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THERMAL CONDUCTIVITY OF A FIBERGLASS MATERIAL WITH A COMPLEX SPATIAL STRUCTURE

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UDC 536.21

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.

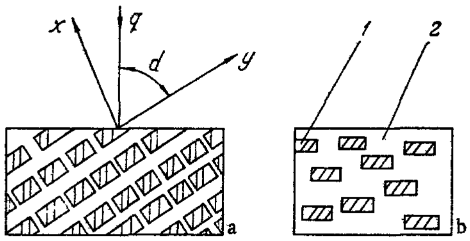
The measurements were performed on a material in which the glass fibers ran in two directions, the fibers in one direction forming flat inclined sheets, while those in the other (winding) direction were randomly disposed but had the same mean density. Figure 1 shows the characteristic winding scheme: 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

Stavropol' Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 35, No. 1, pp. 25-28, July, 1978. Original article submitted July 25, 1977.



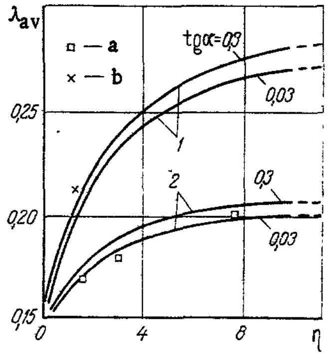


Fig. 1 Fig. 2

Fig. 1. Characteristic glass-fiber winding scheme: a) planar inclined sets of fibers at angle α; b) random winding in a plane perpendicular to the plane of the incident heat flux (1 represents the ends of the fibers in section and 2 represents the bonding agent).

Fig. 2. The $\lambda_{av} = f(\eta, \alpha)$ relation for two types of fiberglass material: a) our experiments; b) data of [5]; 1) 50% ÉD-5 +50% quartz; 2) 50% ÉD-5 +50% Pyrex.

flux, the average thermal conductivity λ_{av} will be dependent on the balance between the components of types a and b (Fig. 1). Then

$$\lambda_{av} = \frac{\lambda(\alpha)\,\eta + \lambda_{II}}{\eta + 1}. \tag{1}$$

Here and subsequently η is the ratio of the numbers of fibers in one direction to the number in the other direction in a unit volume of the material.

Consider the structure of Fig. 1a; the thermal conductivities along the x and y axes will not be identical. The second-order tensor has a matrix λ_{ij} in which nonzero values occur only on the principal diagonal for an orthotropic structure; so the end of the vector describes an ellipsoid in three-dimensional space or an ellipse in two-dimensional space. Therefore,

$$y^2 = \lambda_y^2 - \frac{\lambda_y^2}{\lambda_x^2}\,x^2,\quad y^2 = x^2\,\mathrm{tg}^2\alpha.$$

Then

$$\lambda(\alpha) = \lambda_x\lambda_y / \sqrt{\lambda_y^2 + (\lambda_x^2 - \lambda_y^2)\sin^2\alpha}. \tag{2}$$

The isothermal surfaces are parallel in a composite with this type of structure [2] (Fig. 1a), so the structure gives us the thermal conductivity along the y axis as

$$\lambda_y = \lambda_1\,\frac{v_1}{V - v_1} + \lambda_2\,\frac{v_2}{V - v_2}$$

or in alternative form

$$\lambda_y = \frac{\eta}{\dfrac{\eta + 1}{v_1^1} - 1}\,(\lambda_1 - \lambda_2) + \lambda_2\,\frac{1}{1 - v_2^1}. \tag{3}$$

Here

$$v_1^1 = \frac{\eta}{\eta + 1}\left(\frac{M - \rho_2 V}{\rho_1 - \rho_2}\right)\frac{1}{V};\quad v_2^1 = \frac{1}{\eta + 1}\left(\frac{M - \rho_2 V}{\rho_1 - \rho_2}\right)\frac{1}{V},$$

where v_1^1 and v_2^1 are the dimensionless volume contents of the filler fibers in the mutually perpendicular directions and the reduced quantity $\bar{V}_1$ is defined by

$$\bar{V}_1 = \eta \Big/ \left(\frac{\eta + 1}{v_1^1} - 1\right).$$

The resultant value λ_x is found as the sum of the thermal resistances of the two zones:

$$\lambda_x = \frac{1}{\frac{\bar{V}_1}{\lambda_1} + \frac{1-\bar{V}_1}{\lambda_2}}, \quad \lambda_x = \frac{\lambda_1\lambda_2}{\lambda_2 \frac{\eta}{\frac{\eta+1}{v_1^1} - 1} + \left(1 - \frac{\eta}{\frac{\eta+1}{v_2^1} - 1}\right)\lambda_1}$$

or

$$\lambda_x = \frac{\lambda_1\lambda_2}{\lambda_1 + \lambda_2 - \frac{1}{1 - v_2^1} - \lambda_y}. \tag{4}$$

We substitute these expressions into (2) to get $\lambda(\alpha)$; the thermal conductivity of the second structure (Fig. 1b), namely, λ_{II}, is derived by means of standard relations [1], which after appropriate transformation give

$$\lambda_{II} = \lambda_2 + \frac{\lambda_2 v_1^1}{\eta(1 - v_1^1)\frac{\lambda_1}{\lambda_1 - \lambda_2} + \frac{1}{2}\left(\frac{\lambda_1 + \lambda_2}{\lambda_1 - \lambda_2}\right) - \frac{1}{2v_1^1}}. \tag{5}$$

System (1)-(5) is a complete system for the average thermal conductivity for this complex structure up to the onset of pyrolysis; a distinctive feature of the equations is that they contain the microscopic physical quantities M, ρ_1, ρ_2, and V, that are readily determined by experiment, as well as the major technological parameters α and η.

Figure 2 shows working relationships for λ_{av} for two types of material (quartz fiber with ÉD-5 resin and glass of Pyrex type with ÉD-5 for various values of η and α). The thermal conductivity of Pyrex is $\lambda_1 = 0.725$ W/m·deg, and for quartz $\lambda_1 = 0.835$ W/m·deg [4], while $\lambda_2 = 0.133$ W/m·deg [5] for ÉD-5 bonding agent. The practical significance of the results is obvious. A computer program may be written to examine all possible combinations of bonding agent and filler for any new material, thus giving a series of curves from which λ_{av} and η can be deduced in order to define the type of bonding agent and filler, as well as the optimum value of α. On the other hand, α and η may well be known in advance along with λ_1 and λ_2, in which case one can determine the average thermal conductivity of the product up to the pyrolysis point.

NOTATION

M, sample mass, kg; q, incident heat flux, W/m^2; V, sample volume, m^3; v_1, v_2, filler and binder volumes, m^3; v_1^1, v_2^1, dimensionless values of v_1 and v_2; x, y, coordinate axes, W/m·°K; α, winding angle (inclination of fibers to heat-flux vector); λ_1, thermal conductivity of filler, W/m·°K; λ_2, thermal conductivity of binder, W/m·°K; λ_{av}, thermal conductivity of initial material, W/m·°K; $\lambda(\alpha)$, thermal conductivity of type-a structure (Fig. 1), W/m·°K; λ_{II}) thermal conductivity of type-b structure (Fig. 1), W/m·°K; λ_x, thermal conductivity of type-a structure along the x axis (Fig. 1), W/m·°K; λ_y, thermal conductivity of type-a structure along the y axis (Fig. 1), W/m·°K; ρ_1, filler density, kg/m^3; ρ_2, binder density, kg/m^3.

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