A METHOD FOR COMBINED INVESTIGATION OF THE THERMOPHYSICAL CHARACTERISTICS OF MATERIALS OVER THE TEMPERATURE RANGE 4.2-400°K

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This article describes the method and experimental apparatus for determination of the thermal conductivity, thermal diffusivity, and specific heat capacity of materials as functions of temperature at low temperature.

The thermophysical characteristics of liquid and powdered materials (thermal conductivity λ, thermal diffusivity *a*, and specific heat capacity c are important for calculation of the thermal regimes of various devices operating at low temperatures. Existing methods have a number of drawbacks, principally long experiment duration, complex apparatus, and the need to employ different devices to determine each characteristic. In this connection, high-speed composite methods based on solution of nonsteady state thermal conductivity problems with internal heat sources of constant power are very promising.

It has been suggested that the thermophysical characteristics of liquids, ice, powders, moisture-containing systems, and other materials be investigated by a composite method based on solution of the equation for the temperature field on an unbounded hollow cylinder with a uniform internal heat supply [1]. The initial temperature of the hollow cylinder is assumed to be zero, i.e., the readings are taken from the initial constant specimen temperature. The thermal stress on the inner surface of a cylinder of radius R_1 is assumed to be constant. The temperature at a point located at a distance r from the cylinder axis with a heating time is then τ [1]

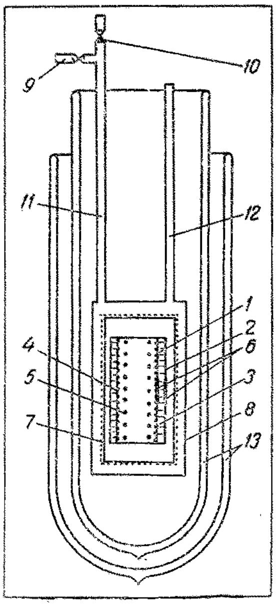

Fig. 1. Diagram of experimental apparatus: 1, 2) thin-walled stainless steel cylinders; 3) material to be tested; 4) heating element; 5) additional shielded heating element; 6) resistance thermometers; 7) adiabatic jacket; 8) vacuum-tight beaker; 9, 10) valves; 11) tube; 12) outlet conduit; 13) helium cryostat.

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TABLE 1. Experimental Data on Thermal Conductivity of Certain Materials

Material	λ	T, °K 100	140	180	220	260	300	340
Powdered Plexiglas, d = 0.5 mm	λ_{exp}	0,070	0,072	0,073	0,075	0,078	0,083	0,089
	λ_{tabl}	0,660	0,070	0,072	0,075	0,080	0,088	0,095[3]
Glass beads and air, d = 1.5 mm	λ_{exp}	0,070	0,098	0,128	0,150	0,165	0,175	0,182
	λ_{tabl}	—	—	—	—	—	—	0,180[2]
Glass beads and air, d = 1,3 mm	λ_{exp}	0,080	0,110	0,145	0,170	0,190	0,209	0,218
	λ_{tabl}	—	—	—	—	—	—	0,220[2,3]
BKZH-94 organosilicon fluid	λ_{exp}	0,200	0,165	0,180	0,162	0,158	0,150	0,145
	λ_{tabl}	0,205	0,162	0,158	0,158	0,156	0,150	0,142[4,5]

Note: λ_{exp}) our data; λ_{tabl}) data of [2-5].

$$t=\frac{q_\omega R_1}{\lambda(R_2^2-R_1^2)}\left\{2a\tau+\frac{r^2}{2}-R_2^2\ln\frac{r}{R_1}+\frac{R_2^4\ln\frac{R_2}{R_1}}{R_2^2-R_1^2}\right.$$
$$\left.-\frac{3R_2^2+R_1^2}{4}-2(R_2^2-R_1^2)\sum_{n=1}^{\infty}\frac{Z_0(X_n)Z_0\left(X_n\frac{r}{R_1}\right)e^{-X_n^2\frac{a\tau}{R_1^2}}}{X_n^2\left[\left(\frac{R_2}{R_1}\right)^2Z_0^2\left(X_n\frac{R_2}{R_1}\right)-Z_0^2(X_n)\right]}\right\}, \tag{1}$$

where X_n are the roots of the characteristic equation

$$I_1(X)Y_1\left(\frac{R_2}{R_1}X\right)-I_1\left(\frac{R_2}{R_1}X\right)Y_1(X)=0, \tag{2}$$

$I_1(X)$ and $Y_1(X)$ are type I and II first order Bessel functions.

Equation (1) describes the temperature field under a nonsteady-state regime during heating of a hollow cylinder with an internal heat source of constant power, while the equation for a quasisteady-state regime has the form

$$t=\frac{q_\omega R_1}{\lambda(R_2^2-R_1^2)}\left\{2a\tau+\frac{r^2}{2}-R_2^2\ln\frac{r}{R_1}+\frac{R_2^4\ln\frac{R_2}{R_1}}{R_2^2-R_1^2}-\frac{3R_2^2+R_1^2}{4}\right\}. \tag{3}$$

The temperature difference between two points in the specimen at distances R_1 and R_2 from the center at the instant τ is then

$$\Delta t=\frac{q_\omega R_1}{2\lambda(R_2^2-R_1^2)}\left\{R_1^2-R_2^2+2R_2^2\ln\frac{R_2}{R_1}\right\}. \tag{4}$$

Hence,

$$\lambda=\frac{q_\omega R_1}{2\Delta t(R_2^2-R_1^2)}\left\{R_1^2-R_2^2+2R_2^2\ln\frac{R_2}{R_1}\right\}. \tag{5}$$

By differentiating Eq. (3) for τ, we readily obtain a computational formula for the thermal conductivity:

$$a = \frac{1}{4\Delta t}\frac{dt}{d\tau}\left(R_1^2 - R_2^2 + 2R_2^2 \ln\frac{R_2}{R_1}\right). \tag{6}$$

The specific heat capacity is determined from the formula

$$c = \frac{q_\omega R_1}{\frac{dt}{d\tau}(R_2^2 - R_1^2)\gamma}. \tag{7}$$

The formulas obtained are valid for adiabatic heating of the specimen.

In order to investigate the thermophysical characteristics of ices, powders, ice-like composition systems, and other materials over the temperature range 4.2-400°K, we designed an appropriate experimental apparatus (Fig. 1).

The chamber consisted of two coaxially arranged stainless steel cylinders with a wall thickness of 0.07 mm and a welded bottom. The test material was placed in the gap between them (4-5 mm wide). The temperature sensors necessary to measure the temperature drop and absolute specimen temperature were attached to the cylinder walls in the gap. The sensors were copper–constantan thermocouples in the liquid-nitrogen temperature range and platinum resistance thermometers in the liquid-helium range. The thermometer readings were continuously recorded on paper tape by a 6-point ÉPP-09 recording potentiometer. In order to ensure adiabatic heating conditions, the experimental chamber was placed in a heating-element jacket, the power supply to which was adjusted automatically by a differential thermocouple that established the temperature difference between the specimen wall and jacket.

A shielded heating element was also used to compensate for the heat flux within the cylinders. Using a system of shielded heating elements with automatic regulation, we were thus able to ensure adiabatic heating of the test material from the temperature of liquid helium to room temperature.

The proposed method is particularly convenient because it permits simultaneous determination of all the thermophysical characteristics (thermal conductivity, thermal diffusivity, and heat capacity) of a wide range of materials over a broad temperature interval within a comparatively short time (4-5 h).

We investigated a number of materials and the data on some of them were compared with those of other authors (Table 1). As can be seen from this table, the experimental error did not exceed 5%.

NOTATION

λ is the thermal conductivity, W/m · deg;
a is the thermal diffusivity, m^2/sec;
c is the specific heat capacity, J/g · deg;
t is the temperature;
r is the distance from cylinder axis;
R_1, R_2 are the radii of internal and external cylinders, respectively;
τ is the time;
q_ω is the heat flux per unit surface;
$dt/d\tau$ is the rate of temperature variation;
γ is the density.

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