COMBINED DETERMINATION OF THE THERMOPHYSICAL PROPERTIES OF VAPORIZED MATERIALS

S. I. Mantulenko and V. V. Kharitonov

Inzhenerno-Fizicheskii Zhurnal, Vol. 14, No. 5, pp. 873–876, 1968

UDC 536.22.083

A nonsteady method is proposed for determining the thermophysical characteristics of poor heat conductors in the form of thin-film vaporized coatings. The heat conduction problem is solved for a system consisting of a bounded and a semibounded rod with a plane heat source of constant power using a thin-film coating with known characteristics as standard.

Steady-state methods [3, 4] of determining the thermophysical characteristics of vaporized thin-film coatings are not very suitable owing to the length of the experiment and the impossibility of a combined determination of all the thermophysical characteristics in the course of single experiment over the entire range of interest.

Most suitable for the investigation of vaporized coatings are the nonsteady methods described in [5, 6]. However, the method described in [5] makes it possible to determine only the thermal conductivity of the material from a single experiment, requires a knowledge of the specific heat of the standard and, what is very important in investigating vaporized materials, necessitates the double deposition of the same material (on two sides of the standard). The method described in [6] makes it possible to determine the thermophysical characteristics in combination, but requires a knowledge of the thermal activity of the semibounded rods and likewise double deposition (on two rods).

Both methods require that the thicknesses of the coatings be strictly equal.

These disadvantages prompted us to develop a new method.

Consider a system (see the figure) consisting of two semibounded rods 2 and 4 with thermophysical characteristics a_2, λ_2, c_2 and two bounded rods 1 and 3 with thermophysical characteristics a_1, λ_1, c_1 and a_3, λ_3, c_3, respectively. The characteristics of body 3 are assumed known.

Starting from a certain time $\tau = 0$, a source of constant power q acts at the section a-a.

The mathematical formulation of the problem for bodies 1 and 2 has the form [1, 2]

$$\frac{\partial t_1(x,\tau)}{\partial \tau} = a_1 \frac{\partial^2 t_1(x,\tau)}{\partial x^2}, \quad 0 \leqslant x \leqslant R_1,$$
$$\frac{\partial t_2(x,\tau)}{\partial \tau} = a_2 \frac{\partial^2 t_2(x,\tau)}{\partial x^2}, \quad R_1 \leqslant x < \infty. \tag{1}$$

An analogous system of equations can also be written for bodies 3 and 4. Then, in accordance with [6], we obtain the solutions for x = R_1 and x = R_3 in the form

$$\Delta t_2 = t_2(R_1,\tau) - t_0 = \frac{2q_1\sqrt{a_1}}{\lambda_1}\sqrt{\tau}(1-m_1)\,\mathrm{ierfc}\,\frac{R_1}{2\sqrt{a_1\tau}}, \tag{2}$$

$$\Delta t_4 = t_4(R_3,\tau) - t_0 = \frac{2q_3\sqrt{a_3}}{\lambda_3}\sqrt{\tau}(1-m_3)\,\mathrm{ierfc}\,\frac{R_3}{2\sqrt{a_3\tau}}. \tag{3}$$

Taking two multiple moments of time τ' and τ'' such that

$$\sqrt{\frac{\tau''}{\tau'}} = \alpha = \mathrm{const},$$

we obtain

$$\frac{\Delta t_2''}{\Delta t_1'} = \beta_2 = \alpha\,\frac{\mathrm{ierfc}(\alpha^{-1}K_1)}{\mathrm{ierfc}\,K_1}, \tag{4}$$

$$\frac{\Delta t_4''}{\Delta t_4'} = \beta_4 = \alpha\,\frac{\mathrm{ierfc}(\alpha^{-1}K_3)}{\mathrm{ierfc}\,K_3}, \tag{5}$$

where

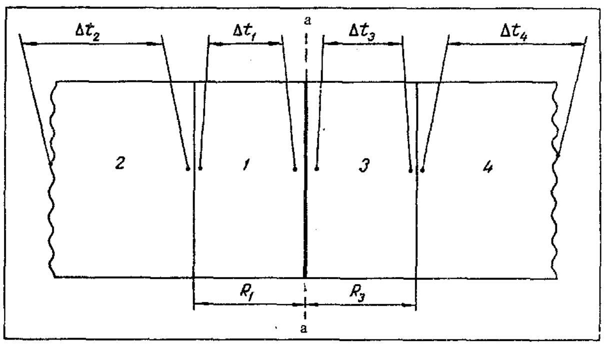
$$K_1 = \frac{R_1}{2\sqrt{a_1\tau'}} \text{ and } K_3 = \frac{R_3}{2\sqrt{a_3\tau'}}.$$

Having determined β and α experimentally from the graphs $\beta = f(K, \alpha)$ [6], we determine K_1 and K_3. (The possibility of determining K_3 by calculation gives a check on the accuracy of the experiment.)

From the equation

$$a_1 = \frac{R_1^2}{4K_1^2\tau'}$$

we determine the thermal diffusivity.



Calculation scheme.

From (2),

$$\lambda_1 = \frac{R_1}{2K_1\sqrt{\tau'}}\left(\frac{4q_1\sqrt{\tau'}\,\text{ierfc}\,K_1}{\Delta t_2^1} - \frac{\lambda_2}{\sqrt{a_2}}\right). \quad (6)$$

From (3),

$$\lambda_3 = \frac{R_3}{2K_3\sqrt{\tau'}}\left(\frac{4q_3\sqrt{\tau'}\,\text{ierfc}\,K_3}{\Delta t_4'} - \frac{\lambda_2}{\sqrt{a_2}}\right). \quad (7)$$

Solving (6) and (7) jointly, we obtain

$$\lambda_1 = \frac{2R_1 q}{K_1\Delta t_2'}\left(\frac{q_1}{q}\,\text{ierfc}\,K_1 - \frac{\Delta t_2'}{\Delta t_4'}\frac{q_3}{q}\,\text{ierfc}\,K_3 + \frac{\lambda_3 K_3\Delta t_2'}{2R_3 q}\right),$$

where $q = q_1 + q_3$ is the power of the plane source.

We can obtain the distribution of heat flux between bodies 1 and 3, if we assume that $\lambda = Rq/\Delta t$ (in accordance with [6]); then,

$$q_1 = \frac{\lambda_1}{R_1}\Delta t_1 \quad (9)$$

and

$$q_3 = \frac{\lambda_3}{R_2}\Delta t_3. \quad (10)$$

Substituting the values of q_1 and q_3 into (8) and solving it for λ_1, we obtain

$$\lambda_1 = \lambda_3\frac{R_1}{R_3}\frac{K_3}{K_1}\frac{1-2\dfrac{\Delta t_3}{\Delta t_4}\dfrac{\text{ierfc}\,K_3}{K_3}}{1-2\dfrac{\Delta t_1}{\Delta t_2}\dfrac{\text{ierfc}\,K_1}{K_1}}. \quad (11)$$

If the material of the standard coating is sufficiently close in its properties to the investigated coatings ($m_1 \approx m_3$), then, taking the ratio of the temperature drops at bodies 2 and 4 at the same moment of time, we obtain

$$\frac{\Delta t_2'}{\Delta t_4'} = \frac{\dfrac{R_1 q_1}{\lambda_1 K_1}\,\text{ierfc}\,K_1}{\dfrac{R_3 q_3}{\lambda_3 K_3}\,\text{ierfc}\,K_3}, \quad (12)$$

whence

$$\frac{\text{ierfc}\,K_1}{K_1} = \frac{\text{ierfc}\,K_3}{K_3}\frac{\Delta t_2'}{\Delta t_4'}\frac{\Delta t_3'}{\Delta t_1'} = \beta'. \quad (13)$$

Having obtained the value of β' experimentally, from the previously calculated dependence $\beta' = f(K_1)$, we find the value of K_1 and then a_1.

When the drop at the semibounded rods 2 and 4 is sufficiently small, solution (8) or (13) is inadmissible. In this case, we use the solution of the starting system of equations (1) for the temperature at the point $x = 0$

$$t_1(0, \tau) - t_0 =$$

$$= \frac{2q_1\sqrt{a_1}}{\lambda_1}\sqrt{\tau'}\left(\frac{1}{\sqrt{\pi}} - 2m_1\,\text{ierfc}\,\frac{R_1}{\sqrt{a_1\tau'}}\right). \quad (14)$$

Then the drop at the investigated coating

$$\Delta t_1 = [t_1(0, \tau) - t_0] - [t_2(R_1, \tau) - t_0] =$$

$$= \frac{2q_1\sqrt{a_1}}{\lambda_1}\sqrt{\tau'}\times$$

$$\times\left[\frac{1}{\sqrt{\pi}} - 2m_1\,\text{ierfc}\,\frac{R_1}{\sqrt{a_1\tau'}} - (1-m_1)\,\text{ierfc}\,\frac{R_1}{2\sqrt{a_1\tau'}}\right]. \quad (15)$$

Taking the ratio of the temperature drops at multiple time intervals and denoting it by β'', we obtain

$$\beta'' = \frac{\Delta t_1''}{\Delta t_1'} =$$

$$= \left[\frac{1}{\sqrt{\pi}} - 2m_1\,\text{ierfc}\,(2\alpha^{-1}K_1) - (1-m_1)\,\text{ierfc}\,(\alpha^{-1}K_1)\times\alpha\right]\times$$

$$\times\left[\frac{1}{\sqrt{\pi}} - 2m_1\,\text{ierfc}\,(2K_1) - (1-m_1)\,\text{ierfc}\,K_1\right]^{-1} \quad (16)$$

Since we assume that $m \ll 1$, and $\text{ierfc}\,2x \ll \text{ierfc}\,x$,

$$\beta'' \approx \alpha\,\frac{\dfrac{1}{\sqrt{\pi}} - \text{ierfc}\,(\alpha^{-1}K_1)}{\dfrac{1}{\sqrt{\pi}} - \text{ierfc}\,K_1}. \quad (17)$$

The latter expression can be tabulated and graphs of β'' versus K_1 can be plotted for various α = const. Then, having obtained the value of β'' and α experimentally, we find K_1 and then the thermal diffusivity a_1. The value of the coefficient λ_1 is determined from the solution of system (9) and (10). As a result we obtain

$$\lambda_1 = \frac{R_1}{\Delta t_1}\left(q - \frac{\lambda_3}{R_3}\Delta t_3\right). \quad (18)$$

NOTATION

λ is the thermal conductivity, W/m·deg; a is the thermal diffusivity, m^2/sec; q is the specific heat flux, W/m^2; τ is the time, sec; R is the thickness of the coating, m; t is temperature, deg; Δt is the temperature drop, deg.

REFERENCES

1. A. V. Luikov, Theory of Heat Conduction [in Russian], GITTL, Moscow, 1952.
2. A. V. Luikov, Theoretical Basis of Structural Thermophysics [in Russian], Izd. AN BSSR, Minsk, 1961.
3. V. H. Gray and T. F. Gelder, Advances in Cryogenic Engineering, 5, N. Y., 1960.
4. G. Wilkes, Refrig. Eng., 52, July, 1946.
5. T. Gast, K. H. Hellwege, and E. Hohlhepp, Kolloid Zeitschrift, 1, 152, 1957.
6. A. B. Verzhinskaya, Candidate's dissertation, AN BSSR, Minsk, 1964.

14 July 1967

Institute of Heat and Mass Transfer AS BSSR, Minsk