PULSE DETERMINATION OF THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY FOR HEMISPHERICAL SPECIMENS: NICKEL

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A method is described for determining the thermal diffusivity, specific heat, and thermal conductivity in a hemispherical volume on the basis of duration of the reference signal.

The pulse method of determining the thermophysical characteristics of materials has become widely used (mainly for plane-parallel specimens) [1, 2]. However, it is difficult to apply at high temperatures [3].

We have therefore developed [4-6] a method enabling one to perform measurements not only for plane-parallel specimens but also for specimens of any shape, which substantially extends the scope for the method. Here we describe one form of the method in which we incorporate factors related to the finite pulse length and also implement the facilities of the method in the joint measurement of the thermal diffisivity a, thermal conductivity λ, and specific heat c_p of specimens of hemispherical form. Hemispherical specimens are examined on the basis of the prospects for using the method not only for solid metals but also for liquid ones.

If heat transfer at the surface can be neglected (which is quite readily attained under experimental conditions [1]), then the following is [7] the expression for the temperature distribution due to an instantaneous hemispherical source of radius r' and energy q_0 acting in a hemisphere of radius R:

$$T(r,\ t)=\frac{q_0}{\rho c_p}\left[\frac{1}{\pi Rrr'}\sum_{n=1}^{n=\infty}\frac{\mu_n^2R^2+1}{\mu_n^2R^2}\sin\mu_n r\,\sin\mu_n r'\exp(-\mu_n^2at)+\frac{3}{2\pi R^3}\right]. \tag{1}$$

Certain transformations of (1) give us an expression for the temperature due to an instantaneous point source:

$$T(r,\ t)=\frac{q_0}{\rho c_p}\left[\frac{1}{\pi Rr}\sum_{n=1}^{n=\infty}\frac{\mu_n^2R^2+1}{\mu_nR^2}\sin\mu_n r\ \exp(-\mu_n^2at)+\frac{3}{2\pi R^3}\right]. \tag{2}$$

Integration of (2) gives a solution for the case where the heat source acts for some time τ_i.

We assume that the input heat flux is defined as a step function:

$$\varphi(\tau)=\begin{cases}0 & \tau<0,\\ 1 & \tau_i\geqslant\tau\geqslant 0,\\ 0 & \tau>\tau_i,\end{cases} \tag{3}$$

where τ_i is the pulse length, and then integrating (2) with respect to time we get

$$T(r,\ \tau)=\frac{q_0/\tau_i}{\rho c_p\pi Rr}\left\{\int_0^{\tau}\left[\sum_{n=1}^{n=\infty}\frac{\mu_n^2R^2+1}{\mu_nR^2}\sin\mu_n r\exp[-\mu_n^2a(\tau-t)]+\frac{3}{2\pi R^3}\right]\varphi(\tau)\,dt+\int_0^{\tau_i}\left[\sum_{n=1}^{n=\infty}\frac{\mu_n^2R^2+1}{\mu_nR^2}\times\right.\right.$$

$$\left.\left.\times\sin\mu_n r\exp[-\mu_n^2a(\tau-t)]+\frac{3}{2\pi R^3}\right]\varphi(\tau)\,dt\right\}=\frac{q_0/\tau_i}{\rho c_p\pi Ra}\times \tag{4}$$

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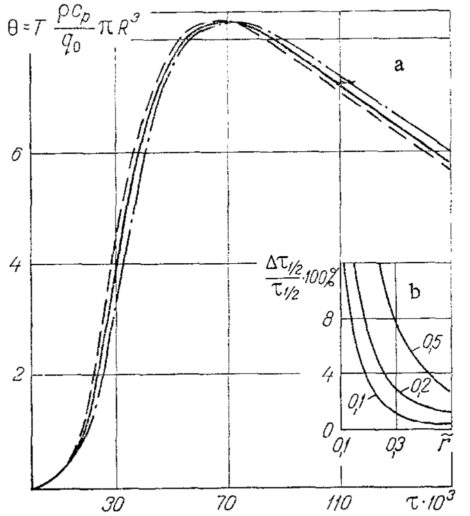

Fig. 1

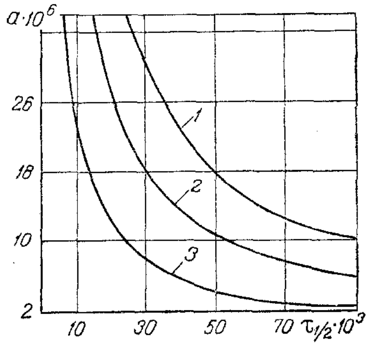

Fig. 2

Fig. 1. Excess temperature as a function of time (a) for a thermal pulse of finite length τ_i = 0.01 sec (dot-dash line), τ_i = 0.001 sec (solid line), and τ_i = 0 (broken line), together with the relative error in the delay in the temperature signal as a function of the dimensionless coordinate (b) for τ_i = 0.001 sec; a in cm^2/sec (the numbers on the curves are the thermal diffusivity).

Fig. 2. Delay in temperature signal in relation to thermal diffusivity: 1) r/R = 0.500; 2) 0.382; 3) 0.250. $a \cdot 10^6$, m^2/sec; τ, sec.

$$\times\left\{\frac{R}{r}\sum_{n=1}^{n=\infty}\frac{\mu_n^2R^2+1}{\mu_n^3R^3}\sin\mu_n r\,[\exp[-\mu_n^2a(\tau-\tau_i)]-\exp(-\mu_n^2a\tau)]+\frac{3}{2}\,\frac{\tau_i a}{R^2}\right\}.$$

Here μ_n are the positive roots of the characteristic equation

$$\mu_n R\operatorname{ctg}\mu_n R-1=0. \tag{5}$$

The first six roots of (5) have been tabulated [8]. An ES 1030 computer was used to calculate the reduced excess temperature

$$\Theta = T(r,\ \tau)\frac{\rho c_p}{q_0}\pi R^3$$

as a function of time in accordance with (4). Figure 1a shows the results for τ_i = 0; 0.001; 0.01 sec; R = 7.000 mm; $\tilde{r}$ = 0.382; a = 0.18 cm^2/sec, while Fig. 1b shows the variation in the relative error in the time needed to attain half the maximum excess temperature as a function of $\tilde{r}$ for various values of the thermal diffusivity (pulse length 0.001 sec). Clearly, for $\Theta = 0.5\Theta_{\max}$ and $\tilde{r}$ = 0.382 the measured values of the time differ by mot more than 2%, while increasing the pulse length to 0.01 sec leads to a correction exceeding 15% of the measured value.

Therefore, this equation enables one to derive the correction for the finite heating time and thus improves the accuracy.

The specific heat is determined from the maximum value of the excess temperature:

$$c_p = \frac{\Theta_{\max}q_0}{\pi R^3\rho T_{\max}}. \tag{6}$$

Then one can determine the thermal conductivity from

$$\lambda = \frac{\Theta_{\max}aq_0}{\pi R^3 T_{\max}}, \tag{7}$$

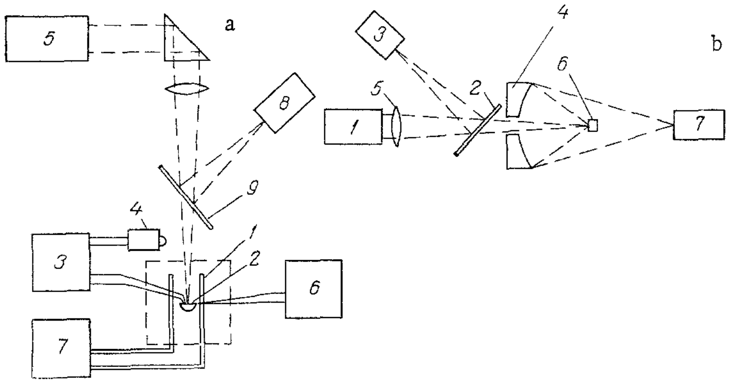

Fig. 3. Theoretical scheme of apparatus.

where Θ_{max} is the maximum value of the relative temperature (Fig. 1); R, radius of the specimen; T_{max}, maximum excess temperature; and a, thermal diffusivity, which is determined from the delay in the temperature signal from the parametric relationship (Fig. 2).

Figure 3a shows an apparatus for measuring these parameters. This consists of a vacuum chamber with a molybdenum heater 1, which contains the specimen 2. A Chromel—Alumel thermocouple with electrode diameter 0.05 mm is attached at the necessary distance from the center of the hemisphere and is connected to an S1-17 oscilloscope 3, which is synchronized by the photodiode 4. The pulsed heat source was a GOR-100 laser 5 with a pulse energy up to 100 J operating at a wavelength of about 0.6 μm and providing a pulse length of 0.001 sec, which was determined with an F-6 photocell and stroboscopic attachment to an S1-17 oscilloscope with photographic recording. The laser beam was focused at the center of the specimen by means of a prism and lens (spot diameter 0.1 mm). The temperature was measured with an additional thermocouple and digital voltmeter 6. The adjustable stabilized power supply 7 provided for varying the temperature from room temperature to 2300°K.

We see from (6) and (7) that an important quantity, but one difficult to measure, is the absorbed energy q_0. An important point is that this varies from pulse to pulse, which can lead to substantial random errors in measuring c_p and λ. The incident energy is measured with the IKT-1M calorimeter 8 with reflecting glass 9. The system is designed in such a way that the specimen receives about 90% of the laser energy and the calorimeter correspondingly 10%. This system allows one to measure the energy of each laser pulse.

The proportion of reflected energy is determined in an independent experiment, which is illustrated in Fig. 3b. This system was built in accordance with the recommendations of [9] and consists of the laser 1, the energy-measuring system 2 and 3 described above, the spherical mirror with a focal length of 84 mm 4 with a hole approximately equal to the beam diameter, the focusing lens 5, the specimen 6, and the IKT-1M calorimeter 7. The proportion of reflected energy is determined by the energy entering the calorimets 3 and 7 as well as by the solid angle.

The error in measuring the thermal diffusivity has been estimated previously [4-6] and is here about 4% on the basis of the finite heating time. The error in measuring the thermal capacity is determined by the errors in measuring the absorbed energy, the amplitude of the excess temperature, and the thermocouple coordinates. The adsorbed energy is measured with an error of about 8%, while the error in measuring the amplitude of the excess temperature is dependent on the working conditions and on the input energy, being about 2% in our case, while the error in determining the coordinates is also about 2%. The overall random error in measuring the specific heat is about 6-8%, as against 9-10% for the thermal conductivity.

Figure 4 shows the thermal diffusivity of nickel between 300 and 1300°K together with the data of [2] and certain other results [10, 11]. The systematic deviation of our results from the published data is not more than 5%. Also, the random deviations of our results from the smoothed curve are not more than 2-3%. Figure 4 gives data on the thermal conductivity of the same nickel specimen in comparison with published data [11, 12]. In that case the systematic deviation in our results is not more than 8%, while the random deviations from the observed smoothed curve are about 5%. This spread could be reduced by stabilizing the laser power.

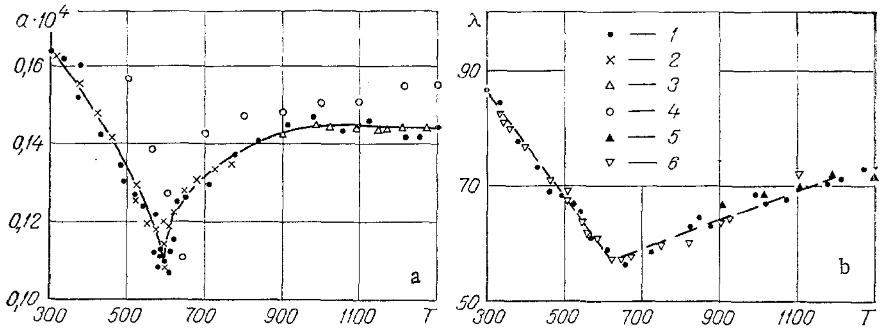

Fig. 4. Temperature dependence of the thermal diffusivity (a) and thermal conductivity (b) for nickel: 1) our results; 2) results of [10]; 3) [11]; 4) [2]; 5) [11]; 6) [12]. $a\cdot 10^4$, m^2/sec; T, K.

NOTATION

r, radius; R, radius; $\tilde{r}$, dimensionless coordinate; Θ, dimensionless temperature; τ, time; τ_i, duration of heat pulse; $\tau_{1/2}$, time for temperature signal at r to attain half the maximum value; q_0, amount of heat; a, thermal diffusivity; λ, thermal conductivity; ρ, density, c_p, heat capacity.

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