THERMAL CONDUCTIVITY OF HEAVY WATER AT HIGH PRESSURES
AND ITS DEPENDENCE ON DENSITY

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We employed the plane horizontal layer method to derive data on the coefficient
of thermal conductivity for heavy water, and these data are compared with values
for ordinary water.

Heavy water (D_2O) is used extensively in numerous heat and power generating installa-
tions, including nuclear plants. Experimental research into the thermal conductivity of D_2O
has been carried out in many countries, and a rather large quantity of papers is presently
in publication [1-14], with brief reviews of these publications presented in [15-17]. An
analysis of all experimental studies published prior to 1976 can be found in [16] which also
provides suggested handbook data on the coefficient of thermal conductivity for D_2O below
250 MPa.

It is the goal of this paper to expand the range of the experimental research dealing
with pressure, as well as to refine existing data on the thermal conductivity of D_2O.

We chose the plane horizontal layer method to investigate the thermal conductivity of
D_2O. The device that we used has been described in [18]. Its main parts are fabricated out
of copper. The wires of the furnaces and thermocouples are insulated with glass filaments
on a special winding stand and placed inside sheaths and small tubes made out of high-strength
steel. Some of the components of the installation and the autoclave were chrome coated.
Prior to being filled, the system was heated to 120-140°C and simultaneously evacuated. The
D_2O used in the experiment was first cleansed of gases, producing a content of 99.75%.

The experimental error was ±1.6%, the mean-square error was 5.17 mW/(m·K) or ±0.75%,
and the arithmetic mean of 2.3 mW/(m·K) or ±0.38% was used to estimate the mean square error.
Provision was made for the monitored losses of the installation in calculating the coeffi-
cient of thermal conductivity.

The experimental values for the coefficient of the thermal conductivity of the D_2O were
obtained at temperatures of 20-200°C and at pressures of 0.1-400 MPa. The studies were con-
ducted along isotherms at pressure intervals of 20 MPa. The minimum temperature drop across
the D_2O layer amounted to 1.205°C. The thermostat temperature fluctuations amounted to 0.02
°C. Each point was checked 4-8 times, with the arithmetic mean value taken as the basis.
The experiment was performed in such a manner that no deviation from the specified tempera-
ture values exceeded 0.3°C. For identical parameters the experimental points deviated from
the arithmetic mean by no more than 0.75%.

Since the thermocouples of the heater and the "refrigerator" are in contact with the
metal, in addition to the "refrigerator" thermocouples we used yet another thermocouple which
was not in contact with the metal of the "refrigerator." This approach was first suggested
and well described in [19].

The pressure was measured by means of an MP-2500 piston manometer, as well as with an
SV26R superhigh-pressure-type manometer whose upper measurement limit was 5000 kgf/cm², with
an error of 1%. To attain the given pressure values in MPa, appropriate weight rings were
added to the weights of the piston manometer.

The data obtained in this paper were compared with the results of [5-10, 13, 14] and
with the recommended handbook data from [16]. These comparisons showed that the experimental
data [5-7, 14] deviate by less than 1.6%, the handbook data [16] by 1.3% at pressures of
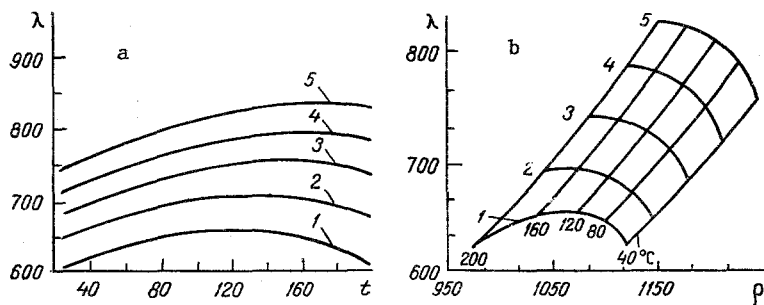
Fig. 1. The thermal conductivity of D_2O as a function of temper-
ature (a) and density (b) at various pressures: 1) P = 20 MPa;
2) 100; 3) 200; 4) 300; 5) 400. λ, mW/(m·K); t, °C; ρ, kg/m³.

0.1-250 MPa, and the results of [8-10, 13] agree within limits of 1.6% with the exception
of individual sections of certain of the references: for example, the data of [8, 9] are
higher by 2-2.5% at pressures of 200-245 MPa and temperatures of 180-200°C, while the data
of [13] are lower by 2-3% at temperatures of 120-200°C and at pressures of 100-150 MPa.

Analysis of the measurement results showed that the isobars of the D_2O thermal conduc-
tivity (Fig. 1a) exhibit a maximum that shifts as the pressure increases toward the higher
temperatures. The shift in the maximum for the D_2O is smaller than in the case of ordinary
water (H_2O); at the 400 MPa isobar the D_2O maximum is found at a temperature close to 170°C,
while for H_2O this displacement is noted as early as the 200 MPa isobar [18]. Similar dis-
placements had been noted earlier in [17, 20, 21].

The D_2O coefficient of thermal conductivity is smaller than the H_2O thermal conductivity.
This is apparently associated with the fact that the mass of the D_2O particle is greater than
the mass of the H_2O particle, i.e., it exhibits greater inertia, and inertia reduces the in-
tensity of the thermal motion and, consequently, the thermal conductivity. Such an explana-
tion is in agreement with [22, 23].

Water is an associated liquid, and if these associates are treated as new "molecules"
which participate in the transport of heat, the larger the associates, the more substantial
the coefficient of thermal conductivity. Eigen in [24] examines the process of energy trans-
fer in association (the energy of breaking and restoring hydrogen bonds) through the struc-
tural diffusion of these associates, which serves to explain the high values for the coeffi-
cient of thermal conductivity in associated compounds. The level of association diminishes
rapidly as the molecular weight increases, since it is easier for the particles of larger
mass to break the hydrogen bond in the case of thermal fluctuations, and the smaller the as-
sociates, the lower the thermal conductivity.

With increasing temperature the destruction of complexes occurs more rapidly in the case
of D_2O than in the case of H_2O [25]. This apparently causes the thermal conductivity of the
D_2O to be smaller than that of the H_2O and for the displacement of the thermal-conductivity
maximum at identical D_2O isobars to be smaller than in the case of H_2O.

Having examined the H_2O thermal-conductivity isobars from [18] and the D_2O isobars of
this paper, we can see that with an increase in temperature the thermal conductivity reaches
a certain point, subsequent to which it diminishes. The following process is taking place
here: first of all, we have an elevation in the intensity of the molecular thermal motion,
i.e., thermal conductivity; secondly, the number of molecules per unit volume diminishes,
i.e., heat carriers; third, the number of associates is reduced, and the smaller this number,
the lower the magnitude of the thermal conductivity. The combined effect of these factors
governs the magnitude of the thermal conductivity.

Figure 1b shows a plot of the D_2O coefficient of thermal conductivity versus density,
while Fig. 2 shows the relationship between the H_2O/D_2O ratio of the thermal conductivities
and temperature at various pressures.

We have derived a relationship to describe the experimental data of the D_2O coefficient
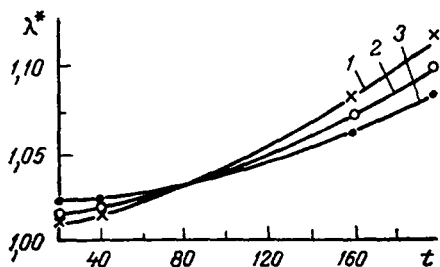of thermal conductivity to temperatures up to 200°C, and this relationship has the form

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Fig. 2. Relationship of $\lambda^* = \lambda_{H_2O}/\lambda_{D_2O}$ to temperature at various pressures: 1) P = 400 MPa; 2) 200; 3) 20. t, °C.

TABLE 1. Thermal Conductivity λ of Heavy Water, mW/(m·K)

P, mPa	Temperature, °C									
	20	40	60	80	100	120	140	160	180	200
0,1	591	611	626	635	—	—	—	—	—	—
20	600	621	636	647	653	653	649	642	629	613
40	610	631	646	657	664	664	662	656	644	630
60	621	643	657	668	675	675	675	670	657	646
80	629	650	666	678	686	685	685	683	674	664
100	638	660	676	688	698	698	698	694	686	675
120	644	667	683	696	707	710	712	707	700	691
140	651	675	691	703	715	720	723	718	712	703
160	658	683	699	713	724	729	735	730	726	718
180	666	690	707	720	733	739	743	742	736	729
200	675	699	717	729	742	750	754	752	747	739
220	682	706	724	739	752	759	765	763	758	750
240	690	713	730	745	760	769	773	772	768	760
260	698	721	739	751	765	775	777	780	777	772
280	704	728	745	658	772	783	785	786	785	781
300	710	735	751	765	779	791	792	794	791	790
320	716	741	758	773	788	796	800	803	802	799
340	722	747	765	779	793	801	809	813	811	809
360	729	753	772	786	800	807	818	820	820	817
380	737	760	778	793	807	815	823	826	826	825
400	743	766	784	801	815	822	829	833	833	832

$$\lambda_{(P,t)} = \lambda_{s(t)}\left(1.990\,\frac{\rho_{(P,t)}}{\rho_{s(t)}} - 0.990\right).$$

In this relationship the values of the D_2O thermal-conductivity coefficient at the saturation line have been taken from [16], the D_2O densities at the saturation line have been taken from [15], and the densities below 100 MPa are obtained from [15, 26], below 350 MPa from [27], and below 400 MPa at a temperature of 25°C, these data are from [28], and the remaining density data have been derived by calculation. The relationship describes the experimental D_2O data for pressures up to 400 MPa and below temperatures of 200°C with an error of 1.3% (see Table 1).

NOTATION

λ, the thermal conductivity; λ_s, the thermal conductivity of the D_2O at the saturation line; ρ, the density of the D_2O; ρ_s, the density of the D_2O at the saturation line; P, pressure; t, temperature.

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