MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

Rocznik Ochrona Środowiska

Volume 22. Year 2020 ISSN 1506-218X 537-548

The Investigation of Thermophysical Characteristics of Porous Insulation Materials Based on Burshtyn TPP Ash

Hanna Koshlak[*], *Anna Kaczan*
Kielce University of Technologies, Poland
[*]*corresponding author's e-mail: kganna.777@gmail.com*

1. Introduction

Reducing heat emissions through the construction of buildings and structures, industrial equipment, heating networks and other facilities is the main goal of energy saving. Therefore, the production and use of thermal insulation materials in thermal technologies and construction is an important component in ensuring the sustainable development of society.

One of the most promising technologies to produce porous structures is the use of fly ash thermal power station as the base material. The authors of (Chudnovsky 1962) explored the possibility of using as solid mineral filler to obtain porous structures solid wastewater and coal ash. Study Dehghan (2016) presents a novel thermal plasma melting technique for neutralizing and recycling municipal solid waste incinerator (MSWI) ash residues. MSWI ash residues were converted to water-quenched vitrified slag using plasma vitrification, which is environmentally benign. Slag is produced as a raw material in producing porous materials for architectural and decorative applications, eliminating the problem of its disposal (Koshlak & Pavlenko 2019). Propose to use fly ash and silicon dioxide in the production of autoclaved aerated concrete. However, in this work, as in all of the above, the aim was not to carry out comprehensive studies aimed at selecting the composition of the raw material mixture based on cheap raw materials (in our case, the technogenic waste – TPP ash).

Thermophysical characteristics of porous thermal insulation materials are generally determined by the structure, size, type and shape of pores, as well as their relative arrangement in the material (Pavlenko & Koshlak 2019). The most important thermophysical properties of porous materials include three characteristics of heat transfer: thermal conductivity, thermal diffusivity and specific heat.

The thermal conductivity of materials depends on the following factors:

1) the physical state and structure, which are determined by the phase state of the substance; degree of crystallization and crystal size; anisotropy of thermal conductivity of crystals and direction of heat flux; the volume of porosity of the material and the characteristics of the porous structure,
2) the chemical composition and the presence of impurities, the latter especially affect the thermal conductivity of crystalline bodies,
3) operating conditions depending on the temperature, pressure, humidity of the material.

The most important of these characteristics is thermal conductivity. The thermal conductivity of porous materials with a constant composition of the solid phase depends on the porosity, type and characteristics of the porous structure.

Also thermophysical characteristics of porous materials will vary depending on the size and location of pores, chemical composition and molecular structure of the components, humidity. The specific heat of the materials depends on their nature and to a small extent on the volume of porosity. Average density is a value that is equal to the ratio of the mass of a substance to its volume, is measured in kg/m^3. It should be noted that the average density of thermal insulation materials is quite low compared to most building materials, because a considerable volume is occupied by pores. The density of thermal insulation materials used in construction ranges from 17 to 400 kg/m^3, depending on their purpose.

Humidity – adversely affects the thermophysical properties of thermal insulation products. As the moisture content of the insulating (and building) materials increases, their thermal conductivity dramatically increases. An important characteristic of a thermal insulation material is the sorption moisture, which is the equilibrium hygroscopic moisture of the material, at different temperatures and relative humidity.

Water absorption (hygroscopicity) – (the ability of a material to absorb and retain moisture in the pores in direct contact with water) has a negative effect on the thermal conductivity of the material, because with increasing humidity the thermal conductivity increases.

Temperature resistance is an important property of thermal insulation materials, especially when used to insulate industrial equipment operating at high temperatures. The application temperature of insulation materials should be slightly lower than their temperature resistance, since it is necessary to take into account destructive phenomena in products with prolonged heating (Muthtamilselvan et al. 2010, Kahveci 2017).

Frost resistance – the ability of a material in a saturated state to withstand repeated alternation of freezing and thawing without signs of destruction. The longevity of the whole structure depends on this indicator.

The mechanical properties of thermal insulation materials include strength (compression, bending, tensile, resistance to the formation of cracks).

Strength – the property of materials to resist the destruction of external forces that cause deformation and internal stresses in the material. The strength of thermal insulation products depends on the structure, strength of their solid component (skeleton) and porosity. Solid material with small pores is more durable than material with large uneven pores.

2. Purpose of work and research methods

Conducting a study of raw material mixture based on TPP Bursthyn ash to identify patterns of change in the thermophysical characteristics of porous materials. Thermal conductivity in porous material is due to various physical processes that can be reduced to three types: conduction, convection, and radiation. Literature sources indicate that the dependence of thermal conductivity has the character of an exponential function (Nield & Bejan 2013). These dependencies are not sufficiently clear and expressive in nature, which makes it impossible to offer an analytical expression to describe this function, especially at large values of material density. In our experiments, the coefficient of thermal conductivity was determined in the dry state and in the state of sorption moisture, which did not exceed 20%.

The thermal conductivity of porous insulation materials was investigated using an IT-λ-400 instrument. The test specimens of cylindrical shape with a thickness of 5 mm and a diameter of 15 mm were placed in the device and subjected to heating to 800°C. In this temperature range, the thermal conductivity of the material was determined according to the standard procedure outlined in the operating instructions of the device.

The thermal conductivity of the samples was calculated by the formula:

$$\lambda = \frac{h}{R_s} \tag{1}$$

where:
λ – thermal conductivity, h – sample thickness, RS – thermal resistance.

To improve the measurement accuracy, the thermal conductivity of each sample was measured three times, followed by averaging. The measurement error was 4-5%. The experimental value of the thermal conductivity of the samples varied from 0.04 to 1.3 W/(mK).

Investigation of the compressive strength of the specimens. The compressive strength of materials was determined by standard methods (Tarasov 2016). To determine the compressive strength, the cubes with rib sizes of 5 and 10 cm were cut. The samples were dried to constant weight at a temperature of 105-110°C. Cubes tested on the press. The maximum effort obtained during the test was taken as the value of the destructive load, such as the compressive strength was in the range of 0.3-8.0 MPa.

Water absorption. To determine the water absorption was made samples of dimensions 100×100 mm with a thickness of the product. The sample was dried to constant weight and immersed in water at 20°C, covered with a mesh and mounted on top of the sample and kept for twenty-four hours. For the first three hours, half the thickness of the specimen was under water, and then completely in water after all the time. After the experiment, the sample was wiped with a cloth, weighed on scales. Water absorption W, % was calculated by the formula:

$$W = \frac{m_1 - m}{m} \cdot 100 \tag{2}$$

where:
m – dry sample mass, g; m_1 – mass of water saturated with the sample, g.

Water absorption in the experiments varied from 1 to 18%.

3. Experimental research

The experimental data were processed using the planned experiment method. As the objective function (Y, W/(mK)), thermal conductivity is accepted. The experiment was based on the program of the central composite rotatable plan of the second order of Box-Hunter (Pian 2016). The kernel of the plan is represented by the semicolon 2^{5-1} ($1 = X_1X_2X_3X_4X_5$). Controlled factors are those investigated in the previous series of experiments. The selected factors satisfy the requirements of controllability, interdependence, uniqueness, which must be satisfied by variational factors when planning the experiment. 16 experiments were implemented at the basic levels, supplemented by another 10 experiments at the star points (the magnitude of the star shoulder in our case is 2) and six experiments at the center of the plan. The main levels, factor variation intervals, and boundaries of the study area were selected from previous experiments and based on information (Table 1).

The feedback function is approximated by a second-order polynomial:

$$Y = b_0 + \sum_{1<i<k} b_i X_i + \sum_{1<i<k} b_i X^2{}_i + \sum_{1<i,l<k} b_{i,l} X_i X_l \tag{3}$$

where:
k – number of independent variables.

Table 1. Basic levels, intervals of variation of factors and boundaries

Factor	Code	Value					Change interval
		-2	-1	0	+1	+2	Δ
Ash content, part of weight	X_1	0	30	60	90	120	30
Clay content, part of weight	X_2	0	20	40	60	80	20
Water content, part of weight	X_3	10	30	50	70	90	20
Temperature, °C	X_4	100	150	300	450	600	150
Content Na_2SO_4, part of weight	X_5	0	3	6	9	12	3

The processing of the experimental results and the analysis of the regression model were performed using the “Experiment Planning” module of the Statgraphics 5.0 Plus statistical program. The significance of the coefficients of the model was determined with the help of the P-level and shown on a standardized Pareto graph (Fig. 1). The vertical line in Fig. 1 corresponds to 95% of the statistical significance of the coefficients. According to Fig. 1, the coefficients for the linear terms of the regression equation for the ash, water and temperature contents are statistically significant. In this case, the coefficients for pair interactions are statistically insignificant and may not be taken into account when calculating the obtained model.

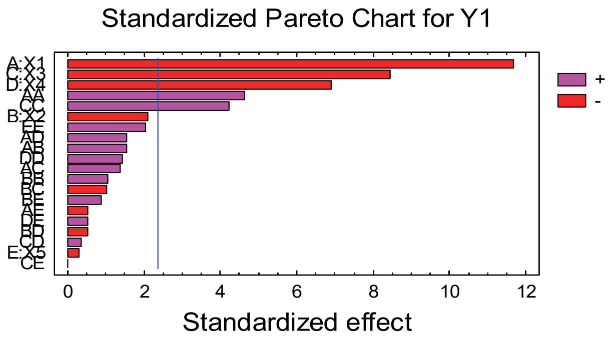


Fig. 1. Significance of model coefficients (Pareto graph)

The regression equation, given the significance of the coefficients, is:

$$Y1 = 0{,}978724 - 0{,}00966389 \cdot X_1 - 0{,}00824062 \cdot X_3 + \\ + 0{,}000705556 \cdot X_4 + 0{,}0000322917 \cdot X^2{}_1 + 0{,}0000664062 \cdot X_3{}^2 \qquad (4)$$

The adequacy of the model of the studied process is confirmed by the high value (about 100%) of the coefficient of determination R_2 = 99,44%, as well as the small value of the standard error of the estimate SE = 0,1598.

As can be seen in many cases, the difference between these data is negligible. Most of the experimental points are near the straight line.

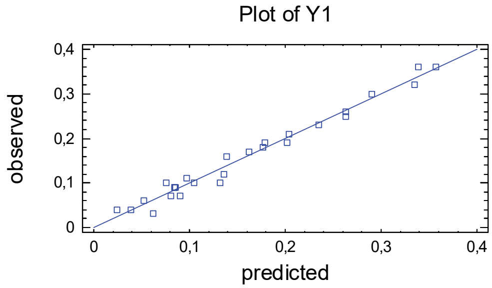


Fig. 2. Comparison of experimental (observed) and estimated (predicted) model data (2)

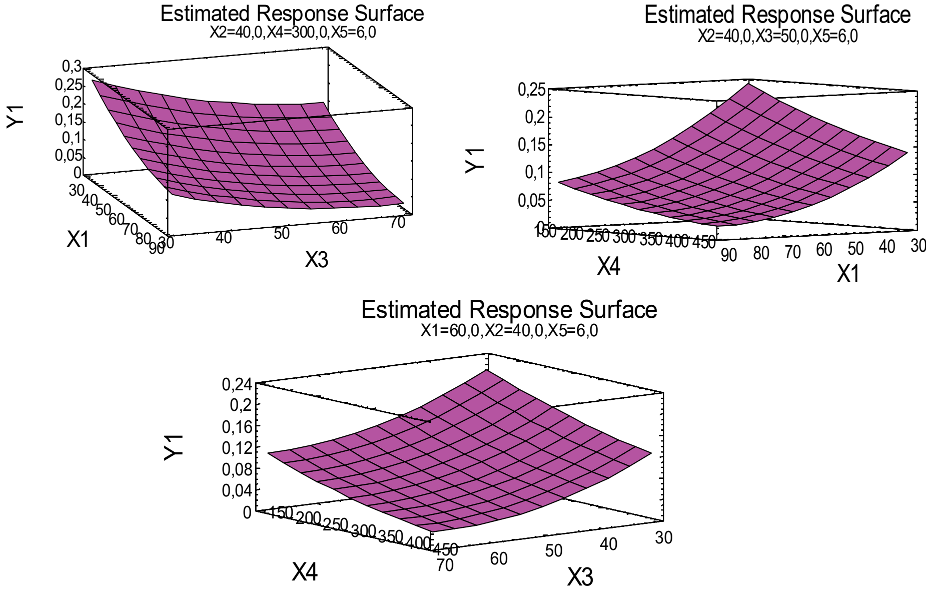


Fig. 3. Surfaces of the influence of paired factors on thermal conductivity of porous materials

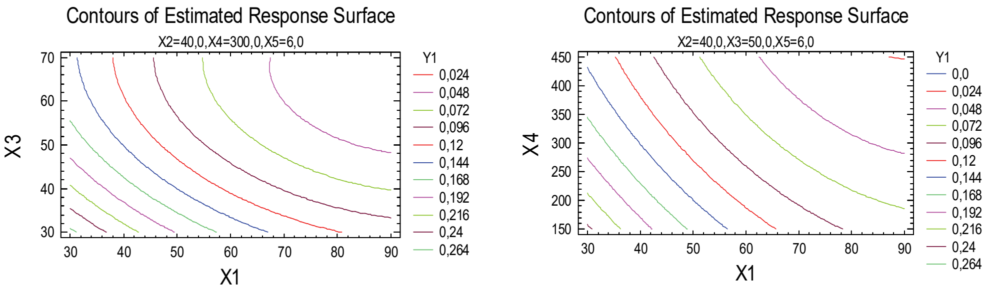


Fig. 4. Surfaces of the influence of paired factors on the thermal conductivity of porous materials

As can be seen from the three-dimensional cross sections of the hypersurface Y_1 (X_i) and the contour curves of these surfaces, the thermal conductivity of the porous thermal insulation materials increases as the mass fraction of amber ash (X_1) and the water content (X_3) decrease and the swelling temperature (X_4) decreases. This is consistent with our understanding of the influence of these factors on thermal conductivity. Another indicator that was investigated under the conditions indicated in table 1 is the strength of porous compression materials (Y_2). As can be seen from the figures in Fig. 5 data, statistically significant are the coefficients for the linear terms of the regression equation for the water content (X_3), clay (X_2), ash (X_1), temperature (X_4) and interaction X_3X_4, X_4X_5.

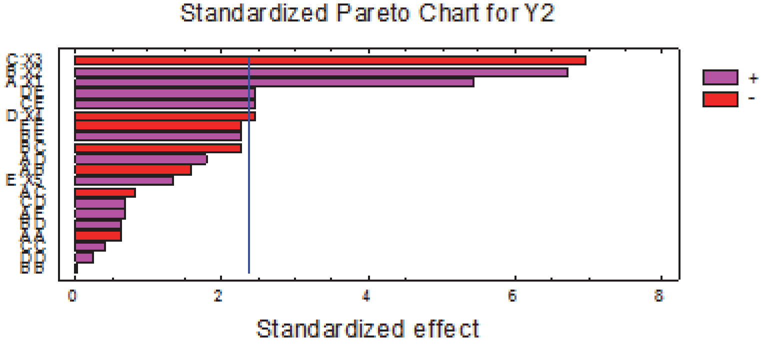


Fig. 5. Significance of model coefficients (Pareto graph)

The regression equation, given the significance of the coefficients, is:

$$Y_2 = 7{,}91641 + 0{,}0415278 \cdot X_1 - 0{,}0693229\ X_2 + 0{,}0771875 \cdot X_3 - \\ - 0{,}0174444 \cdot X_4 + 0{,}0075 \cdot X_3 \cdot X_5 + 0{,}001 \cdot X_4 \cdot X_5. \quad (5)$$

The model was found to be adequate to the process under study (coefficient of determination R_2 = 96.9%, standard error of estimate SE = 0.29).

Figure 6 shows a comparison of experimental and predicted data. The difference between these data is small.

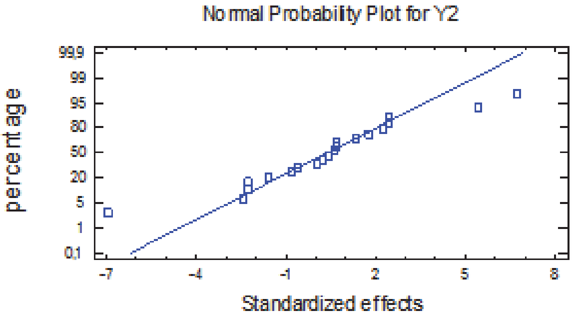
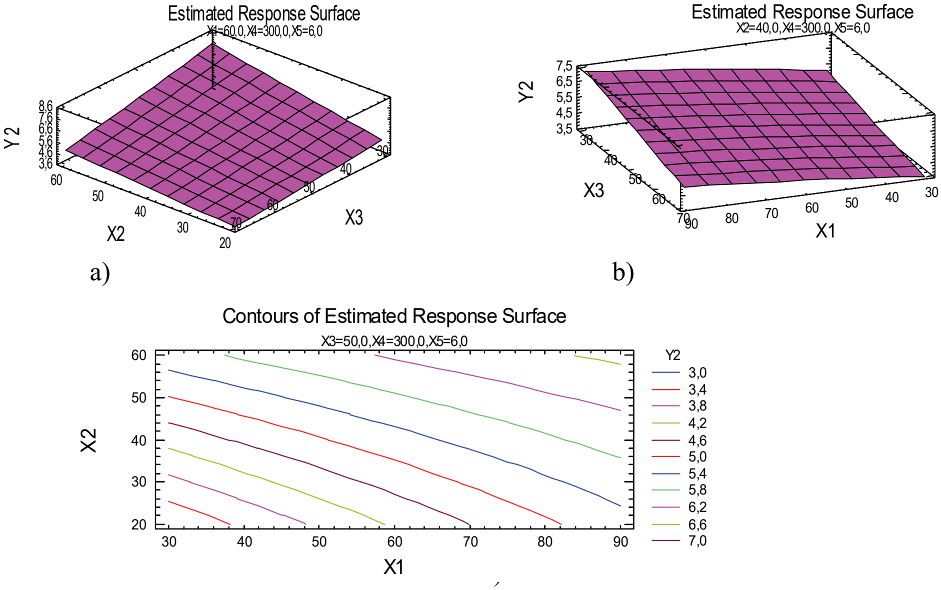


Fig. 6. Comparison of experimental (observed) and estimated (predicted) model data (5)

In Fig. 7 shows the surfaces of the influence of paired factors on the strength of porous materials based on the ash of a thermal power plant.



a)

b)

Fig. 7. Surfaces of influence of factors on the strength of porous ash-based materials: a) $Y_2 = f(X_1,X_3)$; b) $Y_2 = f(X_2,X_3)$; c) $Y_2 = f(X_1,X_2)$

The water absorption (Y_3) of porous materials depends, first of all, on the presence of open porosity of the material. The conditions of the experiments did not change (Table 1). Water absorption was assessed by controlling the change in mass of the test samples of the porous materials. Water absorption in the experiments varied from 1 to 18%.

In Fig. 8, we can distinguish statistically significant coefficients for the terms of the regression equation for Y_3: temperature (X_4, X^2_4), ash (X_1), water (X_3), clay (X_2, X^2_2) and interaction X_1X_4.

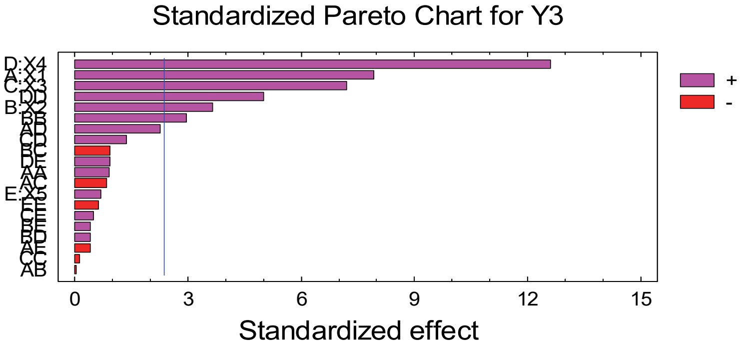


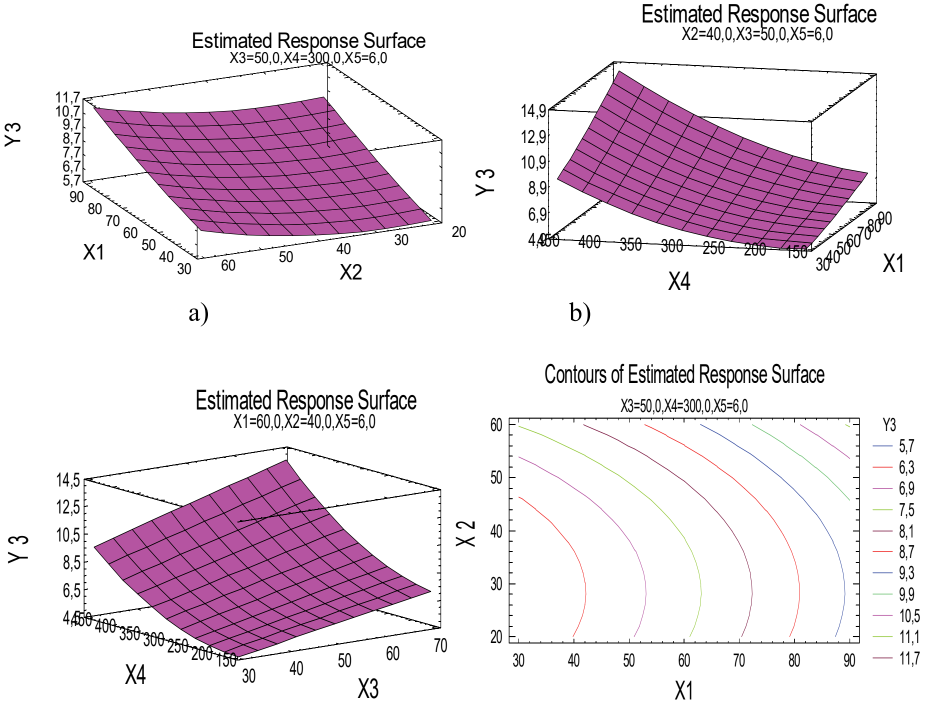
Fig. 8. Significance of model coefficients (Pareto graph)

The regression equation, given the significance of the coefficients, is:

$$\begin{aligned} Y_3 = {} & 3{,}94297 + 0{,}016875 \cdot X_1 - 0{,}00907292 \cdot X_2 + 0{,}0874479 \cdot X_3 - 0{,}0331528 \cdot X_4 + \\ & + 0{,}000141667 \cdot X_1 \cdot X_4 + 0{,}00180469 \cdot X^2_2 + 0{,}0000543056 \cdot X^2_4 \end{aligned} \tag{6}$$

The model proved to be adequate to the process under study (coefficient of determination $R_2 = 97.9\%$, standard error of estimate $SE = 0.2$).

Fig. 9 show the surfaces of the influence of paired factors on the water absorption of porous ash-based materials.



a) b)

c) d)

Fig. 9. Surfaces of influence of factors on water absorption of porous materials based on ash of thermal power stations: a) $Y_3 = f(X_1,X_2)$; b) $Y_3 = f(X_1,X_4)$; c) $Y_3 = f(X_3,X_4)$; d) $Y_3 = f(X_1,X_2)$

From the graphs, for example, Figs. 7, 9, it follows that by increasing the ash content and, thus, replacing it with clay and Na_2SO_4, the same desirable values of thermal conductivity, durability and water absorption can be achieved, which is actually to be proved.

4. Conclusions

The results obtained give a qualitative and quantitative assessment of the components of the raw material mixture based on ash with structural indicators of materials. The very structure of the material affects the thermophysical characteristics in a certain quantitative dimension. The proposed dependencies determine the influence of the studied factors on the thermophysical properties of the obtained samples of porous materials. The proposed methods and solutions allow us to predict the values of thermal conductivity, strength and water absorption, and with the help of variables X_1, X_2, X_3, X_4, X_5 it is possible to control the swelling process to achieve optimal values of these thermophysical parameters. The results obtained suggest that the parameter Y_i can be optimized by selecting the investigated factors.

The project is supported by the program of the Minister of Science and Higher Education under the name: "Regional Initiative of Excellence" in 2019-2022 project number 025 / RID / 2018/19 financing amount PLN 12,000,000.

References

Chudnovsky, A.F. (1962). *Thermophysical characteristics of dispersed materials*. State Publishing House of Physical and Mathematical Literature. 456.

Dehghan, M., Valipour, M. S., Saedodin, S. (2016). Microchannels enhanced by porous materials: Heat transfer enhancement or pressure drop increment? *Energy Conversion and Management*, *110*, 22-32.

Kahveci, K. (2017). Modeling and numerical simulation of simultaneous heat and mass transfer during convective drying of porous materials. *Textile Research Journal*, 0040517516635998.

Koshlak, H., Pavlenko, A. (2019) Method of formation of thermophysical properties of porous materials | [Metoda formowania właściwości termofizycznych materiałów porowatych] *Rocznik Ochrona Srodowiska, 2*, 1253-1262.

Muthtamilselvan, M., Kandaswamy P. K., and Jinho Lee, (2010). Hydromagnetic Mixed Convection in a Two-Sided LidDriven Porous Enclosure, *Int. J. Fluid Mech. Res.*, *37*, 406-423.

Nield, D. A., Bejan, A. (2013) Heat transfer through a porous medium // Convection in Porous Media. *Springer New York*, 31-46.

Pavlenko, A., Koshlak, H. (2019). Heat and mass transfer during phase transitions in liquid mixtures | [Przenoszenie ciepła i masy podczas przemian fazowych w mieszaninach ciekłych], *Rocznik Ochrona Srodowiska, 21*(1), 234-249.

Pian, G. (2016). Porosity and pore size distribution of influenza on thermal conductivity of yttria-stabilized zirconia: Experimental findings and model predictions. *Ceramics International, 42*, 5802-5809.

Tarasov, V.E. (2016). Heat transfer in fractal materials. *International Journal of Heat and Mass Transfer, 93*, 427-430.

Abstract

Thermophysical characteristics of porous thermal insulation materials (PTM) are generally determined by the structure, size, type and shape of pores, as well as by their mutual arrangement in the material. Thermal conductivity is one of the most important among these characteristics, is caused by different physical processes and can be reduced to three types: conduction, convection and radiation. Literature sources imply that thermal conductivity dependence is represented as an exponential function. These dependencies fail to have a sufficiently clear and pronounced nature and do not allow developing an analytical expression to describe this function, especially at high values of material density. In our experiments, the thermal conductivity coefficient was determined in the dry and sorption humidity states, not exceeding 20%. The thermal conductivity of porous thermal insulation materials was studied using an IT-λ-400 device. Cylindrical test specimens, 5 mm thick and 15 mm in diameter, were placed in the device and heated to 800°C. Within this temperature range, the material thermal conductivity was determined according to the standard procedure described in the device operating instructions. The observed data were processed using the designed experiment approach. Thermal conductivity is considered as the target function (Y, W/(m K)). The experiment was conducted according to the program of the central composite rotatable second-order design by Box-Hunter. The factors, studied in the previous series of experiments, are considered as controllable ones. Variable factors shall meet these criteria during experiment design process. 16 experiments were conducted at basic levels and supplemented by another 10 experiments at star points.

Keywords:
porous thermal insulation materials, thermal conductivity, convection, radiation, Burshtyn TPP ash, Box-Hunter

Badanie właściwości termofizycznych porowatych materiałów izolacyjnych na bazie popiołu TPP Burshtyn

Streszczenie

Właściwości termofizyczne porowatych materiałów termoizolacyjnych (PTM) są ogólnie określone przez strukturę, wielkość, rodzaj i kształt porów, a także przez ich wzajemne rozmieszczenie w materiale. Przewodność cieplna jest jedną z najważniejszych spośród tych cech, jest spowodowana różnymi procesami fizycznymi i może być zredukowana do trzech rodzajów: przewodzenia, konwekcji i promieniowania. Źródła literatury sugerują, że zależność przewodności cieplnej jest reprezentowana jako funkcja wykładnicza. Zależności te nie mają wystarczająco wyraźnego charakteru i nie pozwalają na opracowanie analitycznego wyrażenia opisującego tę funkcję, szczególnie przy wysokich wartościach gęstości materiału. W naszych eksperymentach współczynnik przewodności cieplnej został określony w stanie suchym i wilgotności sorpcji, nie przekraczając 20%. Przewodność cieplną porowatych materiałów termoizolacyjnych badano za pomocą urządzenia IT-λ-400. Próbki cylindryczne o grubości 5 mm i średnicy 15 mm umieszczono w urządzeniu i ogrzano do 800°C. W tym zakresie temperatur przewodność cieplna materiału została określona zgodnie ze standardową procedurą opisaną w instrukcji obsługi urządzenia. Obserwowane dane zostały przetworzone przy użyciu zaprojektowanego podejścia eksperymentalnego. Przewodność cieplna jest uwzględniana jako funkcja celu (Y, W/(m K)). Eksperyment przeprowadzono zgodnie z programem centralnego obrotowego kompozytowego projektu drugiego rzędu firmy Box-Hunter. Zmienne czynniki muszą spełniać te kryteria podczas procesu projektowania eksperymentu. Przeprowadzono 16 eksperymentów na poziomach podstawowych i uzupełniono o kolejne 10 eksperymentów w punktach gwiazdowych.

Słowa kluczowe:
porowate materiały termoizolacyjne, przewodnictwo cieplne, konwekcja, promieniowanie, popiół Bursthyn TPP, Box-Hunter