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FINDING OF THE GENERALIZED EQUATION OF THERMAL CONDUCTIVITY FOR POROUS HEAT-INSULATING MATERIALS

Досліджено вплив конвекції в замкнутих порах на коефіцієнт ефективної теплопровідності теплоізоляційного матеріалу. Визначено загальний характер розподілу швидкостей ліній току конвекції в замкнутій сферичній порі з діаметрами 2–20 мм. Встановлено найбільш значимі фактори впливу на коефіцієнт ефективної теплопровідності за допомогою регресійного аналізу. Надано рекомендації щодо створення нових крупнопористих теплоізоляційних матеріалів.

Ключові слова: *конвекція, замкнута сферична пора, регресійний аналіз, ефективна теплопровідність.*

1. Introduction

The prospects of using of porous heat-insulating materials in the industry don't in doubt [1–3]. New porous materials appear every year. Such materials are used as heat-insulating for houses, constructions, pipelines, furnaces, dryers and other industrial equipment. In [4] the creation of new porous heat-insulating heat-proof material on the basis of composite binder and gas agent was described, but thermal properties of such material weren't given and the possibility of porosity regulation wasn't described. Despite the fact that porosity (quantity, size and pores form) influences on the effective thermal conductivity [5, 6].

The generalized equation of thermal conductivity is needed for assessing of the future effective thermal conductivity of porous material, but it doesn't exist. Also the generalized equation will allow controlling the thermal conductivity of porous material at the pores formation stage without numerous experiments. So, finding of the generalized equation of thermal conductivity of porous heat-insulating materials is an actual scientific task, which is useful for the industry.

2. The object of the research and its technological audit

The object of research is the heat transfer through porous insulating materials. The most famous problem is the lack of generalized equation of thermal conductivity, it doesn't allow to predict the effective thermal conductivity of the material at the structure formation stage. The reason of it is lack of complex entrance independent factors of porous structure that influence on the effective thermal conductivity. For determining of this factors the computer simulation was used, results of it was confirmed by laboratory experiment. For finding of the generalized equation of thermal conductivity of porous heat-insulating materials the experimental design method was used. Disadvantages of the obtained equation are the narrowed application boundaries, the pore size of 2 mm, the thermal conductivity of the basic material without pores is 0,95 W/(m·K).

3. The aim and objectives of the research

The aims of this work are creation of the generalized equation of thermal conductivity of porous heat-insulating materials and give the practical recommendations for structure formation of such materials.

To achieve that aims, next objectives must be solved:

1. Research the influence of the convection in the pores on the thermal resistance by the computer simulation.
2. Confirm the obtained dependencies by the practical experiment in the laboratory.
3. Identify the main factors which influence on the coefficient of effective thermal conductivity of porous materials.
4. Find the regression equation of thermal conductivity of porous heat-insulating materials by the experimental design method.
5. Analysis of the regression equation to give the practical recommendations for structure formation of heat-insulating materials.

4. Literature review

Before this time the effective thermal conductivity could be solved by the difficult systems of equations, which taking into account radiation and convection inside the pores [7, 8]. These equations have many simplifications and semi-empirical factors (i.e. only suitable for specific materials). Therefore, they aren't suitable for controlling the thermal conductivity of porous material at the production stage.

In [9] the microporous structure of ceramic insulation material is considered as a fractal. Looking at fractal structure the size and the location of pores can be taking into account, although pore form wasn't considered. The idea, which was proposed in the work is scientifically interesting, but it doesn't allow proposing practical recommendations for the creation of porous insulating material. Also in the work the structure and the equations, which are effective only for microporous structures, were considered. Calculation of thermal resistance was made by electro-thermal analogy. But in this method convective and radiation components were neglected, phonon thermal conductivity wasn't considered (which for ceramic products has significant value).

In [10] three mathematical models of the porous gasars were made and was proven that for this material the pore form (cylindrical, conical, elliptical) doesn't matter, the main thing – the total porosity of the material. But in the conducted research the convection in pores and the number of pores weren't considered. Therefore, the conclusion that only porosity of the material will influence on the effective thermal conductivity, can be real only for the equally spaced micropores. The proofs are given in [11, 12]. Also in [12] the conclusion that the pores form is important (big difference of the coefficient of thermal conductivity between elongated and flattened pores) was made.

The influence of convection in the pores is very difficult task, in which many scientists take part [13, 14]. The characteristic feature of many investigations of the convection in closed pores is their use only for a narrow specific material. So, the decision of three-dimensional task of the gravitational convection in the Boussinesq approximation was given in [15]. But the obtained results are permissible only for specific sizes of the air layer.

In the literature are plenty information about the impact of the porous materials structure on their thermal properties, but there are no practical recommendations for the formation of structural indicators of macroporous thermal insulation materials. Some articles are controversial and needed clarification. Therefore it is necessary to create the generalized equation of thermal conductivity of porous heat-insulating materials and on its basis give practical recommendations for creation of new porous thermal insulation materials.

5. Materials and methods of research

Methods of research were computer simulation and empirical method.

For researching the influence of the convection on the thermal resistance of porous thermal insulating materials were built following computer models. Cube with sides of 0,04 m was modeled. In the center of the cube was spherical pore. Pore was simulated with different diameters. On one of the surfaces of the cube was set heat flux 100 W/m^2 and 10 W/m^2. The opposite surface of the cube was set with convection cooling and with an initial temperature 22 °C. Other cube surfaces were adiabatic. The material in the pore was ideal air with pressure of 1 atm. The gravitational force was set to an axis which was parallel to the heating and cooling surfaces, and was equal to 9,81 m/s^2.

In the laboratory research was used the polystyrene foam of the firm «TechnoNikol ekoplit» with thermal conductivity 0,035 W/(m·K), density 2,6 kg/m^3 and heat capacity 1,45 kJ/(kg·K). The thermal conductivity was measured by the thermal conductivity meter ITP-MH4 of the company «SKB Stroyprybor». The samples were made with closed and open porosity. The open porosity was made by through holes. The diameter of the pores and holes in the samples was 4, 6, 7, 8 and 10 mm. The probe of the thermal conductivity meter before every measurement was anointed with thin layer of the thermal paste KPT-8.

6. Results of the research

6.1. Research of the influence of the convection in pores on the thermal resistance of the porous thermal insulation materials. The mesh was consisted of tetrahedrons. Physical preference was made for the method of calculation hydrodynamics. The boundary layers of the mesh were chosen in number of five both for pore and for material. The material and pore of diameter 20 mm with mesh is shown in Fig. 1.

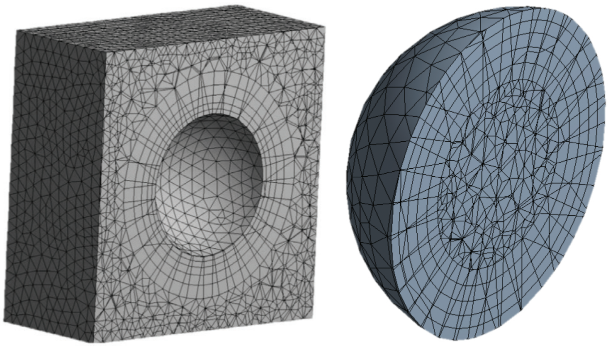

Fig. 1. The estimated mesh on the heat insulation material (*a*) and pore (*b*) with half section

The allocation of convective lines velocity in the closed spherical pore of diameter 20 mm is shown in Fig. 2. Fig. 2 shows that the convection in the pore of diameter 20 mm is perpendicular to the heat flow and along of the lower and upper spherical poles. This is due to the fact that the driving force of convection is the gravitational force. The velocity of air in the pore is low and doesn't exceed 0,00008 m/s. Also velocity near pore center is the smallest and close to zero.

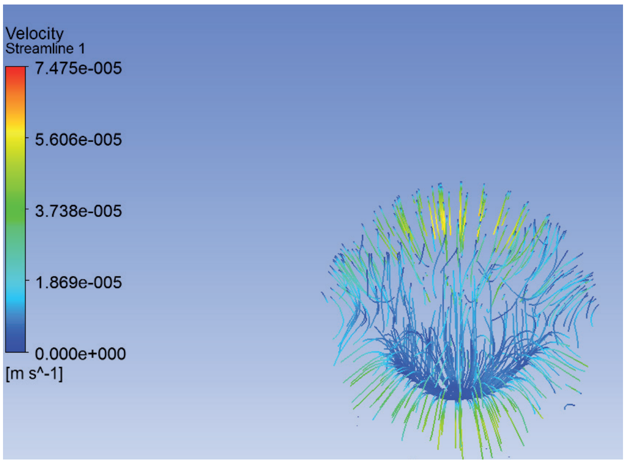

Fig. 2. The allocation of convective lines velocity in the closed spherical pore of diameter 20 mm

The changing of the convective lines velocity in the closed spherical pore of diameter 10 mm must be marked. The allocation of convective lines velocity in the closed spherical pore of diameter 10 mm is shown in Fig. 3. *Fig. 3 shows that the convective lines velocity is allocated spirally. The velocity of air* in *the pore of diameter 10 mm lower than in the pore of diameter 20 mm. The spiral motion of the convective lines velocity can be explained by* *self-organization of the convective cell like the Rayleigh-Bénard convection cell. In the Rayleigh-Bénard cell heat flow is directed along the vector of gravity but in Fig. 3 heat flow is directed perpendicular to gravity.*

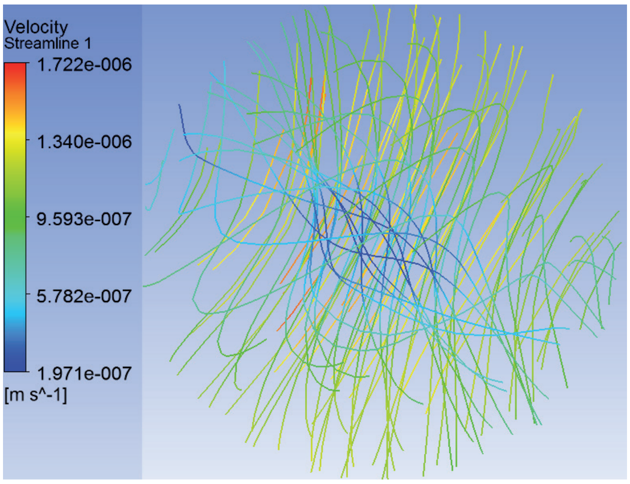

Fig. 3. The allocation of convective lines velocity in the closed spherical pore of diameter 10 mm

Smaller air velocity in the spiral motion of convective lines means that for increasing the thermal resistance of insulation materials the spiral motion of convective lines in a closed spherical pore is better than the transverse motion with partial flow along the lower and upper spherical poles.

Fig. 4 shows the temperature distribution in the body with pore diameter of 20 mm. Also it shows that the temperature of air in the pore is approximately the same. The temperature on the surface of pore is differs maximum of 7 °C, while the temperature difference on the either sides of the material is more than 60 °C. Also Fig. 4 shows that the pore of diameter 20 mm for set conditions has a good heat resistance to heat flow even in porous materials.

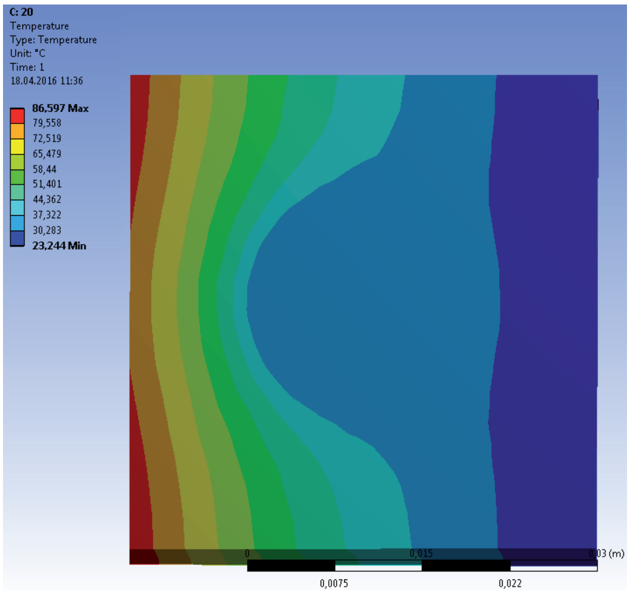

Fig. 4. The distribution of temperature in the material with spherical pore of diameter 20 mm with half section

Fig. 5 shows the vectors of the heat flow in the material with pore of diameter 20 mm (section). The initial heat flow was set to 10 W/m^2. Also it shows that heat flow is significantly reduced in the pore and after it. The heat flow gets maximum values on the front surface of the pore and increases to 20 W/m^2. The increasing of the heat flow becomes clear after combination of Fig. 5 and Fig. 2. *Thus, the increasing of the heat flow is due to the influence of convection. Because the heat flow under the influence of convection is moved of the poles and part of it goes back, where it combines with heat flow that goes to the front of pores.*

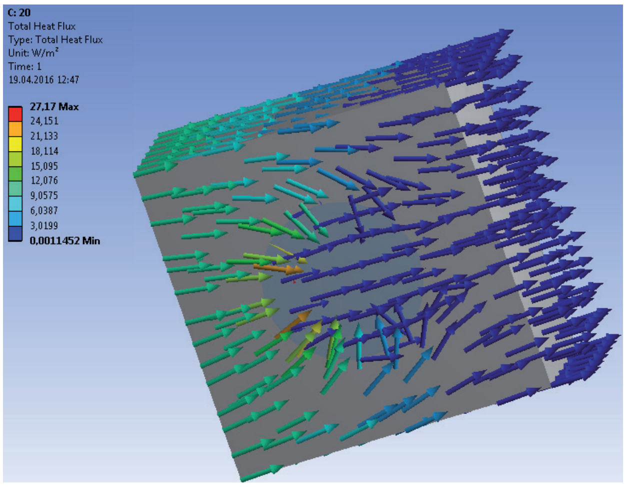

Fig. 5. The vectors of the heat flow in the material with spherical pore of diameter 20 mm

For researching of the influence of convection on the thermal resistant of heat insulation materials, with different pore size, computer models of samples with different pore diameters were made. The diameters of the closed spherical pore were 2, 5, 10, 15, 20 mm. For each diameter, the computer simulations of convection in the pores and the heat static analysis of thermal insulation material were made. As an insulation material was chosen polystyrene foam with a density 40 kg/m^3, thermal conductivity 0,036 W/(m·K) under 20 °C, and heat capacity 1,34 kJ/(kg·K). The minimum number of iterations for the convective analysis was 1100. The maximum estimated error by balance was 10,5.

Fig. 6 shows the dependence of the thermal resistance of thermal insulation material on the pore diameter. Bar dotted purple line shows the thermal resistance of the material with absolute vacuum in the pore. The dotted green line shows the thermal resistance of the material with air in the pore, but without convection. Black horizontal line shows the thermal resistance of the material without pore. The solid blue and red lines show the changing of the material resistance on the diameter of pore with the influence of convection.

The analysis of Fig. 6 shows that without convection, the increasing of pore diameter (as total porosity of material) increases thermal resistance of thermal insulation materials. But convective motions inside the pore significantly reduce thermal resistance. With a diameter of 2 mm pore convection is almost absent. *The convection occurs with pore diameter of 5 mm, but the total resistance of the thermal insulating material with pore above the resistance of the thermal insulation material without it. For a given pore diameter the effect of temperature is essential.* Thus, with a small heat flow of 10 W/m^2, the thermal resistance less than the thermal resistance with heat flow of 100 W/m^2. It can be explained by the temperature gradient on the pore surface. *With pore diameter of 10 mm or more, convection becomes significant and reduces the thermal resistance, so that it becomes smaller than the thermal resistance of the material without pore.*

For creation of porous insulation material it is recommended to use the pores less than 8 mm with a small temperature difference (10 °C).

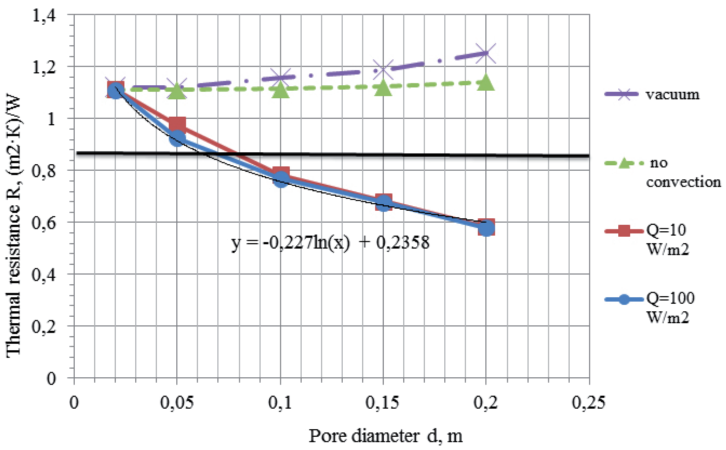

Fig. 6. The dependence of the thermal resistance of heat insulation material on the pore diameter

Fig. 6 also shows that dependence of the thermal resistance on the diameter is logarithmic.

To confirm the obtained dependences the laboratory experiment was conducted. Sheet of polystyrene foam was cut on the rectangular parallelepipeds. The experimental sample was consisted of such 5 parallelepipeds. Before assembling, two parallelepipeds were perforated by nine symmetrically located holes. To remove the contact resistance, the contact surfaces were anointed by thin layer of thermal paste MX-4. The assembly was made by gluing the side surfaces on the joints. At the end surface of the finished sample the blind hole of diameter 5,1 mm and a length of 76 mm under probe for thermal conductivity measuring was made. Schematically the assembly is shown in Fig. 7.

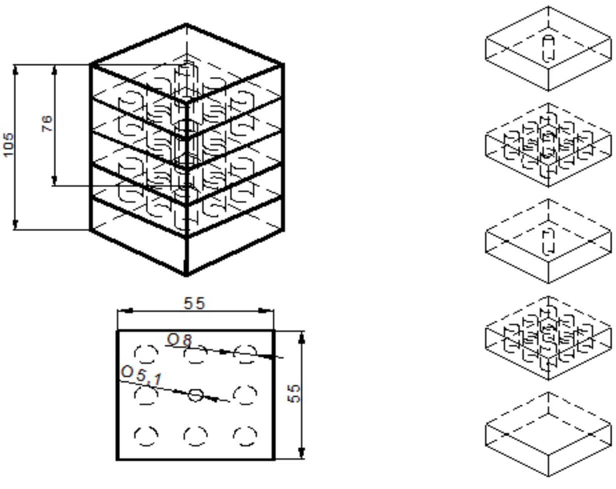

Fig. 7. The scheme of the assembly of experimental sample

By experiment results the dependence of the thermal conductivity on the pore diameter was made (Fig. 8). The black horizontal line shows the thermal conductivity of the material without pores. The obtained dependencies confirm that pores with size of along the heat flux less than 7 mm are increase the heat resistance of insulating materials. In the experiment, the pores with size 7 and 8 mm are increasing the thermal conductivity of insulation material at 2,86 %. It can be explained by the fact that the pores form was cylindrical (not spherical) and the measuring device error was 7 %.

Also Fig. 8 shows that the coefficient of thermal conductivity of material with open porosity is bigger than with closed porosity, except diameter of 4 mm. It can be explained by increasing of the convective part in case with open porosity.

Reduction of the coefficient of thermal conductivity of thermal insulation material with open porosity and pores diameter of 4 mm occurs because the overall porosity in open porosity higher than in closed porosity (in this experiment) and the convective component is missing.

The results of the experiment are allowed to confirm the accuracy of the obtained computer modeling dependencies.

Also, it can be concluded that with pore diameter of 4 mm and during the operation of materials to a temperature of 50 °C the convective component inside the pore is completely absent.

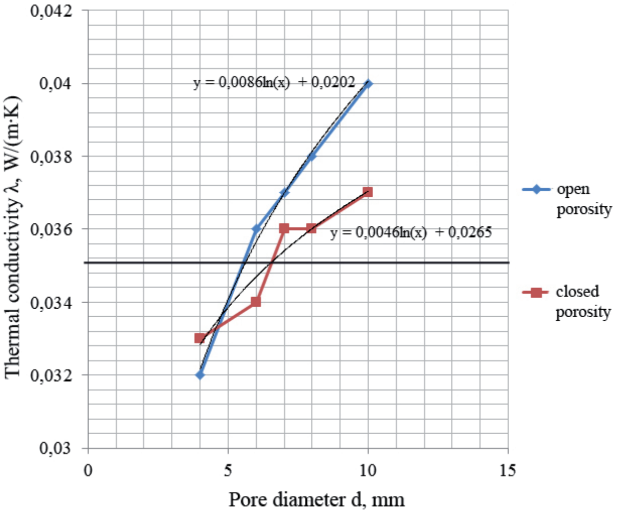

Fig. 8. The dependence of the coefficient of thermal conductivity of experimental samples on the pore diameter

6.2. Finding of the generalized equation of thermal conductivity for porous heat-insulating materials. For creating of the generalized equation of thermal conductivity for porous heat-insulating materials it is necessary to determine the main parameters, which influence on the thermal conductivity of materials. These parameters must be independent of each other. The conducted research in this section are allow to determine the following main parameters: temperature gradient of pore grad T, thermal conductivity of material without pores λ_{mat}, pore diameter along to the heat flow d_1, pore diameter perpendicular to the heat flow d_2, number of the pores per unit volume n. The pore diameters along and perpendicular to the heat flow were chosen because they have the most effect on the changing of effective thermal conductivity. Other geometric dimensions of pore (forms, which are closed to sphere) don't significantly affect the effective thermal conductivity. Since the dependence of thermal conductivity of porous material on the pore diameter is logarithmic, the logarithms of diameters were used. The values and coding factors are given in the Table 1.

Table 1

The conditions of the experiments

Factor	Code	Levels of factors			
		–1	0	1	Δ
The logarithm of the pore diameter along to the heat flow $\ln(d_1)$, mm	X_1	1,386 (4 mm)	1,733 (5,63 mm)	2,079 (8 mm)	0,347
The logarithm of the pore diameter perpendicular to the heat flow $\ln(d_2)$, mm	X_2	1,386 (ln4)	1,733 (ln5,63)	2,079 (ln8)	0,347
Gradient of pore temperature grad T, °C/m	X_3	10	50	90	40
Thermal conductivity of material without pores $\lambda_{мат}$, W/(m·K)	X_4	0,05	0,5	0,95	0,45
Number of the pores per unit volume n, num./$6,4\cdot 10^{-5}$ m^3	X_5	1	5	9	4

Since the dependence of the function on the factors X_1 and X_2 is linear, then for these factors will be enough the second order plan, for other factors will be enough the third order plan.

The mixed composite plan of the second and third order was used. Number of pores was varied in a plane which is perpendicular to the heat flow. The analysis of results was made in the trial version of the program Statistica. After regression analysis the coefficients of generalized equation of thermal conductivity for porous heat-insulating materials were obtained (Table 2). Regression equation was chosen with linear, quadratic and paired coefficients. In the first column next factors are indicated: L — linear coefficients, Q — quadratic coefficients. Also in the Table 2 is set Student's t-test. Important coefficients are marked by italics.

The Pareto distribution of the influence of initial factors shows that the biggest influence on the coefficient of effective thermal conductivity have the pore diameter along to the heat flow and the total impact of the pore diameter perpendicular to the heat flow with temperature gradient.

The generalized equation of thermal conductivity for porous heat-insulating materials without unimportant factors will be the next:

$$\lambda = 0,046 + 0,02X_1 - 0,0255X_3 - 0,0178X_3^2 + \\ + 0,0023\cdot X_2\cdot X_5 + 0,034\cdot X_3\cdot X_5. \qquad (1)$$

The analysis of equation (1) shows that the thermal conductivity of initial material without pores λ_{mat} in investigated range of 0,05 to 0,95 W/(m·K) isn't a significant factor. The increasing of the pore diameter along the heat flow significantly increases thermal conductivity of the material. The temperature gradient doesn't linear and not directly proportional impact on the thermal conductivity of the final material. Number of pores is directly proportional impact on the effective thermal conductivity of material by the coefficients of pair interactions.

Table 2

The encrypted coefficients of the regression equation in the program Statistica

Factor	Effect Estimates; Var.lambda R-sqr=,81775; Adj:,51703 (porous2.sta) 2 2-level factors, 3 3-level factors, 54 Runs DV: lambda MS Residual=,0008348					
	Effect	Std.Err.	t(20)	p	–95, % Cnf.Limt	+95, % Cnf.Limt
Mean/Interc.	0,04593	0,00417	11,0137	0,0000001	0,03723	0,05462
3L by 5L	0,03395	0,01179	2,8784	0,00929	0,00934	0,05855
(3)grad(t)(L)	–0,02551	0,00963	–2,6493	0,01538	–0,0456	–0,00542
2L by 5L	0,02286	0,01021	2,2388	0,03669	0,00156	0,04417
2L by 3L	0,02032	0,01021	1,9896	0,06048	–0,00098	0,04163
(1)ln(d1)(L)	0,01955	0,00834	2,3445	0,02948	0,00215	0,03695
1L by 5L	–0,01907	0,01021	–1,8672	0,07659	–0,04038	0,00223
1L by 3L	–0,01861	0,01021	–1,8218	0,08347	–0,03991	0,00269
grad(t)(Q)	–0,01777	0,00834	–2,1306	0,04571	–0,03516	–0,00037
4L by 5L	–0,01714	0,01179	–1,4534	0,1616	–0,04174	0,00746
4L by 5Q	–0,01635	0,01021	–1,6012	0,125	–0,03766	0,00495
(2)ln(d2)(L)	–0,01566	0,00834	–1,8776	0,07509	–0,03305	0,00173
3Q by 5L	0,01559	0,01021	1,5267	0,14249	–0,00571	0,0369
1L by 2L	–0,01464	0,00834	–1,7556	0,09445	–0,03204	0,00275
1L by 3Q	–0,01361	0,00884	–1,5387	0,13953	–0,03206	0,00484
lambda_m(Q)	0,01301	0,00834	1,5604	0,13434	–0,00438	0,03041
2L by 3Q	0,01273	0,00884	1,4391	0,16558	–0,00572	0,03118
1L by 5Q	0,01047	0,00884	1,84	0,25028	–0,00797	0,02892
2L by 4Q	–0,01033	0,00884	–1,1686	0,25628	–0,02879	0,00811
3Q by 4Q	–0,01	0,00884	–1,1312	0,27133	–0,02846	0,00844
3L by 5Q	0,00995	0,01021	0,9744	0,34146	–0,01135	0,03126
2L by 5Q	–0,00981	0,00884	–1,1097	0,28027	–0,02827	0,00863
1L by 4Q	0,00947	0,00884	1,0711	0,29684	–0,00897	0,02793
3L by 4L	–0,0094	0,01179	–0,7976	0,43441	–0,03401	0,01519
4Q by 5L	–0,00841	0,01021	–0,8235	0,41992	–0,02972	0,01289
4Q by 5Q	0,00707	0,00884	0,79973	0,43326	–0,01137	0,02552
(4)lambda_m(L)	0,00667	0,00963	0,69253	0,49656	–0,01342	0,02675
1L by 4L	0,00513	0,01021	0,5031	0,62037	–0,01616	0,02644
(5)n(L)	–0,00493	0,00963	–0,5119	0,61427	–0,02502	0,01515
2L by 4L	–0,00487	0,01021	–0,4775	0,63818	–0,02618	0,01643
n(Q)	0,00386	0,00834	0,4639	0,6477	–0,01352	0,02126
3Q by 5Q	–0,00233	0,00884	–0,2641	0,79437	–0,02079	0,01611
3L by 4Q	0,00126	0,01021	0,1239	0,90258	–0,02004	0,02257
3Q by 4L	0,00008	0,01021	0,0083	0,99345	–0,02122	0,02139

The encoded simplified equation will be the next (from the Table 3):

$$\lambda = 0,04065 + 0,014d_1 - 0,00527\cdot \mathrm{grad}(t) + \\ + 0,03423\mathrm{grad}(t)^2 + 0,01143\cdot d_2\cdot n + \\ + 0,01697\cdot \mathrm{grad}(t)\cdot n. \qquad (2)$$

Table 3

The encoded coefficients of the regression equation

Factor	Regressn Coeff.	Std.Err.	t(20)	p	–95, % Cnf.Limt	+95, % Cnf.Limt
Mean/Interc.	0,04065	0,01719	2,3644	0,02828	0,00478	0,07652
(1)ln(d1)(L)	0,014003	0,01103	1,2691	0,21897	–0,00901	0,03701
(2)ln(d2)(L)	–0,01278	0,01103	–1,1582	0,26039	–0,03579	0,01023
(3)grad(t)(L)	–0,00527	0,01076	–0,4901	0,62938	–0,02773	0,01718
grad(t)(Q)	0,03423	0,01865	1,8353	0,08136	–0,00467	0,07313
(4)lambda_m(L)	–0,00751	0,01076	–0,6977	0,49337	–0,02997	0,01494
lambda_m(Q)	–0,0091	0,01865	–0,4881	0,63073	–0,048	0,02979
(5)n(L)	0,00232	0,01076	0,2157	0,83134	–0,02013	0,02478
n(Q)	–0,01018	0,01865	–0,5462	0,59095	–0,04909	0,02871
1L by 2L	–0,00732	0,00417	–1,7556	0,09445	–0,01602	0,00137
1L by 3L	–0,0093	0,0051	–1,82183	0,08347	–0,01995	0,00134
1L by 3Q	0,01361	0,00884	1,53875	0,13953	–0,00484	0,03206
1L by 4L	0,00257	0,0051	0,5031	0,62037	–0,00808	0,01322
1L by 4Q	–0,00947	0,00884	–1,0711	0,29684	–0,02793	0,00897
1L by 5L	–0,00953	0,0051	–1,8672	0,07659	–0,02019	0,00111
1L by 5Q	–0,01047	0,00884	–1,18402	0,25028	–0,02892	0,00797
2L by 3L	0,01016	0,0051	1,9896	0,06048	–0,00049	0,02081
2L by 3Q	–0,01273	0,00884	–1,4391	0,16558	–0,03118	0,00572
2L by 4L	–0,00243	0,0051	–0,4775	0,63818	–0,01309	0,00821
2L by 4Q	0,01033	0,00884	1,1686	0,25628	–0,00811	0,02879
2L by 5L	0,01143	0,0051	2,23882	0,03669	0,00078	0,02208
2L by 5Q	0,00981	0,00884	1,1097	0,28027	–0,00863	0,02827
3L by 4L	–0,0047	0,00589	–0,79769	0,43441	–0,017	0,00759
3L by 4Q	–0,00126	0,01021	–0,1239	0,90258	–0,02257	0,02004
3Q by 4L	–0,00008	0,01021	–0,0083	0,99345	–0,02139	0,02122
3Q by 4Q	–0,02001	0,01769	–1,1312	0,27133	–0,05692	0,01689
3L by 5L	0,01697	0,00589	2,8784	0,00929	0,00467	0,02927
3L by 5Q	–0,00995	0,01021	–0,9744	0,34146	–0,03126	0,01135
3Q by 5L	–0,01559	0,01021	–1,5267	0,14249	–0,0369	0,00571
3Q by 5Q	–0,00467	0,01769	–0,2641	0,79437	–0,04158	0,03223
4L by 5L	–0,00857	0,00589	–1,4534	0,1616	–0,02087	0,00373

The pore dimension perpendicular to the heat flow should be 8 mm, but by extrapolation was found that reducing of the thermal conductivity of material also will be if this parameter increase up to 15 mm (extrapolation to 95 %).

7. SWOT-analysis of the research results

Strengths. Among the strengths of this research, results which were obtained by analyzing of generalized equation of thermal conductivity should be noted. These results allow to obtain the necessary thermal conductivity of porous material, by setting of its structural characteristics. Using of these data can significantly reduce the thermal conductivity of modern macroporous heat insulating materials that will increase energy efficiency of equipment.

Weaknesses. Among the weaknesses of this research is the uncertainty of factors impact, which was considered, on the strength of the final material. The thermal conductivity of the material is the main characteristic for heat insulation, but if porous material has low end strength this is significantly narrows area of it application. Also weaknesses include the complexity of manufacturing the material with specific size and location of pores.

Opportunities. The prospect for future research can be upgrade of the found regression equation of thermal conductivity by expanding the input parameters range.

Threats. The complexity of using obtained results is a large capital costs for creation of new porous heat insulation material. For the production of the refractory bricks by semi-dry method, needs to change the mold and the heat treatment mode. For changing the refractory slip production, need creation of the complex spill form and increasing time for spill pouring. For the production of foam glass — the large costs associated with developing a new method of creating the desired porous structure.

8. Conclusions

1. By computer simulation was obtained that decreasing of pore diameter to 10 mm change the motion of the convective air lines in the pore. They become spiral. In this case air velocity in the pore of diameter 10 mm less than air velocity in the pore of diameter 20 mm. The spiral motion of the lines can be explained by self-organization of the convective cell like the Rayleigh-Bénard convection cell. Smaller air velocity in the spiral motion of convective lines means that for increasing the thermal resistance of insulation materials, the spiral motion of convective lines in a closed spherical pore is better than the transverse motion with partial flow along the lower and upper spherical poles.

The heat flow gets maximum values on the front surface of the pore and becomes greater than the heat flow in the material. The increasing of the heat flow is due to the influence of convection. Because the heat flow under the influence of convection is moved of the poles and part of it goes back, where it combines with heat flow that goes to the front of pores.

2. In laboratory, by practical experiment, was found that in the insulation material with spherical pores of diameter 2 mm convection is virtually absent. If pore diameter is 4 mm, convective component inside the pore during the operation of material to a temperature of 50 °C is completely absent. The convection occurs with pore diameter of 5 mm, but the total resistance of the thermal insulating material with pore above the resistance of the thermal insulation material without it. For a given pore diameter the effect of temperature is essential. With pore diameter of 10 mm or more, convection becomes significant and reduces the thermal resistance, so that it becomes smaller than the thermal resistance of the material without pore. For creation of porous insulation material is recommended to use the pores less than 8 mm with a small pore temperature difference (to 10 °C).

3. The main parameters, which influence on the coefficient of effective thermal conductivity, were found: temperature gradient of pore grad T, thermal conductivity of

material without pores λ_{mat}, pore diameter along to the heat flow d_1, pore diameter perpendicular to the heat flow d_2, number of the pores per unit volume n.

4. The regression equation of thermal conductivity of porous heat-insulating materials was found. The encoded simplified equation will be the next:

$$\lambda = 0{,}04065 + 0{,}014 d_1 - 0{,}00527 \cdot \mathrm{grad}(t) + \\ + 0{,}03423 \mathrm{grad}(t)^2 + 0{,}01143 \cdot d_2 \cdot n + 0{,}01697 \cdot \mathrm{grad}(t) \cdot n.$$

5. The analysis of the regression equation was showed that the most influence (80 %) on coefficient of effective thermal conductivity have the pore diameter along to the heat flow and the total impact of the pore diameter perpendicular to the heat flow with temperature gradient. The thermal conductivity of initial material without pores λ_{mat} in investigated range of 0,05 to 0,95 W/(m·K) isn't a significant factor. The increasing of the pore diameter along the heat flow significantly increases thermal conductivity of the material. The temperature gradient doesn't linear and not directly proportional impact on the thermal conductivity of the final material. The number of pores is directly proportional impact on the effective thermal conductivity of material by the coefficients of pair interactions.

The new macroporous heat insulation materials must have the following parameters: the pore dimension along the heat flow 2–4 mm; the pore dimension perpendicular to the heat flow more than 8 mm (15 mm); the number of pores 9 pcs. to $6{,}4 \cdot 10^{-5}$ m^3.

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НАХОЖДЕНИЕ ОБОБЩЕННОГО УРАВНЕНИЯ ТЕПЛОПРОВОДНОСТИ ПОРИСТЫХ ТЕПЛОИЗОЛЯЦИОННЫХ МАТЕРИАЛОВ

Изучено влияние конвекции в замкнутых порах на коэффициент эффективной теплопроводности теплоизоляционного материала. Определен общий характер распределения скоростей линий тока конвекции в замкнутой сферической поре с диаметрами 2–20 мм. Установлены наиболее значимые факторы, влияющие на коэффициент эффективной теплопроводности с помощью регрессионного анализа. Предоставлены рекомендации по созданию новых крупнопористых теплоизоляционных материалов.

Ключевые слова: конвекция, замкнутая сферическая пора, регрессионный анализ, эффективная теплопроводность.

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