EXPERIMENTAL INVESTIGATION OF THERMAL CONDUCTIVITY OF ORDINARY AND HEAVY WATER AT TEMPERATURES OF 25-350°C AND PRESSURES OF 0.1-245.3 mN/m²

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The results of experimental investigations of the thermal conductivity of ordinary and heavy water by the plane-layer method at temperatures of 25-350°C and pressures of 0.1-245.3 mN/m² are given. Equations are given for the thermal conductivity of ordinary and heavy water at pressures of 0.1-245.3 mN/m² and temperatures of 25-350°C.

The thermal conductivity of ordinary and heavy water has been investigated mainly at pressures up to 100 mN/m². In the case of ordinary water there are two investigations which include the region above 100 mN/m² ([1], by the coaxial-cylinder method, at pressures of 0.1-784.5 mN/m² and temperatures of 30-140°C, and [2], by the flat-ended cylinder method at pressures of 0.1-196 mN/m² and temperatures of 20-180°C). In the present work the thermal conductivity of ordinary and heavy water was investigated at temperatures of 25-350°C and pressures of 0.1-245.3 mN/m².

The thermal conductivity of ordinary and heavy water was investigated by the plane horizontal layer method described in [3], adapted for the investigation of water [4, 5] in an autoclave.

Figure 1 shows the autoclave containing the instrument. The instrument and the autoclave are made of Kh18N9T stainless steel. The investigated substance is situated between the heater and cooler, in the space formed by a foil partition 1 welded to the heater plate and the ring 2. The ring is welded to the autoclave 3. Thermocouples and a compensating heater 4 are attached to the foil for control of the heat flux through it. The foil is 0.2 mm thick. The gap above the instrument is fitted with powdered porcelain 5. The pressure is removed from the instrument by the admission of argon through aperture 6.

In the experiment we used a niter thermostat. High-temperature oil was used as the thermostatting liquid up to 200°C. An automatic device kept the temperature in the thermostat constant to within ±0.006°C.

The temperature measurements were made on an R-348 potentiometer (accuracy class 0.002) connected to Chromel—Copel thermocouples. Each thermocouple was annealed and calibrated against a standard resistance thermometer. The junctions of the differential thermocouples were attached with silver beads and VN 15 cement. The absolute temperature was measured to an accuracy of 0.05°C. Each thermal-conductivity value was obtained with two different values of temperature drop in the range 0.76 to 1.44°C.

To calculate the correction for the temperature drop in the metal layer we used the thermal-conductivity data for stainless steel from [14]. It varied from 12 to 27%, depending on the temperature. In calculating the thermal conductivity we introduced a temperature correction for the change in ratio of gap size to the area of working surface. The gap between the heater and cooler is set by a nickel wire 0.301 mm thick. The thickness of the wire was checked on an IKV vertical optimeter with 0.001-mm scale divisions; the error of measurement

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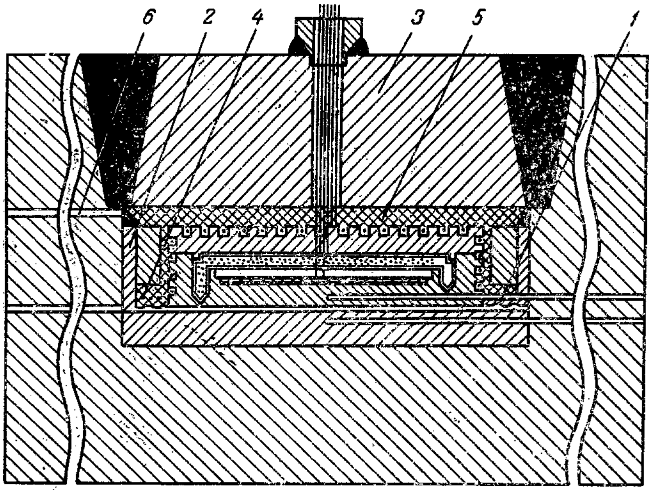

Fig. 1. Diagram of autoclave with instrument for investigation of thermal conductivity of water: 1) foil; 2) ring; 3) autoclave; 4) compensating heater; 5) powdered porcelain; 6) aperture for admission of argon.

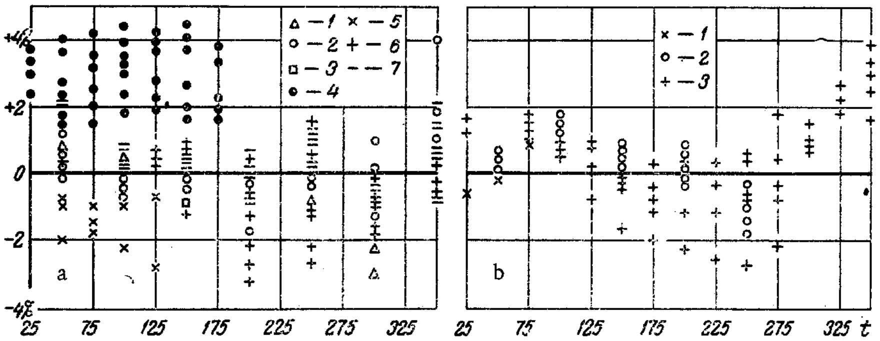

Fig. 2. Comparison of our data for ordinary water (a) and heavy water (b) with data of other authors: the zero temperature axis is our data; a: 1) data of [6]; 2) [8]; 3) [9]; 4) [2]; 5) [1]; 6) [7]; 7) [10]; b: 1) [18]; 2) [15]; 3) [17].

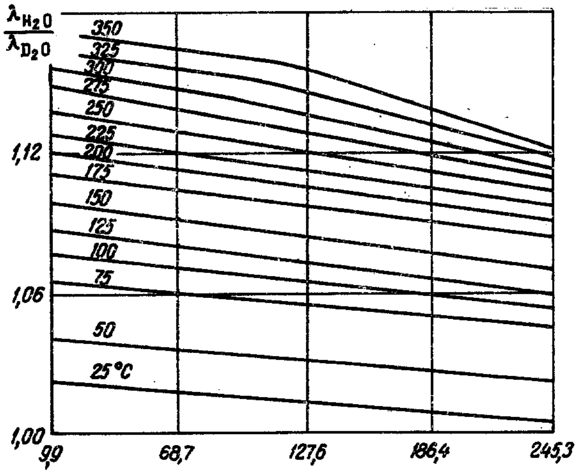

Fig. 3. Ratios of thermal conductivities of ordinary and heavy water on isotherms as function of pressure (mN/m^2).

TABLE 1. Experimental Values of Thermal Conductivity (10^{-3} W/m•deg) of Water

P, mN/m²	Average temperature t, °C													
	25	50	75	100	125	150	175	200	225	250	275	300	325	350
0,1	604	641	664	—	—	—	—	—	—	—	—	—	—	—
9,9	607	646	668	686	694	691	682	670	645	619	585	545	—	—
19,7	611	650	673	692	699	697	691	683	656	632	605	570	522	465
29,5	615	653	677	698	705	704	699	691	668	645	621	585	544	495
39,3	620	658	682	703	711	711	709	701	678	659	636	605	565	522
49,1	623	662	687	709	716	718	716	710	690	673	650	625	585	544
58,9	627	666	692	714	724	725	726	720	700	682	660	636	602	563
68,7	630	671	696	720	728	731	732	729	708	693	672	648	618	582
78,6	634	675	702	725	734	737	740	736	718	700	682	660	631	600
88,4	637	679	706	730	740	745	748	745	729	712	694	669	644	615
98,2	640	684	712	736	746	754	756	753	738	721	701	676	655	625
108,0	644	688	716	742	752	758	764	762	748	732	711	689	666	634
117,8	647	692	719	747	758	765	772	768	756	742	720	699	676	645
127,6	651	696	725	749	764	771	780	780	766	752	730	708	685	655
137,4	655	702	729	754	770	779	788	790	772	761	740	717	694	665
147,2	659	704	734	759	776	784	796	798	784	770	751	725	704	674
157,0	663	711	739	764	782	790	804	805	793	780	757	734	710	680
166,8	667	715	744	770	788	797	812	814	802	788	766	742	718	687
176,6	671	720	748	776	794	804	820	823	810	796	772	750	725	694
186,4	675	725	752	781	800	810	829	832	818	803	778	758	732	702
196,2	678	729	757	786	805	819	834	840	827	810	785	766	740	712
206,0	682	733	762	792	811	825	840	848	833	818	793	773	748	719
215,8	685	737	767	797	817	831	848	853	842	826	800	780	755	726
225,7	689	742	771	802	823	838	855	864	850	834	808	787	762	734
235,5	692	746	776	808	829	845	865	872	860	842	816	795	770	741
245,3	696	750	782	815	835	851	870	879	866	852	825	803	778	752

of l was 0.33%. The diameter of the working surface, equal to 68.01 mm, was measured by a micrometer with 0.01-mm scale divisions; the error in determination of the area S was 0.03%. The current through the working heater was determined by potentiometer; the error in measurement of I was 0.01%. The voltage was measured with a class-0.05 Shch-1412 voltmeter; the error of measurement of U did not exceed 0.13%. The minimal value used of the temperature drop in the layer of investigated material was 0.756°C; the error of measurement did not exceed 0.18%. The pressure was measured with a class-0.05 piston gauge. The reference errors were ignored in view of their smallness; the error of the heat flux through the copper oxide and foil reached 0.5%. The thermal conductivity of stainless steel is known to an accuracy of 3%. This introduces an additional error of 0.8% into the thermal conductivity of water. The total error of measurement was 2%.

The thermal conductivity was calculated from the equation

$$\lambda = (Q/\Delta t)\cdot(l/s) \quad \text{W/m}\cdot\text{deg}.$$

The horizontality of the instrument was checked by a level with scale divisions of 0.05 mm/n.

The purity of the ordinary water was determined by measuring the electrical resistance.

The purity of the heavy water corresponded with the requirements of TU-6-02-628-71 and was 99.75%.

The thermal conductivity of ordinary and heavy water was investigated on isotherms at pressure intervals of 4.9 mN/m².

The results of investigation of ordinary water are given in Table 1, and those for heavy water in Table 2; the pressure interval is increased to 9.8 mN/m² to reduce the size of the tables. We give t_{av}, since the temperature deviations at different pressures were not more than 0.5°C.

The thermal conductivity of heavy water in the investigated region was lower than that of ordinary water. This can probably be attributed to the fact that the mass of the heavy-water particle is greater than that of the ordinary water particle and has greater inertia. The inertia reduces the thermal motion and, hence, the thermal conductivity.

The pressure dependence of the thermal conductivity of both ordinary and heavy water was different at different temperatures. The higher the temperature, the greater the variation with pressure. Increase in pressure shifted the thermal-conductivity maximum toward higher

TABLE 2. Experimental Values of Thermal Conductivity (10^{-3} W/m•deg) of Heavy Water

P, mN/m²	Average temperature, t °C													
	25	50	75	100	125	150	175	200	225	250	275	300	325	350
0,1	588	612	630	—	—	—	—	—	—	—	—	—	—	—
9,9	592	617	635	641	636	633	618	600	576	550	514	475	—	—
19,7	595	622	639	646	643	640	630	610	588	565	533	490	446	397
29,5	600	626	645	652	650	648	640	620	599	572	544	507	465	425
39,3	604	631	649	657	657	656	648	630	607	585	559	523	486	444
49,1	608	636	655	663	665	664	655	639	619	595	570	537	500	463
58,9	613	640	660	669	671	672	664	647	628	603	580	545	513	476
68,7	617	644	665	674	678	680	671	655	634	615	590	559	525	491
78,6	621	648	670	680	685	688	679	665	645	624	600	570	538	505
88,4	626	652	675	685	692	694	686	673	655	634	608	584	550	517
98,2	629	657	680	690	698	701	695	682	663	644	620	593	563	532
108,0	633	662	685	696	705	710	704	690	675	650	630	605	572	543
117,8	636	668	690	702	712	718	714	700	681	663	638	613	583	555
127,6	641	672	695	707	718	724	720	706	692	672	647	622	593	565
137,4	645	676	700	713	726	732	727	714	697	677	656	631	603	575
147,2	649	681	705	718	731	740	735	722	705	686	665	640	612	585
157,0	652	685	710	724	738	746	741	729	712	694	673	650	622	594
166,8	656	690	716	730	743	753	748	736	720	702	682	659	631	602
176,6	660	695	720	736	748	759	755	744	728	710	690	668	640	611
186,4	664	699	725	743	755	766	761	751	735	717	698	675	647	620
196,2	668	704	730	749	762	773	768	758	743	725	707	684	656	628
206,0	674	708	735	755	768	779	774	764	749	733	715	692	665	63[illegible]
215,8	678	713	740	761	774	786	779	770	755	739	722	700	672	643
225,7	684	717	745	768	780	791	785	777	763	748	730	708	680	650
235,5	688	720	750	773	786	796	791	782	770	756	738	715	687	658
245,3	692	725	755	778	792	802	795	789	776	764	745	722	695	669

temperatures. Similar shifts have been reported in [2, 8] for ordinary water and in [17] for heavy water. The probable reason for the shift of the maximum is that the "molecular complexes" become more stable with increase in pressure and break up at higher temperatures. The breakup of the "molecular complexes" of heavy water occurs at lower temperature than in the case of ordinary water.

Figure 2a compares our data for ordinary water with the data of [1, 2, 6-10], while Fig. 2b compares our data for heavy water with the data of [15, 17, 18].

Stein [12] gives an equation that is recommended for temperatures of 0-800°C and pressures of 0.1-100 mN/m². It predicts our experimental data for ordinary water at temperatures of 25-350°C and pressures of 0.1-100 mN/m² to within 2%. A test of its suitability for pressures above 100 mN/m² showed that with increase in pressure the error increased and reached 10% at 245.3 mN/m².

We give equations which predict the thermal conductivity of ordinary and heavy water to within 2% at pressures of 0.1-245.3 mN/m² and temperatures of 25-350°C (Fig. 3):

$$\lambda_{P,t} = \lambda_s + \left(\frac{\lambda - \lambda_s}{P - P_s}\right)_{P=245.3} (P - P_s) + at^4 P \exp(-bP) \text{ W/m} \cdot \text{deg}. \quad (1)$$

The values of P_s for ordinary water are taken from [13], and those for heavy water from [19].

From our experimental data we obtained values of the thermal conductivity of ordinary and heavy water on the saturation line. These data are given by Eq. (2) for ordinary water and Eq. (3) for heavy water:

$$\lambda^{H_2O} = (0.007t^3 - 9.38t^2 + 2114.1t + 556536) \cdot 10^{-6} \text{ W/m} \cdot \text{deg}; \quad (2)$$

$$\lambda^{D_2O} = (0.004t^3 - 6.95t^2 + 1410.2t + 557943) \cdot 10^{-6} \text{ W/m} \cdot \text{deg}. \quad (3)$$

Our recommended values of λ_s of ordinary water are in good agreement with [8, 11] only at temperatures close to 350°C; the values differ by up to 3% from the values in [8], and by up to 1.3% from those of [11].

The values of λ_s of heavy water are in good agreement with those of [11, 17] only at 300-340°C. The differences reach 4.5% in the case of [17], and 1.27% in the case of [11].

The final equations which we give for calculation of the thermal conductivities λ^{H_2O} and λ^{D_2O} have the form

$$\lambda_{P,t}^{H_2O} = (0.007t^3 - 9.38t^2 + 2114.1t + 556536)\cdot 10^{-6} + (0.001122t^2 + 2.494t + 300.8)\cdot 10^{-6}\cdot (P - P_s) + 1.6\cdot 10^{-13}t^4 P\cdot \exp(-0.0143P) \text{ W/m}\cdot\text{deg};$$

$$\lambda_{P,t}^{D_2O} = (0.004t^3 - 6.96t^2 + 1410.2t + 557943)\cdot 10^{-6} + (0.000015t^3 - 0.00571t^2 + 2.855t + 343.6)\cdot 10^{-6}\cdot (P - P_s) + 1.3\cdot 10^{-13}t^4 P\cdot \exp(-0{,}0143P) \text{ W/m}\cdot\text{deg}.$$

NOTATION

Q, amount of heat; Δt, temperature drop in layer; l, thickness of plane layer; S, calculated surface; λ_s, thermal conductivity on saturation line; P_s, pressure for which thermal conductivity is calculated.

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