NOTATION

T_s is the equilibrium boiling temperature;
λ is the conductivity;
ε is the thermal activity coefficient;
ρc is the volumetric heat capacity.

LITERATURE CITED

1. N. V. Bulanev, É. D. Nikitin, and V. P. Skripov, Inzh.-Fiz. Zh., 26, No. 2 (1974).
2. B. I. Il'in, A. V. Gurskaya, V. F. Salokhin, and G. G. Spirin, Inzh.-Fiz. Zh., 29, No. 4 (1975).
3. J. K. Horrocks and E. McLaughlin, Proc. Roy. Soc. (London), A273, 259 (1963).
4. B. I. Il'in, A. V. Gurskaya, V. F. Salokhin, and G. G. Spirin, Vysokomolek. Soed., A17, No. 8 (1975).
5. N. B. Vargaftik, L. P. Filippov, A. A. Tarzimanov, and R. P. Yurchak, Thermal Conductivity of Gases and Liquids (Reference Data) [in Russian], Moscow (1970).
6. V. P. Skripov, Metastable Liquids [in Russian], Nauka, Moscow (1972).

MEASUREMENT OF THERMAL DIFFUSIVITY OF MASSIVE METALLIC SPECIMENS BY THE PULSE METHOD

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A pulse method for measuring the thermal diffusivity of semi-infinite specimens is described. Results of thermal-diffusivity measurements on iron and tin are presented.

The present authors have previously described a pulse method of measuring the thermal diffusivity of metals [1, 2] useful for specimens of hemispherical form. For thin plane-parallel plates the well-known method presented by Parker et al. [3-5] is usually used. However, in many cases creation of specimens with such geometry is difficult, and it is of great interest to consider the possibility of using the pulse method for measurement of the thermal diffusivity of specimens of the simplest form – a semi-infinite mass. Use of powerful point-laser sources permits a quite simple solution of this problem in principle.

The general solution of the thermal-conductivity differential equation

$$\frac{\partial T(x, y, z, \tau)}{\partial \tau} = a\nabla^2 T(x, y, z, \tau) \tag{1}$$

for $-\infty < x, y, < \infty$, $0 < z < \infty$, and $\tau > 0$ with initial

$$\tau_0 = 0, \quad T(x, y, z, \tau) = 0$$

and boundary

$$T(\infty, y, z, \tau) = T(x, \infty, z, \tau) = T(x, y, \infty, \tau) = 0,$$

$$\frac{\partial T(\pm\infty, y, z, \tau)}{\partial x} = \frac{\partial T(x, \pm\infty, z, \tau)}{\partial y} = \frac{\partial T(x, y, \infty, \tau)}{\partial z} = 0$$

conditions for an instantaneous heat source at a point (x_1, y_1, z_1) on the surface of a semi-infinite-mass specimen is given by the function [6, 7]

$$T(x, y, z, \tau; x_1, y_1, z_1) = \frac{q_0}{8(\pi a\tau)^{3/2} c_p \rho} \exp\left[-\frac{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2}{4a\tau}\right]. \tag{2}$$

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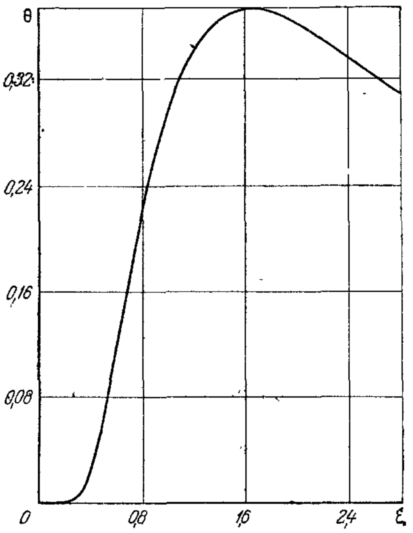

Fig. 1

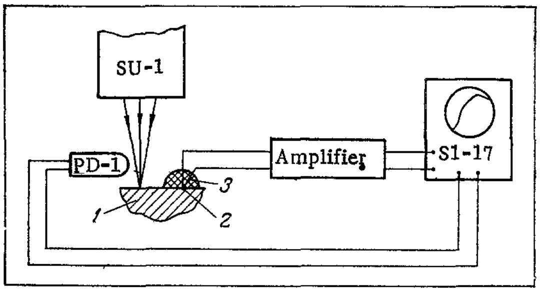

Fig. 2

Fig. 1. Dimensionless temperature θ versus dimensionless time ξ for an instantaneous source.

Fig. 2. Block diagram of apparatus: 1) specimen; 2) thermocouple; 3) Al_2O_3 thermal insulation layer; PD-1) photodiode with amplifier.

If the instantaneous heat source q_0 is located at the point with coordinates (0, 0, 0) and the initial moment $\tau_0 = 0$, then at a point with coordinates (x, 0, 0) at time τ Eq. (2) will have the form

$$T(x,\ \tau) = \frac{q_0}{8\,(\pi a\tau)^{3/2} c_p\rho} \exp\left(-\frac{x^2}{4a\tau}\right). \tag{3}$$

At a distance x from the source, Eq. (3) reaches a maximum at the time

$$\tau = x^2/6a, \tag{4}$$

while its maximum value is equal to

$$T(x)_{\max} = 0.147\,\frac{q_0}{c_p\rho x^3}. \tag{5}$$

Inasmuch as the maximum of this function is diffuse, it will be more convenient to reckon the time τ corresponding to attainment of one half of the maximum value $T(x)_{\max}/2 = T(x,\ \tau_{1/2})$. In this case, Eq. (3) transforms to the transcendental equation

$$\exp\omega = 4.88\omega^{3/2}, \tag{6}$$

where

$$\omega = x^2/4a\tau_{1/2}, \tag{7}$$

the solution of which on a Minsk-32 computer gives

$$a = 0.073x^2/\tau_{1/2}. \tag{8}$$

It is often more convenient to use a graphical solution of Eq. (3). Since we need to know the temperature distribution at a distance l from the instantaneous source along the surface, then for graphical solution of Eq. (3) in the dimensionless coordinates

$$\xi = \pi^2 a\tau/l^2, \quad \theta = 4c_p\rho l^3 T/\pi q_0$$

it is useful to expand Eq. (3) in a Fourier series over the interval from $-l$ to $+l$. Then for sufficiently large l in the integrals which appear, the integration limits can be taken as infinite. In this case we obtain the temperature distribution at the point l,

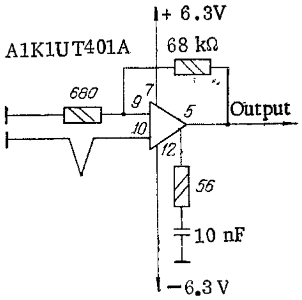

Fig. 3. Schematic diagram of the preamplifier.

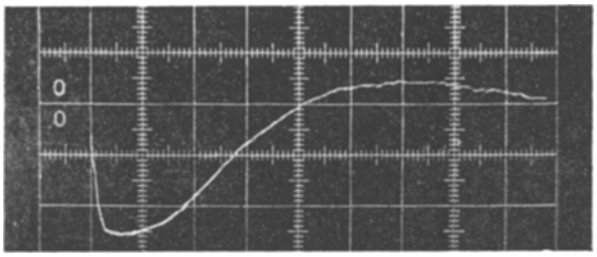

Fig. 4. Oscillogram of thermal-diffusivity measurement of tin: l = 3.050 mm; display, 10 msec/cm.

$$T(l,\ \tau)=\frac{q_0}{4c_p\rho\pi a\tau l}\left[1+2\sum_{n=1}^{n=\infty}\cos\pi n\exp\left(-\frac{\pi^2n^2a\tau}{l^2}\right)\right] \tag{9}$$

or in the dimensionless variables ξ and θ

$$\theta=\frac{1}{\xi}\left[1+2\sum_{n=1}^{n=\infty}(-1)^n\exp(-n^2\xi)\right]. \tag{10}$$

The graph of Eq. (10) established by solving Eq. (10) on a Minsk-32 computer is shown in Fig. 1. We note that use of Eq. (8) and Fig. 1 gives adequate results for a.

A block diagram of the apparatus realizing this method is depicted in Fig. 2. The light flux of the SU-1 laser with duration 10^{-3} sec and energy of 1 J is focused on a spot 0.1 mm in diameter on the surface of the mass specimen. The delay of the temperature signal is recorded by a thin copper–Constantan thermocouple (electrode diameter 50 μm) welded to the specimen surface by the laser beam. The thermocouple is insulated above by an Al_2O_3 layer ~2 mm thick. Because of the large difference in the thermal diffusivities of the insulator and metal, the effect of the former on the measured quantity can be neglected.

The signal from the thermocouple is amplified by a preamplifier with gain of ~100 (Fig. 3), with output fed to an S1-17 pulse oscilloscope, the delayed display of which is triggered by the reflected laser pulse from the photodiode PD-1. Figure 4 shows an example of an oscillogram obtained from the oscilloscope screen during study of the thermal diffusivity of tin at l = 3.05 mm at room temperature. The high resolving power obtained with a material with high thermal diffusivity is evident. For metals with lower a values, τ increases, which leads to increased accuracy in its determination. Table 1 presents results of thermal-diffusivity measurements on tin (0.001% impurities) and "Armco" iron (impurities: C, 0.015%; Si, 0.18%; Mn, 0.17%; S 0.025%; P, 0.006%). Comparison of the present data with the most reliable reference data available indicates that there is satisfactory agreement within the limits of experimental error.

Analysis of errors in the proposed method shows that at medium temperatures the major error sources are those connected with the inaccuracy in coordinate determination of ~2% (achieved by use of an MBS-3 microscope and manipulator which allowed distinguishing between the laser heating cavity and the point of thermocouple attachment) and the time error of ~2%.

At room temperature in the given case Bi ≈ 0.02 (see, for example, [3]) and the contribution to total error from heat transfer by radiation does not exceed 1%, although with increase in temperature it will be necessary to consider the effect of this error source individually.

TABLE 1. Measurements of Thermal Diffusivity a (m^2/sec) of Armco Iron and Tin

Material	Present study	[3]	[4]
Fe	$0{,}17\ (9)\cdot 10^{-4}$	$0{,}18\cdot 10^{-4}$	$0{,}19\cdot 10^{-4}$
Sn	$0{,}29\ (5)\cdot 10^{-4}$	$0{,}31\cdot 10^{-4}$	$0{,}39\cdot 10^{-4}$

Thus, the total error in determination of the thermal-diffusivity coefficient by the proposed method does not exceed 5-7%, which is comparable to the uncertainties of the methods usually employed for studied of specimens which are often difficult or practically impossible to prepare, for example, in the case of aggressive liquid metals.

NOTATION

T	is the temperature;
q_0	is the pulse energy, J;
c_p	is the specific heat, J/kg·°K;
ρ	is the density, kg/m^3;
a	is the thermal diffusivity, m^2/sec;
l	is the thermocouple coordinate;
τ	is the time;
$\tau_{1/2}$	is the time at which temperature signal at point l reaches one half its maximum value.

LITERATURE CITED

1. V. E. Zinov'ev, A. A. Baskakova, N. G. Korshunova, N. A. Baronikhina, and L. D. Zagrebin, Inzh.-Fiz. Zh., 25, No. 3 (1973).
2. A. A. Baskakova, V. E. Zinov'ev, and L. D. Zagrebin, Inzh.-Fiz. Zh., 26, No. 6 (1974).
3. L. P. Filippov, Measurement of Thermal Properties of Solid and Liquid Metals at High Temperatures [in Russian], Mosk. Gos. Univ., Moscow (1967).
4. W. J. Parker, R. J. Jenkins, C. P. Butler, and G. L. Abbott, J. Appl. Phys., 32, 9 (1961).
5. M. I. Aliev, R. É. Guseinov, and D. G. Arasly, Inzh.-Fiz. Zh., 22, No. 6 (1972).
6. A. V. Lykov, Theory of Heat Conduction [in Russian], Vysshaya Shkola, Moscow (1967).
7. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, 2nd ed., Oxford University Press (1959).

THERMISTOR EFFECT IN SWITCHING IN VANADIUM DIOXIDE

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The switching effect in vanadium dioxide is interpreted in terms of a critical temperature on the basis of the temperature dependence of the conductivity for semiconducting VO_2.

It has several times been suggested [1-3] that the temperature dependence of the switching current or voltage for vanadium dioxide is due to change in the mode of switching with the environmental temperature. It has been claimed [1] that the switching in VO_2 occurs on account of the thermistor effect in the range from 223 to 283°K, whereas a semiconductor–metal phase transition occurs at environmental temperatures above 283°K (following [1], we speak in what follows of the thermistor model and the transition model). However, these two models give qualitative agreement between theory and experiment only for certain ranges in the environmental temperature, while the temperature dependence of the switching current or voltage is not described by either of the models for the range 273-314°K.

We have measured the temperature dependence of the switching current and voltage for the range from 160 to 341°K for single-crystal vanadium dioxide; the results are explained via the transition model with a critical temperature on the basis of the temperature dependence of the conductivity of VO_2 in the semiconducting state. We have also measured the specific resistance of VO_2 as a function of temperature.

Curves 1 in parts a and b of Fig. 1 show the switching current and voltage as functions of environmental temperature for single-crystal VO_2; the transition model with a critical temperature has been used [1-3] on the assumption that the conductivity is constant in the metallic state and in the semiconductor state. However,

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