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THERMOPHYSICAL PROPERTIES OF ULTRAFINE BASALT FIBER

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An experimental study of the dependence of the thermal conductivity of an ultrafine basalt fiber on the temperature, pressure, and density of the material is reported.

Among modern heat-insulating materials, there is increasing interest in basalt fibers, and the number of articles in which these fibers are used is increasing. Basalt fiber, in addition to having good heat-insulating properties and a good thermal stability, can be obtained from abundant and inexpensive natural resources and, when mass-produced, is relatively inexpensive.

If subjected to vibrations, basalt fiber can be used at temperatures up to 600-650°C over long periods of time; if there is no vibration, the fiber can be used up to 700°C. The thermal stability of basalt fiber can be raised by a one-time stepped heat treatment involving heating of the material to 900°C. The resulting material can be used at temperatures up to 800°C and (briefly) up to 900°C.

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All previous measurements of the thermophysical properties of basalt fibers have been carried out at normal atmospheric pressure [1, 2]. There is also considerable interest in a comparison of the properties of evacuated and gas-filled layers. In particular, such experiments could give quantitative information about the roles played by the various heat-transfer processes in a dispersed layer. In earlier experiments on evacuated glass-fiber and silica-fiber heat insulators it was established that, at a given density of the layer, the radiative heat transfer varies considerably with the average fiber diameter [3]. Layers of ultrafine fibers (d = 1–2 μ) are the best heat insulators.

We report here an experimental determination of the thermal conductivity of cloth of ultrafine basalt fiber. The experiments were carried in air at normal atmospheric pressure, at a varying pressure, and in a vacuum of $1 \cdot 10^{-4}$–$2 \cdot 10^{-5}$ torr. The thermal conductivities were determined as functions of the average temperature of the layer and as functions of the density of the material.

We studied samples of basalt fiber which were and were not subjected to the heat treatment described above.

The experiments were carried out by two methods: with a steady-state heat flux and with monotonic heating. In the steady-state method, we measured the thermal conductivities of flat samples 400 × 400 mm in size on an apparatus with an electric calorimeter with auxiliary heaters. The cold surface of the apparatus was a screen cooled with running water or a screen with a controllable heater.

The thermal conductivity was calculated from the familiar equation

$$\lambda_{\text{exp}} = \frac{qL}{T_{\text{h}} - T_{\text{f}}}. \tag{1}$$

In the monotonic-heating method we studied the thermal conductivities of cylindrical samples 250 mm long with an outside diameter of 50 mm. The thin-walled calorimeter was placed in a cylindrical furnace having a central heater and two auxiliary end heaters. The temperature of the outer surface of the sample was measured with a thermocouple caulked to the inner wall of the calorimeter. Inside the calorimeter we placed a core 12 mm in diameter and 200 mm long, made of a material with a known specific heat. A thermocouple was caulked to the surface of the core halfway between the ends. The test material was wound around this core.

In the course of an experiment we recorded the temperatures at the outer and inner surfaces of the sample at certain time intervals. The thermal conductivity was calculated from

$$\lambda_{\text{exp}} = \frac{1}{2\Delta T} \cdot \frac{dT_c}{d\tau} R_c^2 C_c \gamma_c \ln \frac{R}{R_c}, \tag{2}$$

where $\Delta T = T_S - T_C$. We held the temperature drops ΔT across the sample constant during the experiments. The magnitude of this drop ranged from 50 to 200°C in different experiments. Equation (2) holds for the heating of an infinite cylindrical object; to approximate this situation in the experiment we held the temperature constant along the length of the sample ± 5°C. The experimental apparatus was described in [4].

The measurements were carried out for temperatures of the hot surface ranging from 110 to 600°C, so that the average temperature of the layer ranged from 50 to 450°C.

The density of the samples varied from 40 to 128 kg/m³. The maximum error in the determination of the thermal conductivities was ± 3% in the monotonic-heating method, ± 7% in the steady-state method with gas-filled layers, and ± 3% in the steady-state method in vacuum.

By comparing the measured thermal conductivities of the basalt fiber in vacuum and at normal atmospheric pressure (Fig. 1), we can evaluate the relative role of radiative heat transfer through the insulating layer. According to the data in Fig. 1, at a sample density of 40 kg/m³, 14% of the heat is transferred by radiation at normal atmospheric pressure at t_{av} = 100°C, while 36% of the heat is transferred by radiation at t_{av} = 400°C. The rest of the heat is transferred by the generalized thermal conductivity of the gas–fiber system. Increasing the density of the material reduces the relative importance of the radiative heat transfer. For a density of 120 kg/m³, the radiative heat transfer is 5% and 11% at the temperatures specified above. These results were obtained on the basis of the assumption that

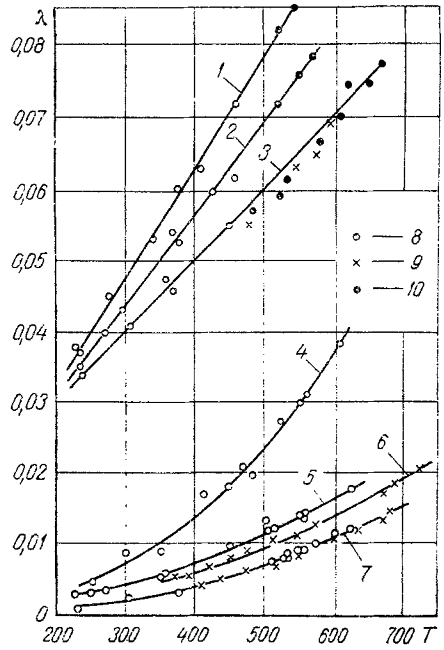

Fig. 1. Effective thermal conductivity of basalt fiber for various densities as a function of the average layer temperature. 1–3) At normal atmospheric pressure; 1) γ = 40 kg/m^3; 2) 80; 3) 120. 4–7) At a pressure of $P \sim 10^{-4}$–$2 \cdot 10^{-5}$ torr; 4) γ = 40 kg/m^3; 5) 80; 6) 100; 7) γ = 120; 8) basalt fiber not subjected to heat treatment, steady-state method; 9) the same, unsteady method; 10) fiber subjected to heat treatment, unsteady method.

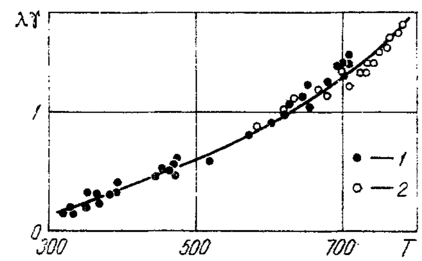

Fig. 2. The parameter $\lambda\gamma$ as a function of the average temperature of the layer of basalt fiber not subjected to heat treatment, for a vacuum of $P \sim 10^{-4}$–$2 \cdot 10^{-5}$ torr. 1) Steady-state method; 2) unsteady method.

the heat transfer along fibers in contact is negligible at these densities. This conclusion is based on the results of earlier work [4].

In the case in which the radiation is the only heat-transfer mechanism in the evacuated porous-fiber layers, the density and the thermal conductivity are related by the simple equation [4]

$$(\lambda\gamma)_{T=\mathrm{const}} = \mathrm{const}. \tag{3}$$

The validity of this equation for the basalt fiber is confirmed by the data of Fig. 2, which generalizes the results found in studies of evacuated layers of various densities. The increase in the effective thermal conductivity with decreasing density of the material (Fig. 3) is due solely to the increase in the rate of radiative heat transfer. This conclusion can also be applied to the gas-filled materials, since natural convection could not play any significant role under these experimental conditions [5, 6].

For porous-fiber materials with a random arrangement of fibers, the thermal conductivity can be calculated as a function of the air pressure on the basis of the semiempirical equation found in [7]:

$$\lambda_{P,T} = \lambda_{P=760,T} - \lambda_K^* \frac{1}{1 + \dfrac{\gamma_d - \gamma}{70\gamma T_{av}} P d\eta (T_{av} + 124)}, \tag{4}$$

where

$$\lambda_K^* = \lambda_{P=760} - \lambda_{P\to 0}. \tag{5}$$

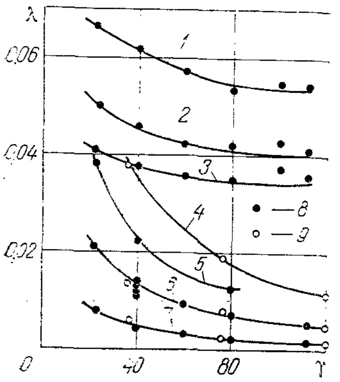

Fig. 3

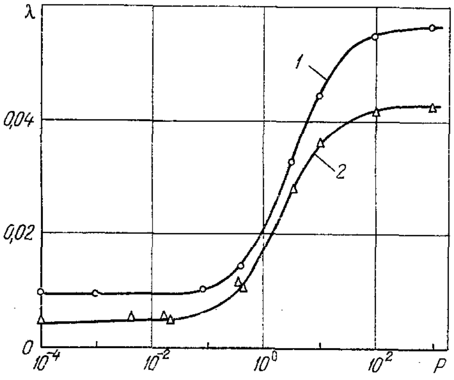

Fig. 4

Fig. 3. Thermal conductivity of basalt fiber as a function of the density (the data from one experimental run are shown). 1-3) Normal atmospheric pressure; 1) T_{av} = 200°C; 2) 100; 3) 50. 4-7) Vacuum of $P \sim 10^{-4}$-$2\cdot10^{-5}$ torr; 4) T_{av} = 420°C; 5) 320; 6) 200; 7) 60; 8) basalt fiber not subjected to heat treatment; 9) fiber subjected to heat treatment.

Fig. 4. Thermal conductivity of basalt fiber as a function of the air pressure. 1) T_{av} = 200°C, γ = 60 kg/m³; 2) 100°C, 60 kg/m³.

This equation can be written in a more general form, which can be used for calculations for porous-fiber layers with any fiber orientation:

$$\lambda_{P,T} = \lambda_{P=760,T} - \lambda_K^* \frac{1}{1 + \frac{\gamma_d - \gamma}{70T_{av}\gamma_d} \cdot \frac{\eta}{kF} P(T_{av} + 124)}, \tag{6}$$

where

$$F = 4\gamma/\gamma_d d, \tag{7}$$

and k is a coefficient governed by the fiber orientation. In particular, for a random arrangement of fibers in the layer [Eq. (4)], the value of k is 1/4 [8].

Lacking quantitative information on the degree of orientation of the fibers, we cannot calculate the values of k for the materials studied in these experiments. Furthermore, we do not have adequate experimental information on the coefficient η, which is a measure of the energy accommodation. The value of the ratio η/k can be determined from (6) if we measure the thermal conductivity of the fiber at normal atmospheric pressure, in a vacuum of $\sim P \leqslant 10^{-3}$ torr, and at one intermediate pressure. The value of η/K determined in this manner for the basalt fibers tested is 0.62 for an average layer temperature of 465°K and 0.98 at T_{av} = 380°K. Figure 4 shows curves calculated from Eq. (6) and these values of η/K. The points on these curves show the values of λ found experimentally for cloth in which the fiber orientation was not random.

This good agreement of the calculated and experimental data means that we can use this method to find the function $\lambda = f(P)$ for materials of this type without carrying out a large number of laborious experiments. In layers of evacuated basalt fiber of relatively low density ($\gamma \leqslant 50$ kg/m³), in which case radiative heat transfer is the only heat-transfer mechanism operating, the thermal conductivity depends on the layer thickness and on the radiative properties of the surfaces bounding the layer. In the experimental results reported here for $P = 10^{-4}$ torr, the influence of these factors is taken into account on the basis of the equations from [9, 10]:

$$\lambda = \frac{1}{\frac{1}{\lambda_\tau} - \frac{1}{4\varepsilon_{re}\sigma T_{av}^3 L}}, \tag{8}$$

where

$$\varepsilon_{re} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}. \quad (9)$$

Comparison of the results found in experiments with basalt fiber which was and was not subjected to the heat treatment (Figs. 1 and 3) shows that the heat treatment does not have any significant effect on the thermophysical properties of the basalt fiber.

By carrying out the experiments with two methods, we were able to compare and check the results.

Comparison of the results found in studies of the ultrafine basalt fiber with data on the thermal conductivity of porous fiberglass materials indicates that the heat-insulating properties of these materials are identical.

NOTATION

q, heat flux, W/m^2; L, sample thickness, m; T_h, T_f, temperatures of the hot and cold surfaces of the sample in the experiments by the steady-state method; T_s, T_c, temperatures at the surface of the sample and at the surface of the core in the unsteady method; $T_{av} = (1/2)(T_h + T_f)$, average temperature of the layer of test material, °K; $dT_c/d\tau$, rate of change of the core temperature, deg/sec; λ_{exp}, λ_τ, λ, experimental thermal conductivity, thermal conductivity of an optically thin layer (for the case in which the radiative characteristics of the surfaces are influential), and of an optically dense layer, W/m·deg; R_c, R, core radius and inside radius of the calorimeter, m; C_c, specific heat of the core material, J/kg·deg; γ_c, γ, γ_d, volumetric densities of the core material, the sample material, and the solid phase of the porous-fiber material, kg/m^3; P, air pressure, torr; d, fiber diameter, μ; η, accommodation coefficient; ε_1, ε_2, ε_{re}, emissivities of the bounding surfaces and reduced emissivity of the system consisting of these surfaces; σ, Stefan–Boltzmann constant, $W/°K^4 \cdot m^2$; F, specific surface area of solid phase, m^3/m^2.

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