RADIANT AND MOLECULAR HEAT TRANSFER IN THERMALLY ISOLATED MATERIALS HAVING SMALL VOLUME DENSITIES

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Molecular and radiant heat transfer and the interaction of these processes in friable fibrous heat insulators are discussed. The results of experimental studies of the efficiency of heat conduction of optically thin layers of material are presented and it is shown that it is inadmissible to use the hypothesis of additivity of heat-transfer processes under these conditions.

Heat insulators having small volume densities (5-30 kg/m^3), made of various friable fibrous masses, are widely applied in modern technology.

However, it is not very widely known at present that light-weight heat insulators have a number of properties connected with the conditions attaching to the progress of complex heat-transfer processes in media of small volume densities. For conclusive studies of thermophysical properties, calculations of heat fluxes and temperature fields should be carried out taking due account of these properties; their neglect may result in significant errors.

The results of experimental studies of the heat conduction of friable porous masses of various volume densities are presented below. The samples studied were manufactured both from Capron fibers with an average diameter of 30 μ, and from superfine fiberglass 1-2 μ in diameter. The classical "plate" method and a steady-state heat flux were used. The instrument for measuring the heat conduction consisted of an electric calorimeter with a protective unit having auxiliary heaters. A shield cooled by circulating water served as the cold surface. The studies were conducted at normal atmospheric pressure, under conditions of partial vacuum, and under high vacuum conditions with $P \le 5 \cdot 10^{-3}$ N/m^2. The mean temperature of the layers was 70°C while the temperature drop across the specimens was 100-110°C. The heat-conduction coefficient was calculated from the well-known formula

$$\lambda = \frac{QL}{(T_1 - T_2)F}. \qquad (1)$$

The maximum measurement error was ±5%.

Since the Fourier hypothesis may only provisionally be extended to the region of thin layers, henceforward we will be dealing with the effective coefficient of heat conduction following formally from Eq. (1).

Heat transfer in the given medium (for the given case in a dispersed thermally isolated layer) is a complicated heat-exchange process. In principle, the possible means of energy transfer are heat conduction of the filling gas, convective movement of the latter, conductive heat transfer in the solid particles (fibers) of the material, and radiant heat exchange. In general the effective heat conduction of the material is not an additive total of the elementary processes.

The presence of convective air movement in a dispersed medium is easily established by measuring the effective heat conduction of specimens under conditions of different filling gas pressures. For all the compositions studied convection was absent, since their effective heat conduction in the shallow vacuum range did not depend on the pressure. A typical result of the measurements is presented in Fig. 1a.

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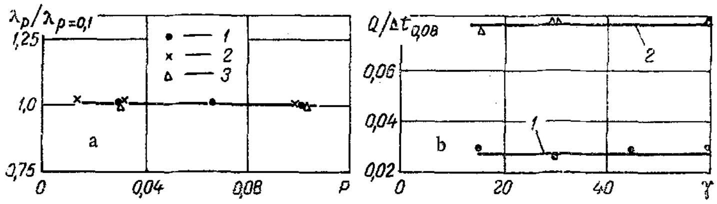

Fig. 1. Dependences: a) of ratio $\lambda_p/\lambda_{p=0.1}$ on air pressure P (N/m^2) for superfine fiberglass: 1) $\gamma = 10$ kg/m^3; 2) 5; 3) 2.5; b) of $Q/\Delta T$ (W/deg) on volume density γ (kg/m^3) of friable fibrous layer: 1) superfine fiberglass; 2) Capron fiber.

It was shown in [1] that contact conductive heat transfer through solid-phase particles of evacuated friable fibrous masses of moderate densities not having any special bonding materials is negligibly small. This result also confirms the measured results of heat fluxes passing through evacuated friable fibrous layers of various volume densities presented in Fig. 1b. The variations in the latter were obtained by compressing the layers, whilst leaving the total mass of material unchanged. At constant boundary temperatures the heat flux passing through the specimens studied did not depend on the degree of compression of the latter, i.e., the conductive heat flux was negligibly small.

Thus, the principal processes of energy transfer for the materials studied were radiant heat exchange and heat transfer by moving air molecules in the pores of the dispersed body.

Strictly speaking, one should understand the latter to be a generalized gas–solid particle heat conduction system. For the layers of low volume density studied (5-30 kg/m^3) the generalized heat conduction does not significantly depend on the heat conduction of the filling gas, growing with increased material density as a linear function. This is confirmed by the data of Fig. 2 in which the results of experimental studies of the dependence of λ^*/λ_a on γ for optically thick layers of superfine fibers are presented.

In evacuated layers, heat conduction is entirely dependent on radiant heat-exchange processes. The continuous radiant heat conduction of a dispersed body λ_∞, inherent to sufficiently thick layers of the latter, and its effective heat conduction in optically thin layers λ_τ are related by the formula

$$\lambda_\infty = \frac{1}{\dfrac{1}{\lambda_\tau} - \dfrac{1}{4\sigma\varepsilon_{re}T_{av}^3 L}}, \tag{2}$$

resulting from the well-known equation for radiant heat transfer in absorbing media (see, for example, [2, 3]):

$$Q = \sigma\frac{T_1^4 - T_2^4}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1 + \dfrac{3}{4}\tau}.$$

Equation (2) holds for cases of diffusely reflecting and radiating boundary surfaces with sufficiently small heat fluxes where an approximation to radiant heat exchange may be used. The accuracy of Eq. (2) was tested experimentally in the temperature range investigated at optical thicknesses of 1-50.

The results of studies of the effective heat conduction of evacuated and gas-filled materials as a function of the volume density of the layer are presented in Fig. 3. Measurements were conducted for various conditions of the boundary surfaces of the instrument. To characterize the latter the reduced emissivity of the instrument was experimentally measured, calculated from the heat flux values between the boundary surfaces occurring under high vacuum conditions ($P \le 5\cdot10^{-3}$ N/m^2) in the absence of specimens of the materials being studied. Changes in the volume density of the specimens in the experiments were produced by compressing them. In this connection the product γL remained constant for each curve plotted in Fig. 3 and equalled 0.3 kg/m^2 for $\varepsilon_{re} = 0.07$ and 0.72 kg/m^2 for $\varepsilon_{re} = 0.27$.

The essential role of radiant heat exchange in lightweight heat insulators even at relatively low temperatures is seen from a comparison of the results presented in Fig. 3a, b. The heat conduction of evacuated layers is connected, as was shown above, exclusively with processes of radiant heat exchange, making up from 10 to 50% of the effective heat conduction of gas-filled materials.

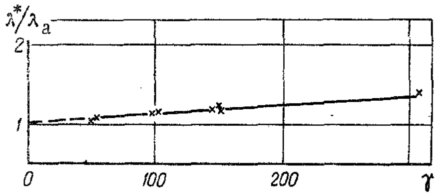

Fig. 2. Dependence of λ^*/λ_a on volume density γ (kg/m^3) for optically thick layers of superfine fiber.

However, one may assume that the role of radiant heat exchange is evaluated by these relations only assuming additivity of the energy transfer processes taking place. The latter assumption is invalid for optically thin layers and may lead to grave errors.

Analytical studies of the effects of the interaction of heat conduction and radiant heat-exchange processes in optically thin layers of dispersed bodies may be carried out on the basis of the solution of a system of equations, including a radiation transfer equation and an energy equation. A number of works [4-8] have been devoted to a solution of problems of this type. The results reported in them, usually obtained by various numerical methods, are connected with many simplifying assumptions and allow only an evaluation of a qualitative picture of the effect. A large number of independent parameters have an influence on the process of heat transfer in an optically thin layer. The most important of these are the optical density of the layer, the emission characteristics of the boundary surfaces, and the thermal conductivity of the filling gas.

In optically thin layers the value of the local radiant flux exhibits an extremal dependence on the optical density of the layer. This shows the inadmissibility of using the additivity hypothesis in heat-transfer calculations in materials having low volume densities.

This is graphically illustrated by the results of the experimental studies conducted. The characteristic form of the dependence $\lambda^* = \lambda^*(\gamma)$ is presented in Fig. 4. The value λ^* represents the increase in effective heat conduction of a dispersed material as a result of filling the layer with air:

$$\lambda^* = \lambda_{p=0.1} - \lambda_{p\to 0}.$$

If one proceeds from the additivity of the processes of molecular and radiant heat exchange, then the value of λ^* represents the generalized heat conduction of the gas–solid particle system, depending only on the thermal conductivity coefficients of the gas and the material of the particles and the geometry and orientation of the latter. In the range of small volume densities studied, the hypothesis of additivity corresponds to dependence 1 presented in Fig. 4, approximately linear and intersecting the ordinate axis at a value corresponding to the heat conduction of the filling gas (in the absence of convection).

The interdependence of the processes of heat conduction and radiant heat exchange leads to a sharp change in the nature of the dependence $\lambda^* = \lambda^*(\gamma)$ in the region of optically thin layers. The increase in efficiency of heat conduction of a layer when it is filled with gas is much greater than the value resulting from the additivity hypothesis.

According to the experimental data obtained the curve of $\lambda^* = \lambda^*(\gamma)$ has an extremal form. A decrease in the emissivity of the boundary surfaces leads to a growth in the influence of the interaction

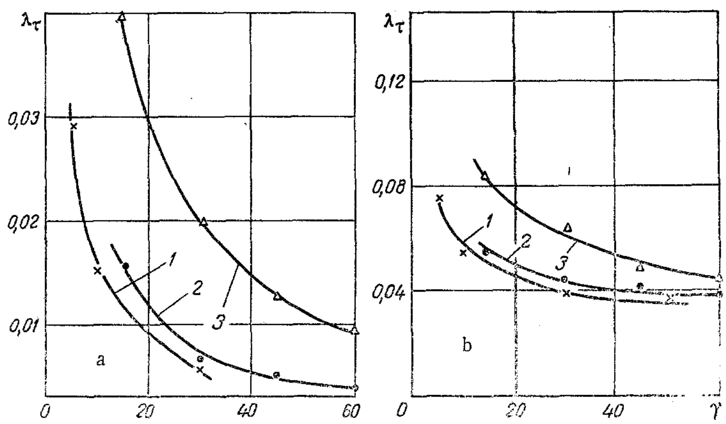

Fig. 3. Dependence of effective heat conduction λ_T (W/m · deg) of evacuated layer (a) and friable fibrous layer at normal atmospheric pressure (b) on volume density γ (kg/m^3) for a mean temperature of the layer of 70°C: 1) superfine fiberglass, $\varepsilon_{re} = 0.07$; 2) superfine fiberglass, $\varepsilon_{re} = 0.27$; 3) Capron fiber, $\varepsilon_{re} = 0.27$.

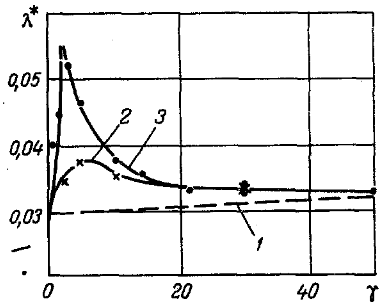

Fig. 4. Dependence of λ^* (W / m · deg) on volume density of layer γ (kg/ m^3) of superfine fiberglass: 1) for case of adiabatic molecular transfer; 2) experimental data for ε_{re} = 0.88; 3) experimental data for ε_{re} = 0.07.

effects in the region of low optical thicknesses. For optically thick layers the influence of interaction effects becomes negligibly small, so that its role enters into the case studied only upon a change in the boundary conditions.

There are very contradictory data in the literature on the thermophysical properties of heat insulators of low volume densities. The large scatter in the experimental data is explained by the fact that in view of the properties of heat-transfer processes in these media mentioned above the experiment gives information on the properties of the experimental specimen–experimental instrument system. If the necessary characteristics of the measuring apparatus are not taken into account the experimental data obtained on the thermophysical properties of optically thin layers of materials have a very limited value.

NOTATION

λ_∞, λ_τ	are the coefficients of radiant heat conduction of optically thick and optically thin layers, respectively, W/m · deg;
λ^*	is the coefficient of the increase in effective heat conduction of a layer when it is filled with gas, W/m · deg;
$\lambda_{0.1}$	is the effective heat conduction of a friable fibrous layer at normal atmospheric pressure, W/m · deg;
λ_p	is the effective heat conduction of layer at intermediate pressures P, W/m · deg;
λ_a	is the coefficient of heat conduction of the air, W/m · deg;
σ	is the Stefan–Boltzmann constant; $\sigma = 5.67 \cdot 10^{-8}$ W/m^2 · deg K^4;
ε_{re}	is the reduced emissivity of boundary surfaces of the instrument;
$\Delta T = T_1 - T_2$	is the temperature drop in the layer of material, °K;
$T_{av} = (T_1 - T_2)/2$	is the average temperature of the layer, °K;
Q	is the heat flux, W;
P	is the air pressure, N/m^2;
γ	is the volume density of the layer, kg/m^3;
L	is the thickness of the layer, m;
F	is the area, m^2;
τ	is the optical density of the layer.

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