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The Investigation of Thermophysical Properties of Fluids by an Alternating Current Hot-Wire Method

L. P. Phylippov,[1] S. N. Nefedov,[1] and S. N. Kravchoon[1]

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A method and an instrument for the measurement of a number of the thermophysical properties (thermal conductivity, thermal activity, volumetric specific heat, thermal diffusivity) are described. The results obtained for thermal conductivity and specific heat of toluene, over a temperature range 30–350°C and pressures of up to 30 MPa, are presented.

KEY WORDS: fluids; hot-wire method; specific heat; thermal conductivity; thermal diffusivity; toluene.

The rapid evolution of science and technology has created a demand for new experimental techniques in many disciplines. This is also apparent in thermophysics. Difficult and time-consuming methods of measurement are being replaced by new, faster techniques, which are adaptable to automation. An important feature of these new methods of thermophysical properties measurement is their complex character, i.e., the possibility to obtain several thermophysical properties in a given experiment simultaneously or consecutively. One such method is discussed in this paper.

In essence, the method consists of electrically heating a metallic probe of small thermal inertia, immersed in the fluid under investigation. The thermophysical properties of the fluid are determined from the temperature oscillations of the probe. For a thin foil probe, the amplitude θ and the phase ϕ of temperature oscillations of the probe depend on the magnitude of the thermal activity, B, of the fluid, defined as $B = \sqrt{\lambda c_p \rho}$. For a wire probe, the amplitude

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[1] Department of Physics, Moscow State University, Moscow, USSR.

and phase of temperature oscillations depend on the thermal conductivity λ and thermal diffusivity a of the fluid, thus enabling the simultaneous determination of both properties.

It is possible to determine thermophysical properties of a substance by the application of different variants of this method. The AF (amplitude-frequency) variant is based on the registration of the amplitude of temperature oscillations at two different frequencies. The PF (phase-frequency) variant is based on the measurement of the phase of temperature oscillations at two frequencies. The AP (amplitude-phase) variant is based on the measurement of the amplitude and the phase of temperature oscillations at single frequency. All three variants can be used in principle, but in practice, the AP variant is the most convenient one. With this method, our instrument gives a random error of 0.5% in the determination of thermal conductivity, 1.5% for thermal diffusivity, 1.5% in the measurement of the volumetric specific heat, and 1% for the thermal activity. Systematic errors in determination of relative values of these properties result in uncertainties less than 0.5% for specific heat and thermal diffusivity, and 0.3% for thermal activity and thermal conductivity.

A schematic view of the apparatus is shown in Fig. 1. Probe Z_1 is inserted into one branch of a triple-bridge arrangement, consisting of branches A, B, and C. Branch C contains a probe analogous to Z_1, which is held in a vacuum. Heating of the circuit by an ac of frequency ω from generator *1* causes oscillations of the probe resistance with a frequency 2ω. These oscillations render the experimental network nonlinear, and lead to the appearance of combined frequencies $2\omega \pm \omega$. Bridges AB, BC, and AC get balanced at frequency ω, and the balance is monitored by a zero-detector (*7*). Signals of tripled frequency E_1 (representing voltage between points A and B

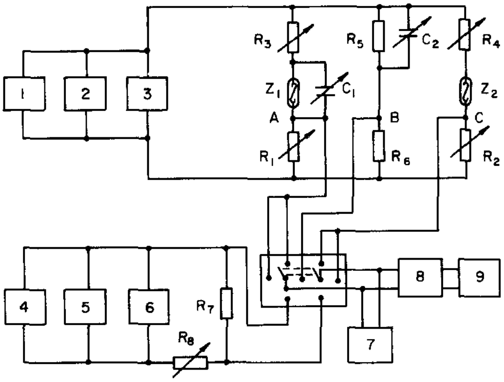

Fig. 1. Schematic diagram of the apparatus.

in Fig. 1), E_2 (voltage between B and C), and E_3 (between A and C) are amplified using an amplifier (*8*) and monitored by a digital voltmeter. Signals are measured by comparison to a reference signal coming from a signal generator (*4*) set at a frequency of 3ω through divider R_7–R_8. The function of the voltmeters (*2*), (*5*), and (*9*) is accomplished by a single digital voltmeter. Frequency meters (*3*) and (*6*) monitor the performance of generators (*1*) and (*4*).

Signal E_1 is directly proportional to the amplitude of the temperature oscillation of the probe θ:

$$E_1 = \alpha V Z_1 \theta R_1 / 2(R_1 + Z_1 + R_3)^3 \qquad (1)$$

Z_1 and α are the average resistance and resistance temperature coefficient of the probe, respectively, and V is the bridge input voltage. To obtain the phase of temperature oscillations, the signals E_1, E_2, and E_3 are measured, and ϕ is calculated from the expression:

$$\phi = \arcsin \{[1 + (E_1/E_2)^2 - (E_3/E_2)^2]/2(E_1/E_2)\} \qquad (2)$$

ϕ is the phase difference between the temperature oscillations and the oscillations of heating voltage. The amplitude and the phase of temperature oscillation of the probe are related to the properties of the substance by [1]

$$\theta = W/[2c'_p m' \omega S(\kappa, \eta)]; \; \phi = \arctan F(\kappa, \eta) \qquad (3)$$

where m' and c'_p represent the mass and the specific heat of the probe, respectively; W is the power of the alternating current; $S(\kappa, \eta)$ and $F(\kappa, \eta)$ are the functions of

$$\kappa = r\sqrt{2\omega/a} \text{ and } \eta = c'_{p'} a/2\lambda$$

and ρ' and r are the density and radius of the wire. The function $S(\kappa, \eta)$ is determined from the values of the signal E_1 obtained with the probe Z_1, placed simultaneously in the liquid and in a vacuum (the vacuum experiment usually carried out first):

$$S(\kappa, \eta) = E_{1\text{vac}}/E_{1\text{liq}}$$

(It is assumed that the bridge input voltages and probe resistance in both experiments, in vacuum and in liquid, are equal.) The properties of the probe that appear in the expressions for κ and η are eliminated with the aid of an

Table I. Results of Measurements of Thermal Conductivity λ, Thermal Diffusivity a, Volumetric Specific Heat $c_p\rho$, and Thermal Activity B for CCl_4 at 20°C

Property	Method variant AF	Method variant PF	Method variant AP	Data of Vargaftik et al. [3]
$\lambda \times 10^3$, W m^{-1}K^{-1}	102	104	103.5	104
$a \times 10^9$, m^{2}s^{-1}	76	78	77	76
$c_p\rho \times 10^{-4}$, J m^{-3}K^{-1}	135	133	135	137
B, J m^{-2}K^{-1}s$^{-1/2}$	371	372	374	378

experiment using a liquid of known properties. For this purpose we have used toluene at 30°C.

The essential feature of the alternating current hot-wire method is the small penetration depth of temperature waves into the liquid. This depth is of the order of 10 μm at the frequencies 10–100 Hz. This fact results in negligible convective effects, with the possibility to accommodate the wire in the cell in any arbitrary way, and the possibility to assume that the probe temperature represents the reference temperature during measurements.

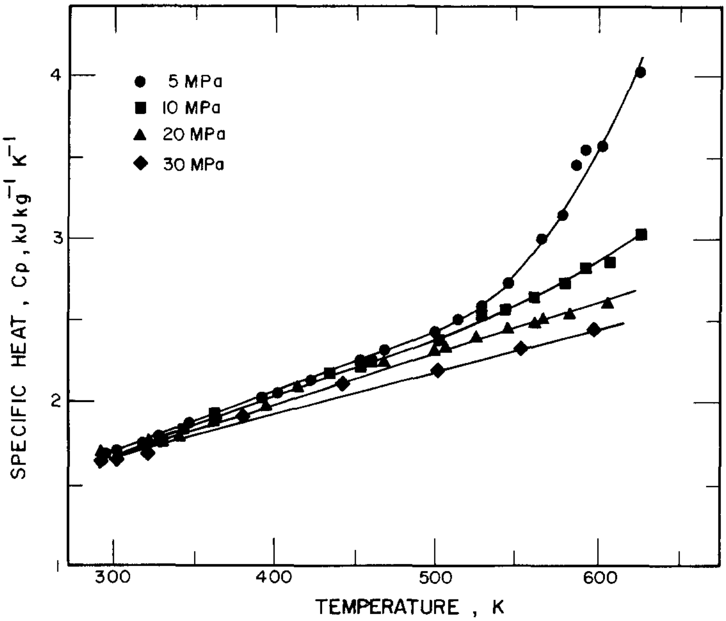

Fig. 2. Results on specific heat as a function of pressure and temperature for toluene.

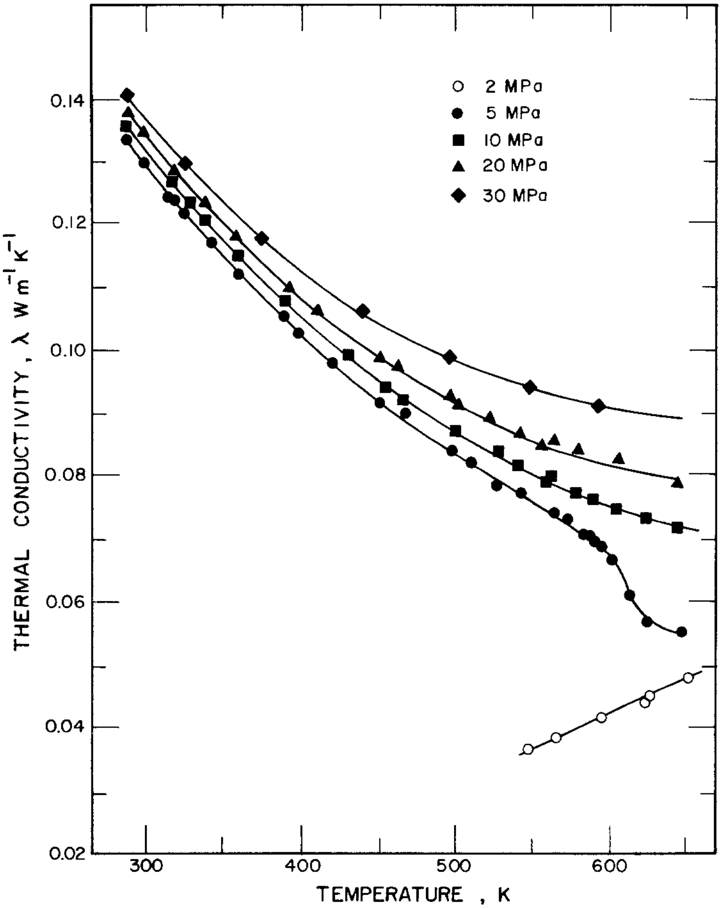

Fig. 3. Results on thermal conductivity as a function of pressure and temperature for toluene.

Another important consequence of the alternating current hot-wire method is that it enables the determination of the conduction component alone, in the absence of radiation heat transfer, which is very difficult to exclude or to estimate in steady state experiments. Solution of the combined conduction-radiation energy transfer problem for the flat foil probe (with the emissivity $1 - R$) heated by an alternating current and placed in a semitransparent substance with index of refraction n and absorption coefficient K (gray medium) shows that the contribution of radiant energy flux to the total heat flux is equal to

$$q_{\text{rad}}/Q_{\Sigma} = (4\delta n^2 \overline{T}^3/\lambda)\sqrt{a/\omega} \cdot H(R, K\sqrt{a/\omega}) \tag{4}$$

where δ is the Stefan–Boltzmann constant, $\overline{T}$ is the average temperature, and $H(R, K\sqrt{a/\omega})$ is a function of R and $K\sqrt{a/\omega}$ ($H_{\max} = H(0, 0) = 0.5$). For organic liquids at room temperature, the radiative contribution is less than a few hundredths of a percent under typical conditions of the experiment ($\overline{T} \sim 300\text{K}$, $\omega/2\pi \sim 20$ Hz or more).

As an illustration, the results of measurements of CCl_4 are presented and compared with literature data in Table I. The measurements were carried out at 20°C, employing different variants of the method. The results of measurements of specific heat and thermal conductivity of toluene at different temperatures and pressure are shown in Figs. 2 and 3. The error of the results of specific heat measurements is 1–2%, and they are in good agreement with the literature data [2]. The error in thermal conductivity measurements is 0.5–1.5%. Thermal conductivity results differ from the literature data at higher temperatures; however, the literature data were obtained basically employing steady state techniques. We believe that the maximum discrepancy between our results and the literature data [3], of about 7% at 160°C, is due to the influence of radiative energy transfer, the investigation of which by using the present method holds much promise.

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