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HEAT TRANSFER IN A DISPERSE INSULATOR

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Results of investigations of the thermophysical properties of disperse materials under vacuum conditions and at normal atmospheric pressure are presented. The role of different heat transfer processes and the effective heat conductivity of the disperse bodies investigated is examined.

Reference [1] gives the results of experimental investigations of the heat conductivity of various disperse thermal insulators under vacuum conditions and at normal atmospheric pressure in the low and normal temperature regions. Below we also present experimental data on the thermophysical properties of loose-fibrous and powdered thermal insulators over a wide temperature range from −100°C to 800° C.

The thermal diffusivity was measured as described in [2].

The heat conductivity was also measured. The tested thermal insulators were placed in a λ-calorimeter consisting of a hollow metal cylinder (copper, nickel) with a core of the same material. The calorimeter was placed in a tubular furnace, having a main heater and two boosters. The temperature of the λ-calorimeter was measured at the center and at the edges 10–15 mm from the ends. The surface temperature of the core was also measured in the center section.

By regulating the operating conditions of the end heaters, a constant temperature was maintained along the cylinder with an accuracy of 1°–3° C.

In carrying out the experiments the calorimeter was heated under conditions of constant temperature difference

$$\Delta t = t(R_2,\ \tau) - t(R_1,\ \tau). \qquad (1)$$

To measure the thermal diffusivity we used similar calorimeters. In this case the core was replaced by the test sample, consisting of a solid cylinder with a thermocouple in the center. This enabled us to reproduce the conditions recommended in [2], both in vacuum and at normal atmospheric pressure.

The heat conductivity of the test material was calculated from the relation

$$\lambda = \frac{1}{2\Delta t}\ \frac{dt(R_1,\ \tau)}{d\tau}\ R_1^2 c_c \gamma_c \ln \frac{R_2}{R_1}\ . \qquad (2)$$

Equation (2) was derived for the case of heating or cooling, under condition (1), of an infinite cylindrical solid, consisting of a core of known heat capacity and radius R_1 surrounded by a layer of test material of outside radius R_2, and is valid for the conditions

$$G_c c_c \gg Gc,\ \ \lambda_c \gg \lambda_0\ .$$

The obtained values of the heat conductivity were referred to the mean temperature

$$t_{\mathrm{m}} = [t(R_2,\ \tau) - t(R_1,\ \tau)]/2. \qquad (3)$$

The validity of the assumed relations for a and λ under the experimental conditions was easily checked by a- and λ-calorimetric control measurements on disperse silica. The heat capacity of the latter calculated from the obtained experimental data conformed, within limits of accuracy of order ±5%, with the data given in [3].

These measurements were carried out both at normal atmospheric pressure and in vacuum conditions.

During the investigation of the thermophysical properties in vacuum conditions the whole apparatus was placed in an evacuated chamber.

A number of experiments was carried out at negative temperatures. In this case the calorimeter was placed in a special container dipping into a liquid nitrogen bath, and measurements were carried out during monotonic cooling of the sample or during subsequent heating.

Besides the data on fibrous and powdered materials, results are also presented below of investigations on samples of so-called screen-vacuum thermal insulation.

The samples consisted of a layered structure of thin aluminum foil with fiberglass interlayers. The bulk density of the fiberglass in the interlayers was 300–600 N/m^3. The number of layers of foil in a thickness of 1 cm did not exceed 35–40. The screen-vacuum insulation was tested only in the λ-calorimeter.

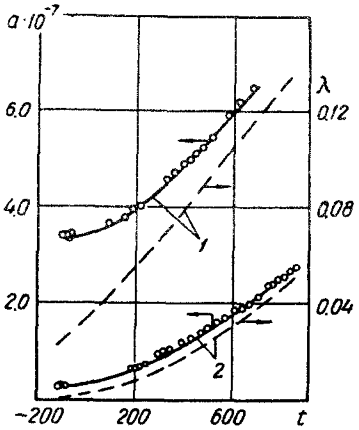

Fig. 1. Thermal diffusivity and heat conductivity of silica gel (γ = 1580 N/m^3) (1) at normal atmospheric pressure, and (2) in vacuum.

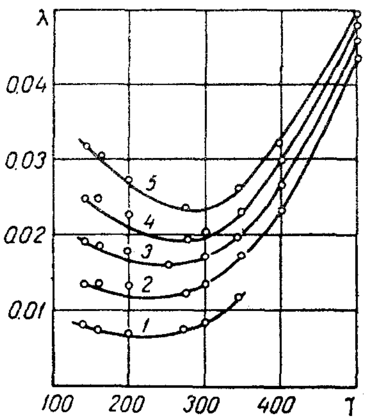

Fig. 2. Dependence of heat conductivity of silica gel on its bulk density at different temperatures in vacuum: 1) t = 200° C; 2) 300°: 3) 400°; 4) 500°; 5) 600°.

The thermocouple for measurement of the core surface temperature in the λ-calorimeter had an over-all length of 4–6 m and was led out to the inside surface of the cylinder of the λ-calorimeter, passing successively between all the layers of foil. This avoided the possibility of a significant influx of heat through the thermocouple electrodes.

The temperature drop Δt in all the tests was of the order of 50°–150° C. The duration of the experiment depended on the thermophysical properties of the samples tested and was, on the average, 1–4 hours for loose fibrous and powdered materials and 1–2 days for samples of screen-vacuum thermal insulation. In the tests in vacuum the air pressure was of the order of 10^{-2}–10^{-3} N/m^2. The thermophysical properties of one of the most effective powdered thermal insulators, silica gel consisting of finely divided silicon dioxide (Figs. 1 and 2), was investigated at normal atmospheric pressure and under vacuum conditions. The results obtained at low temperatures are in agreement with the data given in [1].

The thermophysical properties of loose fibrous masses of fiberglass and silica fibers of different diameter (Figs. 3 and 4) were also investigated.

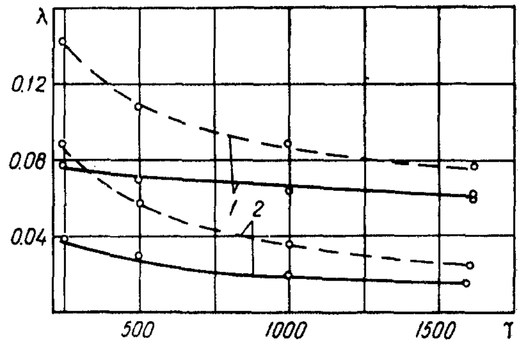

Fig. 3. Heat conductivity of loose fibrous material (mean fiber diameter 1 μ) versus bulk density at different temperatures (solid line t = = 200°C, broken line t = 400° C (1) at normal atmospheric pressure and (2) in vacuum.

Results of measurements of the heat conductivity of samples of screen-vacuum insulation are also given in Fig. 4b.

Comparison of the data of [1] with the results of the investigations described above enabled us to trace the change of structure of the total heat flux through the disperse layers of thermal insulation over a wide temperature range. Whereas at low temperatures the basic heat flux depends on the molecular motion of the gas filling the pores of the disperse medium, with increase in temperature the role of radiative heat transfer sharply increases. Thus, for example, for a bed of fiberglass having a mean fiber diameter of 14 μ evacuation reduces the heat conductivity at a temperature of 560° C by only 4%. More than half of the total heat flux in these conditions is radiative. Under vacuum conditions some heat transfer in the disperse bed still takes place by contact conduction through the solid particles; however, this effect, as will be shown below, is insignificant.

For investigated materials, with increase in temperature the absolute value of the difference in the heat conductivities of the disperse bed measured in vacuum conditions and at normal atmospheric pressure increases approximately proportionally to the temperature dependence of the heat conductivity of air. This property of the heat conductivity of disperse solids was pointed out earlier and used in carrying out experimental investigations of the thermophysical properties of gases and gas mixtures in [4].

Methods like those described in [4] can be used only when there is no natural convection in the bed. The fact that the effective heat conductivity of the disperse material is independent of the temperature gradient in the bed, while its derivative with respect to the air pressure is equal to zero, is an indication of the absence of convective heat transfer.

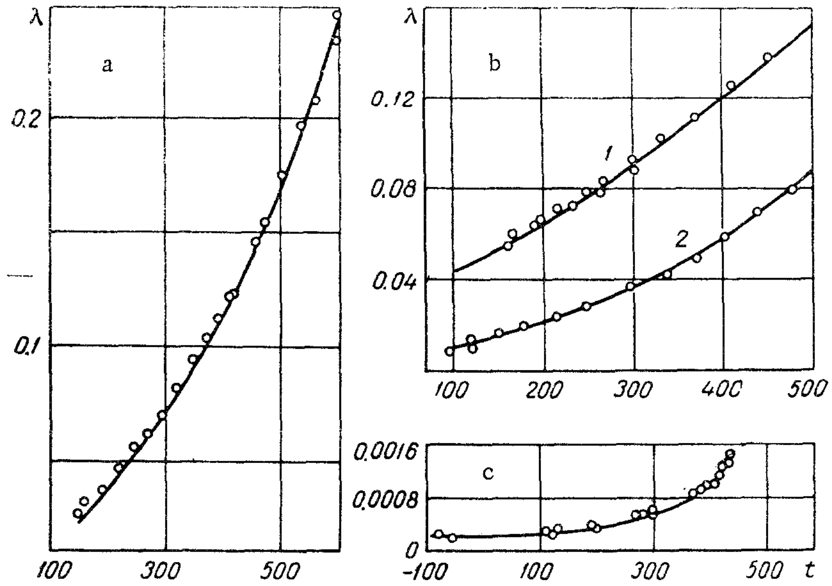

Fig. 4. Heat conductivity of (a) loose fibrous material ($\gamma = 250\ \mathrm{N/m^3}$, mean fiber diameter 1.5 μ) in vacuum, (b) fiberglass (density 1580 $\mathrm{N/m^3}$, mean diameter 14 μ, 1 at normal atmospheric pressure and 2 in vacuum) and (c) samples of screen-vacuum thermal insulation as a function of temperature.

In a partial vacuum, when the mean free path of the gas molecules is comparable with the pore size, the derivative $d\lambda/dp \neq 0$ because of the restrictions imposed on the molecular motion of the gas by the pore walls. However, with increase in gas pressure in the pressure region close to normal atmospheric pressure, with the majority of powdered and loose fibrous materials the derivative $d\lambda/dp$ tends to zero. However, if in this region an increase in gas pressure causes an increase in the derivative $d\lambda/dp$, then the presence of convective heat transfer is indicated.

From the last characteristic it is possible, by analyzing the data of [1], to establish that only in the coarsest disperse materials (mineral wool, coarse fiberglass with diameter ~19 μ) at normal atmospheric pressure did natural convection occur in the bed. We recall, following Bosworth [5], that the modulus of gas convection increases extremely sharply with increase in temperature. It becomes clear that natural convection in loose fibrous and powder materials occurs only in extremely coarse disperse media at low temperatures and high temperature gradients. In all materials investigated convective heat transfer was absent; thus the condition $d\lambda/dp = 0$ was fulfilled at normal atmospheric pressure. The temperature gradient was in the range 3–10 deg/mm.

It has been shown repeatedly in the literature that loose fibrous and powder disperse materials have a minimum heat conductivity corresponding to a certain bulk density. The explanation that at low bulk densities intense heat fluxes due to convective heat transfer develop, is apparently inaccurate. The increase in the effective heat conductivity of a loose fibrous thermal insulator with decrease in bulk density is explained by the increase in the intensity of radiant heat transfer in the layer. This is well illustrated graphically by the data of Fig. 3. With decrease in the density of the loose fibrous mass its heat conductivity increase under vacuum conditions, where there can be no question of convective heat transfer, in exactly the same way as at mormal atmospheric pressure. We obtained analogous results with fiberglass of other diameters (4, 10, 14 μ).

Considerable interest attaches to the estimation of the heat fluxes in a disperse bed due to radiation and heat transfer by contact conduction through the solid particles. Of great significance are the results on samples of screen-vacuum thermal insulation (Fig. 4c). In sufficiently high vacuum conditions (10^{-2}–10^{-3} $\mathrm{N/m^2}$) the samples possessed extremely low heat conductivity of the order of 10^4 W/m•deg. According to the literature data, in the low-temperature region values of the heat conductivity one order lower were obtained [6]. This is possible only if the contact heat conductivity in the loose fibrous layers was even lower. It becomes clear that the effective heat conductivity of a loose-fibrous mass in vacuum, at least at bulk densities down to 600–1000 $\mathrm{N/m^3}$, is almost completely dependent on radiant heat transfer alone, the role of conductive heat transfer being negligible. In the high-temperature region and at a bulk density of the finely disperse mass of 1000–2000 N/m^3 heat transfer by contact conduction plays only an insignificant part, comprising, apparently, no more than a few percent of the total heat flux.

Below we will use the concept of the component of the effective heat conductivity of a material (disperse medium) due to radiant heat transfer. This presupposes the possibility of a gradient representation of the vector of radiant energy propagating in the medium in question and additivity of the radiant heat transfer and contact heat conduction processes. The latter condition may be assumed to be satisfied in the materials examined, at least in the high-temperature region. In fact, the conductive heat flux, which in these conditions has a magnitude one to two orders lower than the heat flux due to radiant heat transfer, can not have much influence on the temperature distribution in the disperse layer or on the radiant heat flux.

In [7] it was shown in general form that a gradient representation of the radiant energy vector is correct only at quite small deviations from thermodynamic equilibrium. For low-density disperse media in whose effective heat conductivity radian heat transfer plays a significant role, the gradient representation of the total heat flux

$$q = \lambda \operatorname{grad} t \tag{4}$$

is approximate and acceptable in practice for sufficiently small temperature drops at the boundaries of the disperse layer.

In [9] the following relationship was derived, which is valid for strongly-absorbing media:

$$\lambda_r = 16\pi\sigma T^3 n^2/3\alpha.$$

The relation (5) was derived on the assumption that the refractive index of the medium n is not a function of temperature. It is of considerable interest that in all the materials we investigated the relation $\lambda = \lambda(T)$ (for vacuum conditions) was very close to cubic over a wide temperature range.

Thus, for example, Fig. 4a shows the curve $\lambda = \lambda(T)$, constructed from the conditions of proportionality between the heat conductivity of the material and the cube of the absolute temperature. Experimental points, obtained from measurements of the heat conductivity of this material, are plotted in the same figure. Very close agreement between the calculated and experimental data indicates that in the media tested (silica, glasses of different composition) not only the refractive index but also the absorption coefficient of the medium can, in practice, be considered constant over a wide temperature range.

Having data on the heat conductivity of materials of this type at normal atmospheric pressure and in vacuum conditions, one can use the given approximation to extrapolate to the region of higher temperatures. In this case it is necessary to proceed from the fact that the effective heat conductivity in vacuum increases in proportion to the cube of the absolute temperature, while the difference in the heat conductivities of the material at normal atmospheric pressure and in vacuum conditions increases with increasing temperature in proportion to the heat conductivity of air. Of course, this relates to the temperature region in which the given disperse material possesses sufficient heat stability and no sintering of the particles and change in structure takes place as a result of heating.

Increase in the density of the disperse mass leads to a growth in the heat flux due to contact between the particles. At the bulk density of the material corresponding to minimum effective heat conductivity (in vacuum) we get

$$\frac{d\lambda_r}{d\gamma} = \frac{d\lambda_c}{d\gamma}\,. \tag{6}$$

The bulk density of the material at which minimum heat conductivity occurs is a function of temperature, and as the temperature increases the minimum of heat conductivity and thermal diffusivity is displaced into the region of higher bulk densities (Fig. 2).

Notation

a and λ – thermal diffusivity and heat conductivity; τ – time; t – temperature; p – gas pressure; R_1 and R_2 – radii of calorimeter core and internal cylindrical surface of calorimeter; C_c and C – heat capacities of calorimeter core and test sample; γ_c – specific weight of core material; γ – bulk density of disperse body; G_c and G – weight of core and test sample; λ_r and λ_c – components of effective heat conductivity determined by radiant heat transfer and contact-conductive heat transfer; λ_c and λ_0 – heat conductivity of core and test sample; σ – Stefan's law constant; n – refractive index; T – absolute temperature; α – absorption coefficient.

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