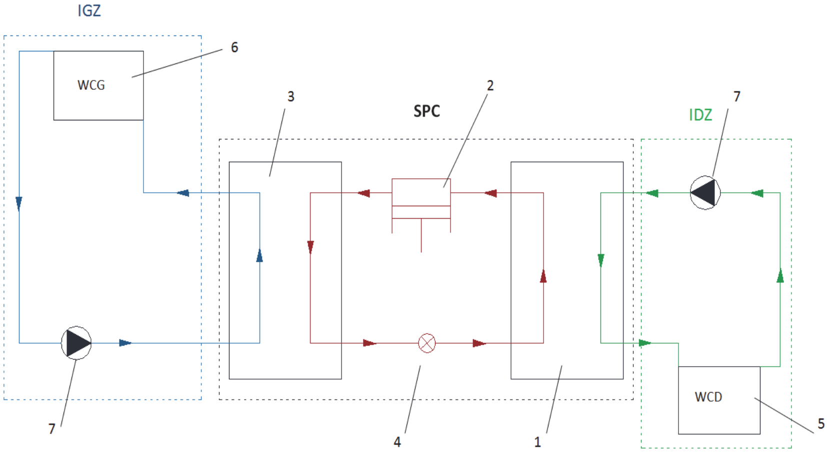

Fig. 3. Schematic diagram of the WH compressor heat pump cooperation with the lower and upper heat sources: 1 – evaporator, 2 – compressor, 3 – condenser, 4 – expansion valve, 5 – lower heat exchanger (WCD), 6 – upper exchanger heat sources (WCG), 7 – brine pumps, SPC – compressor heat pump, IDZ – installation 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.

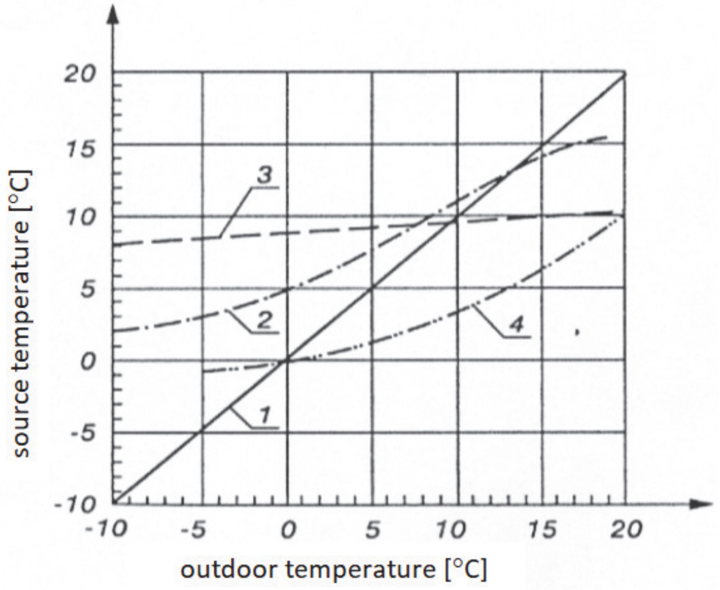

Fig. 4. Comparison of the impact of ambient temperature on the lower heat source temperature: 1 – outside air, 2 – surface water, 3 – ground water, 4 – ground

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.

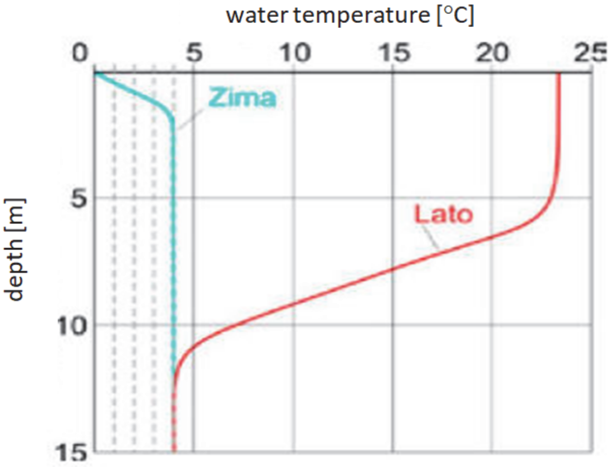

Fig. 5. Changes in surface water temperature depending on depth in winter and summer season (www.solis.pl)

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.

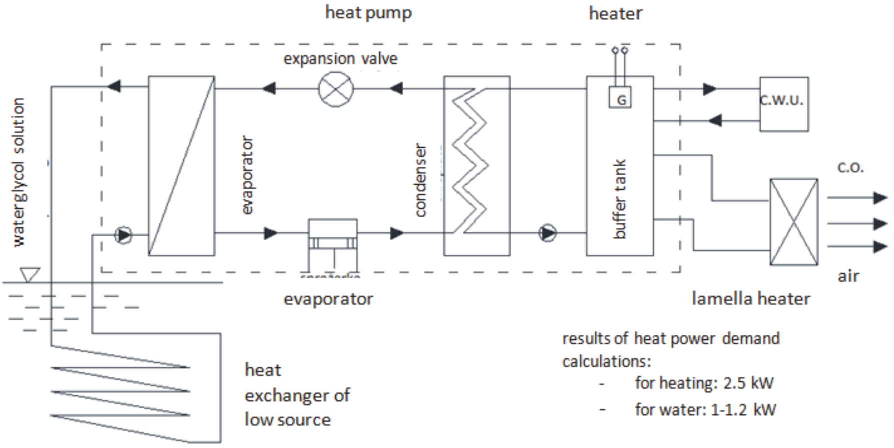

Fig. 6. Diagram of the example solution for the installation of a heat pump in the application of air heating and domestic hot water installation in the WH

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.

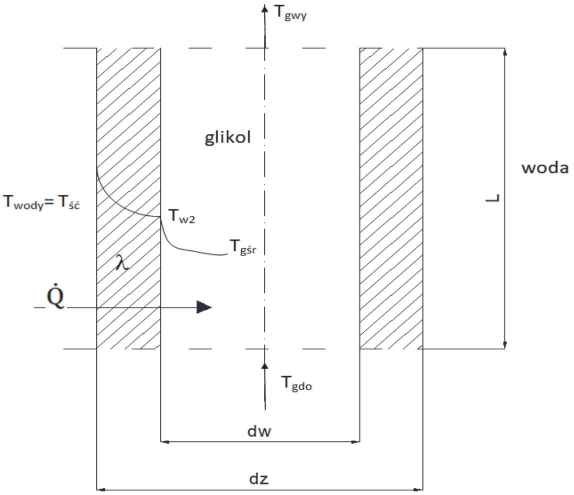

Fig. 7. Calculation model of heat exchange between surface water and an ethylene glycol water solution in a compressor heat pump lower heat exchanger

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 $T_{\acute{s}c} = T_{wody} = 5°C$. In steady-state, the heat flux Q through a single-layer cylindrical wall is described by the relationship:

$$Q = \frac{2 \cdot \pi \cdot \lambda \cdot L \cdot \left(T_{wody} - T_{w2}\right)}{\ln \frac{d_z}{d_w}}, \tag{4}$$

$$Q = \pi \cdot d \cdot L \cdot \left(T_{w2} - T_{gl,\acute{s}r}\right) = k_l \cdot L \cdot \Delta T_{\log} \tag{5}$$

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. $(T_{wody} - T_{gl,\acute{s}r})$. 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.

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"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