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Measurement of Thermal Properties of Liquids with an AC Heated-Wire Technique

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An apparatus for the simultaneous absolute measurement of the thermal activity, thermal diffusivity, thermal conductivity, and heat capacity of nonconducting liquids with the AC heated-wire (strip) technique is described. The main advantage of this technique is that the temperature oscillations field can be confined around the sensor in a liquid layer thin enough to suppress the hydrodynamic currents. This leads to the elimination of the convective heat transport. Carrying measurements at different frequencies, the inertia of the sensor can be considered, and the radiative heat transport can be estimated for liquids with known optical properties. The apparatus was constructed and tested using six different liquids in a limited temperature range. The thermal properties of these liquids at 20°C are reported. The thermal conductivity data of toluene and *n*-heptane (recommended as proposed thermal conductivity standards) are given in the temperature range 10–40°C. Good agreement was found with data reported by other investigators at 20°C, but there is still a considerable discrepancy in the temperature coefficient of thermal conductivity.

KEY WORDS: AC heated-wire technique; heat capacity; liquids; thermal conductivity; thermal diffusivity.

1. INTRODUCTION

Multiproperty methods for the determination of thermal properties of liquids are very advantageous. Such methods enable the measurement of a group of thermal properties—thermal activity (b), thermal diffusivity (a), thermal conductivity (λ), and heat capacity (C_p) coefficients—in one experiment on the same sample. This is very important for the understanding of the heat conduction process in liquids, the properties of which have no complete

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theoretical interpretation. Matters are more complicated because of the presence of convective and radiative heat transport accompanying the conduction process. In this respect, it is important to develop experimental methods which can suppress the convective transport and at least account for the radiative one [1, 2].

2. THEORY

If a metallic strip is immersed in the investigated liquid, and is heated using AC current of a certain frequency, then a third harmonic signal is developed across this strip. Filippov [3] has shown in detail that the amplitude of temperature oscillations (θ_0) of such a strip is related to the thermal activity ($b = \lambda/\sqrt{a}$) of the investigated liquid according to the following formula:

$$b = \frac{d}{2}\sqrt{\tfrac{1}{2}\left(\frac{W_0}{d\sqrt{\omega}S\theta_0}\right)^2 - 1} - 1, \tag{1}$$

where $d = \sqrt{\omega}\,(\rho C_p)_s h$, W_0 is the power, ω is the angular frequency, S is the area of one side of the strip, $(\rho C_p)_s$ is the heat capacity of the strip material, and h is the thickness of the strip.

The amplitude of temperature oscillations of a wire (θ) is related to the thermal properties of the liquid and the wire heat capacity $(\rho C_p)_s$ according to the following relation:

$$\theta = \theta_0 \left\{\frac{her^2(\chi) + her^2(\chi)}{[\chi\eta hei(\chi) + her^1(\chi)]^2 + [\chi\eta her(\chi) - hei^1(\chi)]^2}\right\}^{1/2} \tag{2}$$

where $\chi = \sqrt{(2\omega/a)}r$, $\eta = (\rho C_p)_s/(2\rho C_p)_\ell$, r is the radius of the wire, ρ is the density, θ_0 is the amplitude of the temperature oscillations of a noninertial strip with the same equivalent surface area, and *her*, *hei*, *her*^{1}, and *hei*^{1} are Kelvin functions and derivatives.

From the analysis of these formulas it was found that measurement of the amplitude of temperature oscillations (θ_0) of a strip, or that of a wire for $\chi > 1$ (where the temperature oscillations of the wire are equivalent to those of a noninertial strip of the same surface area), enables one to determine the thermal activity coefficient alone. Through measurement of θ for values of $\chi = 0.2$–0.4 at two different frequencies (f, nf), where $n = 2, 3, \ldots,$ the factor can be found and, consequently, the thermal diffusivity coefficient can be determined. After that, the thermal conductivity coefficient and the heat capacity can be deduced.

The thickness of the layer of the investigated liquid around the sensor

(δ), where the temperature oscillations are totally absorbed, can be calculated according to [3]: $\delta = 2\pi\sqrt{(2a/\omega)}$. For frequencies of 30–300 Hz and thermal diffusivity values of $10^{-7}\ \mathrm{m}^2 \cdot \mathrm{s}^{-1}$, we obtain $\delta = 50$–$200\ \mu\mathrm{m}$. In such a layer, the hydrodynamic currents are suppressed and convective heat transfer is eliminated. Calculations of the Raleigh number according to [4] give a value of 0.032, which is much less than the given values (600–1000), indicating the onset of convection. Such a small thickness of the liquid layer adjacent to the sensor is another favorable factor of this technique. The sensor need not be thoroughly adjusted in the experimental cell, but just immersed in a small amount of liquid. The possibility of using a small amount of the investigated liquid is an additional desirable feature of this technique.

About the radiative heat transport, once we are concerned only with the measurement of the amplitude of the temperature oscillations, the following formula (derived by Poltz [5] and Filippov [3] for the steady-state parallel plate apparatus) can be used to estimate the radiative part of the thermal conductivity coefficient λ_r as follows:

$$\lambda_r = \frac{16}{3}\sigma n^2 T^3 \phi(\alpha, \delta), \tag{3}$$

where σ is the Stefan-Boltzman constant, n is the refractive index of the liquid, α is the absorption coefficient of the liquid, T is the mean temperature of the liquid, and $\phi(\alpha, \delta)$ is a compound function which accounts for the propagation of radiation in an absorbing medium and is given in [3] as a function of (α, δ) with the reflection coefficient of the walls as a parameter.

Analysis of this formula indicates that the radiative part is 2–5% for the low-absorbent medium at room temperature. For high absorbents it is much less.

Moreover, this formula can be used when the thickness of the liquid layer is equal to or less than the diameter of the sensor, the condition which is fulfilled in this experiment. Nevertheless, it is our objective to obtain a formula which accounts for the physical situation related to the propagation of radiation in an absorbing medium for this technique.

A simple situation is considered where we introduce a correction to the power dissipated by radiation in a totally transparent medium (typical correction for such temperature-wave techniques), of the following form:

$$\frac{\Delta\lambda}{\lambda} = \frac{2\pi r\sigma T^3\theta_0}{W_0}. \tag{4}$$

It may be seen that when $\theta_0/T \ll 1$ ($T = 300$ K, $\theta_0 = 0.1$ K), this correction is negligible. This condition is fulfilled in our experiments. Such a correction was considered in experiments for the measurement of thermal properties of gases at high temperature [6].

3. EXPERIMENT

3.1. Description of the Apparatus

The block diagram of the apparatus used in this work is shown in Fig. 1. A platinum strip (1 × 0.02 mm) and platinum wires (diameters, 20 and 50 μm) were immersed in the investigated liquid in the thermostated experimental cell. The platinum sensor was connected as an arm of an AC bridge. The output voltage of an oscillator (1) via a power amplifier (2) was applied to one diagonal of the bridge. The unbalanced third harmonic signal (e_{3f}) and the current signal were displayed on the oscilloscope (3) for coarse balance of frequency f. Then the third harmonic signal was amplified and displayed by means of amplifier (4) and oscilloscope (5) for final balance using capacitance box (10). The frequency, current, and voltage across the sensor and resistance R and the output voltage of amplifier (4) were measured using sensitive digital meters (6, 9). Oscillator (7), potential divider (8), and meter (9) were used for the measurement of the unbalanced signal, keeping the amplifier (4) input resistance the same. The temperature of the investigated liquid was determined from the sensor resistance (γ), the resistivity (ζ) and heat capacity of the sensor were determined separately, but γ and ζ were rechecked from the experimental results. Analysis of the equivalent circuit

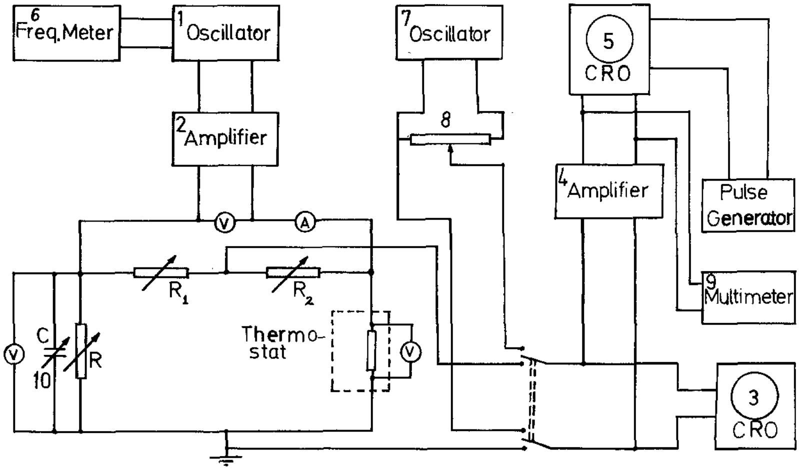

Fig. 1. Block diagram of the apparatus for the measurement of thermal properties of liquids with an AC heated-wire technique.

Table I. Thermal Activity of CCl_4 and H_2O at 20°C (in $W \cdot m^{-2} \cdot s^{1/2} \cdot K^{-1}$)

			CCl_4		
Strip	380	380	378	375	372
Wire	385	381	379	376	375
			H_2O		
Strip	1480	1487	1490	1492	1496
Wire	1486	1491	1495	1498	1501

has shown that the contact resistance of the strip and the internal output resistance of amplifier (4) should be considered.

3.2. Test of the Apparatus

In order to test the described apparatus, six liquids with different but known physical properties were investigated. Our attention was concentrated on the test of the experimental cell to check the presence of convection. It was found that the immersion of the sensor in a layer of the liquid (thickness, 3–4 mm) in the horizontal position gives a very pure and stable third harmonic signal for frequencies above 30 Hz. In Table I, the experimental results of the measurements of thermal activity of CCl_4 and H_2O at 20°C are given using strip (50–90 Hz) and wire (200–600 Hz).

Table II. Thermal Properties of the Investigated Liquids at 20°C

	Benzol	Carbon tetra-chloride	Glycerol	Methanol	Toluene	Water
Thermal activity (b), $W \cdot m^{-2} \cdot s^{1/2} \cdot K^{-1}$						
Strip	473	380	903	644	426	1480
Wire	460	385	908	653	433	14860
Thermal diffusivity (a), $\times 10^7 m^2 \cdot s^{-1}$						
	0.991	0.766	0.899	1.025	0.913	1.420
Heat capacity (C_p), $\times 10^{-3} J \cdot kg^{-1} \cdot K^{-1}$						
	1.710	0.844	2.380	2.523	1.693	3.981
	1.757[a]	0.828[a]	2.259[a]	2.385[a]	1.615[a]	4.184[a]
	1.699[b]	0.850[b]	2.351[b]	2.510[b]	1.661[b]	4.179[b]
Thermal conductivity (λ), $W \cdot m^{-1} \cdot K^{-1}$						
	0.149	0.108	0.205	0.205	0.134	0.560
	0.146[c]	0.103[c]	0.289[c]	0.205[c]	0.136[c]	—
	—	—	—	—	0.135[d]	0.595[d]

[a] Data reported in [7].
[b] Data reported in [11].
[c] Data reported in [3].
[d] Data reported in [1].

The scatter of the experimental data points, which are given in Table I, did not exceed 2% for CCl_4 and 1% for H_2O. This, along with the mentioned stability of the third harmonic signal, indicates that we succeeded in the suppression of the convective heat transport. The results of the measurements of properties for six liquids are given in Table II.

These measurements were performed by varying the experimental parameters (current, frequency, sensor length, etc.). Compared with the data published in [7] and [11], our results for heat capacity show a maximum discrepancy of 6% higher than in [7] for methyl alcohol, but 1% higher than in [11] for benzene and glycerol, and 1% less than in [11] for carbon tetrachloride. For the thermal conductivity coefficient, our results were compared with the available data published in [3] and [1]. A maximum discrepancy of 6% less than in [1] was found for water and 7% less than in [3] for glycerol, but 2% higher than in [3] for benzol, and 2% less than in [3] and 1% less than in [1] for toluene.

The calculated systematic errors of the thermal activity measurements could reach 1.5% for strip and 2% for wire. For thermal diffusivity and heat capacity coefficients, these errors are not more than 2.5%. Maximum errors for the thermal conductivity measurements were 2.2%.

4. RESULTS AND DISCUSSION

The results for thermal conductivity measurements of toluene and *n*-heptane are given in Table III. These two liquids were suggested as thermal conductivity standards [2].

The straight-line fitting of these data gives the following relations: for toluene,

$$(\lambda \pm 0.004)\mathrm{W} \cdot \mathrm{m}^{-1} \cdot \mathrm{K}^{-1} = 0.137 - 1.88 \times 10^{-4}(T - 273.15); \quad (5)$$

and for *n*-heptane,

Table III. Thermal Conductivity ($\mathrm{W} \cdot \mathrm{m}^{-1} \cdot \mathrm{K}^{-1}$) of Toluene and *n*-Heptane

Temperature (°C)	Toluene	*n*-Heptane
10	0.135	0.130
15	0.135	0.129
20	0.134	0.128
25	0.133	0.126
30	0.131	0.126
35	0.131	0.125
40	0.130	0.124

$$(\lambda \pm 0.004)\mathrm{W} \cdot \mathrm{m}^{-1} \cdot \mathrm{K}^{-1} = 0.132 - 2.00 \times 10^{-4}(T - 273.15). \quad (6)$$

The correlation coefficient of the toluene data fitting is $r = 0.977$, which does not support a straight line for seven points as it is outside the level of significance, while for the *n*-heptane data it just touches the required level.

Our results were compared with those reported by Jobst [10], Filippov [3], Nieto de Castro et al. [2], and Ziebland [1]. Near 20°C our results for toluene are 1% less than in [3], 2% less than in [1], 1% more than in [2], and 1% more than in [10]. For *n*-heptane our data are 2% more than in [2].

Although such agreement was obtained, a discrepancy in the temperature coefficient of thermal conductivity (λ) is noticed. This coefficient is important because it is present in many conceptual or semiempirical formulas which describe the behavior of λ with respect to temperature. Such a discrepancy can be explained by the different contributions of convection in a particular experiment; at high temperatures, radiation can also affect the experimental results.

Our calculations for the radiative part of thermal conductivity were carried out according to Eq. (3). The optical properties of the investigated liquids were obtained from [8]. The reduced radiative part (λ_r/λ) in the investigated temperature range was 0.0055% for toluene and 0.005% for *n*-heptane. The correction for the amplitude of the measured temperature oscillations (in a totally transparent medium) was found to be negligible.

Considering the advantages of this technique, further improvement of the accuracy of this apparatus will help analyze the correlation among radiative, convective, and conductive heat transport in liquids in a wide range of temperatures and pressures.

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