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A DESCRIPTION OF THERMAL CONDUCTIVITY
AND DYNAMIC VISCOSITY OF WATER IN THE
CRITICAL REGION

by

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ABSTRACT

The purpose of this study was to establish reasonable estimates of the values of thermal conductivity and dynamic viscosity of water in the critical region. This was accomplished by reviewing the literature and utilizing available experimental measurements. The validity of the estimates was strengthened by the use of the principle of corresponding states after other considerations failed to contribute a description of these two transport properties in the critical region. The final results were expressions of a thermal conductivity excess and dynamic viscosity excess as unique functions of density.

NOMENCLATURE

The following nomenclature is used in this report:

B, C	Virial coefficients.
b, c, m	Constants.
k	Thermal conductivity.
p	Pressure.
R	Gas constant.
T	Temperature.
v	Specific volume.
Z	Compressibility factor.
ρ	Density.
μ	Dynamic viscosity.
c	Subscript denoting the critical value.
o	Subscript denoting the value at one atmosphere pressure, thus, the quantity is a function of temperature only.
$(k - k_o)$	$k(p, T) - k_o(T)$, thermal conductivity excess.
$(\mu - \mu_o)$	$\mu(p, T) - \mu_o(T)$, dynamic viscosity excess.

INTRODUCTION

Because of unique property variations, heat transfer by convection to a fluid near its critical state is of great interest. For instance, in the limit as the fluid approaches this state, the coefficient of volume expansivity and the specific heat at constant pressure become indefinitely large. Thus, small differences in temperature give rise to very large buoyant forces and the Prandtl number for the fluid becomes infinite.

In order that convective heat transfer can be analyzed for these conditions, it is necessary to have accurate information on the thermodynamic and transport properties of the fluid. For water, certain of its thermodynamic properties in the critical region have been (14)* or soon will be (13) correlated and well described. Such was not the case for its transport properties. With thermal conductivity and dynamic viscosity, a brief survey of the literature indicated that there was little consistent data. Therefore, the purpose of the work reported here was to obtain best estimates for the values of thermal conductivity and dynamic viscosity for water in the critical region** so that heat transfer analysis could subsequently be carried out. The estimates described below were arrived at by surveying the available exper-

* Numbers in brackets refer to references found in Bibliography

** The critical region was considered as being close to the critical point where $v_c = .00328 \text{ m}^3/\text{kg} = .0525 \text{ ft}^3/\text{lbs}$, $p_c = 225.54 \text{ kg/cm}^2 = 3208 \text{ psia}$ and $T_c = 374.15^\circ\text{C} = 705.5^\circ\text{F}$. (14).

imental data. Theoretical considerations and the principle of corresponding states were also employed in hopes of putting the final results on a firm base.

THEORETICAL CONSIDERATIONS

Viscosity and thermal conductivity represent the microscopic transport of momentum and of energy, respectively, for unit driving forces; hence, they are called transport properties. Simple relations have been obtained for these properties on the basis of elementary kinetic theory. The results, however, hold only for a very limited range due to the assumptions made in their derivation.*

An elaborate kinetic theory for transport properties was developed by Chapman and Enskog. The final result was that transport properties could be expressed in terms of a set of collision integrals. These integrals involved the dynamics of a molecular encounter and hence the intermolecular force law. Thus, dynamic viscosity and thermal conductivity are intimately connected with the law of force between individual molecules. If the intermolecular forces can be described, an explicit expression between these physical properties and the intermolecular forces (such as contained in the so-called collision integrals), may make it possible to predict properties under conditions where no experimental data is available.

The intermolecular forces are directly related to the potential energy of interaction between the molecules. For the simple, non-polar molecules, the potential energy of interaction may be described by the

* See Ref. (7) for a complete discussion.

Lennard-Jones potential. This potential involves the ratio of the separation of the molecules at zero interaction energy to the actual separation distance. This ratio to the sixth power represents the long range attractive forces while this ratio to the twelfth power corresponds to the short range forces.

This simple model of the intermolecular potential does not apply in the case of polar molecules such as water. To describe the existing angle dependence the Stockmayer potential was formulated. Stockmayer showed that the energy of interaction between a pair of polar molecules could be expressed in terms of the dipole moment and the angular orientation of the molecules. Besides the Lennard-Jones 6-12 dependence, the Stockmayer potential also contains a term which is inversely proportional to the cube of the separation.

In order to properly access this potential, the equation of state for a gas

$$\frac{pv}{RT} = 1 + \frac{B(T)}{v} + \frac{C(T)}{v^2} + \dots$$

must be considered. The coefficients $B(T)$, $C(T)$, ..., are called virial coefficients. The coefficient $B(T)$ is called the second virial coefficient and essentially describes the deviation from the ideal gas, $pv = RT$, due to binary collisions. The third virial coefficient describes the deviations due to ternary collisions. Thus, as the density of the gas is increased, more virial coefficients are needed to describe p - v - T behavior. Using the Stockmayer potential, it was possible to fit the second virial coefficients for simple polar molecules with high precision. There is some question, however, as to the convergence of the

virial expansion in the neighborhood of the critical point since it has been hypothesized that the molecules form clusters in this region.

This introduces still another difficulty.

The chief limitation on the Chapman-Enskog collision integrals is that they are concerned only with binary collisions and consequently can not be used for a fluid in the supercritical state or any dense gas. Further, the theory is good only for angle-independent potential functions and, as such, cannot use the Stockmayer potential. This means that the Chapman-Enskog theory will not give transport properties for polar molecules.

The conclusions to be drawn from this discussion are as follows. The above theories are not applicable in this work due to the complicated nature of the water molecule especially near its critical state. More comprehensive theories are being developed (1) but no work has been published or completed at this time (8). In short, it appears to the writers that the state of development of kinetic theory is such that it can add nothing to the determination of the transport properties of supercritical water.

SURVEY AND INTERPOLATION OF EXPERIMENTAL DATA

It was noted in Reference (14) that there existed significant differences in the values of the transport properties of water tabulated in the various steam tables. In order that a better correlation of the experimental measurements might be obtained, a critical review of the available data was necessary. Most of the published literature was available through the survey and analysis of the thermodynamic and

transport properties of water as given in Reference (14). The data which fell in and near the region of interest was used and these values are tabulated in the various tables of this report.

A. Thermal Conductivity Measurements

The thermal conductivity of water and water vapor has been measured at various temperatures and pressures by several investigators. The range and experimental methods used by these investigators are listed in Table 1. In general, two methods have been used, that of the hot wire and that of coaxial cylinders. The first consists of an electrically heated wire centered in a tube containing the sample of water. The second method contains water in an annulus formed by two coaxial cylinders.

The method of data interpolation eventually employed, required that measurements of thermal conductivity of subcooled water be used. A comprehensive investigation of this has been made by the Schmidt and Sellschopp (15), Timroth and Vargaftik (20), and Vargaftik and Oleschuk (22). The measurements of these different investigations were in good agreement and the values used in this work are tabulated in Tables 2, 3 and 4. Other investigators* had made measurements of thermal conductivity of subcooled water but these were out of the range of interest of this work and were therefore not included.

Extensive measurements of the thermal conductivity of superheated water vapor have been made by Timroth and Vargaftik (14) and by Vargaftik and Tarzhimanov (23). The measurements of these investigators are given in Tables 5 and 6, respectively. Not all of the experimental data

* See Ref. (14).

available for the range of interest in this report has been given for reasons which will be mentioned later.

The experimental values obtained by Keyes and Sandell (14) were considerably lower than those values of Timroth and Vargaftik. Vargaftik and Smirnova (14) carried out measurements at one atmosphere pressure to ascertain the cause of the discrepancies. They concluded that since Keyes and Sandell used a comparative method in conducting their experiments, with nitrogen as a standard, and since the values used for thermal conductivity of nitrogen were erroneous, their experimental values were also in error. For this reason the data of Keyes and Sandell was not used in this report.

The method of comparison of data used in the following section required knowing the variation of thermal conductivity at one atmosphere as a function of temperature. The values in the 1952 steam tables of Timroth (19) were used and these are plotted in Figure 1. The use of these values was justified by the good agreement found among the various investigators of the thermal conductivity at one atmosphere pressure.

B. Interpolation of Thermal Conductivity Measurements

Vargaftik (14) stated that he attempted to summarize all of the available experimental material on the thermal conductivity of various gases with the aim of finding a relation for calculating the thermal conductivity of compressed gases. From the data he observed that the thermal conductivity was a function of specific volume and temperature. He also showed that in a sufficiently broad interval of pressure and temperature, the value of $(k - k_0)$ is a function of specific volume

only.*

For all the compressed gases studied by Vargaftik, including steam, in the range of values $v \geq 2/3$ critical the following relationship was found to be valid (23)

$$k - k_0 = cv^{-m}$$

The constants c and m were evaluated from the experimental data for water by Vargaftik and were found to be $c = 1.33 \times 10^{-4}$ and $m = 1.25$ where v is in m^3/kg^3 and the thermal conductivity has units of $\text{kcal}/\text{m}\cdot\text{hr}^\circ\text{C}$.

In order to test the accuracy of Vargaftik's statement the experimental data for water was replotted in the form of $(k - k_0)$ versus specific volume. The values of specific volume were taken from Reference (14) and Reference (19). Some of the experimental data was omitted from the plot since in these cases, the value of k_0 was quite close to that of k and the difference $(k - k_0)$ was of the same order as the experimental error in the original measurement. The best second order equation fit to the data on a log-log plot was determined by the method of least squares and this is drawn in Figure 2. The equation of this line is as follows.

$$\log [(k - k_0) \times 10^4] = 3.796 - 1.065 \log(v \times 10^3) - 0.1253 [\log(v \times 10^3)]^2$$

The maximum deviation of the data from this line was 39% and the average deviation was about 10%.

The best linear fit was also obtained by the method of least squares with an average deviation of about 12%. The resulting equation was as follows.

* The value k_0 is a function of temperature only.

$$k-k_0 = 1.274 \times 10^{-4} v^{-1.240}$$

The values of the constants c and m obtained above are slightly different than the corresponding values obtained by Vargaftik. However, considerably more data was used in this report. In Figure 3, a comparison is given of the lines taken from various references and the above determined lines.

It should be noted that, as shown in Figure 2, no measurements were available very close to the critical point. It was felt, however, that since the values for subcooled water agreed very well when plotted in the form of $(k-k_0)$ versus specific volume the writers were justified in extending the line across the critical region. This was also supported by considering the principle of corresponding states as will be discussed in a later section of this report.

The lines plotted in Figure 2 are also plotted in engineering units in Figure 8 of this report.

C. Dynamic Viscosity Measurements

Experimental measurements of dynamic viscosity for a wide range of temperature and pressures have been made by numerous investigators. The parameters covered and the methods used along with the estimated experimental accuracies of some of the various investigations have been tabulated in Table 7. Most of the measurements were made with the capillary method. The data used for the interpolation of experimental data is tabulated in Tables 8, 9, 10, and 11.

It was noted in Reference (14) that the measurements made by some of the investigators differed significantly from those of others. These differences were attributed, in part, to incorrect theories used in com-

puting the viscosity and also to incorrect experimental methods. Following the recommendation set down in Reference (14) the data from only a selected set of investigators was used. For a complete discussion of methods used and why some were felt to be in error the reader is referred to Reference (14).

Sigwart (17) made the most extensive measurements of the viscosity of water and water vapor in the critical region. Thomas and Jackson (18) reported a considerable number of measurements very near the critical density. These were helpful in determining the final correlation.

The interpolation of the experimental data required the value of dynamic viscosity at one atmosphere pressure. The best reference available was the work of Shifrin (16). Shifrin used the method of two successive capillaries to obtain his measurements. In this manner, corrections for end effects were neglected since they canceled out of the final result. His measurements, in general, fell between the data of others. He found that, up to 700°C, viscosity was linearly dependent upon temperature. The slope began to decrease at higher temperatures. Due to the completeness of Shifrin's work and analysis of the previously published data, the smoothed curve drawn through his data was used in this report. The curve is plotted in Figure 4.

D. Interpolation of Experimental Data

Many different correlations of viscosity data have been suggested as noted in Reference (14). However, the method of correlation derived by Vargaftik from Timroth's data seemed to be the best since a similar functional relation was highly successful in correlating the thermal conductivity data. This relationship was as follows:

$$\mu - \mu_0 = b \rho^m$$

Vargaftik found the constants b and m to be 4.13×10^{-10} and 1.48 respectively, where ρ is measured in kg/m^3 and μ is in kg-sec/m^2 .

To test Vargaftik's hypothesis further, the variable $(\mu - \mu_0)$ was plotted against density and this is shown in Figure 5. A straight line relationship was found for most of the data far into the subcooled liquid region. A straight line was drawn through the data giving more weight to values where the scatter was comparatively small. The method of least squares was not used in the evaluation of the best line since the necessary assigning of weights to various points would have been rather arbitrary. The equation of the line was found to be as follows.

$$\mu - \mu_0 = 2.38 \times 10^{-10} \rho^{1.57}$$

The maximum deviation of the data from this equation was 110% and the average deviation was 34%. It must be kept in mind that this is not the inaccuracy in the value of the dynamic viscosity but rather in the viscosity excess. A large portion of this scatter was due to experimental error which became somewhat magnified after μ_0 was subtracted from the measured values of viscosity. Part of the scatter was also due to the assumption of the viscosity excess being a function of density only. Kestin and Moszynski (10) showed that the viscosity excess was a slight function of temperature also. This dependence could not be determined since it was often overshadowed by the experimental error in the viscosity excess and therefore it was disregarded.

THE PRINCIPAL OF CORRESPONDING STATES

In engineering problems where theory is inadequate and experimental

data is unavailable the principle of corresponding states is often used to predict the necessary property values. The critical point of a substance is a unique state for the fluid. As such, it was found that properties expressed as multiples of the critical point values should be the same for different substances in the same reduced state.

Upon the accumulation of considerable experimental data for the preparation of a reduced properties chart, it was noted that this principle does not hold exactly. Similar behavior was limited to molecules of similar structure. Apparently, there exists a third parameter necessary to account for the differences in the structure of the various substances. This third parameter is necessary otherwise only data of several chemically related substances could be used to predict the property values of another substance of the same general nature by the principle of corresponding states. For example, the polar molecules that obey the Stockmayer potential require that the reduced dipole moment be the same for the application of the principle of corresponding states.

Such a third parameter for the thermodynamic properties has been found and is called the critical compressibility factor, Z_c , (12). It serves to make the use of the principle of corresponding states more general. No such parameter has been found for the transport properties. A paper by Curtiss, Hirschfelder and Bird (6) served as a survey of the literature concerned with the application of this principle to the transport properties.

One of the most recent papers on thermal conductivity of gases at high pressures was that of Lenoir, Junk and Comings (11). The authors note that the previous papers on this subject are in error at fairly high temperatures and pressures due to the very limited amount of

experimental data available and the inaccuracies in the theoretical considerations employed. Therefore, Lenoir, Junk and Comings prepared a chart of thermal conductivity ratio* versus reduced pressure at various reduced temperatures. They used the data available on the thermal conductivity of gases including their own experimental measurements. It was interesting to note that the thermal conductivity for the critical state could be determined from their charts only within an order of magnitude. It also appears that the only experimental measurements of the thermal conductivity of water used in the preparation of this chart were those of Keyes and Sandell; which, as has been mentioned earlier, are in error. Thus one would not be surprised if the reduced charts did not give reasonably correct values for the thermal conductivity of water in the region of interest of this report. This is indeed the case and the values obtained from the reduced chart of Reference (11) are plotted in Figure 6 so that a comparison may be made to the best line drawn through the experimental data as obtained in the previous section.

Experimental viscosity data for various hydrocarbons and such gases as nitrogen, carbon dioxide and argon has been used to construct charts of the viscosity ratio, μ/μ_0 as a function of reduced pressure and reduced temperature. Comings (4) has presented a chart of this type taken from the work of previous investigators, (2), (3), and (4). The values taken from the work of Comings are plotted in Figure 7 for comparison to the experimental data correlated in this report. It is interesting to note that these values give rather good agreement in the critical region even though they were determined independently of the critical viscosity.

* The thermal conductivity ratio was defined as the thermal conductivity k at any pressure divided by the thermal conductivity at one atmosphere, k_0 , where both are evaluated at the same temperature.

A chart of the viscosity ratio μ/μ_c was also prepared by Uyehara and Watson (21) chiefly from the data for hydrocarbons. These authors claim that there existed large deviations for water particularly in the liquid region. These large deviations are indeed realized as shown in Figure 7. A value of $\mu_c = 5.05 \times 10^{-6}$ kg sec/m² was used in finding μ from the ratio of μ/μ_c . This was the value for μ_c that Hougen and Watson (9) had determined from the charts by using a few experimental measurements. Amazingly good agreement was found in the critical region considering the independence of the two methods.

SUMMARY OF RESULTS

From the preceding discussions and presentations the following conclusions may be drawn.

1. At present, kinetic theory does not permit the determination of the values of thermal conductivity and dynamic viscosity in and near the critical region.

2. The empirical correlation used in this report indicated that the differences $(k-k_0)$ and $(\mu - \mu_0)$ are very closely functions of density as found by Vargaftik. Some scatter in the values of dynamic viscosity were encountered but this must not be considered as serious in engineering problems since it resulted from the experimental error being greatly amplified in the difference $(\mu - \mu_0)$.

3. The principle of corresponding states did not add any exact values. However, the values obtained from these charts were independent of the critical values determined in this report and yet agreement was found within 50% in the difference variable for the entire range considered. This showed that the extrapolation of the thermal conductivity values through the critical state was justified since the charts indicated that the transport properties for all substances did not change greatly as the critical density is approached.

4. The best available values for thermal conductivity and dynamic viscosity near the critical point are given in Figures 8 and 9, respectively.

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FIGURE I THERMAL CONDUCTIVITY AT ONE ATMOSPHERE PRESSURE

* TO CHANGE KCAL / M · HR · °C TO BTU / FT · HR · °F, MULTIPLY BY 0.67154

FIGURE 2 EXPERIMENTAL CONDUCTIVITY DATA

FIGURE 3 COMPARISON OF VARIOUS CORRELATIONS

FIGURE 4 DYNAMIC VISCOSITY AT ONE ATMOSPHERE PRESSURE

* TO CHANGE KG SEC / M^2 TO $\text{LBS}_f \text{ SEC / FT}^2$, MULTIPLY BY 0.2048

FIGURE 5 EXPERIMENTAL VISCOSITY DATA

FIGURE 6 THERMAL CONDUCTIVITY FROM PRINCIPLE OF CORRESPONDING STATES

FIGURE 7 DYNAMIC VISCOSITY FROM PRINCIPLE
 OF CORRESPONDING STATES

FIGURE 8 THERMAL CONDUCTIVITY OF WATER vs DENSITY

FIGURE 9 DYNAMIC VISCOSITY OF WATER vs DENSITY

TABLE 1. THERMAL CONDUCTIVITY MEASUREMENTS ON SUBCOOLED WATER AND SUPERHEATED VAPOR

Investigator(s) and Reference	Year	Method	Temp. Range °C	Pressure Range kg/cm ²	Experimental Error	Phase
Schmidt & Sellschopp (15)	1932	Coaxial cylinders	7-270	1-75	$\pm 1\frac{1}{2}\%$	Subcooled water
Vargaftik (14)	1937	Hot wire	68-475	1-29		Water vapor
Vargaftik & Timroth (14)	1939	Hot wire	255-550	20-300	3%	Water vapor
Timroth & Vargaftik (20)	1940	Hot wire	28-331	1-400		Subcooled water
Keyes & Sandell (14)	1950	Coaxial cylinders	100-350	150		Water vapor
Vargaftik & Smirnova (14)	1956	Coaxial cyl. and hot wire	100-900	1		Water vapor
Vargaftik & Tarzhimanov (23)	1959	Hot wire	350-720	5 to 360	2%	Water vapor
Vargaftik & Olescuk (22)	1959	Coaxial cylinders	21-350	1 to 217	$\pm 0.4\%$	Subcooled water

TABLE 2. THERMAL CONDUCTIVITY OF SUBCOOLED WATER
AS MEASURED BY TIMROTH & VARGAFTIK (20)

Temp. °C	Pressure kg/cm ²	K kcal/m-hr°C	K ₀ kcal/m-hr°C	K-K ₀	Specific Volume m ³ /kg
127.5	33	.5870	.0152	.5718	.001065
152.5	37	.5930	.0246	.5684	.001041
152.5	300	.6070	.0246	.5824	.001075
215.4	58	.5570	.0301	.5269	.00177
322.3	300	.4510	.0400	.4110	.00141
331	166	.4020	.0409	.3611	.001529

TABLE 3. THERMAL CONDUCTIVITY OF SUBCOOLED WATER
AS MEASURED BY SCHMIDT & SELLSCHOPP (15)

Temp. °C	Pressure kg/cm ²	K kcal/m-hr°C	K ₀ kcal/m-hr°C	K-K ₀	Specific Volume m ³ /kg
194.3	29.8	.5770	.0282	.5488	.001146
196.8	34.3	.5770	.0284	.5486	.0011526
243.1	42.0	.5440	.0326	.5114	.0012355
269.2	75.8	.5160	.0350	.4810	.0012940

TABLE 4. THERMAL CONDUCTIVITY OF SUBCOOLED WATER
AS MEASURED BY VARGAFTIK & OLESCUK (22)

Temp. °C	Pressure kg/cm ²	K kcal/m-hr°C	K ₀ kcal/m-hr°C	K-K ₀	Specific Volume m ³ /kg
100		.587	.0203	.5667	.0010435
150		.588	.0244	.5636	.0010906
200		.565	.0288	.5362	.0011565
250		.523	.0332	.4898	.0012512
300	Saturation	.462	.0380	.424	.0014036
350	Pressure	.352	.0430	.309	.001741
310	Corresponds	.446	.0390	.407	.001447
320	To	.429	.0401	.389	.001499
330	Temp.	.410	.0411	.369	.001562
340		.385	.0420	.343	.001639

TABLE 5. THERMAL CONDUCTIVITY OF SUPERHEATED WATER VAPOR
AS MEASURED BY TIMROTH AND VARGAFTIK (14)

Temp. °C	Pressure kg/cm ²	K kcal/m-hr°C	K ₀ kcal/m-hr°C	K-K ₀	Specific Volume m ³ /kg
383.9	100	.0576	.0463	.0113	.02784
374.0	150	.0708	.0453	.0255	.01428
463.2	100	.0664	.0549	.0115	.03124
455.8	150	.0680	.0539	.0141	.01921
448.6	200	.0790	.0531	.0259	.01300
437.8	250	0.1005	.0520	.0485	.00884
434.2	300	0.1354	.0516	.0838	.00618
396.2	100	.0598	.0476	.0122	.02675
445.9	150	.0676	.0528	.0148	.01870
434.5	200	.0805	.0516	.0289	.01231
425.7	250	0.1052	.0507	.0545	.00818
422.3	300	0.1462	.0504	.0958	.00540
455.1	300	0.1194	.0538	.0656	.00723
468.7	250	.0880	.0552	.0328	.01023
399.3	200	.0852	.0479	.0373	.0103

TABLE 6. THERMAL CONDUCTIVITY OF SUPERHEATED WATER VAPOR
AS MEASURED BY VARGAFTEK AND TARZHIMANOV (23)

Temp. °C	Pressure kg/cm ²	K kcal/m-hr°C	K ₀ kcal/m-hr°C	K-K ₀	Specific Volume m ³ /kg
350.19	150	.0874	.0428	.0446	.01201
353.99	100	.0563	.0432	.0131	.02337
358.15	100	.0569	.0437	.0132	.02374
445.37	350	.1562	.0528	.1034	.00486
443.97	350	.1609	.0526	.1083	.00480
443.25	350	.1595	.0526	.1069	.00476
445.54	300	.1188	.0528	.0660	.00679
447.02	300	.1151	.0530	.0621	.00687
444.20	300	.1191	.0527	.0664	.00673
446.69	250	.0933	.0529	.0404	.00928
445.31	250	.0924	.0528	.0396	.00922
446.43	200	.0792	.0529	.0263	.01290
448.00	200	.0791	.0530	.0261	.01298
447.48	150	.0677	.0530	.0147	.01878
449.33	150	.0675	.0532	.0143	.01888
447.19	100	.0610	.0530	.0080	.03022
450.88	100	.0612	.0534	.0078	.03046

TABLE 7. DYNAMIC VISCOSITY MEASUREMENTS ON SUBCOOLED WATER AND SUPERHEATED VAPOR

Investigator(s) and reference	Year	Method	Temp. Range°C	Pressure Range in kg/cm ²	Experimental Error	Phase
Schugajew (14)	1934	Rankine viscometer	100-400	Up to 280	6%	Vapor
Sigwart (17)	1936	Capillary tube	117-383	10.5-270	3%	Subcooled water and vapor
Timroth (14)	1940	Capillary tube	18.9- 601.5	100-300	3%	Subcooled water and vapor
Thomas and Jackson (18)	1958	Annulus type Viscometer	223-463	4.8-318	6%	Vapor
Shifrin (16)	1959	Double Cap- illary tube	149-866	1	1.5 to 2%	Vapor

TABLE 8. DYNAMIC VISCOSITY OF SUBCOOLED & SUPERHEATED
WATER AS MEASURED BY SIGWART (17)

Temp. °C	Pressure kg/cm	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu_0 \times 10^{-8}$ kg-sec/m ²	$\mu - \mu_0$ kg-sec/m ²
152.7	12.5	915	1840	145.4	1694.6
154.8	13.4	912	1809	146.3	1662.7
183.0	18.3	885	1532	157.8	1374.2
220.5	32.5	841	1265	173.3	1091.7
253.4	60.2	796	1120	187.0	933.0
152.6	23.0	915	1855	145.3	1709.7
177.3	29.0	890	1613	155.4	1457.6
243.6	86.0	812	1147	182.7	964.3
278.0	93.0	759	1095	197.2	897.8
310.0	147.0	702	964	210.5	753.5
324.7	163.0	669	906	216.3	689.7
349.8	195.0	594	769	226.7	542.3
351.9	178.5	570	731	227.9	503.1
361.3	212.0	549	667	231.7	435.3
362.0	210.0	539	643	232.1	410.9
370.0	227.0	500	587	235.4	351.6
370.4	241.0	521	621	235.6	385.4
370.5	228.0	496	581	235.7	345.3
371.4	253.0	529	637	236.2	400.8
325.1	106.5	53.9	227	217.0	10.0
325.5	120.0	66.8	226	217.0	9.0

TABLE 8., Continued

Temp. °C	Pressure kg/m ³	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu_0 \times 10^{-8}$ kg-sec/m ²	$\mu - \mu_0$ kg-sec/m ²
350.9	105.5	46.45	236	227	9
350.5	127.0	61.1	238	227	11
350.9	127.5	61.9	237	227	10
350.6	144.5	76.538	238	227	11
350.9	162.5	99.47	245	227	18
361.6	112.5	48.608	243	232	11
362.2	130.0	59.78	241	232	9
361.9	150.0	75.46	241	232	9
361.8	161.0	85.946	245	232	13
362.0	169.0	95.354	247	232	15
361.8	176.5	105.84	255	232	23
362.0	179.5	110.74	258	232	26
362.2	184.5	120.54	265	232	33
375.4	122.0	51.45	255	238	17
375.8	149.0	68.502	259	238	21
375.4	174.0	81.278	266	238	28
375.8	180.5	96.04	264	238	26
376.0	183.5	99.47	261	238	23
375.2	196.0	116.13	268	238	30
375.0	209.0	140.14	272	238	34
375.6	218.0	162.68	287	238	49
382.7	125.0	51.546	250	241	9
382.7	152.5	68.502	256	241	15

TABLE 8., Continued

Temp. °C	Pressure kg/m ³	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu_0 \times 10^{-8}$ kg-sec/m ²	$\mu - \mu_0$ kg-sec/m ²
382.5	179.0	89.572	259	241	18
382.7	203.0	115.64	267	241	26
382.7*	225.5	155.82	293	241	52
382.9	235.0	186.20	304	241	63
382.7	253.0	324.38	393	241	152
382.7	270.0	499.8	610	241	369
382.9	270.0	499.8	615	241	374

TABLE 9. DYNAMIC VISCOSITY OF SUBCOOLED & SUPERHEATED
WATER AS MEASURED BY TIMROTH (14)

Temp. °C	Pressure kg/cm ²	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu - \mu_0$
202.6	355	883.0	1490	165	1325
202.6	100	867.3	1420	165	1255
236.0	349	846.7	1240	180	1060
235.0	196.2	835.9	1220	179	1041
263.0	353	813.4	1150	191	959
261.0	100	788.9	1080	190	890
298.5	352	758.5	1010	206	804
298.5	100	718.3	936	206	730
336.0	350	691.9	905	221	684
335.0	200.5	649.7	835	221	614
343.0	355	678.2	857	224	633
343.0	201	625.2	796	224	572
357.7	362.5	638.0	820	230	590
357.7	251.0	594.9	767	230	537
357.2	203	559.6	726	230	496
363.0	300	599.8	751	232	519
362.7	208	522.3	672	232	440
369.0	149.5	71.64	255	235	20
368.0	149.5	72.23	253	235	18
369.0	202	145.5	284	235	49
382.0	254	355.7	494	240	254
285.5	351	543.9	736	242	494

TABLE 9., Continued

Temp. °C	Pressure kg/cm ²	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu_o \times 10^{-8}$ kg-sec/m ²	μ/μ_o
384.0	301	490.0	643	241	402
380.0	251	396.9	540	239.5	300.5
399.0	204	100.254	275	247.5	27.5
398.0	300	348.39	483	247.0	236.0
393.5	249.5	160.426	319	245.0	74.0
400.0	146	59.682	260	247.8	12.2
446.0	304	151.9	345	267.1	77.9
449.0	249	105.448	305	268.7	36.3
453.0	198.7	75.46	295	270.0	25.0
453.0	151.2	52.822	287	270.0	17.0
500.3	301.0	112.7	340	289.6	50.4
498.5	248.5	86.73	320	289.5	30.5
501.0	199.5	65.758	318	290.0	28.0
501.0	151.0	46.256	311	290.0	21.0
525.5	96.5	101.724	343	298.9	44.1
526.2	249.0	81.536	339	300.4	38.6
526.5	201.3	62.622	326	300.6	25.4
528.0	303.0	103.684	348	301.2	46.8
528.3	305.0	105.056	349	301.3	47.7
532.0	145.5	42.63	315	302.9	12.1
530.6	105.0	29.89	311	302.2	10.8
529.0	307.5	106.134	353	301.5	51.5
531.0	249.0	80.36	340	302.5	37.5

TABLE 9., Continued

Temp. °C	Pressure kg/cm ²	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu_0 \times 10^{-8}$ kg-sec/m ²	$\mu - \mu_0$
531.0	198.5	61.25	327	302.5	24.5
530.0	149.5	44.1	314	302.0	12.0
600.5	296.5	84.672	383	331.2	51.8

TABLE 10. DYNAMIC VISCOSITY OF SUPERHEATED WATER VAPOR NEAR
THE CRITICAL STATE AS MEASURED BY SCHUGAJEW (14)

Temp. °C	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu_r \times 10^{-8}$ kg-sec/m ²	$\mu - \mu_0$
381.0	222.2	387.7	240.0	138.7
380.0	222.2	378.9	239.6	139.3
377.5	222.2	422.6	238.7	183.9
373.0	222.2	419.0	236.7	182.3
372.6	222.2	432.8	236.4	196.4
395.0	166.7	339.1	245.7	93.4
383.0	166.7	322.2	240.7	81.5
374.0	166.7	316.5	237.1	79.4
395.0	138.9	313.3	245.7	67.6
385.0	138.9	302.95	241.6	61.35
372.0	138.9	304.7	236.2	68.5
361.0	138.9	290.4	231.8	58.6
399.0	111.1	314.3	247.5	66.8
375.0	111.1	299.9	237.5	62.4
361.0	111.1	272.2	231.7	40.5
352.0	111.1	266.7	228.0	38.7
400.5	83.33	296.9	248.0	48.9
391.0	83.33	274.9	244.1	30.8
376.6	83.33	287.8	238.2	49.6
369.0	83.33	272.2	235.0	37.2
351.5	83.33	257.8	227.8	30.0
342.0	83.33	248.0	223.8	24.2

TABLE 10., Continued

Temp. °C	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu_o \times 10^{-8}$ kg-sec/m ²	$\mu - \mu_o$
391.0	55.56	259.6	244.3	15.3
358.0	55.56	245.6	230.5	15.1

TABLE 11. DYNAMIC VISCOSITY OF SUPERHEATED WATER VAPOR NEAR THE
CRITICAL STATE AS MEASURED BY THOMAS & JACKSON (18)

Temp. °C	Pressure kg/cm ²	Specific Weight kg/m ³	$\mu \times 10^{-8}$ kg-sec/m ²	$\mu_0 \times 10^{-8}$ kg-sec/m ²	$\mu - \mu_0$
379.1	225.3	175.1	278.6	239.2	39.4
383.8	250.6	304.8	454.3	241.1	213.2
394.5	282.6	322.6	380.5	245.6	134.9
450.1	286.1	131.7	342.5	268.7	73.8
370.0	283.6	565.0	882.0	235.4	646.6
386.5	233.0	163.1	272.6	242.3	30.3
388.4	235.5	161.6	273.6	243.1	30.5
389.5	240.4	170.4	288.3	243.6	44.7
381.4	246.0	311.5	459.6	240.0	219.6
383.6	247.4	275.5	406.4	241.0	165.4
393.3	261.1	218.3	338.9	245.0	93.9
400.3	289.3	265.3	450.0	248.0	202.0
463.7	298.8	130.7	319.1	274.4	44.7
396.4	301.6	355.9	443.6	246.5	197.1
411.1	310.4	257.7	385.0	252.5	32.5
405.6	318.1	321.5	510.8	252.3	258.5