

DETERMINATION OF THE THERMOPHYSICAL CHARACTERISTICS  
OF LIQUIDS BY A HEATED-PROBE METHOD

S. A. Tanaeva

UDC 536.22:536.2.083

This is an examination of the heated-probe method used in studying the thermophysical characteristics of viscous liquids over a wide temperature range, under the pressure of saturated vapors in a closed space. The results of the investigation are given.

The determination of thermophysical properties of liquids is associated with a number of difficulties which arise primarily in the formulation of the experiment. In this paper we propose the utilization of probe methods which are widely used [4] in determining the thermophysical characteristics of such materials as liquids, powders, soils under natural conditions, basalt rocks, etc. The probe method is convenient for practical purposes, since it does not require the preparation of complex measuring apparatus, it is very simple to fabricate, and well-developed formulas are available for the determination of the coefficient of thermal conductivity.

We employed the heated-probe method to determine the thermophysical characteristics of liquids over a broad temperature range from 20-180°C and at the high pressures produced by liquid vapors heated in a closed vessel.

In deriving the calculation formulas for the determination of the coefficients of thermal conductivity, thermal diffusivity, and specific heat capacity we employed a problem [1, 2] which describes the propagation of heat by a linear heat source in a continuous medium.

It is assumed that the cylinder is made from an ideal conductor, that it has a radius  $r$ , and that it is surrounded by an unbounded medium; at  $\tau > 0$  a quantity of heat equal to  $q$  is liberated per unit time per unit length, and the initial temperature of the entire system is equal to zero.

The temperature field of the space is described by the equation

$$\frac{\partial t}{\partial \tau} = a \left( \frac{\partial^2 t}{\partial x^2} + \frac{1}{x} \frac{\partial t}{\partial x} \right), \quad (1)$$

where  $t$  is the temperature;  $\tau$  is the time; and  $x$  is the radial distance from the linear heat source.

For the solution [1] of Eq. (1) we have

$$t = \frac{q}{4\pi\lambda} \int_0^\tau \left[ \exp\left(-\frac{x^2}{4a\tau}\right) / \tau \right] d\tau. \quad (2)$$

Expression (2) can be written in the form

$$t = \frac{q}{4\pi\lambda} \int_0^Y \frac{e^{-\frac{1}{4Y}}}{Y} dY, \quad (3)$$

where the variable  $Y = a\tau/x^2$ .

---

Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR, Minsk. Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 17, No. 1, pp. 80-85, July, 1969. Original article submitted September 20, 1968.

© 1972 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

Since it is impossible to express the integral in (3) in elementary functions, we will expand  $e^{-1/4Y}$  in series, so that (3) assumes the form

$$t = \frac{q}{4\pi\lambda} \int_0^Y \left( \frac{1}{Y} - \frac{1}{Y^2} + \frac{1}{32Y^3} - \dots \right) dY, \quad (4)$$

from which

$$t = \frac{q}{4\pi\lambda} \left( \ln Y + \frac{1}{4Y} - \frac{1}{64Y^2} + \dots \right). \quad (5)$$

We see from an analysis of (5) that for large  $\tau$  the following approximation is valid:

$$t = \frac{q}{4\pi\lambda} \ln Y. \quad (6)$$

We can derive the theoretical formula for the determination of the coefficient of thermal conductivity from (6).

Indeed, for certain rather large time intervals  $\tau_1$  and  $\tau_2$  satisfying (6), i. e., when the temperature curve is close to the logarithmic and before the steady-state heating regime for the medium has set in, we can write the respective temperature values as follows:

$$t_1 = \frac{q}{4\pi\lambda} \ln \frac{a\tau_1}{x^2}, \quad (7)$$

$$t_2 = \frac{q}{4\pi\lambda} \ln \frac{a\tau_2}{x^2}. \quad (8)$$

Here we have in mind the temperature at the identical point, situated at a radial distance  $x$  from the linear heat source.

Then

$$t_2 - t_1 = \frac{q}{4\pi\lambda} \left( \ln \frac{a\tau_2}{x^2} - \ln \frac{a\tau_1}{x^2} \right) \quad (9)$$

or

$$\Delta t = \frac{q \ln \frac{\tau_2}{\tau_1}}{4\pi\lambda}, \quad (10)$$

whence

$$\lambda = \frac{q \ln \frac{\tau_2}{\tau_1}}{4\pi\Delta t}. \quad (11)$$

Considering the thermal losses and the thermal contact resistance of the probe itself, it is necessary that we introduce into (11) some correction factor which is constant for this probe. Finally, the theoretical formula for the determination of the coefficient of thermal conductivity has the form

$$\lambda = \beta \frac{q \ln \frac{\tau_2}{\tau_1}}{4\pi\Delta t}. \quad (12)$$

The probe constant  $\beta$  is determined by its preliminary calibration on the basis of standard liquids.

Thus, the determination of the coefficient of thermal conductivity by the heated-probe method involves no particular difficulties and yields completely satisfactory results. However, in actual practice it is necessary to know the frequency, the coefficient of thermal diffusivity and the specific heat capacity of the material. In this paper we propose an experimental formula for the determination of the coefficient of thermal diffusivity.

As a result of numerous experiments we have noted that the temperature recorded at the linear heat source for the liquid being investigated is inversely proportional to the thermal diffusivity of that liquid. Consequently, for the exact same instant of time we can write

$$\frac{a_1}{a_2} = \frac{t_2}{t_1}, \quad (13)$$

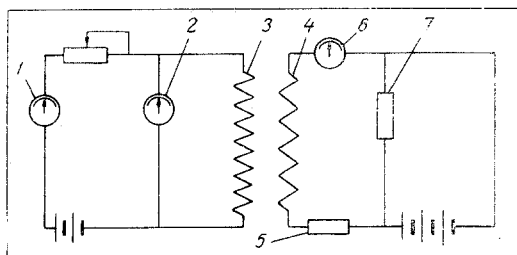


Fig. 1. Electrical circuit of the installation: 1) ammeter; 2) voltmeter; 3) heater; 4) resistance thermometer; 5) KP-49 potentiometer; 6) ammeter; 7) EPP-09 electronic automatic potentiometer.

TABLE 1. The Temperature Coefficient of Thermal Conductivity  $\lambda$  (W/m · deg) as a Function of the Thermal Diffusivity  $a$  (m<sup>2</sup>/sec)

$t, ^\circ\text{C}$	Thickened solution				Liquid rubber		Carboxymethyl-cellulose in water	
	specimen No. 1		specimen No. 2		$\lambda$	$a \cdot 10^{-6}$	$\lambda$	$a \cdot 10^{-6}$
	$\lambda$	$a \cdot 10^{-6}$	$\lambda$	$a \cdot 10^{-6}$				
20	0,145	0,072	0,147	0,067	0,39	0,117	0,29	0,119
40	0,143	0,071	0,145	0,066	0,41	0,121	0,31	0,122
60	0,143	0,071	0,143	0,065	0,44	0,125	0,32	0,125
80	0,142	0,0708	0,141	0,065	0,47	0,129	0,33	0,128
100	0,141	0,0705	0,140	0,064	0,50	0,133	—	—
120	0,140	0,070	0,138	0,063	0,53	0,136	—	—
140	0,140	0,070	0,136	0,063	0,57	0,140	—	—
160	0,139	0,070	0,135	0,062	0,59	0,144	—	—
170	0,139	0,070	0,134	0,062	0,61	0,146	—	—

where  $a_1$  and  $t_1$  are, respectively, the coefficient of thermal diffusivity and the temperature of the standard liquid. Here we have in mind the fact that the electrical power for the heater and the resistance thermometer are constant for all of the experiments.

Consequently, knowing the function  $t = f(\tau)$  and the value of the coefficient of thermal diffusivity for the standard liquid from the experiment, it is always possible to determine  $a_2$  for the liquid being studied.

The coefficient of specific heat capacity is calculated from the formula as follows:

$$c = \frac{\lambda}{a\gamma} \quad (14)$$

Usually, in the fabrication of the probe we use a heated wire as the linear heat source, with the junction of the thermocouple connected to that wire to record the extent to which it is heated in various media; however, in this design the wire is not heated uniformly, since there are large heat losses at the ends. In our case the probe is produced in the following manner.

The heater is made in the form of a thin ( $d = 1$  mm) spiral of manganese-coated wire  $d = 0.1$  mm, with the total resistance of the heater on the order of 100 ohms. For the temperature gauge we use a resistant thermometer made of copper wire with  $d = 0.1$  mm, double-wound with the heater. The resistance of the thermometer is approximately 5-6 ohms. The resulting spiral is placed into a thin glass capillary one of whose ends is sealed, and the other serving as the outlet for the heater and resistant-thermometer lead. To reduce the thermal resistance of the probe, the capillary is filled with an organosilicon liquid. The electrical circuit for the probe is shown in the figure. Electrical power of approximately 0.6-0.8 W is applied to the probe heater from a high-stabilization dc source.

In conducting these tests under pressure, for the closed vessel we used a calorimeter bomb to whose lid the probe was attached by means of epoxy resin. The bomb together with the liquid being tested was placed into a thermostat, where it was heated to the specified temperature. After establishment of a steady temperature field within the specimen, the thermophysical characteristics were measured by means of the heated-probe method. The measurements were carried out at each 20-30°C.

The resistance thermometer is powered by an alkali battery (with a voltage of up to 80 V) through a KP-49 potentiometer which offsets the voltage drop across the thermometer. At the instant that the electrical energy is applied to the heater, because of a rise in the temperature of the probe, the resistance of the thermometer is altered, thus generating an additional voltage drop across its ends. The change in the

voltage is reported on the graph-paper strip of the ÉPP-09 electron automatic potentiometer, with a scale of 1 mV, and the speed of the tape set in advance.

After a single experiment we find the relationship between the voltage drop across the resistance thermometer and the time when the probe is heated by a constant-power source. Based on the extent to which the probe is heated in various media, we can judge the thermophysical characteristics of these media.

To determine the correction factor for the probe, we used tabular data for such thoroughly investigated liquids as glycerin, gasoline, alcohol, etc. [6]. Knowing the coefficients of thermal conductivity and thermal diffusivity, and using experimental data, we determined the probe constants from (12) and (13). Maintaining the power at the heater constant throughout all of the experiments, we can present (12) in the form

$$\lambda = \beta' \frac{\ln \frac{\tau_2}{\tau_1}}{\Delta t}, \quad (15)$$

where  $\Delta t$  can also be expressed in millivolts, without changing to degrees, since the transfer coefficient can also be included in the universal constant  $\beta'$  of the probe.

The above-described method and the corresponding installation were used to investigate the thermophysical characteristics of thickened solutions in the temperature range 20–180°C under the pressure of saturated vapors, attaining substantial magnitudes at high temperatures because of the capacity of the liquids to form gas throughout the entire volume.

The results of the investigation into the thermal properties of certain materials are presented in Table 1.

As we can see from the experimental results, the coefficients of the thermal conductivity and thermal diffusivity for thickened solutions diminish with a rise in temperature (and, consequently, with a rise in pressure), although this reduction is insignificant in comparison with pure liquid. At the same time, the thermophysical characteristics of liquid rubber and a solution of carboxymethylcellulose in water increase substantially with a rise in temperature.

The described method and installation thus provides for extensive possibilities in the investigation of such materials as liquids, free-flowing materials, soils, etc., within a wide temperature range. The method is unique because of the simplicity of design for the experimental installation and the processing of the experimental data. The relative error in the measurement of the thermophysical characteristics, as demonstrated by the experiments with the standard materials, falls well within 7–10%.

#### NOTATION

t	is the temperature;
$\tau$	is the time;
$\lambda$	is the coefficient of thermal conductivity;
$a$	is the coefficient of thermal diffusivity;
r	is the probe radius;
x	is the radial distance;
q	is the quantity of heat per unit length of the probe;
$\beta$	is the probe constant;
$\gamma$	is the density;
c	is the specific heat capacity.

#### LITERATURE CITED

1. H. Carslaw and J. Jaeger, *The Conduction of Heat in Solids* [Russian translation], Nauka (1964).
2. S. T. Hsu, H. S. Kao, and W. W. Lee, *Proceedings of the Third International Heat Transfer Conference, August 7–12 (1966)*, pp. 113–151.
3. L. L. Vasil'ev, *Author's Abstract of Candidate's Dissertation* [in Russian], Institut Teplo- i Mas-soobmena AN BSSR (1964).
4. A. F. Chudnovskii, *Heat Transfer in Disperse Media* [in Russian], Gostekhizdat (1954).
5. S. A. Tanaeva, in: *Heat and Mass Transfer in NonNewtonian Fluids* [in Russian], Énergiya (1968).
6. N. V. Vargaftik, *Handbook on the Thermophysical Properties of Gases and Liquids* [in Russian], Fizmatgiz (1963).