NOTATION

$\overline{\lambda}_z(x_0, y_0)$, mean thermal conductivity of the interlayer along a straight line parallel to the z axis and passing through the point (x_0, y_0); $\lambda(x_0, y_0, z)$, current thermal conductivity; λ_1, λ_2, thermal conductivities of the components; λ_{1n}, λ_{2n}, thermal conductivities of components 1 and 2 in the n-th inclusion; δ, thickness of the interlayer; T_0, T_δ, temperatures at the boundaries of the interlayer; z, direction along which the thermal conductivity of the interlayer is defined; n, serial number of inclusions of components 1, 2 along the straight line under consideration; N_1, N_2, number of inclusions of the components; δ_{1n}, δ_{2n}, extent of the inclusions of components 1, 2 along the straight line; ΔT_{1n}, ΔT_{2n}, temperature drop in the n-th inclusion of components 1, 2; ΔT_1, ΔT_2, total temperature drops in the components along the straight line; λ_{mix}, thermal conductivity of the mixture; c_1, c_2, volumetric concentrations of components 1, 2.

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MEASUREMENT OF THE THERMAL ACTIVITY OF LIQUIDS IN THE METASTABLE REGION

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A method of measuring the thermal activity of superheated liquids is described. Transition through the saturation line is effected under isobaric conditions by the pulsed heating of a thin layer of liquid bordering the resistive element used as the heater.

Owing to the instability of liquids in the region beyond the saturation line, any experimental analysis of their properties is very difficult. The specific volumes [1-3] and viscosity [4] of a number of liquids have been measured, but the literature contains no data at all regarding the thermophysical characteristics of superheated liquids. Yet the properties of liquids in this region need to be known for a whole series of theoretical and practical reasons. At present, such data are usually obtained by extrapolating the results obtained in the stable region. The validity of this extrapolation lacks experimental verification.

We have accordingly developed a pulse measuring method in which shock heating of the liquid briefly realizes the superheated state and at the same time enables

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the thermal activity to be measured. The method envisages two successive pulses acting on the resistive element of a thin-film resistive sensor immersed in the test medium, one of which (a pulse of length τ) heats the layer of liquid in contact with the resistive element, while the second (measuring) pulse, of length τ', carries information as to the thermal activity. The resistive element is simultaneously used as a heater and resistance thermometer.

It is well known [5] that in the pulsed heating of a liquid by a steady thermal flux q the temperature of the resistive element (made in the form of a metal strip applied to a dielectric substrate) varies in accordance with the equation

$$T = \frac{q\sqrt{\tau}}{\sqrt{\pi}(\varepsilon + \varepsilon_0)}. \tag{1}$$

If we record the temperature of the resistive element during the period of action of the measuring pulse, we may determine the thermal activity of the liquid under test; the first pulse ensures a controlled transition of the layer of liquid under test into the metastable state.

It is not difficult to see that, when measuring the system with the aid of two pulses, the following conditions should be satisfied in order to reduce the distortions of the temperature field of the measuring pulse by the temperature field of the heating pulse:

$$\frac{dT(\tau)}{d\tau} \Big/ \frac{dT'(\tau')}{d\tau} \ll 1. \tag{2}$$

Considering Eqs. (1) and (2) together and neglecting the dependence of the thermal flux on the degree of heating of the resistive element, and also the temperature dependence of the thermal activity, we may convert Eq. (2) to

$$\frac{T\tau'}{T'\tau} \ll 1. \tag{3}$$

Condition (3) should be supplemented by the inequality

$$\frac{l'}{l} \ll 1. \tag{4}$$

Since $l \sim \sqrt{a\tau}$, condition (4) is equivalent to the requirement that $\tau \gg \tau'$.

The use of thin-film sensors with resistive elements of small thickness enables us to reduce the time of the measuring pulse to the order of 10 μsec [6]. In this case, if the heating pulse is 10-20 μsec long, inequalities (3) and (4) are satisfied quite adequately.

For executing the measurements we used the apparatus illustrated (its main features) in Fig. 1. The apparatus contains the following principal elements: pulse generators G_1 and G_2, a delay unit DU, a measuring bridge, and an S1-15 oscillograph to measure the bridge signals.

The generator G_1 supplies a rectangular current pulse to the bridge circuit; at the same time as this pulse begins, a signal passes to the input of the delay unit. After a time τ the delayed pulse simultaneously triggers the generator G_2, from which a pulse of length τ' is fed to the bridge circuit, and the oscillograph. The information is read by transmitting periodic pulses from the generator G_1. The choice of frequency is determined by the condition that the temperature field should practically vanish in the pause between pulses.

In order to increase the accuracy we used a differential measuring circuit. We connected two cells (measuring and compensating, respectively) to the bridge; these were made in the form of glass vessels filled with liquid and containing thin-film sensors having resistances R_i and R_k. The sensors were made by spraying chromium onto glass substrates. The resistive elements had the following geometrical dimensions: area 20 × 1 mm, thickness of deposit 200-400 μ. The compensation cell was

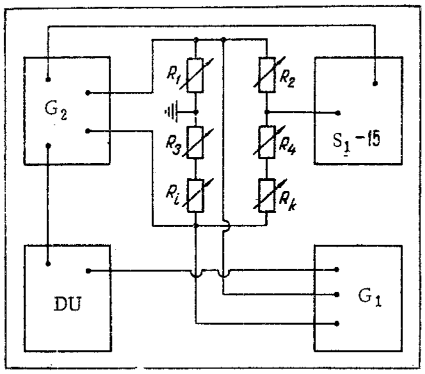

Fig. 1

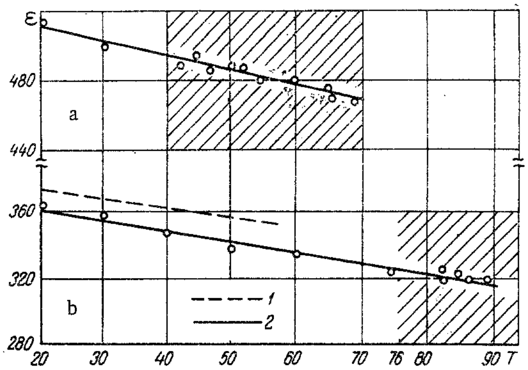

Fig. 2

Fig. 1. Arrangement of the apparatus.

Fig. 2. Coefficients of thermal activity $\varepsilon\,[\mathrm{J}/(\mathrm{m}^2 \cdot \mathrm{deg} \cdot \mathrm{sec}^{1/2})]$ of CCl_4 and CH_2Cl_2 as functions of temperature, °C: 1) published data; 2) experimental data; a) methylene chloride; b) carbon tetrachloride.

filled with Vaseline oil and thermostated at 20°C; the measuring cell was filled alternately with the test liquid and a standard substance. The measuring cell was thermostated at a temperature close to the equilibrium boiling point of the test liquid.

Let us consider the sequence of measurements. First the measuring cell is filled with the standard liquid. During the action of the pulses complete balance of the bridge circuit is established, i.e., balance with respect to both dc and ac voltages. Complete balance is achieved over a time interval corresponding to the length of the measuring pulse by varying the resistances R_1 and R_3. Calculation of the bridge circuit shows that, on establishing this balance, the following equation is obeyed:

$$\frac{R_i(t)}{R^3_{1\,\mathrm{st}}(t)\,[\varepsilon_0(t)+\varepsilon_{\mathrm{st}}(t)]} = \frac{R_k}{R_2^3(\varepsilon_0+\varepsilon_k)}\,. \tag{5}$$

After balancing the circuit the resistance R_1 is recorded.

The temperature increment of the resistive element as the heating pulse passes is determined as follows. Replacing R_k by the constant resistance R_6, equal to the resistance of the compensating sensor at room temperature, and operating with the measuring pulse only, using the oscillograph as an indicator, we make the beginning of the signal from the bridge circuit coincide with the zero line of the oscillograph. We make a note of the resistance R_1. On operating with two pulses (heating and measuring), the beginning of the signal is displaced as a result of the heating of the sensor by the heating pulse. By changing the resistance R_1 (ΔR_1) we may restore the beginning of the signal to the zero line. In view of the fact that the parameters of the compensating arm are chosen so as to satisfy the relation $R_2/(R_4 + R_6) = 1$, we have $\Delta R_1 = \Delta R_i$, where ΔR_i is the increment in the resistance of the measuring sensor due to heating by the heating pulse. Correspondingly, the magnitude of this heating is $T = \Delta R_i/\alpha R_{i0}$ and the temperature of the sensor is $t = t_0 + T$.

The same sequence of operations, with the same experimental conditions (t_0, pulse voltage amplitudes, pulse length, and delay time), is then carried out after placing the measuring sensor in the liquid under test.

By analogy with (5), the condition for the complete balancing of the bridge may be written in the form

$$\frac{R_i(t^*)}{R_1^3(t^*)\,[\varepsilon_0(t^*)+\varepsilon(t^*)]} = \frac{R_k}{R_2^3(\varepsilon_0+\varepsilon_k)}\,. \tag{6}$$

Since the right-hand sides of Eqs. (5) and (6) remain constant during the experiments, we may equate their left-hand sides:

$$\frac{R_i(t)}{R_1^3(t)\,[\varepsilon_0(t)+\varepsilon_{st}(t)]}=\frac{R_i(t^*)}{R_1^3(t^*)\,[\varepsilon_0(t^*)+\varepsilon(t^*)]}. \quad (7)$$

Equation (7) gives the relationship for computing ε:

$$\varepsilon(t^*)=[\varepsilon_0(t)+\varepsilon_{st}(t)]\left[\frac{R_1(t)}{R_2(t^*)}\right]^3\frac{R_i(t^*)}{R_i(t)}-\varepsilon_0(t^*). \quad (8)$$

This method was employed to study the thermal activity of certain low-boiling-point organic liquids: CCl_4 (equilibrium boiling point T_s = 76.7°C) and CH_2Cl_2 (T_s = 40°C). The liquids were of the analytically pure type. The durations of the heating and measuring pulses were, respectively, τ = 15 msec and τ' = 50 μsec. The heating of the sensor due to the action of the measuring pulse was no greater than 5°C. The depth of penetration into the metastable zone was 40°C. The standard liquid was analytically pure toluene T_s = 110°C.

The results of the measurements are presented in Fig. 2. The thermal-activity coefficients in the stable region obtained experimentally by the method under consideration are in satisfactory agreement with published data for CCl_4 [8, 9].

In estimating the experimental error we must remember both the errors associated with the deviation of the real physical model from the idealized one (the intrinsic heat capacity of the resistive element, boundary effects, the actual nonlinearity of the thermal problem), the apparatus errors, and the error associated with determining the ε of the substrate. The thermal activity of the substrate was determined by the pulse method [5] in the temperature range 20-110°C. The thermal-activity coefficients ε of the glass substrate of the sensor for t values of 20, 30, 40, 50, 60, 70, 80, 90, 100, 110°C were, respectively, 1520, 1530, 1545, 1560, 1575, 1590, 1605, 1620, 1635, 1650 $J/(m^2 \cdot deg \cdot sec^{1/2})$. Toluene was the standard liquid. The error in the determination of ε_0 was 2%.

An additional source of error is that due to the existence of a transient thermal field created by the heating pulse. Corresponding calculations show that the total error arising from all these factors is no greater than 3%.

The foregoing results show that, for the depths of penetration into the metastable region achieved in the case of the test liquids studied here, the thermal-activity values lie neatly on the straight line extrapolated from the stable region.

The depth of penetration into the metastable region in our measurements was limited by the thermal flux evolved in the resistive element. The maximum degree of superheating of the liquid, especially under conditions of shock heating [10], is determined by the spontaneous nucleation frequency. The latter quantity is characterized by a substantial temperature dependence, and on reaching a certain degree of superheating the number of vaporization centers "avalanches" over a narrow temperature range, initiating explosive boiling. However, the attainment of the explosive boiling temperature may be impeded by the existence of vaporization centers of artificial orgin, in which the liquid boils without reaching the explosive point. According to [10], explosive boiling may be achieved by shortening the heating pulse.

NOTATION

τ, duration of heating pulse; τ', duration of measuring pulse; q, thermal flux; T, heating of the resistive element due to the heating pulse; ε_0, thermal activity of the substrate; ε, thermal activity of the test liquid; T', heating of the resistive element under the influence of the measuring pulse; l, depth of penetration of the temperature field created by the heating pulse; l', depth of penetration of the temperature field created by the measuring pulse; a, thermal diffusivity of the liquid; R, resistance; t_0, temperature at which the measuring cell is thermostated; t, temperature of the sensor after the action of the heating pulse in the standard liquid; t^*, temperature of the sensor after the action of the heating pulse in the test substance; ε_k, thermal activity of the liquid in the compensating cell; ε_{st}, thermal activity of the standard liquid; α, temperature coefficient of the resistance of the measuring sensor.

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THERMAL CONDUCTIVITY OF AQUEOUS SOLUTIONS OF NaCl

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We present the results of an experimental study of the thermal conductivity of aqueous solutions of sodium chloride at concentrations of 5, 10, 15, 20, and 25% NaCl over the temperature range 20-330°C.

At the present time, the problem of seawater and saline-water use in industry is aquiring real importance. Up to this time, however, reliable experimental data on the thermophysical properties of saline water over a broad range of temperatures and salt concentrations is lacking. As is well known, seawater has a rather complex salt and gas composition. The main part of the ionic component is chlorine and sodium (about 78% of all salts),which characterize the hydrochemical nature of seawater by their presence and lend great importance to the study of the thermophysical properties of aqueous solutions of sodium chloride as a basic component of seawater. Studies of aqueous solutions of electrolytes may prove to be fruitful for studies of the structure of liquids and of the nature of the thermal motion of their particles.

The structure of the solvent, i.e., water, plays a decisive role in the determination of the properties of electrolyte solutions. At the present time, the theory of Samoilov [3] has received the greatest recognition of all the numerous models of the structure of liquid water. According to [18], the thermal conductivity of water, to a first approximation, is defined as the sum of the thermal conductivity of a quasicrystalline framework and the thermal conductivity of a system of molecules located inside voids within the framework which move through the system of voids. The main contribution to the total thermal conductivity is made by the thermal conductivity of the framework, which decreases as the temperature increases, as it does in ice. The anomalous rise in the thermal conductivity of water in the range 0-130°C is explained by the positive contribution from the thermal conductivity of the system of molecules in the voids. Where movement of molecules within voids is made difficult by small passages between voids in the structure of ice [3], the passages increase in size in the liquid phase as the temperature rises and the thermal motion of the molecules in the voids increases. Further rise in temperature produces a reduction of short-range order through which the thermal conductivity of the molecular system within the voids is reduced and becomes small in comparison with the thermal conductivity of the framework [18].

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