THERMOPHYSICAL CHARACTERISTICS OF THERMAL INSULATION ON METAL BACKING

Yu. A. Zagromov, V. V. Kulikov, and B. Z. Tokar'

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An experimental method is described for determining the thermophysical characteristics of a coating of thermal insulation on metal backing. Results of measurements of samples of polymethyl methacrylate and a composite material in the 10-80°C temperature range are presented.

Very detailed summaries of a large number of experimental methods for determining the thermophysical properties of solids are given in [1, 2]. However, an increasing variety of practical situations frequently necessitates the development of new or the modification of known methods for determining such characteristics as the thermal conductivity and the volumetric heat capacity.

One such situation arises when it is necessary to measure thermal properties of a coating on metal backing. Since the coating is thin, only the temperature of the metal can be measured.

In addition, the medium in direct contact with the coating (vacuum, a specific gas, etc.) affects the measurements. This makes it impossible to use reference materials or steady-state methods for measuring the thermal conductivity. For this reason, the heat source must be placed on the side of the metal backing, since the absorbing power of the coating is generally not known, and radiative heating (recommended, for example, in [3]) cannot be used.

By using the proposed method and taking account of the features noted, one can determine the thermal conductivity and volumetric heat capacity of the insulation under study from a single experiment by measuring the temperature of the metal if its volumetric heat capacity is assumed known.

The theory of the method is based on the solution of the problem of the propagation of heat in a two-layer system with one surface heated by a steady heat flux and the other thermally insulated. The change in temperature of the heated metal layer when $\lambda_m \gg \lambda$ is described in dimensionless form by the relation [4]

$$\frac{\theta_m(\mathrm{Fo})}{\mathrm{Ki}} = \frac{K\,\mathrm{Fo}}{1+K} + \frac{1}{3}\left(\frac{K}{1+K}\right)^2 - 2K\sum_{n=1}^{\infty}\frac{\exp(-\mu_n^2\,\mathrm{Fo})}{\mu_n^2(1+K+\mu_n^2/K)}, \tag{1}$$

where the μ_n are the roots of the characteristic equation $\tan\mu_n = -\mu_n/K$.

Calculations show that the value of $\mathrm{Fo_{qu}}$ corresponding to the onset of a quasistationary heating regime when the series in (1) can be neglected does not exceed 0.8.

For $\mathrm{Fo} > \mathrm{Fo_{qu}}$, Eq. (1) can be written in dimensionless form as

$$\vartheta_m(\tau) = \frac{q\tau}{c\rho l + c\rho l_m} + \frac{ql}{3\lambda}\left(\frac{K}{1+K}\right)^2, \tag{2}$$

and knowing the experimental dependence of ϑ_m on τ (Fig. 1), the volumetric heat capacity and thermal conductivity can be determined from the equations

$$c\rho = \frac{q}{al} - \frac{c\rho l_m}{l}, \tag{3}$$

$$\lambda = \frac{ql}{3b}\left(\frac{K}{1+K}\right)^2. \tag{4}$$

The experimental value of $K = c\rho l/c\rho l_m$ is substituted into (4).

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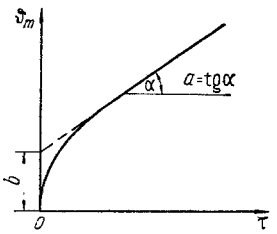

Fig. 1. Scheme for the derivation of Eqs. (3) and (4); ϑ_m, °C; τ, sec.

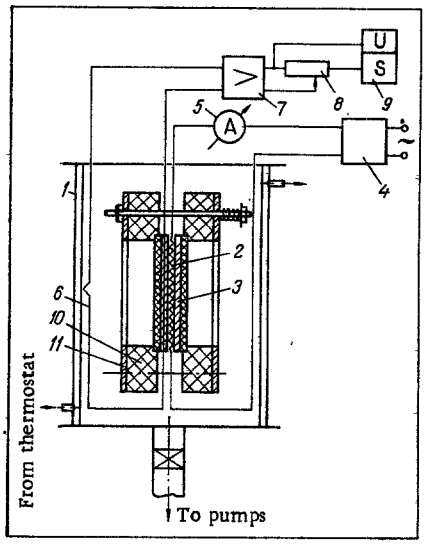

Fig. 2. Schematic diagram of experimental arrangement.

The proposed method for measuring λ and $c\rho$ was tested experimentally on the arrangement shown schematically in Fig. 2.

The samples under investigation were placed in a constant-temperature all-metal double-walled chamber 1 in which the required vacuum was produced by a VN-2MG fore pump and an AVP-0.5 vacuum unit, monitored by pressure transducers in an assembly with a VIT-2 vacuum gage.

The samples were heated from the side of the metal backing by a quick-response heater 2 made of Constantan foil covered on both sides with mica sheets. The total thickness of the heater placed between two identical samples 3 did not exceed 0.07 mm and it had a resistance $R = 102\ \Omega$. As a consequence of the symmetry of the system, the heat flux needed to calculate the thermophysical characteristics by Eqs. (3) and (4) is given by $q = I^2R/2F(W/m^2)$, where the heater current I is furnished by a UIP-1 power supply 4 and measured with an M-502 ammeter 5.

The temperature of the metal backing was recorded by a 0.1-mm-diameter copper–Constantan differential thermocouple 6 with its cold junction placed on the wall of the constant-temperature chamber and kept at a steady temperature equal to the initial temperature of the sample during the measurement. The thermocouple signal was fed into an F116/1 photoelectric amplifier 7 whose output current produced a potential difference across the calibrated resistance 8 proportional to the thermoelectromotive force being measured and was recorded by a KSP-4 automatic potentiometer 9.

In order for the thermophysical characteristics to remain constant during the measurement, the maximum increase in sample temperature above its initial value must not exceed 3-4°C. This is achieved by an appropriate choice of heat flux. The amplification factor and writing speed $\vartheta_m(\tau)$ are chosen so as to yield maximum accuracy in the determination of the parameters a and b appearing in Eqs. (3) and (4).

Thermal contact was produced by clamping the samples and heater between two Teflon plates 10 without overlapping the surface of the material under study. The compressive force was kept constant by springs and the metal rings 11. The contact thermal resistance can significantly affect measurements in vacuum. It was reduced by polishing the surfaces of the metal backings and coating them with a thin layer of vacuum grease mixed with copper dust.

Using the experimental arrangement described above, measurements were made of the thermal conductivity and volumetric heat capacity of polymethyl methacrylate, which is considered the reference material. The samples measured were plates 1.2 mm thick and $32 \times 32\ mm^2$ in area. The metal backing plates were aluminum of the same area and 1.32 mm thick.

The values of λ and $c\rho$ for samples of polymethyl methacrylate were measured between 8 and 80°C in air at atmospheric pressure and compared with data in the literature. The results shown in Fig. 3 are in good agreement with data from [5]. The somewhat too low values of the thermal conductivity appear to be due to thermal resistance at the contact between the plastic plates and the metal backing. In our experimental arrangement good contact depends solely on mechanical compression.

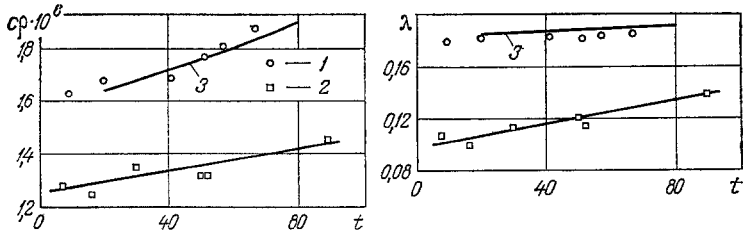

Fig. 3. Thermal conductivity (W/m · °C) and volumetric heat capacity (J/m³ · °C) as functions of temperature (°C): 1) polymethyl methacrylate; 2) composite material; 3) data from [5].

The value of the volumetric heat capacity of aluminum which is needed in Eqs. (3) and (4) to calculate the thermophysical properties of the material under investigation was taken from [6].

The thermal conductivity and volumetric heat capacity of a coating of composite material consisting of zinc oxide and an organic binder (polymethylsiloxane) were measured in a vacuum of 10^{-5} torr. A coating 0.7 mm thick was deposited on aluminum metal backing by a paint sprayer. The results of the measurements are shown in Fig. 3.

Analysis of Errors. In addition to such factors as the nonuniformity of the temperature distribution, the heat capacity of the heat source, the temperature dependence of the thermophysical properties, etc., which can be taken into account by well-known procedures, the finite values of the thermal conductivity of the metal backing of the sample and the heat loss from the free surface of the coating cause important deviations of the experimental conditions from the theoretical.

The effect of the thermal conductivity of the metal backing can be estimated by comparing Eq. (2) with the solution of an analogous problem with $\lambda_m \neq \infty$. According to [7], after certain transformations the quasistationary part of the solution can be written as

$$\vartheta_m(\tau) = \frac{q\tau}{c\rho l + c\rho l_m} + \frac{ql}{3\lambda}\left(\frac{K}{1+K}\right)^2\left[1+\beta\left(\frac{1}{K^2}+\frac{3}{K}+3\right)\right], \tag{5}$$

where $\beta = (l/\lambda)/(l_m/\lambda_m)$ is the ratio of the thermal resistance of the insulation to that of the metal backing.

It is clear from (5) that the finite value of λ_m does not distort the measurement of the volumetric heat capacity of the material under study. The error in determining the thermal conductivity is found from the relation

$$\delta\lambda = \frac{\beta\left(\frac{1}{K^2}+\frac{3}{K}+3\right)}{1+\beta\left(\frac{1}{K^2}+\frac{3}{K}+3\right)}\ 100\%. \tag{6}$$

Values of $\delta\lambda(\beta)$ calculated by Eq. (6) for several values of K are shown in Fig. 4. Clearly, the error in determining the thermal conductivity for a given value of β decreases with increasing K.

The error arising from heat losses is determined by using the solution of the problem of heating a two-layer system by a steady heat flux when boundary conditions of the third kind are specified on one surface [8]. Going to the limit $\lambda_m \to \infty$, we obtain

$$\frac{\theta_m(\mathrm{Fo})}{\mathrm{Ki}} = \frac{1+\mathrm{Bi}}{\mathrm{Bi}} - 2K\sum_{n=1}^{\infty}\frac{\left(1+\frac{\mathrm{Bi}\,\mathrm{tg}\,\mu_n}{\mu_n}\right)\exp(-\mu_n^2\,\mathrm{Fo})}{(2+\mathrm{Bi}+K)\,\mu_n^2+(\mathrm{Bi}\,K+\mathrm{Bi}+K-\mu_n^2)\,\mu_n\,\mathrm{tg}\,\mu_n}, \tag{7}$$

where the μ_n are the roots of the characteristic equation

$$\mathrm{tg}\,\mu_n = (\mathrm{Bi}\,K-\mu_n^2)/\mu_n(\mathrm{Bi}+K).$$

It should be noted that as $\mathrm{Bi}\to 0$, Eq. (7) goes over identically into (1).

Calculations show that over a rather wide range of Fo values the relation between θ_m and Fo determined by (7) for $\mathrm{Bi} < 1$ can be represented by a linear relation whose parameters deviate from the quasistationary part of (1) as a result of the error sought. The values of $\delta c\rho$ and $\delta\lambda$ shown in Tables 1 and 2 were calculated for several values of Bi and K by using (7). The first six roots μ_n were taken from [9].

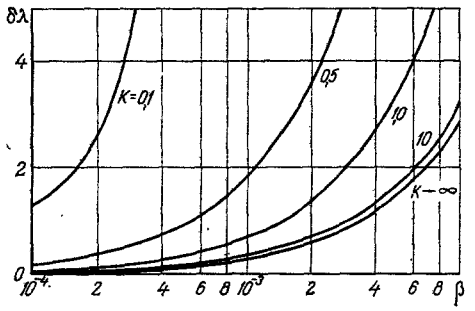

Fig. 4. Error in determining thermal conductivity by proposed method as a function of the ratio of the thermal resistances of the insulating layer under study and the metal backing; $\delta\lambda$, %.

TABLE 1. Error in the Determination of the Volumetric Heat Capacity of the Cladding Resulting from Its Nonadiabaticity ($\delta c\rho$, %)

K	Bi					
	1,00	0,50	0,20	0,10	0,05	0,02
5,0	24,59	13,16	5,04	2,08	0,55	0,06
1,0	21,36	11,30	3,53	0,57	0,04	0,00
0,1	9,30	4,85	1,24	0,08	0,00	0,00

TABLE 2. Error in the Determination of the Thermal Conductivity of the Cladding Resulting from Its Nonadiabaticity ($\delta\lambda$, %)

K	Bi					
	1,00	0,50	0,20	0,10	0,05	0,02
5,0	18,53	11,80	4,78	1,41	0,79	0,38
1,0	16,12	10,12	3,34	0,39	0,06	0,00
0,1	7,01	4,35	1,17	0,05	0,00	0,00

The analysis performed imposes certain restrictions on the dimensions, the thermophysical properties, and the conditions for cooling the samples under study when using the proposed procedure. In particular, a significant decrease in heat loss from the surface of the insulation is achieved by making measurements in vacuum, but for thin enough samples measurements in the low-temperature region can be performed at atmospheric pressure.

In all our experiments the errors indicated are estimated to be 2% or less, and the total error in the determination of the thermophysical characteristics λ and $c\rho$ is 7-8%. An analysis of Eqs. (3) and (4) shows that the main contribution to the total instrumental error in λ and $c\rho$ comes from the values of the volumetric heat capacity of the metal $c\rho_m$, which is determined from data in the literature with an error of 3%. The remaining quantities are measured with high-accuracy instruments. Thus, the proposed method is not free of the fault of relative methods of measurement, which require rather accurate knowledge of the properties of the reference material – the backing of high-conductivity metal.

In conclusion, it should be noted that in performing measurements by the proposed method in vacuum it is obviously more advantageous to use electron heating of the metal backing. With this method of supplying heat, contact resistance between the heat source and the sample is eliminated, and two identical samples are no longer required.

NOTATION

$\theta = \vartheta(\tau)/t_0$, dimensionless temperature; $Ki = q \cdot l/\lambda \cdot t_0$, Kirpichev number; Bi, Biot number; $\vartheta(\tau) = t(\tau) - t_0$, temperature excess above initial temperature t_0; τ, time; q, heat-flux density; l, thickness; λ, coefficient of thermal conductivity; $c\rho$, volumetric heat capacity; R, resistance of heater; F, area of heater. Indices: m, metal backing of sample.

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THERMAL CONDUCTIVITY OF A FIBERGLASS MATERIAL WITH A COMPLEX SPATIAL STRUCTURE

V. A. Loshkarev and A. I. Cheprasov

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A method is given for calculating the thermal conductivity of a fiberglass material having a complicated spatial structure. This method can be applied up to the onset of pyrolysis.

Particular attention has been devoted to the temperature dependence of thermophysical parameters in work on fiberglass materials [1, 2]; on the other hand, it is extremely important to be able to evaluate the effects of structural form of the filler and type of bonding agent on the physical parameters in applications, particularly in designing production techniques.

Here we consider an engineering approach and design formulas for the thermal conductivity of fiberglass materials in which the filler has a complicated spatial structure; these formulas apply up to the onset of pyrolysis, and they contain technological parameters and other parameters readily determined by experiment.

The measurements were performed on a material in which the glass fibers ran in two directions, the fibers in one direction forming flat inclined sheets, while those in the other (winding) direction were randomly disposed but had the same mean density. Figure 1 shows the characteristic winding scheme: In Fig. 1a, the flat inclined bundles of fibers are at an angle α to the incident heat flux q, while in Fig. 1b we have random winding in a plane perpendicular to the plane of the incident heat flux. It is clear that in limiting cases this structure passes into common structures widely used in fiberglass materials.

The thermal conductivity of a material of this type was examined in two stages in sequence for each of the structures (Fig. 1a, b); we assumed that the fibers were rectangular parallelepipeds. Experience shows that the deformation involved in processing such a material converts the originally circular fibers into rectangles whose longer sides are parallel to the plane of the surface of the product. The change in fiber shape occurs because each fiber itself consists of a large number of elementary filaments (of the order of 100-400, diameters 2.5-12 μm), and therefore such a fiber is reasonably plastic [3].

Superposition of the particular solutions gives the thermal conductivity for the entire system.

Since the thermal conductivity of the entire system is equal to those of the elementary volumes, and since the structure has a periodic component having a definite orientation with respect to the incident heat

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