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THERMAL CONDUCTIVITY CALCULATION METHOD: POROUS STRUCTURES

Abstract. *The article describes the transfer of thermal energy through porous bodies with closed and open porosity. The semi-empirical equation for finding the effective coefficient of thermal conductivity of bodies with a porous structure is derived. The equation of finding the thermal permeability of the porous material and the geometric characteristics of the porous structure are presented.*

Keywords: *heat flux, porous materials, coefficient of thermal conductivity, porous structure, thermal permeability.*

Introduction

Porous materials are widely used in various industries such as, in energy, as thermal insulation materials; in metallurgy, as insulating materials; in aerospace, as titanium or aluminum sandwich panels; in shipbuilding, as hulls of passenger ships; in the automotive industry, as structural elements; in medicine, as implants in the human body. The transfer of thermal energy everywhere these materials in most modern scientific works was investigated in individual cases and for a specific task. Thus, in most cases, the effective coefficient of thermal conductivity for the porous materials is empirically determined and the heat transfer is calculated according to the Fourier law. In these cases, a small change in the porous structure (deformation of the body) will affect the effective coefficient of thermal conductivity.

In the present literature sources, which we are familiar, there is no single method for describing the complex indices of a porous structure and the porosity is uncertain as an environment with special conditions for the flow of thermal energy everywhere. Therefore, it is necessary to design a mathematical model for the transfer of thermal energy through bodies with microporous structure, which generalizes the empirical and analytical studies of modern scientific works and will be valid for most porous materials with microporous structure.

Literary review and problem statement

Among the scientific works describing the process of transfer of thermal energy throughout the porous structure, as well as thermophysical properties of porous materials, it is worth mentioning the works Koshlak G.V. [1], Freire-Gormaly M. [2], Fesmire J.E. [3], Yanjun Yu [4]. Based on their works, it is necessary to create a generalized model for the transfer of thermal energy throughout the body with a microporous structure. The dynamics of pore development in the mixture is described in [1]. [2] provides a detailed description of the complex characteristics of the porous structure of a material that will affect the energy transfer through it. The transfer of thermal energy and the dependence of the temperature gradient on the pore size in fractal materials are described in [3], but the article does not take into account the energy transfer by convection. The effective thermal conductivity of porous materials with micropores can also be calculated through the model proposed in [4]. But this model also does not take into account convection. And in [5] it is proved that when the pore size is more than 2 mm, microconvective flows occur, which significantly changes the energy transfer through such a porous body. Therefore, it is necessary to analize the transfer of thermal energy throughout the porous body with a new non-classical approach.

The change in the energy balance in a porous body considering the radiation energy is given in [6]. The impact of the Darcy number on the transfer of thermal energy throughout porous structures is proved in [7]. A model for the transfer of thermal energy during fluid motion throughout porous structures is given in [8, 9]. The model has many advantages, but the only parameter of the porous structure that is considered is overall porosity. The calculation of the effective thermal conductivity of the porous material is also doubtful. The basic equations of motion of a liquid and the equation of storage of mass on porous material are given in [10]. However, regression equations of changes in the thermophysical parameters of a material are given for cotton only and cannot be used for a general model of energy transfer through porous structures.

As we can see, the previous literature sources gives a great number of information on the effect of the structure of porous materials on the flow of thermal energy through them, but there are no practical recommendations for the calculation of the effective coefficient of thermal conductivity. Some studies are controversial and need clarification. Therefore, it is necessary to design a generalized mathematical model for the transfer of thermal energy through bodies with a microporous structure.

The aim and objectives of the study

The aim of this work is to design a methodology for determining the effective thermal conductivity of porous structures with closed and open porosity.

To achieve this aim, the following objectives were formulated:

- mathematically derive the equation for the calculation of the effective coefficient of thermal conductivity for closed porous structures of thermal insulation materials;
- to determine the main parameters on which the pressure of the fluid on the volume of the porous depends;
- to develop a design model of the transfer of thermal energy through porous and fibrous-porous structures.

Mathematical description of thermal energy transfer through a porous body with a closed porous structure

For a macroporous body, energy transfer will be characterized by an effective thermal conductivity or thermal resistance. Let's represent thermal energy as a fluid. So, the heat flux through the porous body can be divided into many heat pipes, the lateral boundaries of which are formed by the projection of the lateral surface of the pores with a diameter d_2. The pore itself is located in the heat pipe and has the dimensions shown in Figure 1.

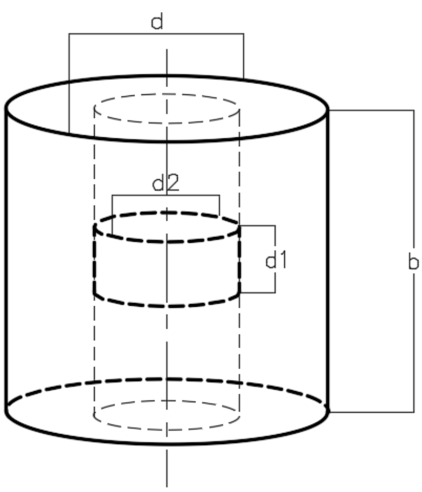

***FIGURE 1.** Steam heat pipe*

For a stationary flow through each section of the tube heat flow flows per unit time specific heat flow in the amount, W/m²

$$q = \frac{Q_i}{\pi \cdot d_2 \cdot d_1}$$

where:

Q_i – the heat flow through the tube, W;

d_2 – diameter of the lateral surface of the pores, m;

d_1 – the pore size, m.

Consider the heat flux lines throughout the porous structure (Fig. 2). The heat current lines near lines 1-1 and 2-2 become parallel and do not intersect. Lines 1-1 and 2-2 are conventionally taken for adiabatic planes [11]. If we consider the heat flux bounded by adiabats 1-1 and 2-2, which are directed along the heat flux between the pores, then we obtain the heat flux channel between the considered pore and the channel of conditional thickness *d* (Fig. 2). Conditional thickness *d* is shown in the Figure 1. The value of the conditional thickness *d* exceeds diameter *d*2 at least twice. Consider the transfer of thermal energy through this channel only due to the thermal conductivity of the material.

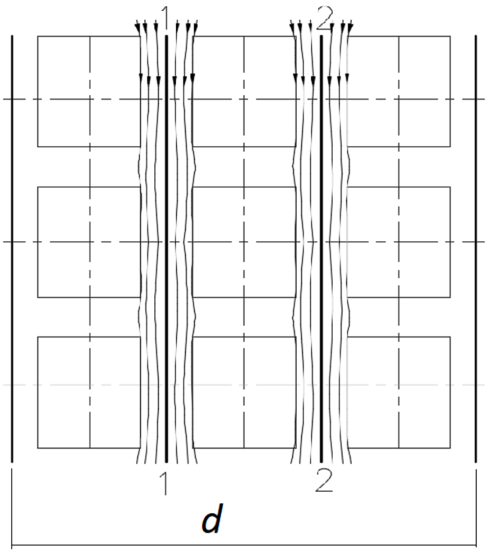

FIGURE 2. *Adiabatic lines on porous material*

The heat flow that passes through this channel will set the following temperature difference at the ends of this channel

$$\Delta T = \frac{q \cdot \Delta S \cdot b}{\lambda}$$

where:

ΔS – area of the thermal channel through which heat transfer is only due to the thermal conductivity of the material;

q – specific heat flow, W/m²;

λ – coefficient of thermal conductivity of the material;

b – length of the channel.

Substituting the temperature difference of the channel, the heat flow passing through the heat pipe will give the minimum temperature at the end of the heat channel

$$T_2 = T_1 + \frac{Q_i \cdot \Delta S \cdot b}{\lambda \cdot \pi \cdot d_2 \cdot d_1}$$

When $d_1 = b$ (the pore size is equal to the size of the thermal channel) and in case of one pore, it is easy to prove that

$$\Delta S = \frac{\pi d^2 (1 - \varPi)}{\varPi}$$

where $\varPi$ is the porosity of the material.

For the general case, the following relation holds

$$\frac{b}{d_1} = \frac{n_b}{\varPi_b}$$

where:

n_b – number of pores in the thermal channel;

$\varPi_b$ – porosity of this channel.

In addition

$$\Delta S = \frac{\pi \left(d^2 - {d_2}^2 \right)}{4}$$

Then the heat flow flowing through the heat tube with the pores can be expressed by the minimum temperature (minimum temperature difference) at the ends of the heat channel

$$Q_i = \frac{\lambda \cdot \pi \cdot d_2 \cdot \varPi_b \cdot \Delta T}{\Delta S \cdot n} \quad (1)$$

In this formula, we highlight

$$\phi_i = \frac{\varPi_b}{n_b}$$

The value ϕ_i represents the thermal permeability of the heat channel and is dimensionless.

Also in formula (1) we separate the geometric characteristic of the heat channel, which is equal to the ratio of the length of the line of cross-section of the pore to the surface area of the material in section with the pore.

$$\varGamma_i = \frac{\pi \cdot d_2}{\Delta S}$$

The dimension of this value is *m* – 1. The greater this difference is, the smallest difference between the heat channel and the heat pipe are. That is, the larger the geometric characteristic, the smaller the difference between d_2 and *d*.

From equation (1) the heat flow through the heat pipe with the pores will be equal

$$Q_i = \lambda \cdot \phi_i \cdot \varGamma_i \cdot \Delta T$$

The minimum heat flux through the porous material will be equal to the sum of the minimum heat fluxes through the heat channels. Assuming that the number of pores and their size in material thickness is constant, we obtain

$$Q = \lambda \cdot \phi \cdot \varGamma \cdot \Delta T \quad (2)$$

Where ϕ is the thermal permeability of the porous material.

So

$$\lambda_{ef} = \lambda \cdot \phi \cdot \Gamma \tag{3}$$

Geometric characteristic of a porous material for a heat pipe

$$\Gamma = \frac{\pi \sum d_2}{S - \sum \frac{\pi d_2^2}{4}}$$

where S is the area of the material to which thermal energy is directed.

The geometric characteristic of the porous material for the multiple pores can also be written in the integral form

$$\Gamma = \frac{\int_S f(d_2) dS}{S - \oiint_S f(d_2) dS}$$

where $f(d_2)$ is a function that describes the projection of the location of pores on the plane $S + b$ onto the area S.

From equation (3) it follows that the decrease in the thermal conductivity of the porous material due to the pores will depend on the product of $\phi \cdot \Gamma$

$$\phi \cdot \Gamma = \frac{\Pi_b}{\overline{n}_b} \cdot \frac{\int_S f(d_2) dS}{S - \oiint_S f(d_2) dS} \tag{4}$$

where $\overline{n}_b$ is the average number of pores in the thickness of the material b along the heat flux Q.

Thus

$$\lambda_{ef} = \lambda_m \cdot \frac{\Pi_b}{\overline{n}_b} \cdot \frac{\int_S f(d_2) dS}{S - \oiint_S f(d_2) dS} \tag{5}$$

The obtained equation (5) makes it possible to analytically calculate the effective coefficient of thermal conductivity for closed porous structures. The decrease in the coefficient of thermal conductivity of the porous material due to the pores will depend on the coefficient of thermal permeability and geometric characteristics of the porous structure.

Mathematical description of heat transfer through a porous body with an open porous structure

Since there is a connection between thermal and hydrodynamic resistance [12] then for the mathematical modeling of processes of transfer of heat and mass transfer through a porous body with an open porous structure we use the Darcy's law [13]

$$\overline{V} = -\frac{K}{\mu} \overline{\nabla} P$$

where:

$\overline{V}$ – velocity vector of the fluid;

K – permeability of porous material;

μ – coefficient of dynamic viscosity;

P – pressure.

To account for the high porosity of the material or to prevent slippage on the solid walls, the model is expanded using the Brinkman model.

The process of mass, momentum and energy transfer is described by a system of non-stationary Brinkman-Boussinesq equations in a porous medium and a non-stationary heat conduction equation. The differential equation of heat transfer in a porous body is as follows [14]

$$(\rho c)_m \frac{\partial T}{\partial \tau} + (\rho c)_f v \nabla T = \nabla\left(k_{ef} \nabla T\right) + q_m \qquad (6)$$

where:

m – index relating to all the porous material with fluids;

f – index relating to fluids;

$v\nabla T$ – rate of change of temperature in the elementary volume of fluid due to convection.

Effective heat transfer coefficient is

$$k_{ef} = (1 - \Pi)k + \Pi k_f$$

where k is the coefficient of heat transfer of the material.

The internal heat source can be shown as follows [15]

$$q_m = L \cdot \frac{A}{P} \cdot B \cdot T^n \cdot c_f \cdot \nabla T$$

where:

L – specific heat of vaporization;

A, B, n – empirical coefficients;

c_f – moisture concentration.

Navier-Stokes equation for two-dimensional steady-state flow is

$$\begin{cases} v_x \dfrac{\partial v_x}{\partial x} + v_y \dfrac{\partial v_y}{\partial y} = -\dfrac{1}{\rho}\dfrac{\partial P}{\partial x} + \upsilon \Delta \vec{v} \\ v_x \dfrac{\partial v_x}{\partial x} + v_y \dfrac{\partial v_y}{\partial y} = -\dfrac{1}{\rho}\dfrac{\partial P}{\partial y} + \upsilon \Delta \vec{v} \\ \dfrac{\partial v_x}{\partial x} + \dfrac{\partial v_y}{\partial y} = 0 \end{cases}$$

Where ρ is the average density of the fluid calculated by the Boussinesq approximation

$$\rho = \rho_\infty \left[1 - \beta\left(T - T_\infty\right)\right]$$

Consider the transmission of fluids along a porous body along the y axis. Given the gravitational forces that are opposite to the y axis and given the permeability of the porous material according to Darcy's law, we obtain

$$\begin{cases} v_y \dfrac{\partial v_y}{\partial y} = -g - \dfrac{1}{\rho}\dfrac{\partial(P)}{\partial y} + \upsilon \dfrac{\partial^2 v_y}{\partial y^2} \\ v_y = -\dfrac{K}{\mu}\dfrac{\partial(P+\rho g h)}{\partial y} \end{cases}$$

Taking into account a constant coefficient of filtering on the volume of the body after some transformations we get

$$\left(\frac{K}{\mu}\right)^2 \frac{\partial(P+\rho g y)}{\partial y}\frac{\partial^2(P+\rho g y)}{\partial y^2} = -\left[g + \frac{1}{\rho}\frac{\partial(P)}{\partial y} + \frac{K}{\rho}\frac{\partial^2(P+\rho g y)}{\partial y^2}\right]$$

From this equation, the pressure distribution over the volume of the porous body depends only on the properties of the fluid, the force of gravity, and the filter coefficient

$$\left(\frac{K}{\mu}\right)^2 \left(\frac{\partial P}{\partial y} + \rho g\right)\left(\frac{\partial^2 P}{\partial y^2} + \rho g\right) = -\left[g + \frac{1}{\rho}\frac{\partial(P)}{\partial y} + \frac{K}{\rho}\left(\frac{\partial^2 P}{\partial y^2} + \rho g\right)\right]$$

After some transformations we get

$$\frac{\partial P}{\partial y}\frac{\partial^2 P}{\partial y^2}\left(\frac{K}{\mu}\right)^2 + \rho g \frac{\partial P}{\partial y}\left(\frac{K}{\mu}\right)^2 + \frac{1}{\rho}\frac{\partial(P)}{\partial y} + \rho g \frac{\partial^2 P}{\partial y^2}\left(\frac{K}{\mu}\right)^2 + \frac{K}{\rho}\frac{\partial^2 P}{\partial y^2} = -g - \frac{K}{\rho}\rho g - \rho^2 g^2 \left(\frac{K}{\mu}\right)^2$$

To solve this equation let us introduce the following notation:

$$a = \left(\frac{K}{\mu}\right)^2, \quad b = \rho g \left(\frac{K}{\mu}\right)^2 + \frac{1}{\rho}, \quad c = \rho g \left(\frac{K}{\mu}\right)^2 + \frac{K}{\rho}, \quad d = -g - \rho g \frac{K}{\rho} - \rho^2 g^2 \left(\frac{K}{\mu}\right)^2$$

Then

$$aP'P'' + bP' + cP'' = d \tag{7}$$

Where

$$P' = \frac{\partial P}{\partial y}, \quad P'' = \frac{\partial^2 P}{\partial y^2}$$

Equation (7) of the second-order equation, which allows the order to be reduced by the following replacement of the variable

$$Z = P' = \frac{\partial P}{\partial y} \tag{8}$$

Replacing (8) in (7), we arrive at the following first-order equation

$$aZ\frac{dZ}{dy} + bZ + c\frac{dZ}{dy} = d$$

The resulting equation allows for the separation of variables

$$\frac{aZ+c}{d-cZ}dZ=dy \Rightarrow \int\frac{aZ+c}{d-cZ}dZ=\int dy \Rightarrow \frac{\left(ad+c^2\right)\ln\left|cZ-d\right|+acZ}{c^2}=y+C_1 \tag{9}$$

Where C_1 is constant of the integration.

Returning to equation (9) to the initial variable, we finally arrive at the following nonlinear equation, but in the first order:

$$\frac{\left(ad+c^2\right)\ln\left|cP'-d\right|+acP'}{c^2}=y+C_1 \tag{10}$$

This equation must be further analyzed, for example, using asymptotic series theory or other mathematical apparatus. However, equation can be simplified when equality is satisfied

$$c^2=-ad \Leftrightarrow \left(\rho g\left(\frac{K}{\mu}\right)^2+\frac{K}{\rho}\right)^2=\left(\frac{K}{\mu}\right)^2\left(g+\rho g\frac{K}{\rho}+\rho^2 g^2\left(\frac{K}{\mu}\right)^2\right) \tag{11}$$

Having opened the brackets we have

$$\rho^2 g^2\left(\frac{K}{\mu}\right)^4+2\rho g\frac{K}{\rho}\left(\frac{K}{\mu}\right)^2+\left(\frac{K}{\rho}\right)^2=g\left(\frac{K}{\mu}\right)^2+\rho g\frac{K}{\rho}\left(\frac{K}{\mu}\right)^2+\rho^2 g^2\left(\frac{K}{\mu}\right)^4$$

Shortcutting some terms of the equation and showing the fluid density through dynamic and kinematic viscosity, we obtain

$$gK\left(\frac{K}{\mu}\right)^2+\upsilon\left(\frac{K}{\mu}\right)^2=g\left(\frac{K}{\mu}\right)^2$$

Since $\left(\frac{K}{\mu}\right)^2\neq 0$ for a porous body, equality must be satisfied

$$K=\frac{g-\upsilon}{g}\to 1 \tag{12}$$

Therefore, the following solutions are made for bodies with good permeability. Receiving the filter coefficient by equation (12), equation (10) has the simplest form

$$\frac{a}{c}P'=y+C_1 \tag{13}$$

After integration we get

$$\int dP=\frac{c}{a}\left(\int ydy+\int C_1 dy\right) \Rightarrow P=\frac{c}{2a}y^2+C_1 y+C_2$$

Thus, the initial equation has the following solution

$$P=\frac{\rho g\left(\frac{K}{\mu}\right)^2+\frac{K}{\rho}}{2\left(\frac{K}{\mu}\right)^2}y^2+C_1y+C_2$$

where C_1, C_2 – constants of integration.

It follows from equation (10) that

$$P'\neq\frac{d}{c}$$

So

$$P\neq\frac{-g-\rho g\frac{K}{\rho}-\rho^2g^2\left(\frac{K}{\mu}\right)^2}{\rho g\left(\frac{K}{\mu}\right)^2+\frac{K}{\rho}}y$$

The differential thermal conductivity equation will look like this

$$(\rho c)_m\frac{\partial T}{\partial\tau}+(\rho c)_f v\frac{dT}{dy}=k_{ef}\frac{d^2T}{dy^2}+L\cdot\frac{A}{\frac{\rho g\left(\frac{K}{\mu}\right)^2+\upsilon\frac{K}{\mu}}{2\left(\frac{K}{\mu}\right)^2}y^2+C_1y+C_2}\cdot B\cdot T^n\cdot c_f\cdot\frac{dT}{dy}$$

Considering the transfer of thermal energy as a movement of fluid, we can say that $\frac{K}{\mu}$ characterizes the thermal permeability of the body due to phonons. The product ρg reflects the energy transfer by convection, which depends on the square of the geometric length of the pore (since for channel porosity under boundary conditions $y = b$, $b = d1$, then $y2 = d12$). Concentration is the quantity of fluid per unit volume, and it is possible to represent it as the product of the volumetric heat capacity at temperature and at constant. Moreover, heat capacity and density of fluid at atmospheric pressure can be described as values dependent only on temperature. The product of the fluid density per unit volume will be equal to the mass of the fluid. The combined empirical coefficients and constants of the differential thermal conductivity equation will look like this

$$(\rho c)_m\frac{\partial T}{\partial\tau}=k_{ef}\frac{d^2T}{dy^2}+\left[C_3\frac{f(T)}{\chi y^2+C_1y+C_2}-M\right]\frac{dT}{dy}$$

where C is a constant values.

We shall accept that the mass of elementary fluid is constant. Given formula (2) and the fact that the effective coefficient of heat transfer in this case does not take into account the energy transfer by convection and radiation, we obtain

$$(\rho c)_m\frac{\partial T}{\partial\tau}=\lambda\cdot\phi\cdot\Gamma\frac{d^2T}{dy^2}+C_5\left[C_4\frac{f(T)}{\chi y^2+C_1y+C_2}-1\right]\frac{dT}{dy}$$

where $\chi = \dfrac{\rho g \left(\dfrac{K}{\mu}\right)^2 + \upsilon \dfrac{K}{\mu}}{2\left(\dfrac{K}{\mu}\right)^2}$ is the coefficient expressing the thermal permeability of the material for convection currents.

Given equations (12) and after some transformations we obtain

$$\chi = \frac{\dfrac{g-\upsilon}{\upsilon} + \upsilon}{2\dfrac{g-\upsilon}{g\mu}}$$

We reduce to the common denominator, and given that the fluid density is equal to the ratio of dynamic to kinematic viscosity, we obtain

$$\chi = \frac{g\rho\left(g-\upsilon+\upsilon^2\right)}{2(g-\upsilon)} \tag{14}$$

It is known from [5] that the effective function of the dependence of the coefficient of thermal conductivity on the temperature gradient is a polynomial of the second degree. Suppose that convection energy transfer is a second-order polynomial. Therefore, under the boundary conditions $y = b$ (ie only for open through porosity) we have

$$Q = \lambda \cdot \phi \cdot \Gamma \Delta T + \frac{C_7 T^2 + C_8 T + C_9}{\chi d_1^{\,2} + C_1 d_1 + C_2}$$

It must also be borne in mind that at zero temperature energy transfer is not possible

$$Q = \lambda \cdot \phi \cdot \Gamma \Delta T + \frac{C_7 T^2 + C_8 T}{\chi d_1^{\,2} + C_1 d_1 + C_2}$$

We introduce an additional symbol – the geometric characteristic of open porosity

$$\Gamma_O = \frac{1}{\chi \overline{d_1}^{\,2} + C_1 \overline{d_1} + C_2} \tag{15}$$

This function is constant for a specific material with known pore structure. Then

$$Q = \lambda \cdot \phi \cdot \Gamma \Delta T + \Gamma_O\left(C_7 T^2 + C_8 T\right) \tag{16}$$

The equation found describes the transfer of thermal energy by fluids in open porous structures. The equation describes not only the energy transfer in the channel pores but also takes into account the existing closed pores in the material. To find integration constants, we will conduct empirical studies.

After the experiments, the geometric characteristics of the porous structure and the thermal permeability of the porous thermal insulation materials were determined. The results of the experiments are listed in Table 1. The use of these characteristics allows to determine the effective thermal conductivity of any porous structure knowing the material thermal conductivity and geometric characteristics of the porous structure. Thus, the developed method allows to reduce the complexity of work in determining the effective coefficient of thermal conductivity of porous structures. The error of the method is less than 8%.

***TABLE 1.** Characteristics of porous structure and thermal permeability of porous thermal insulation materials*

Porous material	$\phi \cdot \Gamma \cdot \delta$	$\Gamma_0 C_7$ **W/(m² ·K²)**	$\Gamma_0 C_8$ **W/(m² ·K)**
Metal sponge with 12X17 P = 70%	0.529	0.241	104.76
Metal sponge with 12X17 P = 50%	0.529	0.16148	70.19
Metal sponge with 12X17 P = 30%	0.529	0.0583	25.34
Foamed concrete	0.434	0	0
Foam-pumice concrete	0.388	0.011	17.35
AE (air entrained) concrete	0.681	0	0
Firebrick	0.824	0	0
Refractory brick with 22% void	0.824	0.18962	81.24
Refractory brick with 40% void	0.824	0.2734	116.18
Shell deposit	0.712	0	0
Chamotte brick	0.871	0	0
ISOVER thermal insulation	0.482	0.162	68.24
Mineral MMVF (man-made vitreous fibre)	0.473	0.188	72.39
Backfill of expanded clay	0.878	0.037	54.36

The geometric characteristics of the porous structure and the thermal permeability of fourteen porous materials widely used in industry have been found.

Conclusions

A calculation model for the transfer of thermal energy through porous and fibrous-porous structures was developed, which made it possible to reduce the complexity of work in determining the effective thermal conductivity of porous structures. The error of the method is less than 8%.

To calculate the transfer of energy through a porous-fibrous body previously used numerous empirical characteristics and corrections. The new dependencies are based on the theory of thermal energy transfer by fluids and allo to calculate the amount of energy passing through a porous structure, taking into account the operating conditions, calculating only two semi-empirical coefficients previously. Thus, the product of the constants of the integration of the energy transfer equation by fluids and the geometric characteristics of the porous structure and the thermal permeability of fourteen porous materials used as thermal protection elements were found.

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