*Journal of Engineering Physics and Thermophysics, Vol. 72, No. 2, 1999*

# PULSE METHOD OF MEASURING THE THERMAL DIFFUSIVITY OF SPHERICAL SAMPLES

S. V. Buzilov and L. D. Zagrebin

UDC 536.2.083

*Consideration is given to a version of the pulse method of measurement of the thermal diffusivity of spherical samples with the use of laser heating. The method is based on solution of the heat-conduction equation in a spherical coordinate system. The computerized experimental setup used is described. Measurement results for the thermal diffusivity of Zr, Ni, Fe, Al are reported. The measurement error is no more than 5%.*

In [1-3] a pulse method of determination of the thermal diffusivity of liquid metals in a hemispherical form is considered where the heat source is at the center of the flat surface and the delay time of the temperature signal is measured at a point located some distance from the source of the thermal disturbance. High-temperature investigations of thermal diffusivity using this version of the method have demonstrated the difficulty of introducing corrections for heat transfer, especially for a flat surface. In connection with this it is reasonable to use a sample in the form of a small-diameter drop, which in calculations can be approximated by a sphere of radius $R$ with a point source at a pole.

The temperature $T$ at the point with the spherical coordinates $(r, \theta, \varphi)$ caused by the action of a single instantaneous point source, located at the pole $(R; 0; 0)$ at the initial moment of time, at $d^2 = R^2 + r^2 - 2Rr\cos\theta$ is of the form [4]

$$T(d; t) = \frac{Q}{(4\pi at)^{3/2}\rho c_p}\exp\left(-\frac{d^2}{4at}\right), \tag{1}$$

Expression (1) satisfies the equation

$$\frac{\partial T(r; \theta; t)}{\partial t} = a\left[\frac{\partial^2 T(r; \theta; t)}{\partial r^2} + \frac{2}{r}\frac{\partial T(r; \theta; t)}{\partial r} + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial T(r; \theta; t)}{\partial\theta}\right)\right] \tag{2}$$

and is the solution of the problem of the temperature distribution in an unbounded medium.

Using the image method with account for the boundary conditions

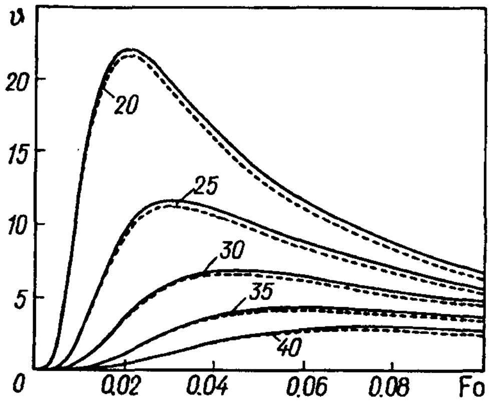
$$T(r; \theta; 0) = 0; \quad -\lambda\left.\frac{\partial T}{\partial r}\right|_{r=R} = \alpha T; \quad 0 \le r \le R; \quad 0 \le \theta \le \pi$$

and expression (1), one can obtain the distribution of the temperature field in a sphere

$$T(r; \theta; t) = \frac{2Q}{\rho c_p}\frac{\exp\left(-\frac{d^2}{4at}\right)}{(4\pi at)^{3/2}}\left[1 - \frac{\alpha}{\lambda}\sqrt{\pi at}\,\times\right.$$

Izhevsk State Technical University, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 72, No. 2, pp. 236-239, March-April, 1999. Original article submitted January 12, 1998; revision submitted May 19, 1998.

 1062-0125/99/7202-0212$22.00 



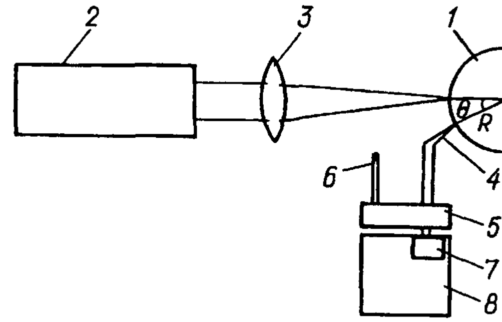




Fig. 1. Relative-temperature ($\vartheta$) distribution as a function of dimensionless time (Fo) (the figures at the curves are values of $\theta$, the solid curves refer to Bi = 0, the dashed curves refer to Bi = 0.1).

Fig. 2. Schematic of the experimental setup.

$$\times \exp\left(at\left(\frac{2R - 2r\cos\theta}{4at} - \frac{\alpha}{\lambda}\right)^2\right) \operatorname{erfc}\left(\sqrt{at}\left(\frac{2R - 2r\cos\theta}{4at} - \frac{\alpha}{\lambda}\right)\right)\Bigg]. \quad (3)$$

The temperature $T(r;\ \theta;\ t) = T' - T_0$ will be referred to as the excess temperature if the ambient temperature $T_0 \neq 0$ and $T'$ is the sample temperature.

To measure thermal diffusivity, it is convenient to use dimensionless parameters. For this, expression (3) at $r = R$, which corresponds to the temperature-field distribution on the sphere surface, can be written in terms of the relative quantities $\vartheta(\theta;\ \mathrm{Fo};\ \mathrm{Bi})$ as

$$\vartheta = \frac{\exp\left(-\frac{1-\cos\theta}{2\mathrm{Fo}}\right)}{2\sqrt{\pi}\,\mathrm{Fo}^{3/2}}\left[1 - \mathrm{Bi}\sqrt{\pi\,\mathrm{Fo}}\exp\left(\mathrm{Fo}\left(\frac{1-\cos\theta}{2\mathrm{Fo}} - \mathrm{Bi}\right)^2\right)\operatorname{erfc}\left(\sqrt{\mathrm{Fo}}\left(\frac{1-\cos\theta}{2\mathrm{Fo}} - \mathrm{Bi}\right)\right)\right], \quad (4)$$

where $\vartheta = 2\pi R^3 \rho c_p T/Q$; $\mathrm{Fo} = at/R^2$ has the meaning of dimensionless time; $\mathrm{Bi} = \alpha R/\lambda$.

Figure 1 shows calculated dependences of the relative excess temperature on the Fourier number at different points of the spherical surface for Bi = 0 and Bi = 0.1.

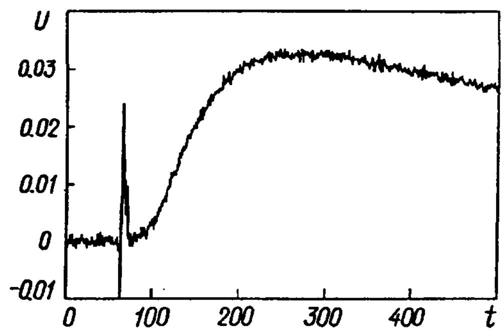
Obtained expression (4) allows determination of the thermal diffusivity of metals and alloys on the experimental setup (Fig. 2). A thermal pulse generated by GOR-100M laser 2 with a wavelength of 0.694 $\mu$m is sent to the pole of spherical sample 1 of radius $R$. The condition of a point source, the size of which is 0.3 mm (0.3 << $d$), at the point of exposure is achieved by focusing the thermal pulse by lens 3 with a focal power of 10 diopters. To record a temperature signal in time, chromium-nickel thermocouple 4 with an electrode thickness of 0.05 mm was welded to the sphere surface at the angle $\theta$. The thermocouple was protected against direct thermal radiation with $Al_2O_3$ paste. The angle $\theta$ was measured by means of a BMI-1Ts toolmaker's microscope with an accuracy of up to 1′. Since the temperature drop reaches ~2°C on the sphere surface with the coordinates ($R$; $\theta$; 0), amplifier 5 is used in the setup. To obtain a low level of noise and a high common-mode rejection factor, the input stages of the amplifier are connected as differentiators on low-noise operational amplifiers of the type K140UD17. To determine the reference point of a thermal signal, photodiode 6 is used. Amplified signals of the photodiode and the thermocouple are sent via analog-to-digital converter 7 to computer 8 of the type IBM PC [5].

The value of $\mathrm{Fo}_{1/2}$ found from the theoretical (see Fig. 1) and computer-processed experimental (Fig. 3) curves for the given $\theta$ allows determination of the thermal diffusivity by the formula

TABLE 1. Thermal-Diffusivity Values ($a \cdot 10^6$, $m^2$/sec) According to Experimental Data

| Metal | 1 | 2 | 3 |
|---|---|---|---|
| Nickel | 16.5 | 16 | 22.7 |
| Iron | 17.4 | 18 | 22.0 |
| Zirconium | 13.3 | – | 12.7 |
| Aluminum | 92.4 | 94 | 93.2 |

Note: 1 denotes data of the present authors; 2, [6]; 3, [7].



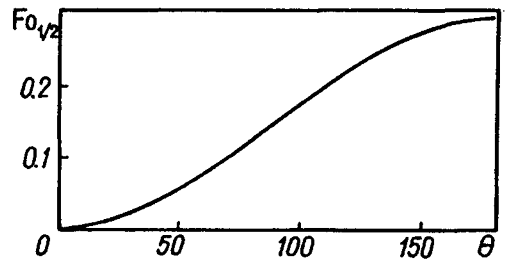




Fig. 3. Experimental curve of the thermoelectromotive force obtained by a Chromel-Alumel thermocouple for a nickel sample at $R$ = 6.967 mm, $\theta$ = 33°51', $U$, mV; $t$, msec.

Fig. 4. Plot of $Fo_{1/2}$ vs. the angle $\theta$.

$$a = Fo_{1/2} \frac{R^2}{\tau_{1/2}}. \quad (5)$$

Figure 4 shows $Fo_{1/2}$ as a function of the angle $\theta$.

The results of measurement of the thermal diffusivity of Ni (99.99), Zr (99.9), Al (99.99), and Armco iron carried out at a temperature of 300 K (see Table 1) agree with the values obtained by the Parker pulse method [6] and the method of temperature waves [7]. It should be noted that the method of temperature waves gives the overestimated results as compared to the pulse methods, and the discrepancy in the thermal-diffusivity values obtained by different methods reaches 30% (see the references in [7]). The error in thermal-diffusivity measurement does not exceed 5% and consists of:

a) the measurement error due to the inaccuracy in the geometric dimensions of the sample in the experiment (no more than 1%);

b) the standard deviation of the thermal diffusivity due to time measurement (in the course of the same experiment it does not exceed 1%);

c) the error of thermal-diffusivity measurement related to inaccurate determination of the angle $\theta$, which is related, in turn, to $Fo_{1/2}$ (within the limits of 2–2.5%).

To sum up, the developed version of the pulse method of thermal-diffusivity measurement will allow determination of thermophysical characteristics of small samples in the form of a drop at high temperatures in both the solid and liquid states without changing the sample itself.

## NOTATION

$R$, sphere radius; $\theta$, angle; Fo, Fourier number; $\vartheta$, relative temperature; Bi, Biot number; $Fo_{1/2}$, Fourier number corresponding to half the maximum relative temperature; $\tau_{1/2}$, time in which the temperature signal reaches half the maximum value; $Q$, released heat; $\rho$, density; $a$, thermal diffusivity; $c_p$, heat capacity; $\alpha$, heat-transfer coefficient; $\lambda$, thermal conductivity.

## REFERENCES


1. V. E. Zinov'ev, A. A. Baskakova, and L. D. Zagrebin, Inzh.-Fiz. Zh., 25, No. 3, 450-494 (1973).
2. A. A. Baskakova, V. E. Zinov'ev, and L. D. Zagrebin, Inzh.-Fiz. Zh., 26, No. 6, 1058-1061 (1974).
3. L. D. Zagrebin, V. E. Zinov'ev, and V. A. Sipailov, Inzh.-Fiz. Zh., 40, No. 5, 864-869 (1981).
4. H. Carslaw and D. Jaeger, Conduction of Heat in Solids, Clarendon Press, Oxford (1959).
5. S. M. Perevozchikov and L. D. Zagrebin, Pribory Tekh. Éksper., No. 3, 155-158 (1998).
6. W. J. Parker, R. S. Jonkins, C. P. Butler, and C. L. Abbott, J. Appl. Phys., 32, No. 9, 1679-1684 (1961).
7. V. E. Zinov'ev, Kinetic Properties of Metals at High Temperatures [in Russian], Moscow (1989).