APPLICATION OF PULSE HEATING METHOD FOR VARIOUS THERMAL STUDIES

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An experimental device is described, which uses the pulse heating method for a low-inertia transducer with an automatic system of information gathering and processing. The possibility of measuring the thermal conductivity of the liquid, gaseous, and solid materials by linear and planar transducers is shown. The thermal conductivity of n-tetracosane at the phase transition is measured. A method of measuring the thickness of layers is proposed.

Introduction. The main trends in development of thermal measurements are a) increasing use of fast methods that permit research under conditions not accessible to conventional methods; b) miniaturization of measuring cells and apparatus; c) introduction of systems with automatic data acquisition and processing. The pulse heating method of transducer combined with automatic acquisition of the original experimental data and their statistic processing satisfy these trends to a considerable extent. This method is a nonstationary method based on use of the following equation [1]:

$$\frac{\partial T}{\partial \tau} - a\nabla^2 T = 0 \qquad (1)$$

with appropriate boundary conditions for a particular problem. The solution of this equation carries information on the space-time variations of the temperature field. In this connection the nonstationary methods make it possible in principle, to determine both thermal conductivity and other thermal properties of materials as well, i.e., the thermal conductivity, the ratio of heat intensity, and the isobaric thermal heat capacity for a unit volume [2].

1. Description of the Experimental Apparatus. The main idea of measurement by the pulse heating method is in the short-term heating of a low-inertia transducer placed in the fluid being studied, and in the determination of its temperature change with time. For realization of this principle of measurement an experimental plant [3] was created, but supplemented with an automatic system of information gathering and processing [4]. Figure 1 shows the functional scheme of the experimental plant.

The resistance of transducer R_H (Fig. 1) was incorporated in the bridge scheme. Power supply was from a direct current storage cell E. The optron and transistor switch formed the pulse voltage. The optron decouples the defining circuits from the bridge scheme. Resistors R1-R4 are the low-induction magazines of P483011 resistance with 0.02 accuracy rating. The pulse duration (5-500 msec) is set from the keyboard of the BK-0010 personal computer. The disbalance voltage of the bridge scheme is determined by the analog digitizer ATsP F-4223 with an accuracy rating of 0.25. The amplifier and normalizer U matches the voltage disbalance levels of the bridge to the upper limit of ATsP range. The amplifier consists of the thermostatic normal element NE 303 with an accuracy rating of 0.02. The gain ratio of the amplifier is determined automatically before each reading with the help of the normal element. The computer is connected with the optron and transistor switch K1, the gercon switch K2, and the ATsP via the matching unit MU. The K2 switch is necessary for current measurement or voltage measurement.

On the diagonally opposite pair of junctions of the bridge 20 values of the disbalance voltage are measured during one heating pulse of the transducer. The K2 switch automatically switches after that; during the second heating pulse the current I going through the transducer is measured. The current is measured by the ACP and the reference coil of the resistor R5, meant for 1 Ω (R324 mark, accuracy rating of 0.002).

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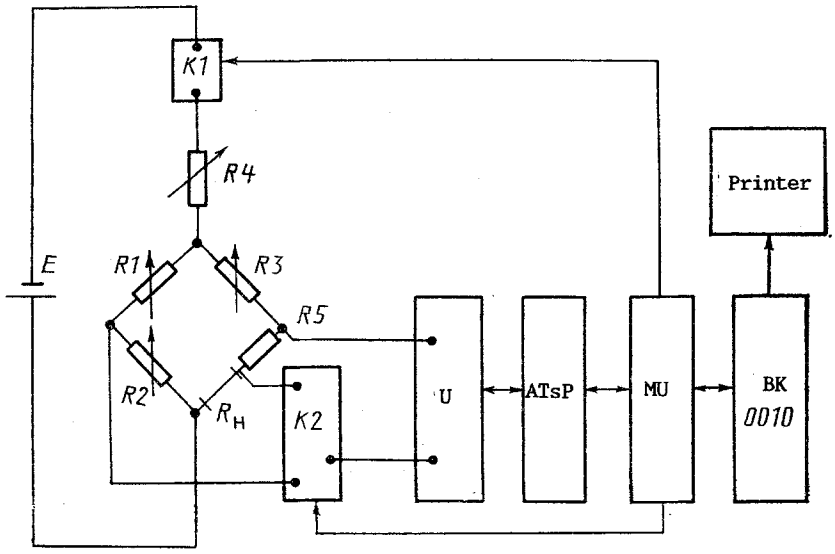

Fig. 1. Scheme of unit.

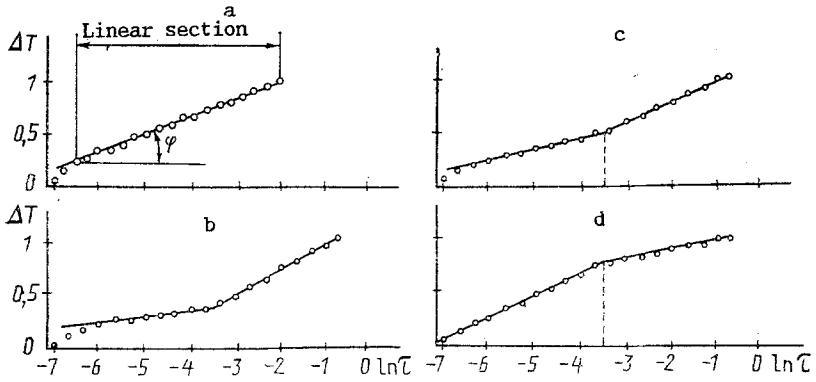

Fig. 2. ΔT and ln τ relation: a) linear transducer under n-tridecane conditions, where T = 298 K; b, c, d) planar transducer with Lavsan backing; T = 295 K in air (b), in n-hexane (e), and between the quartz glass plates (d). ΔT, K; τ, sec.

The automatic system of measurements can be operated in a cyclic mode. By the computer's command the optron switch forms a given quantity of pulses and the sequential measurement of every cycle of survey is performed. Statistical processing of results takes place after the information is gathered. The received 20 disbalance voltage values of the bridge scheme are converted to the transducer's resistance increment ΔR and then to the temperature increment ΔT. The ΔR to ΔT convertion is done according to the equation obtained from the results of calibration of the transducer. The calibration was done using the model reference platinum thermometer with the resistance of PTS10. The error in the value of the temperature is ± 0.01 K. ΔT allows a correction for deviations from the theoretical model (influence of the transducer's thermal heat capacity, change in the length of the transducer with temperature, emission from the surface of the transducer). The sum of all the corrections evaluated according to [5] for all the measurements does not exceed 2%.

The computer displays the thermograph $\Delta T = f(\ln \tau)$ (Fig. 2) of the calculated ΔT values. The subsequent processing of the thermograph is made according to the applicable equations depending on the type of transducer (linear or planar). The computer does the calculations in accordance with the program, and displays and prints the tables of results.

2. Measurement of the Thermal Conductivity by the Linear Transducer. A platinum wire with the radius 2.5 μm and length of $L = 36 \cdot 10^{-3}$ m is used as the linear transducer for measurement of the thermal conductivity. This transducer, connected to the scheme (Fig. 1), realizes the infinite linear constant power source of the radial thermal flow q.

From Eq. (1), under the applicable initial and limiting conditions, it is possible to obtain an expression to determine the λ of the material in which the transducer is submerged [3]:

$$\lambda = \frac{q}{4\pi} \frac{1}{\operatorname{tg}\varphi}. \quad (2)$$

The value of tan φ is determined automatically on the computer according to the thermograph (Fig. 2a) and using the least squares method after the skeleton of the linear section.

The thermal conductivity of the Ch mark n-tridecane at T = 294-370 K and P = 0.1 mPa was measured. The heating pulse duration was not more than 100 μsec. With this, the depth of the temperature wave's penetration into the examined liquid was very small (hundredths of a millimeter); this is why the thin layers can be considered transparent to infrared emission.

The correction for the emission was made as for transparent conditions [5], and at 370 K it was not more than 0.01%. Thus this method of measuring allows one to obtain data on the molecular thermal conductivity of the semitransparent materials, i.e., materials not distorted by the radiation heat transfer [6, 7]. The measurement error does not exceed 1% [3]. The thermal conductivity of n-tridecane was measured in two ways. First, time the temperature of the examined medium was kept constant (these data are circled on Fig. 3). Second, the cell's temperature was changed (decreased) at an approximate rate of 1 K/min. The discrepancies between the results of these two measurements do not exceed 0.5%. They agree well with experimental results [8, 9] obtained by the methods of periodic heating and pulse heating of a thin wire. Therefore, the use of the automatic system for the initial data gathering and processing at short (less than 100 μsec) periods of heating of the transducer allows one to depart from the precise thermostating of the measuring cell.

3. Measurement of the Thermal Conductivity by the Planar Transducer. A metal film of small thickness serves as the transducer; it is connected with two semibounded media; one is the backing covered by the film, and the other is the examined medium. The film is heated up under the pulse voltage. It is possible to ignore the finiteness of the width and the length of the film and consider the problem as single-valued, because of small durations of the heating pulse. Then the solution of the Eq. (1) gives a formula to determine the thermal conductivity of the material in which the transducer is installed [10]:

$$\lambda = \frac{q}{2\pi} \frac{1}{\operatorname{tg}\varphi} - \lambda_b, \quad (3)$$

where q and tan φ are determined the same way as for Eq. (2). With this the thermal conductivity λ_b of the backing should be known. When the backing is not used, the metal film contacts via both sides with the examined medium, $\lambda_b = \lambda$, and Eq. (3) transforms into Eq. (2).

The Lavsan film is used as the planar transducer. One of its surfaces is vacuum coated by aluminum with a thickness of 200 Å. Then a strip of 1 mm width and 100 mm length was cut from that film. The resistance of the aluminum layer on the film was close to 200 Ω at room temperature. The planar transducer was calibrated in the same way as the linear transducer. The transducer was placed in the medium under study. In our case it was placed in turn in air and in n-hexane, and was clamped between two quartz glass optical plates (glass mark KV). The current value was chosen so that the transducer's overheating was 1 K at the end of a 500 μsec duration pulse. The thermograms obtained for the mentioned materials under 295 K are shown in Fig. 2b, c, d. It is obvious that all the thermographs show a characteristic bend. This fact has the following explanation. The temperature wave from the heated metal film extends both to the material studied and to the Lavsan film. From the current pulse, beginning through a certain period of time the thermal wave crosses the Lavsan film and begins to extend to the medium studied. Thus, the first part of the thermograph (Fig. 2b, c, d) before the bend characterizes the sum of the thermal conductivities of the medium λ and the backing λ_b according to Eq. (3). The second part of the thermograph (after the bend) characterizes the thermal conductivity of the medium only. The λ_b values are in the reference literature. In [11] λ_b = 0.152 W/(m·K) for Lavsan at 297 K. It is possible to determine the λ_b value experimentally by measuring the thermal conductivity of the well studied material, for example n-hexane (Fig. 2c). It is known that the molecular thermal conductivity of n-hexane equals 0.119 W/(m·K) at 295 K. Let us calculate the sum $\lambda + \lambda_b$ = 0.270 W/(m·K) from the first section of the thermograph (Fig. 2c) using the Eq. (3). From here λ_b = 0.151 W/(m·K), which agrees with the experimental data. Using the calculated λ_b value in Eq. (3) and the first section of the thermograph (Fig. 2b, d) we determine the air's thermal conductivity λ =0.0255 W/(m·K) and the quartz glass thermal conductivity λ = 1.39 W/(m·K) at 298 K. The recommended value of the air's thermal conductivity is given in [7] and equals 0.0258 W/(m·K). The recommended thermal conductivity of the mark KV quartz glass is given in [12] and equals 1.36 W/(m·K). Satisfactory agreement is obvious.

We obtain λ = 0.0257 W/(m·K) for air, λ = 0.120 W/(m·K) for n-hexane and λ = 1.35 W/(m·K) for quartz glass using the second thermograph sections and Eq. (2). These values agree with above data. The error of measurement of the thermal conductivity using this method is 1.5-2% for the second thermograph section and 2-3% for the first section.

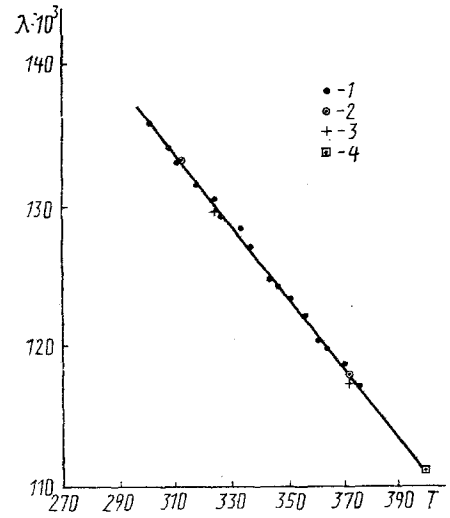

Fig. 3. λ and T relation for n-tridecane at P = 0.1 MPa: 1, 2) data of the authors, 3) [9], 4) [8]. λ, W/(m·K), T, K.

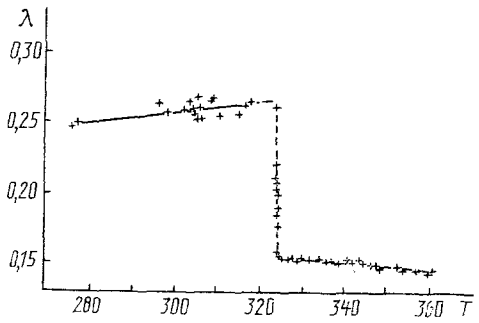

Fig. 4. λ and T relation for n-tetracosane at P = 0.1 MPa.

4. Measurement of Thermal Conductivity during the Phase Transition. The experimental apparatus allows one to measure the thermal conductivity under dynamic process conditions, for example, during phase transitions in the material. The n-tetracosane's thermal conductivity was measured by this method in the vicinity of the melting point. The linear transducer (platinum, 5 μm) was placed first into the melted n-tetracosane. After cooling down to 273 K the temperature of the thermostat with the measuring cell was increasing monotonically up to 360 K at a rate of not more that 0.5 K/min. With this the n-tetracozanes thermal conductivity was measured in the automatic mode with short temperature intervals. Figure 4 shows the results of the experiments. The thermal conductivity of the solid state n-tetracosane equals 0.248 W/(m·K) at T = 273 K and increases slightly with increase in T. In the liquid state of n-tetracosane the reverse temperature course takes place. λ = 0.146 W/(m·K) at T = 360 K, which agrees with the reference data [7]. The great spread (up to 3%) of data in the solid phase is because of the change in the value of the contact thermal resistance between the transducer's surface and the medium's surface. A slight sloping of the thermograph during transition from the solid state to the liquid state may occur because of this reason, or because of impurities present. The error of measurement of the solid state n-tetracosane's thermal conductivity is 3-5%; the effect of the contact resistance is taken into consideration.

It is necessary to stress that the thermograph (Fig. 4) can be used for determination of the melting point (T_m = 324 K); the error is approximately 0.2-0.3 K.

5. Measuring the Layer's Thickness. The equation for the effective thickness of the temperature fields penetration into the medium [13]

$$l = \frac{2}{\sqrt{\pi}} \sqrt{a\tau} \tag{4}$$

may be used to measure the thicknesses of different layers, both solid and liquid. As seen from Figs. 2b, c and d, all the ther-

mograms have bends at ln τ = -3.49 or τ = 30.5 μsec from the onset of the pulse. As was shown earlier, the bend in the thermograms is caused by the egress of a thermal wave from the Lavsan layer. Using the value of $a = 8.2 \times 10^{-8}$ m^2/sec and Eq. (4), we determine the layer thickness $l = 56 \cdot 10^{-6}$ m for Lavsan 293 K. In this case, to calculate $a = \lambda/(\rho c_p)$, use was made of the values of ρ and c_p from [11].

The estimated error of layer thickness measurements is 4-5%; this mainly depends on the reliability of the data on thermal diffusivity.

Conclusions. As shown by the above, experiments on the method of pulse heating of low-inertia pick-ups using microcomputers for selection and processing of information may be successfully used to study different thermophysical problems, including those that cannot be solved by traditional methods of measurement (for example, measuring the molecular thermal conductivity of semitransparent media, studying phase transitions, probing the properties of a substance through a layer thickness, etc.).

NOTATIONS

λ, substance thermal conductivity W/(m·K); $\Delta T(\tau_0)$ and $\Delta T(\tau_0)$, excess temperatures of a pick-up at time instants τ_0 and τ; a, thermal diffusivity, m^2/sec; ρc_p, isobaric heat capacity of a volume unit, J/(m^3·K); I, current strength, A; R, resistance, Ω; L, length of pick-up wire, m; $q = I^2R/L$, heat flux from unit length of the heat source, W/m; l, effective depth of temperature field penetration, m; $\tan \varphi = [\Delta T(\tau) - \Delta T(\tau_0)]/[\ln (\tau)/\tau_0)]$.

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