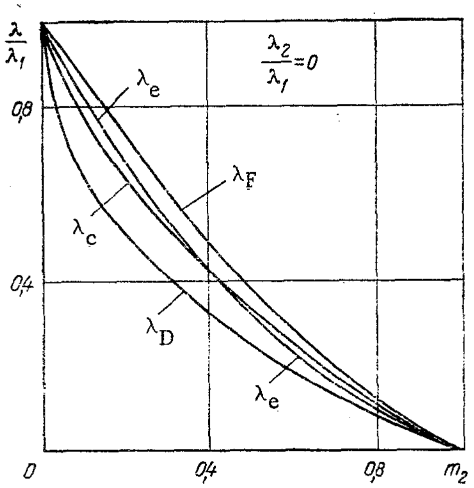

Fig. 2. Effective conductivity of a system with interpenetrating components as a function of concentration.

Instead of the widely used Eqs. (6) and (8) for calculating the conductivity of heterogeneous systems with interpenetrating components Eq. (9) should be used.

NOTATION

$\langle \vec{j} \rangle$, average heat flux; $\langle \nabla \vec{T} \rangle$, average temperature gradient; $\vec{j}_i(\vec{r})$, local heat flux in i-th component; λ_i, thermal conductivity of i-th component; λ, effective thermal conductivity; $\nabla \vec{T}_i(\vec{r})$, local temperature gradient in i-th component; $C = \Delta/L$, relative size of block of unit cell; λ_F, λ_D, λ_e, λ_c, effective thermal conductivity calculated by the son Frey and Dul'nev equations, obtained by a numerical method (exact value), and by the combination equation (9).

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SOME PROBLEMS IN MEASURING THERMAL CONDUCTIVITY USING THE COAXIAL CYLINDERS METHOD. II

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UDC 536.22

The results of an investigation of the thermal conductivity of five liquids using an apparatus based on the absolute coaxial cylinders method are presented. The measurements are made using three different measuring gaps. Procedural problems in measuring thermal conductivity are considered.

To investigate the thermal conductivity we used equipment based on the absolute coaxial cylinders method [1]. In the present paper we give the results of an experimental study of the thermal conductivity of water, toluene, n-heptane, and n-propyl and isopropyl alcohols in the temperature range from 20°C to 140°C. The measurements were made for three different thicknesses of the layer of material being investigated in order to clarify how the value of

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TABLE 1

D, mm	δ_C, mm	C, pF	A_e, m	A_m, m
19,570	0,696	167,79	18,94	19,20
19,989	0,487	241,51	27,26	27,16
20,488	0,238	501,10	56,56	56,09

TABLE 2. Results of an Experimental Investigation of the Thermal Conductivity of Water

Measurement gap δ_C, mm					
0,238		0,487		0,696	
t, °C	λ, W/m·°K	t, °C	λ, W/m·°K	t, °C	λ, W/m·°K
31,0	0,619	29.5	0,617	22,8	0,606
31,3	0,618	46.5	0,641	36,1	0,624
32,1	0,621	58,7	0,654	48,3	0,640
37,8	0,628	72,4	0,667	59,6	0,651
40,1	0,629	85,7	0,675	61,8	0,652
50,4	0,641	100,4	0,682	80,4	0,667
60,2	0,652	112,6	0,686	90,5	0,671
70,7	0,661			102.8	0,677
81,8	0,668			109,0	0,678
97.6	0,675			119,5	0,682
110,1	0,680				
118,2	0,682				

λ and the temperature coefficient of the thermal conductivity depend on the thickness of the layer of liquid in the measuring gap of the cell. A knowledge of this relationship enables one to make quantitative estimates of the effect of the radiative component of the transport on the measured value of thermal conductivity.

In recent years a number of theoretical and experimental studies have been made of this problem [2-5]. It follows from these investigations that the transfer of heat by radiation may have a considerable effect on the results of thermal-conductivity measurements for weakly absorbing liquids even at moderate temperatures. However, for a number of reasons it has not been possible until now to make a quantitative estimate of the radiation effect with a sufficient degree of accuracy.

According to theoretical predictions [2, 3], the effect of the radiative component should be most important in the case of the thermal conductivity of toluene and n-heptane, which are weakly absorbing liquids. Water and n-propyl and isopropyl alcohols are liquids with quite high absorption, and the effect of radiation in this case should be small.

For the successful solution of this problem it is necessary, as far as possible, to eliminate the effect of systematic errors on the measured value of the thermal conductivity, or at least to make the error the same for different thicknesses of the liquid layers. The main source of systematic error in the measuring cell employed is the leakage of heat from the ends of the cell and along the thermocouple junctions. The value of the systematic error due to this phenomenon depends to a large extent on the thickness of the layer and the thermal conductivity of the liquid in the measuring gap. Incorrect consideration of the heat leakage from the ends of the cell will mean that the measured value of λ will be a function of the thickness of the layer of material. When this is the case it becomes impossible to distinguish correctly the actual value of the radiative component.

Toluene and isopropyl alcohol (investigated in this experiment) have approximately the same values of the thermal conductivity at 30°C. Comparison of the measured values of λ for these liquids enables one to reveal any ignored systematic error when measurements are made using different gaps. If, for example, we obtain the same dependence of λ on the value of the gap for toluene and isopropyl alcohol, this will indicate any ignored systematic errors, since the radiation effect when investigating toluene should be considerably greater than in the strongly absorbing isopropyl alcohol. If a dependence of λ on the value of the gap is found only for toluene, this would confirm that this is due to the radiative component of heat transfer, but not due to systematic errors.

TABLE 3. Values of λ_{30} and the Temperature Coefficient of Thermal Conductivity B for the Liquids Investigated

Material	Measurement gap δ_C, mm					
	0,238		0,487		0,696	
	λ_{30}, W/m·°K	$B\cdot 10^4$, W/m·°K^2	λ_{30}, W/m·°K	$B\cdot 10^4$, W/m·°K^2	λ_{30}, W/m·°K	$B\cdot 10^4$, W/m·°K^2
Toluene	0,1299	2,51	0,1295	2,63	0,1305	2,59
Heptane	0,1209	3,05	0,1209	2,87	0,1211	2,67
n-Propyl alcohol	0,1527	2,21	0,1530	2,11	0,1512	1,93
Isopropyl alcohol	0,1351	1,98	0,1351	1,92	0,1344	1,94

We chose water as the subject of the investigation because it has been investigated in some detail and has a high thermal conductivity. This enabled us to check fairly completely the method of making corrections to the measured value of λ, since they have a maximum value in this case.

The construction of the measuring cell employed enabled us, when changing the inner cylinder to change the gap, to keep the position of the thermocouple junctions and the heater fixed. The method of making the corrections, which is characteristic of the measuring cell employed, is similar to that considered in [1].

The thermal conductivity of the liquid is found from the equation

$$\lambda = \frac{Q}{A_e \Delta t_c}. \quad (1)$$

Table 1 shows values of the cylindrical gaps and values of the cell constants A_e obtained by measuring the electrical capacitance and by a direct measurement of the geometrical dimensions of the cylinders. The capacitance was measured using an R521 ac bridge, type MIE, class 0.1.

When determining the constants by the capacitance method we introduced corrections for the constructional features of the cell and the parasitic capacitance of the leads. The maximum error in determining A_e by measuring the electrical capacitance in all three measurement gaps was constant and did not exceed 0.3%. In the case of a direct measurement of the geometrical dimensions the maximum error in determining A_m was greater and, for example, for a gap of 0.238 mm was ∿4%. By comparing the values of the constants obtained by the two methods it can be seen that the disagreement does not exceed the overall measurement error. Taking into account the fact that the cell constant obtained from a capacitance measurement is more accurate, we used the value of A_e for the corresponding gaps in later calculations using Eq. (1).

In the measurements of the thermal conductivity the value of Ra in all cases was less than 1000.

Analysis of the errors in measuring λ showed that the maximum error of an individual measurement did not exceed 1.3%.

The results obtained for the thermal conductivity of water are shown in Table 2. It is seen from the table that the data obtained for three different measuring gaps agree well with one another. The maximum difference between the measured values of λ and the values given in [6] does not exceed 0.7%.

Figure 1 shows the results of an experimental study of the thermal conductivity of toluene, n-heptane, and n-propyl and isopropyl alcohols. The measurements of λ at temperatures above the boiling point were made at pressures of 0.2-0.3 MPa above the saturation pressure. It is seen from the figure that the thermal conductivity of these liquids decreases linearly with temperature. This can be expressed by the equation

$$\lambda_t = \lambda_{30} - B(t - 30).$$

The difference between the experimental values of λ and the values calculated from the equation does not exceed ±0.2%. The values of λ and the temperature coefficient B are given in Table 3.

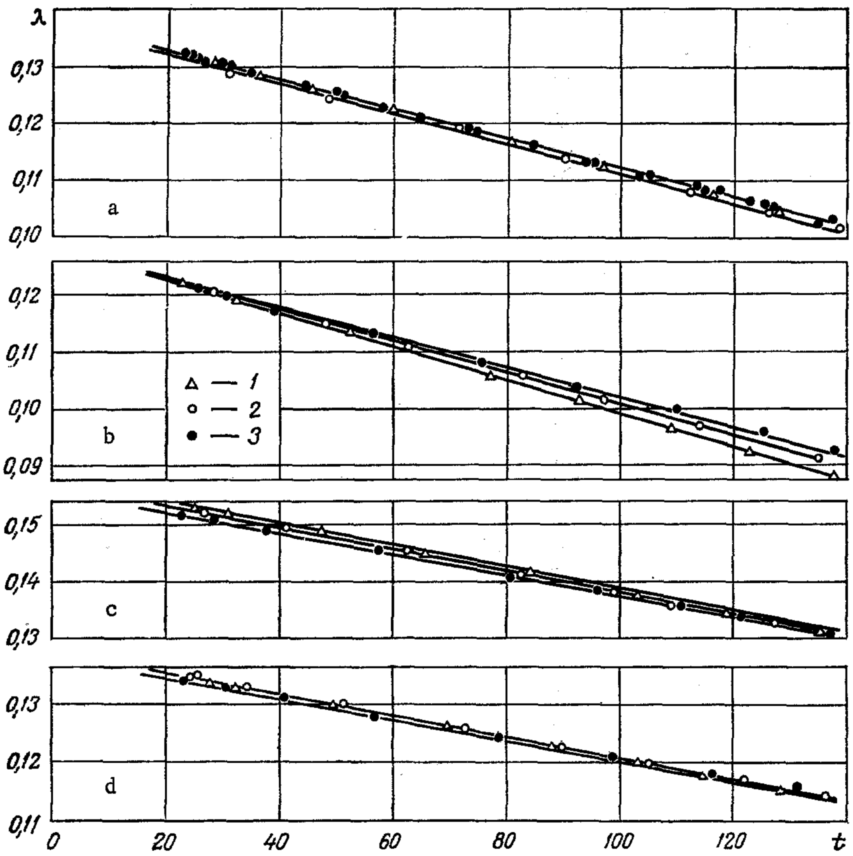

Fig. 1. Temperature dependence of the thermal conductivity λ (W/m•°K) for toluene (a), n-heptane (b), n-propyl alcohol (c), and isopropyl alcohol (d) for different thicknesses of the measuring gap δ_C: 1) 0.238 mm; 2) 0.487 mm; 3) 0.696 mm.

It is seen from Table 3 that the values of λ of all the liquids investigated are practically independent of the thickness of the layer of liquid. The variation in the temperature coefficient B also lies within the limits of experimental error. Only for n-heptane is there a regular variation of B from $3.05 \cdot 10^{-4}$ for $\delta_C = 0.238$ mm to $2.67 \cdot 10^{-4}$ W/m•°K^2 for $\delta_C = 0.696$ mm.

The thermal conductivity of toluene in cells with gaps of 0.26, 0.76, and 1.5 mm has been measured in [7] using the coaxial cylinders method. No variation of λ of toluene with the gap was found. Similar results have been obtained in cells using the plane layer method [8].

In conclusion, it should be noted that the existing considerable differences between the experimental data obtained by different investigators for the thermal conductivity of liquids at medium temperatures cannot be explained by the effect of the radiative component of thermal conduction. In our opinion, the disagreement is due to the experimental method and possible impurity of the materials employed.

NOTATION

Q, heat flux from electric heater; Δt_c, calculated temperature difference in the layer of liquid tested; D, external diameter of the inner cylinder; δ_C, annular gap thickness; C, electrical capacitance of the measuring cell; A_e, constant obtained from a measurement of the electrical capacitance of the cell; A_m, constant obtained from direct measurement of cell dimensions; λ, thermal conductivity of the liquids investigated; B, temperature coefficient of thermal conductivity of the liquids tested; t, temperature; λ_{30}, thermal conductivity of the liquids tested at 30°C; Ra, Rayleigh number.

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INVESTIGATION OF THE THERMODYNAMIC PROPERTIES OF NITROGEN AT PRESSURES UP TO 8 kbar AND TEMPERATURES UP TO 1800°K

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A procedure is described and the results are given of the experimental determination of the density of nitrogen at high pressures and temperatures.

For a number of the present-day domains of science and technology, information about the thermodynamic properties of industrially important gases at high pressures and temperatures is necessary. In particular, for the planning and operation of high-pressure aerodynamic facilities, intended for the generation of hypersonic gas flows with high Reynolds numbers, data are required concerning the thermodynamic properties of nitrogen at pressures of 5-20 kbar and temperatures up to 1000-3000°K.

However, the overwhelming majority of experimental papers on the determination of the thermodynamic properties of gases at high pressures is limited to temperatures of 600-700°K. This is due to the use of high-pressure equipment with external heating. The use of equipment with internal heating of the gas for thermophysical investigations was made difficult because of the intense gas convection arising in this equipment and disturbing the homogeneous nature of the temperature distribution inside the equipment [1].

The range of the parameters of state of nitrogen, investigated experimentally by different authors [2-5], is shown in Fig. 1.

Data which have appeared recently [5] at pressures up to 5 kbar and temperatures up to 1000°C are in need of verification. They disagree with the repeatedly verified data of [3], and this discrepancy at pressures of 1000 bar and a temperature of 1000°C reaches a magnitude of about 4%.

The tables of thermodynamic properties of nitrogen at high pressures and temperatures available at the present time, and obtained by a computational method [6, 7], have not been verified experimentally. The limits of applicability of the equations of state used, and also the validity of the assumptions made, can be determined only on the basis of experimental P—v—T data.

The present paper is devoted to the experimental investigation of the thermodynamic properties of nitrogen at pressures of up to 3-8 kbar and a temperature range of 400-1800°K.

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