THERMAL CONDUCTIVITY OF A REFRACTORY BOARD IN HELIUM, AIR, AND VACUUM

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Measurements have been made on the thermal conductivity of a refractory board over the range 400-1300°K in air, helium, and vacuum.

Heat is transferred at high temperatures through porous thermal insulation to a considerable extent by heat conduction in the gas and by radiative heat transfer. Considerable interest is attached to distinguishing the various mechanisms in order to make optimal use of such materials under various conditions. Major importance is attached also to verification of theoretical calculations, since the available data are inaccurate, particularly for fibrous structures at high temperatures. Such information can be obtained by measuring the effective thermal conductivity of a dispersed material in various gases and under vacuum. Here we report results for a new and promising form of thermal insulation, namely, a board made from refractory fibers.

This refractory sheeting* is provided as sheets of thickness 0.7-0.9 mm made on paper-making machines from fibers containing 55% Al_2O_3 and 45% SiO_2 (fibers 4-5 μm in diameter and 10-20 mm in length). The fibers are bound by an organic bonding agent. The bulk density of the material is about 2500 N/m^3, the porosity is 90%, and the long-term working temperature is 1400°K.

The thermal conductivity was measured with a system employing steady-state methods applicable to plates and cylinders. In the first case, the thermal conductivity was measured by comparison with a fused-quartz standard, which is a suitable metrological material [1] up to 600°K. The diameter of the cell was 150 mm. A cooler and weight were set up on the standard, the latter producing a pressure of $4 \cdot 10^3$ N/m^2. The specimen was a stack of several sheets previously fired to oxidize the organic bonding agent. The thickness of the specimen was determined with an optical microscope before and after measurement of the thermal conductivity. It was found that the thermal conductivity was independent of the thickness in the range 1.6-4.2 mm. The thermometry plates were of dimensions 10 mm × 10 mm × 0.05 mm and were made of platinum foil, to which the flattened junctions of platinum–platinum/rhodium thermocouples of wire diameter 0.2 mm were spot-welded. The lateral heat losses were minimized by insulation made of refractory fiber. Tests showed that the temperature gradient along the surface at the center of the standard was not more than 0.1 deg/mm up to 1400°K at the hot side of the specimen, which corresponded to a radial heat flux of 0.5-2% of the axial heat flux.

The cylinder method was operated with a corundum tube of outside diameter 20 mm and length 300 m, which contained a linear wire heater; three or four layers of the board were closely wound on this. The experiments were done with absolute measurement of the heat flux in terms of the electrical power input to the central part over a length of 60 mm.

The instrumental error in measuring the thermal conductivity by the plate method was estimated as a 12-17% for λ above 0.05 W/m•°K, as against 10-15% for the cylinder method, the exact value varying with the thickness of the specimen and the temperature. The results from the two methods on a single specimen agreed to within 10%, while the spread of the points around the smoothed values was not more than 5-8%. The error of the plate method increases for low conductivities, and it may be 25-30% for λ of around $1 \cdot 10^{-2}$ W/m•°K.

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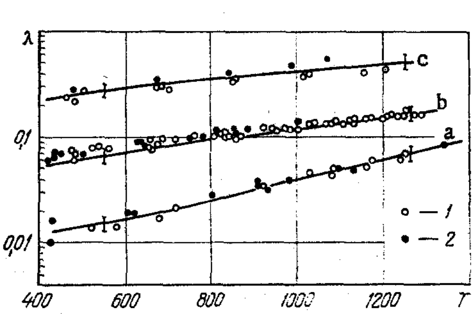

Fig. 1

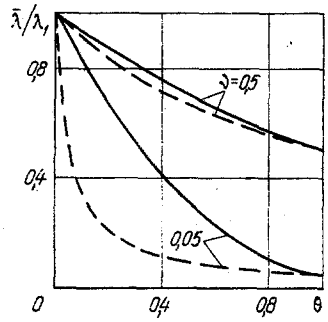

Fig. 2

Fig. 1. Thermal conductivity (W/m•°K) of alumina-rich fiber sheet: a) under vacuum; b) in air; c) in helium. The solid lines are as follows: a) by calculation from (7); b, c) from (4); 1) cylinder method; 2) plate. The vertical lines correspond to a ±15% error.

Fig. 2. Effective thermal conductivity as a function of porosity; solid lines from (4); dashed lines from (5).

Both instruments were operated in sealed vessels and measurements were made at atmospheric pressure in air or helium or with a pressure of about 1 N/m^2. Figure 1 shows the results. The data from the two methods are in satisfactory agreement, although the plate method gives somewhat higher values for the thermal conductivity. The temperature dependence of the thermal conductivity is of the form usual for high-porosity fibrous materials, as is the marked reduction in the thermal conductivity under vacuum and the increase in helium by comparison with air [2-5].

There are many different forms of finely divided insulation (powders, fibers, composites, and so on), and these differ in physicochemical parameters, structural state, and conditions of use; thus, a unified theoretical description of heat propagation would encounter considerable difficulties, particularly since several transport mechanisms are involved [6]. A comparison with experiment frequency requires a knowledge of additional characteristics of the material, together with evidence that the model for the structure is adequate. It is usual at present to interpret measurements via phenomenological representation of the heat transport. It is usually assumed for solid–gas systems that the heat fluxes are additive to a first approximation, particularly for the radiation fluxes through the pores and particles. This description presupposes a gradient representation of the fluxes, which may not always be justified, particularly for the radiation component.

A detailed model has been developed [6, 8, 9] for calculating the effective thermal conductivity of a fibrous system, in which the components are taken as interpenetrating. If the fibers have a random distribution, it is suggested that the thermal conductivity should be calculated from

$$\bar{\lambda} = \lambda_1 \left[c^2 + \nu (1-c)^2 + \frac{2\nu c(1-c)}{1-c(1-\nu)} \right], \quad \nu = \frac{\lambda_2}{\lambda_1}. \tag{1}$$

The structure parameter c is the least positive root of $\theta = 2c^3 - 3c^2 + 1$;* if convection is neglected because the pores are small and if the fibers are considered opaque to the thermal radiation, then the thermal conductivity of the gas component can be put as

$$\lambda_2 = \lambda_m + \lambda_c + \lambda_r. \tag{2}$$

Subsequently, a simpler model which incorporates the distribution of the fibers around the heat-flux direction was suggested [10]:

$$\lambda = \lambda_1 \left\{ (1-\theta)(1-\tau) + \frac{[1-(1-\theta)(1-\tau)]^2}{\tau(1-\theta) + \theta\nu^{-1}} \right\}. \tag{3}$$

Equations (1) and (3) give results in agreement to 1% for $\tau = {}^2/_3$ (uniform distribution of the fibers with respect to the coordinate axes) and $\theta \geq 0.80$; in that approximation, (1)

*An error occurs in [9] in defining c by means of trigonometric expressions.

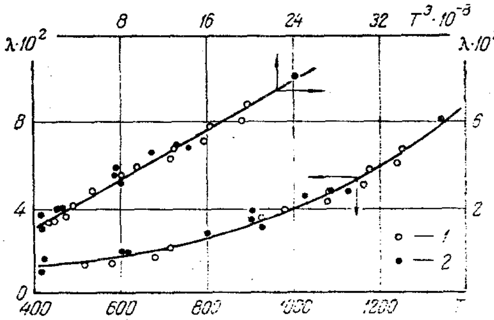

Fig. 3

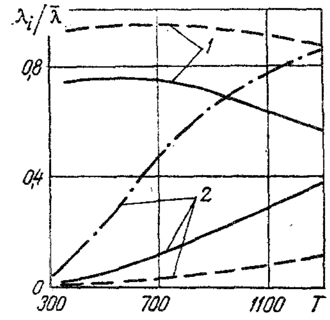

Fig. 4

Fig. 3. Temperature dependence of the thermal conductivity (W/m•°K) for the board under vacuum: 1, 2) as in Fig. 1.

Fig. 4. Contributions to the effective thermal conductivity from: 1) gas conduction; 2) radiation. The solid lines are for atmospheric pressure in air; the dashed lines are the same for helium; and the dashed-dot lines are for vacuum.

and (3) give values several times the observed ones for vacuum at low temperatures ($\lambda_2 \simeq 0$, $\lambda_1 \simeq 1$) [3, 5]. A similar situation is observed for our specimens: c = 0.196 for $\theta = 0.90$, while we get $\bar{\lambda}_v \gtrsim 4 \cdot 10^{-2}$ from (1) and $\gtrsim 3.3 \cdot 10^{-2}$ from (3) for room temperature, whereas experiment gives $\lambda_v \simeq 1 \cdot 10^{-2}$. This discrepancy is due to the excessively large value of the terms in (1) and (3) that are independent of ν, whereas experiment shows clear-cut proportionality between $\bar{\lambda} - \bar{\lambda}_v$ and λ_2 [3, 4]. Our coefficients of proportionality are about 1.0 for helium and 1.3 for air, which are close to the values given in [3].

It would seem that the method of making the specimens tends to produce an ordered structure with preferential disposition of fibers in planes perpendicular to the heat flux. In that case, the effective thermal conductivity may be put in the form [6]

$$\bar{\lambda} = \theta^2\lambda_2 + (1-\theta)^2\lambda_1 + \frac{4\theta(1-\theta)\lambda_1\lambda_2}{\lambda_1 + \lambda_2}, \tag{4}$$

and (3) for $\tau = 1$ becomes Krisher's formula:

$$\bar{\lambda} = \lambda_1 \left[1 + \theta\left(\frac{\lambda_1}{\lambda_2} - 1\right)\right]^{-1}. \tag{5}$$

Figure 2 shows that there is a very large discrepancy between (4) and (5) for small ν, which corresponds to air.

Formula (4) is in satisfactory agreement with experiment for a great variety of fibrous materials [6], and so it is more reliable than the simplified (5); we therefore used (4) to process the experimental data, although (4) and (5) give almost identical results for this range in θ.

A further point is that $\lambda_m \simeq \lambda_g$ at normal pressures, whereas $\lambda_m \simeq 0$ at about 1 N/m²; then if we put $\lambda_r = AT^3$, $\lambda_c + \lambda_r \ll \lambda_1$, the effective thermal conductivity of the board in vacuum can be put as

$$\bar{\lambda}_v = (1-\theta)^2\lambda_1 + \theta(4-3\theta)(\lambda_c + AT^3). \tag{6}$$

Since λ_1 and λ_c are only slightly dependent on temperature, it is obvious that $\bar{\lambda}_v \sim T^3$, which is clear also from the temperature dependence of the thermal conductivity in vacuum, which can be linearized if the appropriate coordinates are used (Fig. 3). The line fitted by least squares in Fig. 3 is

$$\bar{\lambda}_v = 1.06 \cdot 10^{-2} + 2.81 \cdot 10^{-11} T^3 \tag{7}$$

and this may be used with (6) to put $\lambda_c \simeq 0$, $\lambda_1 \simeq 1.1$, and $\lambda_r \simeq 2.4 \cdot 10^{-11} \cdot T^3$; these values are quite reasonable, since the contact conductivity is almost zero, while the thermal conductivity of the fiber corresponds to that of glass [10]; the expression of [9] for λ_r for an optically thick layer is derived from [11]* and takes the form

*See [7] for a criticism of the work of Poltz.

$$\lambda_r = \frac{4\sqrt{\pi}}{3} \cdot \frac{d\sigma T^3}{c^2(2-c)} \simeq 1.0 \cdot 10^{-11} T^3, \tag{8}$$

which agrees as to order of magnitude with experiment. The formulas for λ_r suggested in other papers give even lower values for the radiation component of the thermal conductivity. Since the heat transport by radiation in an inhomogeneous medium is complicated and the calculations are approximate, one should not take too much notice of the numerical values for the coefficients in formulas for λ_r. On the other hand, the $\lambda_r \sim dT^3$ functional relation has repeatedly been confirmed by experiment. The value for λ_r may also be determined by the mode of reflection of the radiation from the boundaries. We made an attempt to detect this in the experiments in air with the cylindrical specimen, where the outer surface was covered with aluminum foil or graphite; however, no appreciable effect was detected, since in both cases all the points lie on curve b of Fig. 1.

These values for λ_1 and λ_r may be used with the λ_g of [12] with (4) to calculate the effective thermal conductivity of this board in air and helium; the solid lines in Fig. 1 show the results. The discrepancies between the calculated and observed values for the gases are almost within the apparatus error. Somewhat larger deviations occur for air at temperatures up to 900°K.

These results are described adequately by the model based on interpenetrating components with an ordered disposition of the fibers, so one can assume that λ_1 and λ_2 do correspond more or less to the actual situation. At first sight, the structure of (4) does not allow one to distinguish λ_g and λ_r, since the additivity is complete. However, $\lambda_1 \gg \lambda_2$, so the coefficients to λ_g and λ_r vary only slightly with temperature, namely, from 1.16 to 1.13 in the range 400-1400°K for air or from 1.12 to 1.06 for helium. This allows one to calculate the contributions separately (Fig. 4), since the gas and radiation provide the two predominant transport mechanisms. In helium, the heat transport is overwhelmingly determined by thermal conductivity of the gas, with the radiation component amounting to only 10% at 1300°K. The dominant role is still played by λ_g in air, but up to 40% of the heat is transmitted by radiation at high temperatures. This mechanism is the main one under vacuum at temperatures above about 900°K.

NOTATION

T, temperature, °K; θ, porosity; $\bar{\lambda}$, $\bar{\lambda}_v$, effective thermal conductivities in gas and vacuum, respectively; λ_1, λ_2, thermal conductivities of fiber and gas components; λ_m, λ_c, λ_r, λ_g, molecular, contact, radiation, and gas thermal conductivities, W/m·°K; τ, probability of fiber orientation perpendicular to heat flux; d, fiber diameter, m; σ, Stefan–Boltzmann constant, W/m²·°K⁴.

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