ADVANTAGES OF THE DILATOMETER INVESTIGATION OF THE HEAT-TRANSFER COEFFICIENT OF A DIELECTRIC LAYER

V. S. Batalov

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A dilatometer method for the comparative determination of the heat-transfer coefficient of dielectrics which is fast, accurate, and simple is described.

When using rapid dilatometry to determine such important thermal characteristics as the heat-transfer coefficient k of a dielectric layer, the method not only possesses high accuracy, simplicity of the apparatus design, and the possibility of recording the kinetic characteristics of the thermal expansion of the objects being investigated in arbitrary scale units [1, 3], but also, which is no less important, the complete absence of the need to measure the temperature or the thermal fluxes in these specimens [4] and, to an equal extent, of the layer thickness h (on which, like the thermal conductivity of the material of the layer λ, depends the quantity $k = \lambda_1/h$ [5]). This fact is particularly convenient when studying free-flowing and paste-like materials.

One of the fundamental theoretical assumptions which makes dilatometry attractive for the "nontemperature" determination of the coefficient k of a dielectric layer is the behavior of the comparative thermal expansion of two semiinfinite prismatic bodies with a common initial constant temperature T_1. Heating (or cooling) of the specimens occurs due to sudden simultaneous contact of their fixed bases with a heat carrier (a coolant) at a fixed temperature T_2 for a heat-exchange factor which is the same for both ends, ensuring uniform heat transfer in both specimens, the side surface of which is heat insulated, and one is justified using the laws of heat transfer in a uniform infinite half-space.

It is easy to see that the same behavior also holds for bodies in the initial stage of the propagation of a thermal disturbance in objects of finite size when the opposite heated end has an initial temperature T_1 [6]. The velocity of motion of this end W is proportional to the thermal expansion coefficient β, its thermal diffusivity a, and the gradient $(\partial T/\partial x)(0, t)$ at the heated end [6];

$$W = a\beta \frac{\partial T}{\partial x}(0, t). \tag{1}$$

The temperature gradient at the fixed end $(\partial T/\partial x)$ (0, t) immediately after contact with the thermal carrier flow depends on the parameters a, λ, and α [7]:

$$\frac{\partial T}{\partial x}(0, t) = \frac{\alpha}{\lambda}(T_2 - T_1)\exp\left(\frac{\alpha^2}{\lambda^2}at\right)\left[1 - \varphi\left(\frac{\alpha}{\lambda}\sqrt{at}\right)\right], \tag{2}$$

where $\varphi(z)$ immediately after contact with the thermal carrier flow depends on the parameters $z = (\alpha/\lambda)\sqrt{at}$.

It is easy to show that the rate of expansion W_0 when $t = 0$ (at the initial instants of the process) is independent of the time t:

$$W_0 = \alpha\beta(T_2 - T_1)\frac{a}{\lambda}. \tag{3}$$

If one of the specimens (the characteristics of which are exactly the same as the characteristics of a standard cylinder) is placed in the same part of the channel for the flow of heat carrier, but the heated end of which is separated from the heat carrier by the plane-parallel layer being investigated, the rate of expansion

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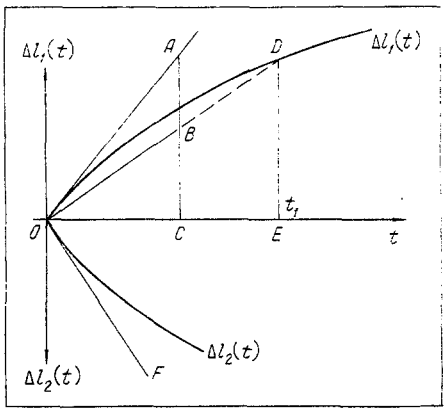

Fig. 1. Schematic graphic calculation of the initial velocities of thermal expansion of the standard specimen and the specimen being investigated; $\Delta l_2(t)$ and $\Delta l_1(t)$ are the kinetic thermal deformation curves of the standard specimen in the presence of the dielectric layer being investigated and when there is no dielectric layer; t_1 is the instant when the standard specimen reaches an expansion Δl_1; $W_0 = \tan \angle AOC$; $W_1 = \tan \angle FOC$; $\Delta l_1 = DE$; $(BC/AC) = 0.57$.

of this cylinder at the initial instants of the process W_1 will differ analytically from Eq. (3) by a factor which contains, instead of the coefficient α, a certain effective parameter α_1:

$$W_1 = \alpha_1 \beta (T_2 - T_1) \frac{a}{\lambda}. \tag{4}$$

The value of the effective heat-transfer coefficient α_1 is determined, following the well-known rule for the addition of thermal resistances [5], in terms of the required characteristic of the layer k and the heat-transfer coefficient α:

$$\frac{1}{\alpha_1} = \frac{1}{k} + \frac{1}{\alpha}. \tag{5}$$

Substituting the value of α_1 from Eq. (5) into Eq. (4) and dividing the equation obtained by Eq. (3), we have

$$\frac{W_1}{W_0} = \frac{k}{\alpha + k}. \tag{6}$$

It will be convenient henceforth to eliminate the heat-transfer coefficient α. To do this we express the velocity (1) in terms of the gradient (2) and integrate it with respect to time over the expansion Δl (t):

$$\Delta l(t) = \beta (T_2 - T_1) \frac{\lambda}{\alpha} \left[\exp\left(\frac{\alpha^2}{\lambda^2} at\right) \left\{1 - \varphi\left(\frac{\alpha}{\lambda} \sqrt{at}\right)\right\} - 1 + \frac{2}{\sqrt{\pi}} \frac{\alpha}{\lambda} \sqrt{at} \right]. \tag{7}$$

It is easy to show by direct substitution that the expression in square brackets of Eq. (7) for a value of the argument z_1 given by

$$z_1 = \frac{\alpha}{\lambda} \sqrt{at_1} = 1 \tag{8}$$

has a value of 0.57, and then, taking into account property (3), the expansion of the standard specimen Δl_1 from the time when the process starts up to the instant t_1, calculated from Eq. (8), reaches the values

$$\Delta l_1 = \Delta l(t_1) = 0.57 W_0 \frac{\lambda^2}{a\alpha^2}. \tag{9}$$

Multiplying the numerator and denominator of the fraction in Eq. (9) by the time factor t_1 and bearing in mind Eq. (8), we obtain

$$\Delta l_1 = 0.57 W_0 t_1. \tag{10}$$

By solving Eq. (10) graphically it is easy to find the point t_1 at which the expansion Δl_1 satisfies condition (10). However, in practice, finding the instant t_1 is considerably simplified by the obvious fact that the ratio $\Delta l_1/t_1$ is nothing more than the slope of the section of line which connects the origin of coordinates and the experimental curve of the expansion Δl (t) of the standard cylinder without the layer being investigated (see Fig. 1). Consequently, if by definition the velocity W_0 is the slope of the curve Δl (t) at the origin of coordinates (see the figure), then, by choosing, using condition (10), the point B on the section AC such that the length

of BC is 57% of the value of AC, it is extremely simple to find the required value of the expansion Δl_1 (and the point t_1) by connecting the point B to the origin of coordinates and then extending the section OB until it intersects the curve $\Delta l(t)$ at the point D.

The value of t_1 obtained in this way and a number of elementary calculations, related to changing from the heat-transfer parameters λ and a to the coefficient $g = \lambda/\sqrt{a}$ [5], enable us to express the parameter in Eq. (8) in terms of the well-known quantities g and t_1:

$$\alpha = \frac{g}{\sqrt{t_1}}. \tag{11}$$

From Eqs. (6) and (11) we obtain an equation for calculating the heat-transfer coefficient k of the plane-parallel layer in question:

$$k = g\frac{W_1}{\sqrt{t_1}(W_0 - W_1)}. \tag{12}$$

The fairly small error in recording the time section t_1, not exceeding 0.2%, and also the high accuracy of the data on the parameter g (up to 0.5% in the handbook literature) for a small relative error in measuring the characteristics W_1 and W_0 (not greater than 1.5% each) ensure good accuracy of the method, reaching 2-3%.

The possibility of reducing the length of the section t_1 [by increasing the parameter α in Eq. (11)] ensures that the thermal action on the material will be of short duration, which is particularly convenient when studying heat-labile materials (which lose their chemical stability when the temperature is raised).

The "nontemperature" measurement by the dilatometer express method described above for determining the heat-transfer coefficient of dielectric materials was checked using glycerin in the temperature range 90-100°C on the apparatus described previously [8]. The medium being investigated filled an end disk cavity in a cylinder of stainless steel (the disk cavity of thickness 1 mm was coaxial with the cylinder).

The thermal expansion of the cylinder with the glycerin was compared with the kinetic features of the thermal deformation of a continuous cylinder made of the same brand of stainless steel.

The value of the heat-transfer coefficient of the plane-parallel layer of glycerin of thickness 1 mm was $6.4 \cdot 10^{-3}$ cal/cm^2·sec·deg, which is in good agreement with existing data [9].

NOTATION

a, thermal diffusivity; λ, thermal conductivity; α, outer heat-transfer coefficient; t, time; k, inner heat-transfer coefficient; β, thermal expansion coefficient; V, volume; T, temperature.

LITERATURE CITED

1. V. S. Batalov, Teplofiz. Vys. Temp., 8, No. 5 (1970).
2. V. S. Batalov, Inzh.-Fiz. Zh., 17, No. 1 (1969).
3. V. S. Batalov and Yu. S. Grigor'ev, Zavod. Lab., 41, No. 1 (1975).
4. V. S. Batalov, L. N. Linnik, and S. P. Oshkaderov, Inventor's Certificate No. 381010; Byul. Izobr., No. 21 (1973).
5. P. Schneider, Practical Problems of Heat Conduction [Russian translation], IL, Moscow (1960).
6. V. S. Batalov and V. É. Peletskii, Teplofiz. Vys. Temp., 6, No. 5 (1968).
7. V. S. Batalov and L. N. Linnik, Teplofiz. Vys. Temp., 8, No. 4 (1970).
8. V. S. Batalov, L. N. Linnik, and K. I. Lobachev, in: Heat Conduction and Diffusion [in Russian], Rizhsk. Politekh. Inst., Riga (1969), p. 26.
9. B. P. Nikol'skii (editor), Chemical Handbook [in Russian], 3rd ed., Khimiya, Leningrad (1971), p. 757.