SOME RESULTS OF INVESTIGATION OF THE THERMAL CONDUCTIVITY OF FIBER GLASS-REINFORCED PLASTICS

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Results of determination of the temperature dependence of the thermal conductivity from thermocouple measurements at two points at different depths in the material are given.

The high strength, low bulk density, and good heat-insulating properties of fiber glass-reinforced plastics have promoted their wide application in engineering. This, in turn, has necessitated an investigation of the thermophysical characteristics, particularly the thermal conductivity, in a wide temperature range. The use of devices and apparatus for thermophysical measurements based on classical methods is limited for materials of this class to 200-300°C, since fiber glass-reinforced plastics contain components which decompose and give off a certain amount of gaseous products. Hence, to determine the thermal conductivity we used a method based on a solution of the inverse heat-conduction problem [1]. A program written for the M-220 computer enabled us to process the numerous experimental data and obtain $\lambda(T)$ relationships for several compositions. In the calculations we used unsteady temperature fields obtained on different apparatuses employing diverse model specimens and gauges.

The processing of the experimental data revealed the main factors affecting the error of determination of the temperature dependence of the thermal conductivity: deviations of the bulk density and specific heat from the nominal values, errors in measurement of the temperature fields, and errors in determination of the position of the thermocouples. The last error was the decisive one, since the error in determining the position from thermocouple to thermocouple could have different signs. This means that in advancing from step to step of the piecewise-constant approximation of $\lambda(T)$ the error built up and could distort not only the result, but also the nature of the curve.

Several measures enabled us to reduce the error of the apparatus and the error of determination of the position of the thermocouples in the material, but did not eliminate the main fault — the possible build-up of the error.

Carry et al. [2] made an analysis of the errors and altered the position of the thermocouples in the thermal model to obtain coincidence of the calculated $\lambda(T)$ curve with that measured on laboratory apparatus. In the case under discussion this method was unsuitable because the actual nature of the curve was unknown to us beforehand.

Better results are given by a modification of method [1] of determining thermal conductivity. It consists essentially in using the temperature field, measured at two points at different depths in the material (Fig. 1). The temperature dependence $T_1(\tau)$ is used as a condition on the outer boundary, while $T_2(\tau)$ is used for comparison with the calculated temperatures. The whole range $0 - \tau_n$ is divided into a series of time intervals $0 - \tau_1$, $\tau_1 - \tau_2$, ..., $\tau_{i-1} - \tau_i$, ..., $\tau_{n-1} - \tau_n$. For each instant τ_i the curve of $T_1(\tau)$ has a corresponding temperature T_i, which is the maximum for the considered interval $\tau_{i-1} - \tau_i$. This is true for a $T(\tau)$ relationship whose derivative $\partial T/\partial \tau$ is positive and does not change sign. For the selected time intervals there are corresponding well-defined temperature intervals in which the thermal conductivity is assumed constant. In the first temperature interval ΔT_1 we assign to λ an arbitrary value

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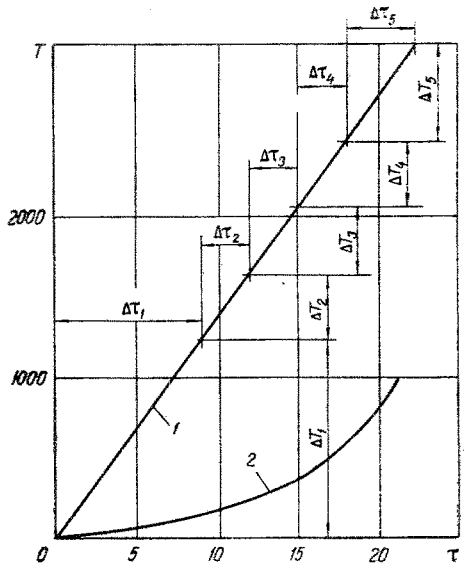

Fig. 1. Temperature field in material: 1) surface temperature; 2) temperature at a distance of 2 mm from surface; $\Delta\tau$ is the time interval; ΔT is the temperature interval. T is in °C; τ is in sec.

from which we calculate the temperature curve $T_2(\tau)$ in the corresponding time interval $0 - \tau_1$. The temperature is determined from the solution of the nonlinear differential equation of unsteady heat conduction. The deviation of the calculated curve from the experimental curve is estimated from the root-mean-square error, calculated from the formula

$$\sigma = \frac{\sqrt{\sum_{j=1}^{m} (T_{j\,\mathrm{calc}} - T_{j\,\mathrm{exp}})^2}}{m},$$

where $m = \tau_{j\,\mathrm{exp}}/\Delta\tau_{\mathrm{calc}}$; $T_{j\,\mathrm{calc}}$ and $T_{j\,\mathrm{exp}}$ are the calculated and measured temperatures at time τ_j. By varying the value of λ in the first interval and calculating the values of the error for each of them, we construct the relationship $\sigma = f(\lambda_1)$. From the minimum root-mean-square error we find the optimum value of the thermal conductivity $\lambda_{1\,\mathrm{opt}}$ in the interval ΔT_1 (Fig. 1).

Proceeding to the second interval ΔT_2 we use a two-step $\lambda(T)$ relationship in the calculation: the first step is the determined constant optimum value, and the second is the arbitrary λ_2 in the interval ΔT_2. From the minimum deviation of this curve $T_2(\tau)$, but in the interval $0 - \tau_2$, we calculate the optimum value of λ_2. Finding λ_{opt} in the third and subsequent intervals in a similar way, we obtain a piecewise-constant $\lambda(T)$ relationship in the considered range.

An example of the reconstruction of $\lambda(T)$ by the proposed method is shown in Fig. 2. The continuous line is the actual temperature dependence of the thermal conductivity and the dashed line is the reconstruction. In the calculation we used one approximation. The time used on the M-220 computer was 15 min.

The proposed method is superior to the preceding method in that the error in determination of the position of the thermocouples is constant in passing from one temperature interval to another. As a result, the relationship $\lambda(T)$ can have an equidistant shift of different sign, demarcating a "corridor" of thermal conductivity values. By estimating the errors of the particular method of adjusting and checking the position of the thermocouples it is easy to establish the limits of deviation of $\lambda(T)$ determined by the proposed method.

The developed program has been checked over two years in the processing of unsteady temperature fields obtained on radiation and gasdynamic apparatuses. Some results of the investigations are given in Fig. 3. Constant values of ρ_c were used in the calculations.

Relationship 1 was calculated for a fiber glass-reinforced plastic with a phenolformaldehyde binder. The thermal conductivity of the material, as for all amorphous substances, increased up to the temperature at which the binder began to decompose. At 250-300°C, however, the process slowed down, and the thermal conductivity then began to decrease. The reason for this is the increase in porosity of the material due to decomposition of the binder. A further increase in temperature again led to a further, and very substantial, increase in the thermal conductivity. This can be attributed to the increase in thermal conductivity of the framework of the material and to the ever-increasing radiative heat transfer in the pores.

Relationship 2 was obtained for a fiber glass-reinforced plastic with an alumophosphate binder. Curve 2, which is otherwise similar to curve 1, shows an increase in thermal conductivity of the fiber glass-reinforced plastic with the alumophosphate binder in the interval 250-600°C, which can be attributed to the exothermic effect accompanying heating. Relationships 3 and 4 were calculated for fiber glass-reinforced plastics based on epoxy resin and silicon rubber, respectively. In the interval 0-200°C the thermal conductivity of the epoxy-resin material increases, while that of the rubber material decreases. Further increase in temperature leads to an equal reduction of the thermal conductivity of both materials due to the almost complete decomposition of the binder. For comparison Fig. 3 shows the thermal conductivity of the initial quartz cloth measured at normal temperature. The rapid increase in thermal conductivity at temperatures above 700°C is due not only to radiative heat transfer, but also to an appreciable increase in the density of the material due to deposition of pyrolytic carbon in its pores and channels.

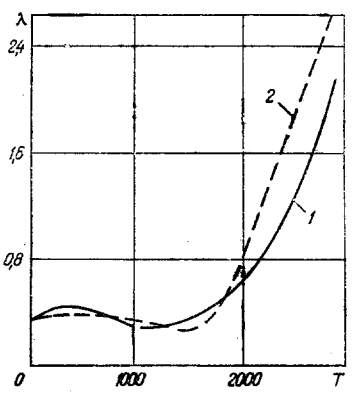

Fig. 2

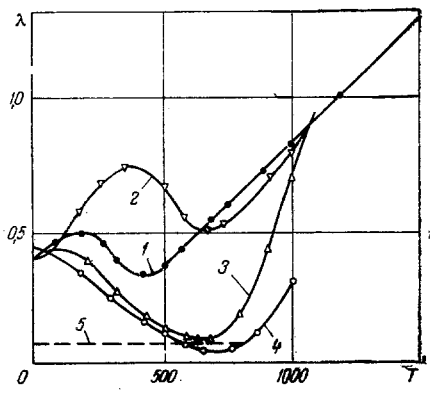

Fig. 3

Fig. 2. 1) Actual λ(T) relationship; 2) relationship reconstructed from temperature field shown in Fig. 1. ΔT is the temperature interval; T is in °C; λ is in W/m·°K.

Fig. 3. Temperature dependence of thermal conductivity of fiber glass-reinforced plastics: 1) with phenol-formaldehyde binder; 2) with alumophosphate binder; 3) with epoxy binder; 4) with rubber binder; 5) glass cloth without binder. T is in °C; λ is in W/m·°K.

The decomposition of most fiber glass-reinforced plastics is accompanied by the release of a small amount of gaseous products and, hence, in the processing of the experimental data we used a program containing the solution of the ordinary Fourier heat conduction equation. The application of a complex method which takes into account mass transfer in the substance and chemical reactions of different kind would not present any difficulty. There is no need for this, however, since the advantage of this method of determination of the thermophysical properties over classical methods (steady, monotonic heating, etc.) lies in the fact that it uses the same physicomathematical model of unsteady heating as the direct problem. In other words, the accuracy of determination is equal to the accuracy of calculation of the temperature field (depth of heating).

NOTATION

λ, thermal conductivity; c, specific heat; ρ, density; T, temperature in °C; τ, time. Subscripts: 0 refers to the initial value; i refers to the number of point; opt refers to the optimum value.

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