

difference of 5-10°C, although the data in Tables 1 and 2 lead us to expect that this error would be less for the platinum-rhodium-platinum thermocouples. Such a large error is possibly a reflection of inexact positioning of the thermocouple junctions relative to the specimen height and the insulation of the electrodes, and it is always present in these experiments despite precautions that are taken. Thus, the complete study shows that platinum-rhodium-platinum thermocouples offer no distinct advantages over Chromel-Alumel thermocouples in determining the thermal conductivity of solids in an actual thermophysical experiment.

#### NOTATION

T, t, temperature;  $\vartheta$ , temperature difference;  $\Delta y$ , thermocouple readings;  $A_i$ , parameters of approximating equation;  $\beta$ , sensitivity of thermocouple;  $\langle\beta\rangle$ , sensitivity found from the generalized function;  $\beta_{st}$ , "standard" values of sensitivity;  $S_0$ , standard deviation of sensitivity for a given series;  $\delta$ , maximum deviation of  $\beta$  from  $\langle\beta\rangle$  in different series; I, II, indices indicating that the values pertain to platinum-rhodium-platinum and Chromel-Alumel thermocouples, respectively.

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#### RELATIONSHIP BETWEEN THERMAL CONDUCTIVITY, SPEED OF SOUND, AND ISOBARIC HEAT CAPACITY OF LIQUIDS

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Using two liquids - water and toluene - as an example, the author determines the dependence of the coefficient of thermal conductivity on the speed of sound and isobaric molar heat capacity for high state parameters.

The relationship between the coefficient of thermal conductivity, speed of sound, and isobaric molar heat capacity for pure liquids at atmospheric pressure was established by the formulas of Sakiadis and Kouts [1] and Filippov [2]:

$$\lambda = Lu(c_p\rho), \quad (1)$$

$$\lambda = \psi u(c_p\rho)^{2/3} k^{1/3}. \quad (2)$$

Equations (1) and (2) were derived with the assumption that heat transfer occurs by means of hyperacoustic oscillations of the medium. Values of  $\lambda$  were computed from Eq. (1) for 69 different liquids, where the standard deviation was 13% [1], and from Eq. (2) for 19 normal liquids, with a standard deviation of 7% [2].

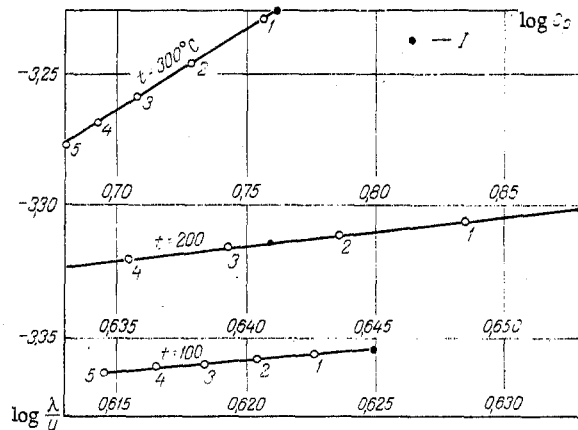


Fig. 1. Isotherms in the coordinates  $\log \lambda/u$  and  $\log c_p$  for water: 1) 100 bars; 2) 200; 3) 300; 4) 400; 5) 500; I) saturated liquid.

In view of the inadequate amount of study that has been given the relationship between the above parameters, we attempted to establish the relationship between  $\lambda$ ,  $u$ , and  $c_p \rho$  for high state parameters.

In accordance with the tabulated data for water and water vapor in [3], our study showed that, while preserving the structure of Eqs. (1) and (2), we need to proceed on the basis of the following expression in the case of high state parameters

$$\lambda = \varphi u c_p^n, \quad (3)$$

in order for the isotherms in the coordinates  $\log \lambda/u$  and  $\log c_p$  to be straight lines, as shown in Fig. 1. Coefficients  $\varphi$  and  $n$  of this formula, dependent on the temperature and nature of the liquid, may be calculated from two points.

Although empirical formula (3) gives good results, the variability of exponent  $n$  and the complexity of the approximations of the temperature functions  $\varphi(t)$  and  $n(t)$  do not permit us to recommend it for finding the relationship between parameters  $\lambda$ ,  $u$ , and  $c_p$ .

We established earlier [4] that a number of thermophysical quantities which are dependent on temperature and pressure (including the coefficient of thermal activity and the speed of sound) are expressed through equations similar to the equation of state of a liquid. In particular, for water these equations have the form

$$pv/RT = 1 + B\rho + E\rho^4, \quad (4)$$

$$\kappa/\kappa'_s = 1 + B_\kappa\rho + E_\kappa\rho^4, \quad (5)^*$$

$$u/u'_s = 1 + B_u\rho + E_u\rho^4. \quad (6)$$

In considering the ratio

$$-B_\kappa/E_\kappa = -B_u/E_u = \rho_s^3 \quad (7)$$

we obtain from Eqs. (5) and (6) a linear relationship between the coefficient of thermal activity and the speed of sound, i.e.,

$$\kappa = a + bu \quad (8)$$

or

$$\kappa = \kappa'_s + b(u - u'_s), \quad (9)$$

where  $a = \kappa'_s - bu'_s$ ;  $b = \frac{\kappa'_s}{u'_s} \frac{E_\kappa}{E_u}$ . Equations (8) and (9) are valid for water (Fig. 2) in accordance with the data in [5, 6].

As is apparent from Eq. (9), if  $\kappa'_s$  and  $u'_s$  are known, then the relationship between  $\kappa$  and  $u$  is determined by a single empirical constant. In the opposite case, according to Eq. (8), the relationship between  $\kappa$  and  $u$  is determined by two empirical constants  $a$  and  $b$ . Using numerical values of the coefficient of thermal activity [5] and  $u$  [6] for water and values of  $\kappa$  [7-9] and  $u$  [10, 11] for toluene, we were able to establish the character of the dependences of coefficients  $a$  and  $b$  of Eq. (8) on temperature. As can be seen from Fig. 3a and b, coefficients  $a$  and  $b$  change according to curvilinear and linear laws for water and toluene within the ranges 50-300°C and 25-125°C, respectively, regardless of the nature of the liquid.

Since  $\kappa'_s$  and  $u'_s$  were known, we approximated only coefficient  $b$ :

\*  $\kappa = \sqrt{\lambda c_p \rho}$  (5').

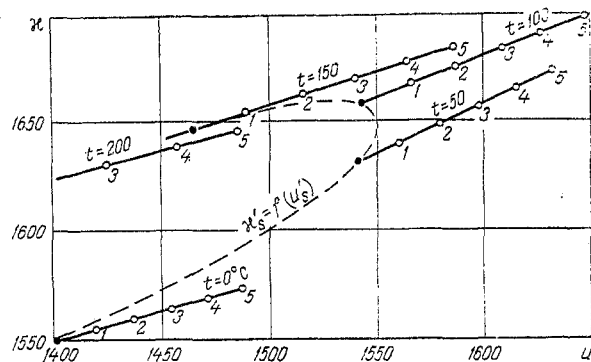


Fig. 2. Isotherms in the coordinates  $\kappa$ ,  $J/m^2 \cdot \text{deg K} \cdot \text{sec}^{1/2}$ , and  $u$ , for water.

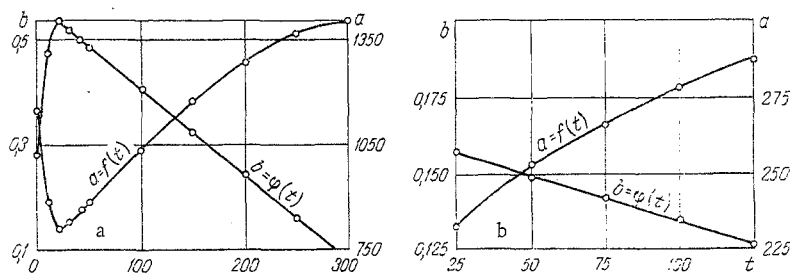


Fig. 3. Dependence of coefficients  $a = f(t)$  and  $b = \varphi(t)$  of Eq. (8) for water (a) and toluene (b),  $b$ ,  $J/m^3 \cdot \text{deg K} \cdot \text{sec}^{1/2}$ ;  $t$ ,  $^{\circ}\text{C}$ ;  $a$ ,  $J/m^2 \cdot \text{deg K} \cdot \text{sec}^{1/2}$ .

for water

$$b = 0.482 - 0.00161(t - 50), \quad (10)$$

for toluene

$$b = 0.156 - 0.00030(t - 25). \quad (11)$$

Equation (8) describes  $\kappa$  for both water and toluene with a high degree of accuracy.

For the range  $0-50^{\circ}\text{C}$ , coefficient  $b$  may be expressed by a fifth-degree polynomial

$$b = \sum_0^5 b_i t^i, \quad (12)$$

where  $b_0 = 2820 \cdot 10^{-4}$ ,  $b_1 = 2750 \cdot 10^{-5}$ ,  $b_2 = -8325 \cdot 10^{-7}$ ,  $b_3 = -4000 \cdot 10^{-9}$ ,  $b_4 = 4750 \cdot 10^{-10}$ ,  $b_5 = -5000 \cdot 10^{-12}$ .

Taking Eq. (8) into account, we obtain from Eq. (10)

$$\lambda = \frac{(a + bu)^2}{c_p \rho}. \quad (13)$$

Equation (13) allows us to very accurately calculate the value of  $\lambda$  in relation to  $u$  and  $c_p \rho$  for water and toluene within the temperature intervals  $0-300^{\circ}\text{C}$  and  $25-125^{\circ}\text{C}$  and at the pressures  $p_s \sim 500$  bars and  $p_s \sim 250$  bars, respectively. The mean divergence from the data in [3] for normal water is  $\pm 0.23\%$ , the maximum reaching  $-1.52\%$  at  $t = 300^{\circ}\text{C}$  and  $p = 300$  bars. In the anomalous region for water, i.e., for the temperatures  $0-20^{\circ}\text{C}$  and pressures  $p_s \sim 500$  bars, the divergence averages  $\pm 0.16\%$ . The average deviation from the data in [7] for toluene is  $\pm 0.17\%$ .

In conclusion, we should note that we have demonstrated the validity of Eqs. (8) and (13) using as an example liquids (water and toluene) belonging to different classes. Reliable empirical values of  $u$ ,  $\lambda$ ,  $c_p$ , and  $\rho$  were found for these liquids at high state parameters. It must be assumed that these formulas will prove valid for other liquids as well.

#### NOTATION

$\lambda$ , coefficient of thermal conductivity;  $u$ , speed of sound;  $u'_s$ , same for a saturated liquid;  $c_p$ , isobaric molar heat capacity;  $\rho$ , density;  $\rho_s$ , same, for a saturated liquid;  $p$ , pressure;  $p_s$ , same, for a saturated liquid;  $R$ , gas constant;  $T$ , absolute temperature;  $\kappa$ , coefficient of thermal activity;  $\kappa'_s$ , same, for a saturated liquid;  $L$ ,  $\psi$ , constants in Eqs. (1) and (2).

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## INVESTIGATION OF HEAT EXCHANGE IN THE WATER-SPRAY COOLING OF HIGH-TEMPERATURE METAL SURFACES

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A method is described and certain results presented of an experimental study of local heat exchange in the forced cooling of metal surfaces heated to high temperatures.

The practice of cooling heated metal surfaces with water sprayed from nozzles is common in several sectors of industry, particularly metallurgy [1].

Analysis of the literature shows that most of the well-known studies have been devoted to the cooling of heated surfaces by single drops [2-4], and little attention has been given to the process of heat exchange occurring when a system of drops strikes a heated surface [1].

The rate of heat exchange in the field of action of a jet on a heated metal surface is generally determined by the method in [5]. The essence of this method is as follows. A steel specimen in the form of a plate [5] or disk [6] of known dimensions containing thermocouples, the junctions of which are located a precisely measured distance from the front surface (the holes for the thermocouples are drilled and the latter inserted through the back surface), is placed in a furnace with an inert atmosphere to be heated to 900-1100°C. The specimen is then transferred to the working chamber, and water is delivered to the front surface at a known rate of flow from a nozzle. The temperature of internal points of the metal is measured as a function of time as the specimen is cooled. Numerical solution of the problem of nonsteady heat conduction using the temperature values obtained for characteristic points in the metal from the experiment make it possible to determine the temperature field in the specimen at any moment of time and the distribution of the heat flux on the sprayed (front) surface. The calculated heat flux and known temperature of the surface are then used to find the heat-transfer coefficient at each moment of time. The foregoing method has the following shortcomings: 1) the laboriousness of the

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