POSSIBILITY OF MEASURING THERMOPHYSICAL PROPERTIES OF LIQUIDS IN FLOWS BY THE PERIODIC HEATING METHOD

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The possibility of using the periodic heating method to measure thermophysical properties of liquids in flows is demonstrated.

The necessity of measuring thermophysical properties of materials during development and refinement of technological processes and apparatus as well as during chemical production requires the development of methods which permit measurements of liquids in flows. The periodic heating method may be used for this purpose. A unique feature of this method, the short temperature wave damping length, ensures that the flow will have negligible effect on measurement results over a certain velocity range. The same fact is responsible for the weak effect of the flow produced by convection (a special case of flow hydrodynamics), a factor which often complicates measurement of the thermal conductivity of gases and liquids.

The periodic heating method is one of a number of promising techniques for study of the thermophysical properties of liquids [1-4]. It consists of recording the temperature oscillations of a thin platinum wire heated by an ac current. The amplitude and phase of wire temperature oscillations depend on the thermophysical properties of the liquid in which it is immersed (the thermal conductivity λ and heat capacity per unit volume $c_p\rho$). Amplitude and phase measurements by radio techniques permit determination of the thermophysical characteristics.

As the probe is heated by the ac current, aside from the pulsation component of the temperature which is used to determine the thermophysical properties, it is unavoidable that a constant temperature head develops in the probe relative to the cell walls. The frequency ν of the temperature oscillations ($\nu \geqslant 40$ Hz) is relatively high, while the time for establishment of convection, 1-10 sec, is many times greater than the characteristics time of the process, $\tau = 1/\nu$, and therefore the temperature oscillations cannot set a liquid at rest into motion. The value of the constant temperature head may vary from several tenths of a degree to several degrees depending on experimental conditions. In the latter case it is difficult to avoid convective flow. In [5] experiments were performed in cells of various diameters with varying mean temperature heads so that the value Pr Gr varied over a range of almost 100 : 1. Up to Pr Gr $\sim 10^5$ convection had no effect on the measurement results. In [6] it was suggested that the small effect of convection in the periodic heating method might be expected due to the presence of a boundary layer which develops when the liquid flows along the probe surface: if the temperature wave damping length is less than the thickness of the boundary layer, then practically immobile liquid is tested.

A special experiment was performed to determine the limits at which hydrodynamic flow begins to affect measurement results and to verify the proposal referred to above. A wire probe ($2r \sim 5$ μm, $L \sim 2$-3 cm) was placed in a tube with diameter $D \sim 6$ or 8 mm, 3-4 m long. The probe was oriented along the tube axis, but not placed under great tension, nor were special measures taken to ensure centering of the probe, which corresponds to real experiment conditions for measuring thermophysical properties. The liquid used was iso-octane (with the exception of one experiment with n-pentane) at a temperature of ~ 298°K. The mean velocity over tube section was determined from the mass flow rate of the liquid.

Results of temperature oscillation amplitude and phase measurements as a function of flow velocity, normalized to corresponding values in a medium at rest, are shown in Fig. 1.

Figure 2 shows temperature pulsation amplitudes at four with increase in velocity the temperature pulsation amplitude $|\vartheta|$ slowly increases, reaching a maximum which exceeds the

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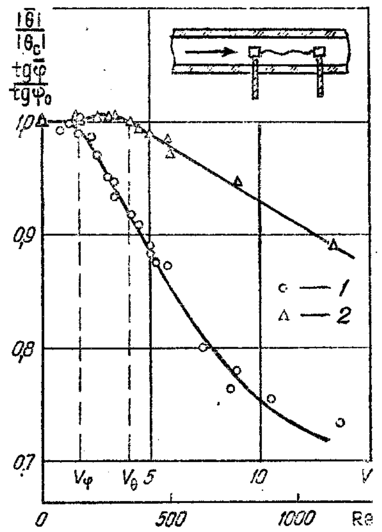

Fig. 1

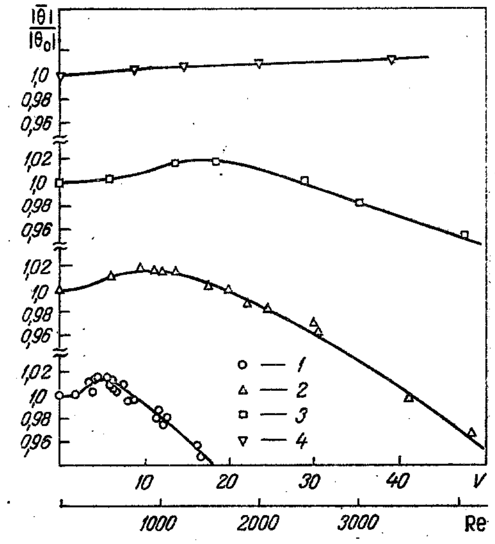

Fig. 2

Fig. 1. Diagram of experimental apparatus and measurements of relative pressure pulsation amplitude $|\bar{\theta}|/|\theta_0|$ (2) and phase angle $\tan\bar{\varphi}/\tan\varphi_0$ (1) versus flow velocity V (cm/sec) and Reynolds number Re.

Fig. 2. Relative probe temperature pulsation amplitudes versus flow velocity V and Re for various frequencies: 1) 23.3 Hz; 2) 70.1; 3) 119.0; 4) 230.3 Hz.

value $|\theta_0|$ for the liquid at rest by 0.5-2%, and then begins to fall off relatively rapidly. For the tangent of the temperature oscillation phase $\tan\varphi$ (φ characterizes the lag of the temperature oscillations relative to the phase of the power introduced into the probe) the value is constant over a certain velocity range, after which $\tan\varphi$ begins to decrease with increase in flow velocity. The velocity V_φ at which the phase angle begins decrease is much lower than the corresponding velocity V_θ for temperature pulsation amplitude. These limiting velocities increase with increase in temperature pulsation frequency. Experiments were performed with various probes and vertical and horizontal orientations of the tube. There was some difference in velocities V_φ and V_θ and the slopes of the curves $|\bar{\theta}|/|\theta_0| = f_1(V)$ and $\tan\bar{\varphi}/\tan\varphi_0 = f_2(V)$ for velocities above V_θ and V_φ, which is apparently connected with some difference in the probe position relative to the direction of flow in each individual experiment. However, the principles enumerated above were confirmed in all cases.

In order to show the correspondence of the principles observed with the explanations offered above, we will consider a simplified problem modeling the existence of a boundary layer. Let the probe wire be located in a layer of liquid at rest of thickness δ, while due to motion of the liquid, the medium beyond this layer is thermally stabilized, i.e., outside the layer the temperature pulsation amplitude is equal to zero. Thus, it is necessary to find a solution of the thermal conductivity equation for the complex temperature pulsation amplitude [6]

$$\frac{\partial^2\theta}{\partial x^2} = \frac{2i\omega}{a}\theta. \tag{1}$$

The boundary conditions at x = 0 are the equation of thermal balance for the wire, reflecting the fact that the power dissipated in the wire W_0 by the electrical current of frequency ω is expended in heating the probe and is removed from its surface by a thermal conductivity

$$\frac{W_0}{s} = \frac{2c'_p m'\omega}{s} i\bar{\theta} - 2\lambda \left.\frac{\partial\theta}{\partial x}\right|_{x=0}; \; \bar{\theta} = \theta(0). \tag{2}$$

The second boundary condition will be equality to zero of temperature pulsation amplitude on the boundary of the layer $\theta(\delta) = 0$. Solution of Eq. (1) leads to the following expression for the complex amplitude of the wire temperature pulsations:

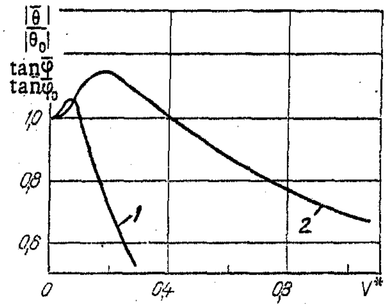

Fig. 3

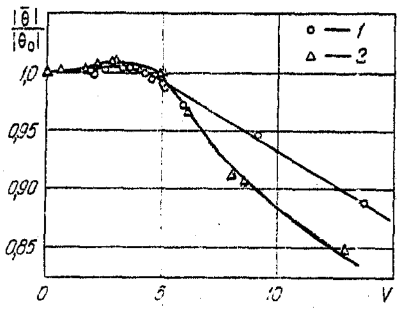

Fig. 4

Fig. 3. Relative temperature oscillation amplitude and phase versus dimensionless flow velocity V*, corresponding to Eqs. (4), (5): $|\bar{\theta}|/|\theta_0|$ — 2; $\tan\bar{\varphi}/\tan\varphi_0$ — 1.

Fig. 4. Measurements of relative probe temperature oscillation amplitudes versus flow velocity V for iso-octane (1) and n-pentane (2).

$$\bar{\theta} = \frac{W_0}{2s\sqrt{\omega}}\left\{di + b(1+i)\frac{1+\exp[-(1+i)z]}{1-\exp[-(1+i)z]}\right\}^{-1} \quad (3)$$

($z = 2\sqrt{\omega/a}\delta$), from which there follow expressions for the amplitude $|\bar{\theta}|$ and phase $\tan\varphi$ of the temperature oscillations:

$$|\bar{\theta}| = \frac{W_0}{2s\sqrt{\omega}\,b\sqrt{A^2(z)+B^2(z)+2B(z)\xi+\xi^2}}, \quad (4)$$

$$\mathrm{tg}\,\bar{\varphi} = -\frac{B(z)+\xi}{A(z)}, \quad (5)$$

where

$$A(z) = \frac{1-\exp(-2z)+2\exp(-z)\sin z}{1+\exp(-2z)+2\exp(-z)\cos z};$$

$$B(z) = \frac{1-\exp(-2z)-2\exp(-z)\sin z}{1+\exp(-2z)-2\exp(-z)\cos z}; \quad \xi = \frac{d}{b};$$

the quantity d characterizes the thermoinertial properties of the probe. If we identify the quantity δ with some effective boundary layer thickness, then the dependence of δ on flow velocity will have the form $\delta \sim 1/\sqrt{V}$ [7]. Considering this, we will assume that $z = 1/\sqrt{V^*}$, where $V^* = V/V_M$ is the dimensionless velocity; V_M is the velocity scale factor, which aside from frequency depends on a number of other factors which are difficult to define without solving a more precisely formulated problem. The dependence on V* of the quantities $|\bar{\theta}|/|\theta_0|$ and $\tan\bar{\varphi}/\tan\varphi_0$ at $\xi = 0$ is shown in Fig. 3, whence it is evident that this quite coarse model properly describes the principles observed in experiment: over the limits of some velocity interval neither $|\bar{\theta}|$ nor $\tan\bar{\varphi}$ are dependent on V*. For $|\bar{\theta}|$ there is a maximum, with a significantly weaker one in $\tan\varphi$ (the appearance of maxima can be explained as the result of reflection of a temperature wave from the boundary of the layer). The frequency dependence of the curves is determined by the fact that $V_M \sim \omega$, i.e., the maxima are shifted toward higher velocities in direct proportion to the frequency (at $\xi > 0$ the maxima decrease somewhat, spread out, and shift to the right, while the dependence of their positions on probe heating frequency becomes more complex).

It should be noted that the maxima of the curve $|\bar{\theta}|/|\theta_0| = f_1(V)$ at a frequency of $\sim$ 23 Hz correspond to Reynolds numbers much less than the critical value Re $\sim$ 2000, so that the observed phenomena are not related to flow turbulization.

The quantity δ, which defines the velocity interval over which the effect of the hydrodynamic flow on temperature pulsations is insignificant, must be related to the thickness of the temperature, rather than the dynamic, boundary layer. This is indicated by the general considerations stated above. It is outside of this temperature layer that the liquid has an unperturbed temperature, the temperature of the flow incident on the probe, i.e., the boundary of the temperature layer is the thermostabilization line of the model considered above, beyond which thermal perturbations from the probe do not penetrate. This is also indicated by experiment. In one of the experiments n-pentane was used instead of iso-octane. At one end and the same flow velocity the ratio of dynamic boundary layer thickness to the temperature wave damping length $z = 2\delta/l$ ($l = \sqrt{a/\omega}$ is the temperature wave damping length) for iso-octane is ∿ 1.5 times greater than for pentane. Therefore the velocity V_θ at which a maximum is observed in $|\theta|$ for pentane would be markedly less than for iso-octane, if δ were identified with the dynamic boundary layer thickness. In fact, the velocities V_θ are approximately equal (Fig. 4), corresponding to the fact that the quantity δ which defines the dependences is the thickness of the temperature layer.

Thus, if we take as the limit V_φ, then in the velocity range $0-V_\varphi$ the periodic heating method will allow measurement of thermophysical properties of liquids in flows. Under the conditions studied here at ∿ 23 Hz V_φ is ∿ 1.5 cm/sec, and depends, in particular, on the ratio of the temperature boundary layer thickness to the temperature wave damping length. The useful velocity range can be extended by increasing the operating frequency. The uncertainty in measuring thermal conductivity λ in the flow is estimated to be ∿ 2-3%, while that in heat capacity per unit volume $c_p\rho$ ∿ 4-6%, so that in this respect the periodic heating method is equal to the method specially developed for measurement of liquid thermophysical properties in a laminar flow regime [8]. The studies performed also indicate the possibility of using the method for measurement of thermal conductivity under developed convection conditions, for example, in study of the region adjacent to the critical point of a material, in which it is difficult to avoid convection.

NOTATION

λ, thermal conductivity; c_p, specific heat; ρ, density; a, thermal diffusivity; $b = \sqrt{\lambda c_p \rho}$, thermal activation; $d = \sqrt{\omega} c_p' \rho' h$, parameter characterizing thermoinertial properties of foil; c_p', specific heat of foil; ρ', foil density; h, foil thickness; r, radius of wire probe; L, probe length; $\overline{\theta}$, θ_0; $\overline{\varphi}$, φ_0, complex amplitudes and phases of probe temperature oscillations in moving and at-rest liquid; s, area of one side of foil; ω, cyclical frequency of electrical current exciting probe; W_0, probe heater power; V, mean liquid flow velocity over section; $Re = \rho V D/\eta$, Reynolds number; D, tube diameter; η, viscosity.

LITERATURE CITED

1. L. P. Filippov, S. N. Nefedov, S. N. Kravchun, and E. A. Klykhalova, "Experimental study of the complex of liquid thermophysical properties," Inzh.-Fiz. Zh., 38, No. 4, 644-649 (1980).
2. F. G. Él'darov, V. M. Shul'ga, and C. B. Kiselev, "Compensation method of measuring liquid thermophysical properties at low temperatures," in: VI All-Union Conference on Thermophysical Properties of Materials. Summaries of Reports [in Russian], ITMO Akad. Nauk SSSR, Minsk (1978), pp. 75-76.
3. A. A. Varchenco, "Measurements of thermal properties of liquids by the method of radial temperature waves," in: Thermal Conductivity, Proc. 15th Int. Conf., New York—London (1978), pp. 255-260.
4. S. R. Attala, A. A. El-Sharkawy, and F. A. Gasser, "Measurement of thermal properties of liquids with an ac heated wire technique," Int. J. Thermophys., 2, No. 2, 155-162 (1981).
5. S. N. Nefedov, "Methods for study of liquid thermophysical properties," Candidate's Dissertation, Moscow (1980).
6. L. P. Filippov, Study of Liquid Thermal Conductivity [in Russian], Moscow State Univ. (1970).
7. H. and K. Schlichting, Boundary Layer Theory, McGraw-Hill (1968).
8. V. V. Vlasov, M. V. Kulakov, S. V. Ponomarev, and S. V. Mishchenko, "On the question of using laminar regime methods to measure liquid thermophysical properties," in: VI All-Union Conference on Thermophysical Properties of Materials. Summaries of Reports [in Russian], ITMO Akad. Nauk SSSR, Minsk (1978), pp. 79-80.