NOTATION

a, empirical parameter taking account of nonuniform sections oriented parallel and perpendicular to the general direction of heat flow in the model; b, empirical parameter taking account of the fact that only a part of the surface of the solid frame is wetted and contributes to the diffusive heat transfer due to evaporation and condensation of moisture; m_S, m_W, m_L, m_{LP}, volume concentration of the solid component, liquid, and pores with dry and wet walls, respectively; λ, effective thermal conductivity of moist materials; λ_S, λ_W, λ_L, λ_{LD}, thermal conductivity of the solid component, liquid, dry air, and air — vapor mixture (diffuse component); λ_{dry}, λ_{sa}, thermal conductivity of dry porous and completely moist material; δ, diffusion coefficient; P, total pressure of the mixture; P_D, saturated vapor pressure; R_D, universal gas constant; r, heat of evaporation.

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THERMAL-CONDUCTIVITY RANGE FOR A COMPOSITE HAVING KNOWN RANGES IN PARAMETERS FOR THE COMPONENTS

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The known ranges in thermal conductivity for the components may be used to determine the range in thermal conductivity for a composite; formulas have been derived for the distribution coefficients, which provide detailed values in each case.

There are presently many different methods of calculating thermal conductivities for composites in terms of the known conductivities of the components; these methods form the subject of several reviews [1-4].

In these methods it is assumed that the thermal conductivity and the degree of filling are known exactly, whereas in any measurement there is always some experimental error, and the final spread is governed by the error of measurement as well as by variations in the properties of the material itself. In either case, the measured value for the thermal conductivity is to be treated as a random quantity, one of the characteristics being the mathematical expectation (most likely value) and another being the standard deviation.

In this connection it is of interest to determine how the spread in the thermal conductivity for each of the components affects the spread in the same for the composite for various proportions of the components.

Further, a real composite also has a degree of filling in a finite volume that may also be considered as a random quantity, which deviates to some extent from the mean value. Therefore, the thermal conductivity of the composite should vary even within the volume of a specimen. We show below that in certain instances one can determine in simple fashion the spread in the thermal conductivity of the composite as a function of the spread in the degree of filling.

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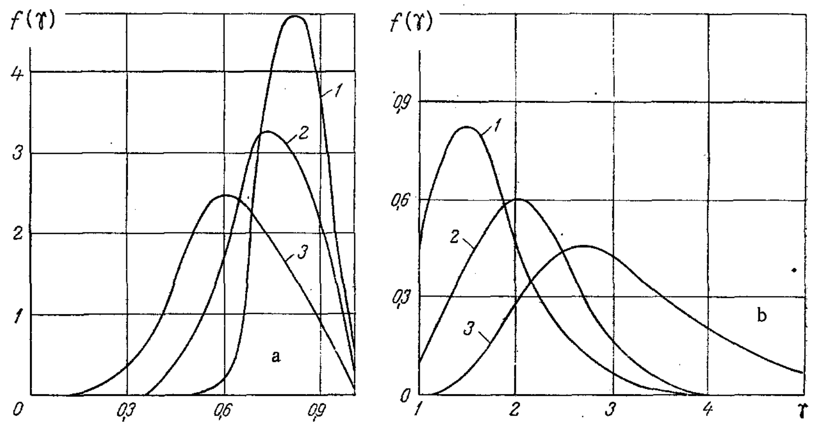

Fig. 1. Thermal-conductivity distributions: a) composite with a normal distribution for the thermal conductivity of the filler; b) filled material with a normal distribution for the degree of filling in specimens of finite size. Mean degrees of filling: 1) 0.3; 2) 0.5; 3) 0.7.

The theory of probability [5] shows that if a random quantity Y is a function of another random quantity X, namely, $Y = \varphi(X)$, then the distribution for Y is defined by

$$f_1(y) = f[\psi(y)]\,|\psi'(y)|, \tag{1}$$

where $\psi(y) = x$ and $f_1(y)$ is the desired density, $f(x)$ is the distribution for x, which is related to y by $y = \varphi(x)$ or $x = \psi(y)$, and $|\psi'(y)|$ is the absolute value of the derivative of ψ with respect to y.

Therefore, the distributions for the conductivities of the components can be used with the relationship between these conductivities and the conductivity of the composite in conjunction with (1) to define the distribution for the conductivity of the composite. This enables one to define the mean thermal conductivity and the standard deviation.

This is the simplest when the thermal conductivity of the composite is linearly related to the conductivities of the components; for example, several formulas [6-10] are available, which can be represented in one of the following forms:

$$\left.\begin{aligned} \lambda &= a_1 + b_1\lambda_1, \\ \lambda &= a_2 + b_2\lambda_2. \end{aligned}\right\} \tag{2}$$

Usually, thermal-conductivity measurements for the components can be represented as normal distributions, the distribution for component i taking the form

$$f(\lambda_i) = \frac{1}{\sqrt{2\pi}\,\sigma_{\lambda i}} \exp\left[-\frac{(\lambda_i - \lambda_{i0})^2}{2\sigma_{\lambda i}^2}\right]. \tag{3}$$

If λ is linearly dependent on λ_i, the distribution for λ will also be of normal form, whose mean and standard deviations are defined by

$$\lambda_0 = a_i + b_i\lambda_{0i}, \tag{4}$$

$$\sigma_\lambda = \sigma_{\lambda i}\,|b_i|. \tag{5}$$

If a linear relationship does not apply, it is possible to derive an expression for the distribution for the composite only in certain particular cases. As an example, we consider the distribution for a composite in which the matrix has a constant thermal conductivity while the filler has a normal distribution, for which purpose we use the formula of [11] for matrix systems, which takes the form

$$\frac{\lambda}{\lambda_1} = 1 + \frac{P}{\dfrac{1-P}{3} + \dfrac{1}{\dfrac{\lambda_2}{\lambda_1} - 1}}. \tag{6}$$

We transform (6) to get

$$\lambda_2 = \lambda_1 \frac{P + \dfrac{2+P}{3}\left(\dfrac{\lambda}{\lambda_1} - 1\right)}{P - \dfrac{1-P}{3}\left(\dfrac{\lambda}{\lambda_1} - 1\right)}. \tag{7}$$

Then

$$|\psi'(\lambda_2)| = \frac{P}{\left[P - \dfrac{1-P}{3}\left(\dfrac{\lambda}{\lambda_1} - 1\right)\right]^2}. \tag{8}$$

We substitute (7) and (8) into (1) to get f(λ) for this case:

$$f(\lambda) = \frac{1}{\sqrt{2\pi}\sigma_{\lambda_2}} \cdot \frac{P}{\left[P - \dfrac{1-P}{3}\left(\dfrac{\lambda}{\lambda_1} - 1\right)\right]^2} \exp\left[- \frac{\left\{\lambda_1 \dfrac{P + \dfrac{2+P}{3}\left(\dfrac{\lambda}{\lambda_1} - 1\right)}{P - \dfrac{1-P}{3}\left(\dfrac{\lambda}{\lambda_1} - 1\right)} - \lambda_{20}\right\}^2}{2\sigma^2_{\lambda 2}} \right]. \tag{9}$$

This is clearly not a normal distribution; Fig. 1a shows the distribution given by (9) for various degrees of filling when $\lambda_1 = 1$ W/m·°C, $\lambda_{20} = 0.5$ W/m·°C, and $\sigma_{\lambda_2} = 0.2$ W/m·°C.

There are also no essential difficulties in defining the distribution of λ when λ_1 has a normal distribution, but the expression then becomes very cumbersome and is not given here.

It is also of interest to consider the case where the filler is unevenly distributed over the volume of the composite, provided that we can assume that the degree of filling for specimens taken from different points will have a normal distribution:

$$f(P) = \frac{1}{\sqrt{2\pi}\sigma_P} \exp\left[- \frac{(P - P_0)^2}{2\sigma_P^2} \right]. \tag{10}$$

If (6) is used, with $\lambda_2/\lambda_1 = \nu$ and $\lambda/\lambda_1 = \gamma$, we get

$$\psi(\gamma) = P = \frac{\gamma - 1}{2 + \gamma} \cdot \frac{2 + \nu}{\nu - 1}; \tag{11}$$

$$|\psi'(\gamma)| = \frac{2 + \nu}{|\nu - 1|} \cdot \frac{3}{(2 + \gamma)^2}. \tag{12}$$

Then

$$f(\gamma) = \frac{2 + \nu}{|\nu - 1|} \cdot \frac{3}{(2 + \gamma)^2} \cdot \frac{1}{\sqrt{2\pi}\sigma_P} \exp\left[- \frac{\left(\dfrac{\gamma - 1}{2 + \gamma} \cdot \dfrac{2 + \nu}{\nu - 1} - P_0\right)^2}{2\sigma_P^2} \right]. \tag{13}$$

Figure 1b shows graphs for this function for $P_0 = 0.3$, 0.5, 0.7; $\sigma_P = 0.2$; and $\nu = 5$.

Then these formulas allow one to define the distribution of the thermal conductivity for a composite if the parameters of the normal distribution are known for each of the components, together with those for the degree of filling. These distributions allow one to calculate the mean and standard deviations of the thermal conductivity of the composite.

Analogous formulas can be derived when other working formulas are employed, and also when the distributions for the thermal conductivity or degree of filling are not normal.

NOTATION

λ, effective thermal conductivity of composite; λ_1, λ_2, thermal conductivities of matrix and filler; λ_i, thermal conductivity of i-th component; P, degree of filling; f(y), distribution density of random quantity Y; a_1, a_2, b_1, b_2, coefficients dependent on specific formula; y_0, mean value of y; σ_y, standard deviation of y.

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CONTACTLESS METHOD OF DETERMINING THE COEFFICIENT OF THERMAL DIFFUSIVITY OF LOCAL DOMAINS OF SURFACE LAYERS AND THIN FILMS

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A method is proposed for measuring the coefficient of thermal diffusivity of microsections of surface layers and thin films. The coefficient of thermal diffusivity is calculated from the time dependence of the heat flux emitted by the heated surface.

The possibility of determining the physical parameters characterizing micron regions of surface layers of bulk specimens and thin films is important in the miniaturization of technical apparatus.

X-ray spectrum electron-probe microanalysis [1] is extensively used at this time. In particular, this method is used to investigate semiconductor materials and thermoelectric substances, which permits obtaining data about the microinhomogeneity of the substance, the composition of the shallow phases, the intermediate layers, the behavior of the doping impurities, etc. [2]. Knowledge of only the results of an x-ray spectrum microanalysis is insufficient for an estimation of the role of the microinhomogeneities, the shallow phases, and the intermediate layers in semiconductor instruments. Knowledge of the physical parameters of the microdomains under investigation, particularly the thermophysical properties, is also important.

We used an electron beam x-ray microanalyzer of MS-46 type in combination with a high sensitivity infrared radiation detector to determine the coefficient of thermal diffusivity of surface or film microsections. Since the diameter of the electron beam of instruments of the type mentioned equals approximately 1 μm, the measured values of the coefficient of thermal diffusivity will characterize a domain several microns in size. The crux of the method is the following.

A cylindrical section of radius a and thickness l (Fig. 1) of the surface of the specimen 3 under investigation is exposed to the axisymmetric electron beam 1 whose density is normally distributed.

Heat will be liberated at the site of electron beam incidence on the surface being investigated, part of which will be dissipated in the substance and part of which will be radiated by the surface into surrounding space. It may be considered that the quantity of energy being radiated is negligible compared to the quantity which is dissipated within the substance.

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