DETERMINATION OF THE THERMOPHYSICAL CHARACTERISTICS OF MATERIALS BY L. A. SEMENOV'S METHOD

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The first and fifth variations proposed by L. A. Somenov are discussed, for determining the thermophysical characteristics of materials under quasi steady-state conditions. An improved calculation procedure by these alternatives is proposed and data are presented which have been obtained from tests using this procedure.

During tests of materials by Prof. L. A. Semenov's method, the possibility arose for introducing additions to the proposed procedure for determining the thermophysical coefficients which will permit simplification in carrying out the experiments and calculations.

The experimental equipment (Fig. 1) comprises a thermostat into which four plate samples with thickness R are stacked one on the other. The two central plates with fixed proximity are considered as an "unbounded wafer" with thickness 2R heated from two sides by a thermal flux of uniform density and for constant time, which is generated by plane electrical heating elements positioned between the edges of the samples. The gap formed between the central plates has no effect on the conduct of the experiment, as the thermal flux at the center of the unbounded wafer is zero for the stated conditions. The edges of the plates are thermally insulated at the outer face, which permits any nonuniformity of distribution of the thermal flow between the samples to be almost completely eliminated. By arranging thermocouples at specified points the nature of the change of temperature with time at these points is determined by a galvanometer during the experiment. Before starting the experiment, the samples are thermostated with the positioned heaters and thermocouples.

A most detailed description of the experimental apparatus and the proposed methods of testing (five variations) is given in [1] by L. A. Semenov. We shall concern ourselves here with two of the most interesting variations (the first and fifth).

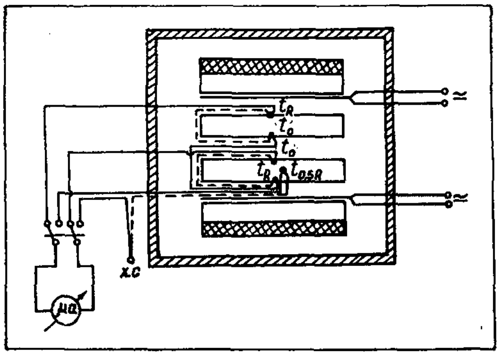

Fig. 1. Diagram of equipment for carrying out investigations by L. A. Semenov's method.

First Variation. During the experiment to determine the thermophysical characteristics, it is necessary to use two thermocouples: one to determine the value of the temperature difference Δt at the surface and in the center of the sample under test when quasisteady-state conditions are researched and which is then substituted in the formula for determining the coefficient of thermal conductivity λ; the other to measure the linear change of temperature at a chosen point of the plate, which makes it possible to determine the rate of rise of temperature t' from which the specific heat C is found.

However, to obtain the value of the specific heat C and the temperature conductivity coefficient a, it is possible to use only the first thermocouple for determining λ.

With double-sided heating of the plate, the temperature difference at stated points at any instant will be determined by the expression

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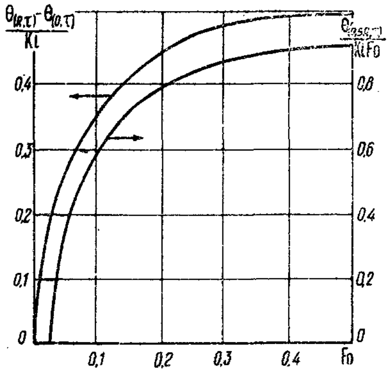

Fig. 2

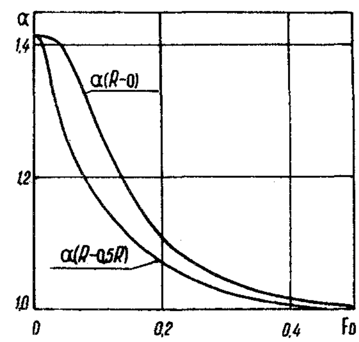

Fig. 3

Fig. 2. Graph of the dependence of $\theta_{(R,\ \tau)}-\theta_{(0,\ \tau)}/\mathrm{Ki}$ and $\theta_{(0.5R,\ \tau)}/\mathrm{KiFo}$ on Fo.

Fig. 3. Dependence of the ratio of the temperature differences $\alpha(R-0)$ and $\alpha(R-0.5R)$ on the Fo number for k = 2.0.

$$\frac{\theta_{(R,\tau)}-\theta_{(0,\tau)}}{\mathrm{Ki}}=0,5-\sum_{n=1,3,5,\ldots}^{\infty}\frac{4}{\mu_n^2}\exp(-\mu_n^2\,\mathrm{Fo}), \tag{1}$$

where

$$\mu_n=n\pi.$$

It is obvious that the quantity $\theta_{(R,\ \tau)}-\theta_{(0,\ \tau)}/\mathrm{Ki}$ depends only on Fo (Fig. 2) from the other side.

$$\frac{\theta_{(R,\tau)}-\theta_{(0,\tau)}}{\mathrm{Ki}}=\frac{\Delta t_\tau\lambda}{qR}. \tag{2}$$

By making the corresponding substitutions of the temperature difference Δt_τ over defined intervals of time $\Delta\tau$, we determine λ [1] by the final value of Δt and by the known value of λ, having chosen an arbitrary value of Δt_τ (near the start of the experiment) and by formula (2) we find the quantity $\theta_{(R,\ \tau)}-\theta_{(0,\ \tau)}/\mathrm{Ki}$ for a given instant τ. We obtain the value of Fo from the graph (Fig. 2) corresponding to this same time, after which the temperature conductivity coefficient is given by the expression

$$a=\frac{\mathrm{Fo}\,R^2}{\tau}, \tag{3}$$

and the specific heat by the formula

$$C=\frac{\lambda}{a\gamma}. \tag{4}$$

Thus, the additional thermocouple is not necessary and hence the time of the experiment is shortened and, as the experiment shows, the accuracy of the result obtained is almost unchanged.

The second possibility of finding the thermophysical characteristics using only the second thermocouple (with the cold junction at constant temperature) is also of interest for this variation. As is well-known, the specific heat C is determined from the data of this thermocouple.

In finding C, we consider the possibility of determining λ and a by setting the hot junction of the thermocouple at the point $x/R = 0.5$. The change of temperature at the point $x/R = 0.5$ is subject to the law

$$\frac{\theta_{(0,5R,\tau)}}{\mathrm{Ki}}=\mathrm{Fo}-\frac{1}{24}-\sum_{n=2,4,6,\ldots}^{\infty}(-1)^{\frac{n}{2}}\frac{2}{\mu_n^2}\exp(-\mu_n^2\,\mathrm{Fo}). \tag{5}$$

We divide both parts of expression (5) by Fo

$$\frac{\theta_{(0,5R,\tau)}}{\mathrm{Ki\,Fo}}=\frac{1}{\mathrm{Fo}}\left[\mathrm{Fo}-\frac{1}{24}-\sum_{n=2,4,6,\ldots}^{\infty}(-1)^{\frac{n}{2}}\frac{2}{\mu_n^2}\exp(-\mu_n^2\,\mathrm{Fo})\right] \tag{6}$$

TABLE 1. Comparative Results of Determining the Thermophysical Characteristics of Gypsum

Method of investigation		Thermophysical characteristics: λ, $\frac{\text{kcal}}{\text{m·h·deg}}$	c, $\frac{\text{kcal}}{\text{kg·deg}}$	$a\cdot 10^3$, $\frac{\text{m}^2}{\text{h}}$
First variation	Method proposed by L. A. Semenov	0,360	0,275	0,119
	Use of a differential thermocouple	0,362	0,274	0,120
	Use of thermocouple with constant temperature of cold junction	0,358	0,270	0,120
Fifth variation	Method proposed by L. A. Semenov	0,362	0,273	0,120
	Use of generalized numerical procedure	0,362	0,273	0,120

and we expand the left hand part

$$\frac{\theta_{(0,5R,\tau)}}{\text{Ki Fo}} = \frac{[t_{(0,5R,\tau)} - t_0]\, RC\gamma}{q\tau} \quad (7)$$

Obviously, by taking any value of $t_{(0.5R,\ \tau)} - t_0$ from the experiment corresponding to the instant τ, we can determine expression (7) which, on the basis of Eq. (6) is a function only of Fo.

From the graph (Fig. 2) showing the function $\theta_{(0.5R,\ \tau)}/\text{KiFo} = f(\text{Fo})$, we find the value of Fo corresponding to the time τ and then we determine a by formula (3). The coefficient of thermal conductivity λ is

$$\lambda = aC\gamma. \quad (8)$$

Fifth Alternative. In the proposed form, this alternative has many drawbacks: first of all, a formula is used in it which simplifies the calculations only at small values of Fo; secondly, the numerical part is too complicated for determining the ratios of the temperature difference at two points during a finite instant of time and thirdly, in order to determine the required characteristics for each experiment it is necessary to construct a graph of the functions $\Delta t_1 = f(\tau_1)$ and $\Delta t_2 = f(k\tau_1)$, which considerably complicates the calculations and gives an extremely cumbersome method.

The solution of this problem can be simplified considerably.

In order to determine the temperature differences Δt_1 and Δt_2 at the instants τ_1 and $k\tau_1$, we can write on the basis of Eq. (1) and (2)

$$\alpha = \frac{\theta_{(R,k\tau_1)} - \theta_{(0,k\tau_1)}}{\theta_{(R,\tau_1)} - \theta_{(0,\tau_1)}} = \frac{t_{(R,k\tau_1)} - t_{(0,k\tau_1)}}{t_{(R,\tau_1)} - t_{(0,\tau_1)}} = \psi(\text{Fo}_1). \quad (9)$$

Figure 3 gives the graph of this function for cases of measurement of temperature differences $t_{(R,\ \tau)} - t_{(0,\ \tau)}$ and $t_{(R,\ \tau)} - t_{(0.5,\ \tau)}$ when $k = 2.0$. It can be seen from what has been said above that, using the readings of only one thermocouple giving the temperature difference at the stated points, the value of Fo_1 can be found easily and then, from expression (3) we can find a; knowing Fo_1 we determine the quantity $\theta_{(R,\ \tau_1)} - \theta_{(0,\ \tau_1)}/\text{Ki}$ from the graph (Fig. 2), from which we obtain λ, and we obtain C from formula (4).

In order to obtain greater accuracy of the results, the functions plotted in Fig. 2 and 3 are tabulated and this facilitates the work considerably.

Using this method, experiments which showed the excellent results were carried out in the structural physics laboratory of the Rostov-on-Don Engineering-Construction Institute. Gypsum samples with dimensions 250 × 250 × 40 mm were tested; this dimensional ratio permits samples with thickness 2R to be accepted for the unbounded plate, as no disturbance of the one-dimensionality of the temperature field is observed throughout the entire experiment. This situation is substantiated theoretically and experimentally [1, 2].

Table 1 shows the comparative results of determining the thermophysical characteristics of gypsum, tested by different methods. It can be seen from the table that all the results obtained are in good agreement; in the fifth variation there is no deviation on the whole, as a numerical procedure is not involved, and these same data are processed in generalized form.

NOTATION

$\theta(x, \tau)$	is the relative temperature at point x at the instant τ;
Ki	is the Kirpichev's criterion;
Fo	is the Fourier number;
n	is the number of terms of series;
q	is the specific thermal flux, $kcal/m^2 \cdot h$;
R	is the half-thickness of plate, m;
γ	is the volume weight of material, kg/m^2.

LITERATURE CITED

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2. N. N. Volkovskii, in the collection: Proceedings of the Rostov-on-Don Institute of Engineering-Construction, [in Russian], No. 9, Izd. RISI, Rostov-on-Don (1957).