JOINT DETERMINATION OF THERMAL PROPERTIES BY A PROBE METHOD

L. N. Novichenok and Yu. M. Pikus

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A method for jointly determining thermal properties by a relative probe method is described, and the corresponding equations are given. Results found for certain lubricants are reported.

The theoretical basis for probe methods is the solution of the heat-conduction problem for the heating of objects of various shapes (spheres, cylinders) in an unbounded medium with a constant heat source.

Several investigators [1-3] use the heat-conduction problem of the heating of an infinite cylinder in an unbounded medium, since the probes are usually cylindrical or approximately so. The solutions found by Laplace transforms for large Fourier numbers $Fo = a\tau/R^2$ are complicated functions of the type

$$t = \frac{q}{4\pi\lambda}\left[\ln\left(4\frac{a\tau}{R^2}\right) - \gamma + f(C, H)\right], \quad (1)$$

where the term f(C, H) incorporates the heat capacity of the probe itself and the thermal contact resistance between the probe and the medium under study. Analysis of the experimental data on the basis of solution (1) is a complicated matter, requiring knowledge of the specific properties of the probe.

For this reason, many investigators [4-6] turn to a simpler equation, taking the limit $f(C, H) \to 0$; this approach introduces some additional error. As was shown previously [7-9], this error is negligible when miniature probes, made from wire materials which are good conductors and having a good contact with the medium (i.e., when there is no protective sheath), are used.

All the equations which have been proposed for calculating thermal properties on the basis of probe methods are applicable for long times; thus only the thermal conductivity can be determined. It is therefore necessary to work out a method for analyzing the experimental data in which it is also possible to

TABLE 1. Thermal Properties of Certain Oils

Oil	t, °C	Thermal conductivity λ, W/(m·deg)			Thermal diffusivity $a \cdot 10^7$, m²/sec		
		expt.	value from it	% discrep.	expt.	value from it	% discrep.
Transformer	20	0,114	0,111	2,70	0,69	0,74	6,75
	50	0,111	0,108	2,78	0,64	0,67	4,50
	80	0,109	0,106	2,84	0,60	0,63	4,75
Industrial type 12	20	0,130	0,129	0,77	0,75	—	—
	50	0,125	0,126	0,79	0,69	—	—
	80	0,120	0,123	2,44	0,63	—	—
Industrial type 20	20	0,133	0,132	0,76	0,71	0,79	10
	50	0,128	0,128	0,00	0,67	—	—
	80	0,123	0,125	1,60	0,63	—	—
Vaseline	20	0,125	0,127	1,57	0,79	—	—
	50	0,124	0,122	1,64	0,70	—	—
	80	0,121	0,117	3,42	0,60	—	—

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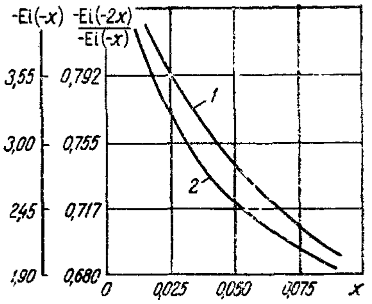

Fig. 1. The analytic functions $-\text{Ei}(-2X)/-\text{Ei}(-X) = f(x)$ (1) and $-\text{Ei}(-X) = f(X)$ (2).

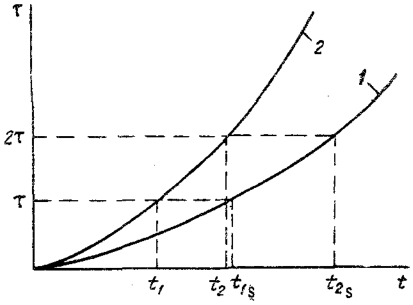

Fig. 2. Thermograms of the standard (1) and test (2) media.

calculate the thermal diffusivity, i.e., to use the solution of the heat-conduction problem for small values of the Fourier number also.

For this purpose we use the solution of the heat-transfer problem in an unbounded medium for the case of a line heat source of constant strength:

$$t = \frac{q}{4\pi\lambda}\left[-\text{Ei}\left(-\frac{R^2}{4a\tau}\right)\right]. \tag{2}$$

It should be noted that the solution in (1) becomes a particular case of (2) in the limit $f(C, H) \to 0$ and can be found by means of a series expansion of the integral exponential function.

In deriving the equations for calculating the thermal properties it is more convenient to take a relative approach, i.e., to compare the thermal properties of the test medium with those of a standard medium. This approach speeds up the experiments considerably and reduces the errors mentioned above.

We can thus write the temperatures of the probe surface at the two instants τ and 2τ in the test and standard media, along with their ratios, as follows:

$$t_1 = \frac{q}{4\pi\lambda}\left[-\text{Ei}\left(-\frac{R^2}{4a\tau}\right)\right], \quad t_2 = \frac{q}{4\pi\lambda}\left[-\text{Ei}\left(-\frac{R^2}{8a\tau}\right)\right]; \tag{3}$$

$$t_{1s} = \frac{q}{4\pi\lambda_s}\left[-\text{Ei}\left(-\frac{R^2}{4a_s\tau}\right)\right], \quad t_{2s} = \frac{q}{4\pi\lambda_s}\left[-\text{Ei}\left(-\frac{R^2}{8a_s\tau}\right)\right]; \tag{4}$$

$$\vartheta = -\text{Ei}\left(-\frac{R^2}{4a\tau}\right)\Big/-\text{Ei}\left(-\frac{R^2}{8a\tau}\right); \tag{5}$$

$$\vartheta_s = -\text{Ei}\left(-\frac{R^2}{4a_s\tau}\right)\Big/-\text{Ei}\left(-\frac{R^2}{8a_s\tau}\right). \tag{6}$$

We denote the arguments of the integral exponential function by

$$X = \frac{R^2}{8a\tau}; \quad X_s = \frac{R^2}{8a_s\tau}. \tag{7}$$

Then Eqs. (5) and (6) can be written

$$\vartheta = -\text{Ei}(-2X)/-\text{Ei}(-X), \tag{8}$$

these equations are plotted in Fig. 1.

Accordingly, after some straightforward analytic manipulations, using (2), (7), and (8), we find the following simple equation for the thermal diffusivity:

$$\lambda = \lambda_s \frac{t_{2s}}{t_2}[-\text{Ei}(-X)]/[-\text{Ei}(-X_s)], \tag{9}$$

$$a = a_s X_s / X. \tag{10}$$

The temperatures and temperature ratios at the indicated times are indicated from the experimental thermograms (Fig. 2), while X and X_s are determined from the analytic curve (Fig. 1).

Since Eqs. (9) and (10) contain a temperature ratio, it is not necessary to calibrate the temperature probe.

The maximum error of these measurements was less than 8%, which is completely tolerable for engineering calculations.

This new procedure was used with an existing experimental apparatus [10] to measure the thermal properties of certain oils over the temperature range 20-80°C. The experimental results are listed in Table 1. Comparison of these results with data from the literature [11-13] reveals that the error lies within the calculation error. This agreement consistutes evidence for the applicability of this method for studying liquid and finely dispersed materials.

NOTATION

- t is the temperature;
- τ is the time;
- λ is the thermal conductivity;
- a is the thermal diffusivity;
- R is the probe radius;
- γ is the Euler constant;
- q is the specific thermal power;
- C is the heat capacity of probe;
- H is the conductivity at probe–medium interface.

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