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Viscosity Measurement of Water and Steam at High Temperatures and High Pressures*

By Akira NAGASHIMA** and Ichimatsu TANISHITA***

Viscosity of water and steam was experimentally investigated in a wide range of temperatures up to 900°C and of pressures up to 1 000 bar. In this investigation, a capillary viscometer was used in the closed circuit system with a high pressure injector and a mercury manometer.

Measured results are compared with the standard values of the ICPS Skeleton Table (1964), and with experimental values of other investigations.

A newly correlated equation represents experimental results within about 2% deviations.

1. Introduction

Although a group of successful investigations has been reported in recent years, still there exist many problems in the field of the viscosity study of water and steam. For example, at around 475°C and 400 bar, the discrepancy between the experimental values of Whitelaw⁽¹⁾ and of Timroth and Flopkins⁽²⁾ amounts to about 8%, and at 385°C and 200 bar, the discrepancy between Tanaka⁽³⁾ and Mayinger⁽⁴⁾ is about 10%. Around the critical temperature, reliable experimental values are so scarce.

To get a set of consistent values for wide ranges of temperature and pressure, the experimental investigation using capillary viscometer was carried out for water and steam at temperatures up to 900°C and pressures up to 1 000 bar (1 020 kg/cm²).

Here described are method, measured results, empirical correlation and some comparisons. Some of more detailed discussions are given in the reports⁽⁵⁾.

2. Symbols

- C : the capillary constant cm⁴
 f : density ratio
 Δh : travel of manometer cm
 k : averaged dimension of irregularities inside a capillary
 l : length of capillary cm
 m : kinetic energy correction factor
 N : rotating speed of the injector gear rpm
 P : pressure bar
 Q : flow rate cm³/sec
 r : radius of capillary cm

- R : gear ratio
 R_e : Reynolds number
 t : temperature °C
 α : thermal expansion coefficient
 ν : kinematic viscosity cm²/sec
 ρ : density g/cm³
 ζ : slip correction factor
 η : dynamic viscosity μ P

Subscripts:

- 1: entrance of the capillary, atmospheric pressure
 2: exit of the capillary

3. Method

The intended range of this investigation is from 50°C to about 900°C in temperature and from 70 bar to about 1 000 bar in pressure, which corresponds to the density range of 0.03 to 1.03 g/cm³ and to the viscosity range of 200 to 10 000 μ P. In order to measure this extensive range by a single apparatus, the capillary method was chosen as the most suitable and reliable. For the capillary viscometer, the dimensions, the material and the calibration method of the capillary play a very important role. The platinum capillaries used in this investigation were calibrated against the "standard" glass capillaries and the variation of the capillary constant with Reynolds number was examined.

Measured results were calculated using the modified Hagen-Poiseuille equation.

4. Experimental apparatus

The apparatus used is a sort of so-called capillary viscometer with a constant flow rate injector. The schematic diagram of major portions is shown in Fig. 1. Steady flow was produced by the injector-16. The capillary system in the autoclave 1 was

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** Lecturer, Faculty of Engineering, Keio University, Koganei.

*** Professor, Faculty of Engineering, Keio University.

heated up by heaters 3, 5 and 7 through a thick copper cylinder 2, whose temperature was controlled and measured by thermocouples and Pt resistance thermometer 6 with an automatic controller 9, a double bridge 10 and/or a potentiometer.

Pressure drop was measured by a manometer 12. The system was pressurized by a high pressure water pump 25 while the pressure was measured by a dead weight gage system 17. Four platinum pipes from the capillary system extend to the connecting chamber 8, where they are connected with stainless steel pipes to the injector and the manometer.

4.1 Capillary system

The capillary, as shown in Fig. 2, is straight and made of a platinum-rhodium (5%) alloy. Dimensions are approximately 0.03 cm for the inner diameter and 30 cm for the length. At the inlet of

Fig. 1 The schematic diagram of the viscometer

- ① Driving screw
- ② Worm gear mechanism
- ③ Plunger
- ④ Cylinder
- ⑤ Gears
- ⑥ Counter sensing element
- ⑦ Controller
- ⑧ Motor

Fig. 3 The injector system

the capillary, a platinum chamber of approximately 4 cm³ is welded with gold solder, where are connected water (steam) flowing pipes with a coiled pipe of about 100 cm long for preheating and also pipes to manometer, all made of platinum.

This capillary system is horizontally installed in a heavy walled autoclave made of special Ni-Cr-Mo-W steel and heated from the outside of the autoclave through a thick copper cylinder.

4.2 Injector

Injector system is shown in Fig. 3. Steady flow is produced by an injector which consists of two pairs of plungers and cylinders, together with the driving mechanism. While the steady flow through the capillary is produced, the total inner volume of the system is kept constant.

Flow rate Q can be calculated from the driving speed of the plunger driven by a screw and a worm gear whose rotating speed N is measured by an electrical counter, as follows;

$$Q = 2.5598 \times 10^{-5} R N f \text{ cm}^3/\text{sec} \dots (1)$$

where the injector constant 2.5598×10^{-5} was calibrated by weighing the discharged water at room temperature and at atmospheric pressure for a wide range of flow

- ① Platinum capillary
- ② Entrance chamber
- ③ Exit chamber
- ④ Platinum pipe (in)
- ⑤ Platinum pipe (out)
- ⑥, ⑦ Pipes to manometer

Fig. 2 The capillary system

Fig. 4 Principle of the manometer

rate. A small correction for high pressure deformation of plungers was applied. The error caused by flow rate measurement is estimated as less than 0.5%.

4.3 Manometer

Figure 4 schematically shows the manometer. The larger chamber A is fixed on a table and the chamber B with flexible coiled pipes can travel vertically. During measurements, height of the chamber B was controlled manually so as to keep the level of mercury through a window at the position of the hair line in the field of a microscope.

The travel Δh of the chamber B was measured by a micrometer to the accuracy of 0.01 mm. The "zero position" was checked for each run. The correction for deformation of the coiled part was determined by calibrating with the water U-tube manometer and found to be about 0.3% of the total pressure difference.

The compressibilities of water and mercury in the manometer were calculated using the equations of state; for water, the 1967 Formulation of International Conference on the Properties of Steam⁽⁶⁾, and for mercury, the newly correlated equation which reproduces the density values of mercury in International Critical Tables within 0.05% error.

4.4 Measurement of temperature and pressure

Autoclave containing the capillary was heated up and controlled by a group of electrical heaters which were two main heaters, two end heaters and one preheater. The power input to one of main heaters was controlled by an automatic controller which maintains the temperature of the capillary within $\pm 0.1^\circ\text{C}$ from the aimed temperature.

To get a better temperature distribution along the capillary, the autoclave is surrounded with a thick wall copper cylinder which has dimensions of 8 cm ID, 16 cm OD and 67 cm length. On the inner surface of the copper cylinder there are straight gutters which house a platinum resistance thermometer or a Pt-PtRh thermocouple, and CA thermocouples. Temperature distribution along the axis of the capillary was checked by sliding the resistance thermometer or the thermocouple along the gutters. One thermocouple was used as the sensing element for the automatic temperature controller.

Up to about 630°C the temperature was measured by a platinum resistance thermometer which was calibrated at solidifying points of Sb (630.5°C), Zn (419.5°C), Pb (327.3°C) and ice point, and also compared with a standard mercury-in-glass thermometer below 150°C . Over 630°C a Pt-PtRh (10%) thermocouple was used which had been calibrated at National Research Laboratory of Metrology at Au point (1063°C), Ag point (960.8°C) and Sb point (630.5°C). Both devices were calibrated separately,

and while the experiments were going on, both were compared at 500°C , and it was found that platinum resistance thermometer showed higher temperature by 0.57°C than the Pt-PtRh thermocouple. Below 630°C the value by the resistance thermometer was used, since it was supposed to be more stable than the thermocouple. The estimated maximum error of temperature measurement was about $\pm 0.5^\circ\text{C}$ at 500°C and $\pm 1.5^\circ\text{C}$ at 900°C .

The pressure of the viscometer system was controlled by a high pressure plunger pump and was measured by a dead weight gage which was calibrated at National Research Laboratory of Metrology. The estimated accuracy of pressure measurement was about 0.2%.

5. Calibration of capillaries

5.1 Method of calibration

It is quite difficult to get a metallic capillary having a smooth and exact circular cross section. This irregularity of the inner wall of the capillary causes two major difficulties in calibrating the capillary and in measurement.

Firstly, it makes us difficult to calibrate the capillary using water as a calibrating fluid. When the capillary constant C , which corresponds to r^4 in Hagen-Poiseuille equation, of platinum capillary was calibrated by steady flow of water, it decreased by several per cent in about one hour of flowing, while for glass capillaries of similar dimensions the constants never changed and agreed with the values by the mercury weighing method. This phenomenon is supposed to be caused by growth of small air bubbles formed at irregularities of the wall of the platinum capillary.

Secondly, the critical Reynolds number where the flow changes from laminar to turbulent or transient is made considerably lower because of disturbances by irregularities at the inner wall of the capillary. For that case the variation of the capillary constant with Reynolds number should be examined, in order to perform all measurements under laminar flow condition.

Then in this study, the capillary constant used in measurements was obtained by calibrating against the known glass capillaries using air, and also experiments to check the critical Reynolds number were carried out in several ways.

The apparatus for calibration is shown in Fig. 5. The unknown platinum capillary 2 is connected after the standard glass capillary 1 in series. If dimensions of these two capillaries are similar, then the capillary constant C_2 of the platinum capillary 2 can be obtained by comparing with C_1 of the glass capillary. In the modified Hagen-Poiseuille equation

derived by Erk⁽⁷⁾ for the compressible fluid, $P_1 Q_1$ is equal to $P_2 Q_2$, and C_2 is determined as;

$$C_2 = \frac{l_2}{l_1} \frac{P_1^2 - P_2^2}{P_2^2 - P_3^2} C_1 - \frac{l_2}{\pi^2 (P_2 - P_3) \left(1 - \frac{P_2 - P_3}{2P_2}\right)} \times \left\{ \frac{\rho_1 P_2}{l_1 P_1} \left(m + \ln \frac{P_1}{P_2}\right) - \frac{\rho_2}{l_2} \left(m + \ln \frac{P_2}{P_3}\right) \right\} Q_2^2 \dots (2)$$

where P_1, P_2, P_3 correspond to pressures before and after the capillary 1 and after the capillary 2. If P_1, P_2, P_3 and the dimensions of both capillaries are chosen properly, the second term of Eq. (2) can be made negligibly small. Then it is possible to get the capillary constant without knowing the exact viscosity value of the fluid.

5.2 Capillary constant

For the standard glass capillary, r^* (given as C_1 in Eq. (2) for the platinum capillary) was given as;

$2.9748 \times 10^{-8} \text{ cm}^4$ with water (1.0019 cP at 20°C, 1 atm)

$2.9805 \times 10^{-8} \text{ cm}^4$ by mercury weighing method
The former was adopted for calibration standard.

After the second series of experiment, the platinum capillary was subjected to a high internal pressure caused by leakage at an outside valve part. And the constant C was slightly changed. After that it was found unchanged after the fifth series of experiment.

Used capillary constants are:

$3.4995 \times 10^{-8} \text{ cm}^4$ for the first and second series

$3.5333 \times 10^{-8} \text{ cm}^4$ for the third, fourth and fifth series.

The length of the platinum capillary is $30.189 \pm 0.001 \text{ cm}$.

5.3 Critical Reynolds number

For the metallic capillary having a rough surface the critical Reynolds number can be lower than 2300 of the smooth walled tube. One

example of checking experiments is shown in Fig. 6. C_0 is the value of C at lower R_e . Figure 6 shows results by n-pentane at 14°C and 1 atm. This curve demonstrates the fact that at Reynold number R_e of more than 300, the capillary constant does not remain constant but changes with Reynolds number. Also in pressurised water and steam region, similar checking experiments were made and this trend was confirmed. Examples at 500°C, 400 bar are also shown in Fig. 6.

When the actual dimension k of irregularities at the inner surface is less than one third the thickness of the laminar boundary layer, the wall is often assumed as "hydrodynamically" smooth. This means, if ku^*/ν exceeds 4, the capillary constant C changes not only with R_e but also with the dimension of irregularities, where u^* is the friction velocity and ν the kinematic viscosity. For the capillary used in this investigation, this limit of R_e becomes about 300, if irregularities which magnitude is roughly 4% of the capillary diameter exist.

After the capillary was cut apart from the longer capillary, the remaining portion was cut into five pieces and their cross sections were carefully checked with a microscope. Also from this observation the above estimation of the dimension of irregularities seems to be quite reasonable.

In this study all measurements have been performed with R_e of below 300. For the region where kinematic viscosity is low (from 100 to 400 bar below 500°C), R_e easily reaches to higher values. In that case, if the measurement is made with the pressure difference whose magnitude is similar to that of the measurement at, for example, 700°C and 300 bar, then R_e exceeds the critical value and the measured viscosity becomes higher.

6. Calculation and results

6.1 Equation

Viscosity was calculated by the modified Poiseuille equation

Fig. 6 An example of the capillary constant varying with R_e

Fig. 5 The apparatus for calibration

$$\eta = \frac{\pi C}{8l} \frac{1}{Q} \frac{P_1^2 - P_2^2}{2P_1} \left(1 + \frac{4\zeta}{r}\right) (1 + 3\alpha \Delta t) - \frac{\rho Q}{8\pi l} \frac{\left(m + \ln \frac{P_1}{P_2}\right)}{(1 + \alpha \Delta t)} \dots (3)$$

The coefficient α for thermal expansion of Pt-Rh alloy was chosen as $1.02 \times 10^{-5}/^\circ\text{C}$.

Table 1 Measured results in compressed water region

t °C	P bar	ρ g/cm ³	η μP	$\nu \times 10^6$ cm ² /sec	Re	t °C	P bar	ρ g/cm ³	η μP	$\nu \times 10^6$ cm ² /sec	Re
50.17	57.9	0.990 47	5 443	5 496	9	300.34	498.2	0.776 03	1 018	1 312	144
50.10	58.4	0.990 52	5 448	5 501	12	300.32	498.2	0.776 06	999.3	1 288	172
49.70	66.9	0.991 07	5 629	5 679	10	300.26	496.9	0.776 00	994.3	1 281	117
50.11	102.5	0.992 42	5 520	5 562	10	300.36	493.7	0.775 49	1 004	1 295	189
50.20	102.5	0.992 38	5 571	5 614	14	300.34	493.7	0.775 51	1 006	1 298	159
50.31	102.5	0.992 33	5 565	5 608	14	300.40	491.8	0.775 21	1 019	1 315	223
50.33	251.5	0.998 58	5 540	5 548	11	300.32	491.3	0.775 27	1 022	1 319	211
50.33	502.3	1.008 6	5 586	5 538	14	300.33	490.3	0.775 15	1 020	1 316	273
50.31	501.9	1.008 6	5 517	5 469	12	300.23	973.0	0.820 35	1 100	1 341	161
50.40	995.2	1.027 1	5 506	5 361	12	300.20	971.4	0.820 26	1 085	1 323	138
50.36	995.4	1.027 1	5 578	5 430	14	320.60	136.3	0.672 80	800.3	1 190	195
50.40	995.4	1.027 1	5 492	5 347	13	320.69	121.0	0.667 58	815.0	1 221	192
95.47	101.0	0.966 04	2 990	3 095	37	320.69	121.0	0.667 58	822.0	1 231	190
95.33	101.8	0.966 17	3 002	3 107	33	345.03	155.0	0.592 68	713.1	1 203	215
95.15	101.8	0.966 30	3 030	3 136	42	345.04	155.0	0.592 63	706.0	1 191	216
100.65	114.7	0.963 05	2 816	2 924	23	345.10	154.9	0.592 25	702.0	1 185	218
100.58	114.7	0.963 10	2 800	2 908	36	344.96	174.1	0.605 82	710.2	1 172	205
100.60	113.7	0.963 04	2 823	2 931	26	345.09	174.6	0.605 56	720.7	1 190	213
99.97	491.6	0.980 08	2 945	3 005	25	345.10	174.6	0.605 52	707.9	1 169	217
99.68	975.1	0.999 33	3 016	3 018	23	345.37	185.5	0.610 74	728.0	1 192	215
99.68	975.1	0.999 33	3 008	3 010	26	345.39	185.5	0.610 66	720.2	1 179	230
125.08	107.7	0.944 12	2 271	2 405	36	345.55	185.8	0.610 19	726.7	1 191	215
125.11	105.9	0.944 01	2 281	2 417	43	345.47	186.0	0.610 61	719.7	1 179	259
125.10	105.9	0.944 01	2 261	2 395	52	345.40	261.4	0.643 34	772.0	1 200	178
125.00	105.9	0.944 10	2 260	2 394	66	345.39	262.3	0.643 71	793.5	1 233	226
124.96	105.9	0.944 13	2 269	2 403	40	345.33	709.0	0.733 73	927.8	1 265	172
200.81	107.9	0.870 73	1 368	1 571	67	345.23	707.8	0.733 72	945.8	1 289	174
200.84	107.4	0.870 66	1 384	1 590	86	362.08	197.6	0.527 46	619.2	1 174	211
200.86	403.8	0.896 09	1 471	1 641	85	362.20	197.8	0.526 72	621.7	1 180	223
200.96	403.8	0.895 99	1 446	1 614	79	362.34	215.8	0.550 08	649.4	1 181	235
200.86	492.0	0.895 98	1 456	1 625	97	362.24	215.8	0.550 71	647.7	1 176	211
200.86	492.0	0.895 98	1 456	1 625	85	370.23	216.5	0.477 89	568.9	1 190	237
200.90	984.6	0.922 56	1 566	1 697	82	370.28	217.4	0.480 25	570.7	1 188	272
200.96	984.6	0.922 50	1 577	1 709	72	370.26	216.2	0.476 11	559.4	1 175	275
200.94	976.9	0.922 14	1 547	1 677	91	370.20	220.7	0.491 23	569.2	1 159	274
226.85	81.9	0.836 67	1 223	1 461	121	370.16	220.9	0.492 36	589.7	1 198	265
226.87	81.8	0.836 63	1 211	1 448	130	370.12	221.1	0.493 50	574.8	1 165	269
226.72	81.6	0.836 81	1 200	1 434	152	370.32	229.7	0.509 75	601.1	1 179	224
226.55	80.9	0.836 97	1 214	1 450	285	370.21	229.7	0.510 74	608.0	1 190	253
226.29	80.4	0.837 27	1 229	1 468	192	370.20	239.6	0.526 16	627.1	1 192	224
300.42	99.2	0.714 23	903.2	1 265	184	370.19	240.1	0.526 89	619.9	1 177	272
300.41	99.2	0.714 26	918.1	1 285	174	369.95	503.4	0.652 86	788.1	1 207	227
301.13	99.1	0.712 57	911.6	1 279	210	369.98	504.9	0.653 16	805.1	1 233	178
300.86	99.1	0.713 20	913.8	1 281	219	369.89	505.3	0.653 47	783.2	1 199	162
300.40	97.1	0.713 82	902.0	1 264	163	369.85	990.5	0.732 51	921.0	1 257	163
300.36	91.2	0.712 58	909.1	1 276	149	369.76	990.3	0.732 61	916.5	1 251	201
300.33	91.2	0.712 65	895.5	1 257	155	372.29	221.1	0.459 71	551.3	1 199	298
300.04	134.1	0.722 49	904.5	1 252	173	372.01	226.5	0.484 42	582.4	1 202	281
300.11	134.1	0.722 34	902.1	1 249	189	372.29	237.8	0.506 71	616.9	1 217	267
300.22	134.1	0.722 10	898.9	1 245	141	372.32	238.0	0.506 80	610.7	1 205	293
300.46	286.4	0.748 15	969.9	1 296	128	371.25	260.9	0.543 74	650.7	1 197	238
300.43	285.9	0.748 13	964.4	1 289	148	371.42	260.9	0.542 79	662.6	1 221	235
300.46	285.9	0.748 08	956.6	1 279	178	372.16	261.8	0.539 55	651.7	1 208	276
300.30	498.9	0.776 17	1 004	1 294	128						

The kinetic energy correction factor m in the modified Poiseuille equation⁽³⁾ was taken as 1.12. The magnitude of this correction term is less than 1% of the total viscosity value. The "end correction factor n " is not written here. This correction

is included in the capillary constant C , because the same equation was applied for calibration and for measurement. The slip correction factor ζ was calculated by Knudsen's equation;

Table 2 Measured results in superheated steam region

t °C	P bar	ρ g/cm ³	η μ P	$\nu \times 10^6$ cm ² /sec	Re	t °C	P bar	ρ g/cm ³	η μ P	$\nu \times 10^6$ cm ² /sec	Re
346.27	72.3	0.029 825	214.2	7 183	201	600.68	224.9	0.062 698	334.3	5 332	173
346.09	140.0	0.078 357	216.9	2 768	291	600.64	224.9	0.062 703	336.9	5 373	194
375.58	229.7	0.430 60	508.2	1 180	268	601.26	226.0	0.062 972	336.1	5 338	164
375.34	229.2	0.433 57	508.5	1 173	244	601.92	225.2	0.062 650	345.0	5 507	227
375.57	229.5	0.428 95	502.7	1 172	267	602.02	225.2	0.062 639	345.0	5 507	193
375.48	232.3	0.449 33	531.9	1 184	253	602.08	223.6	0.062 141	346.0	5 569	192
375.52	232.1	0.447 43	520.3	1 163	259	602.04	223.6	0.062 145	337.2	5 426	154
375.56	231.8	0.445 22	520.6	1 169	258	602.08	224.5	0.062 416	341.1	5 465	168
375.59	237.2	0.467 79	550.1	1 176	266	600.68	305.6	0.089 228	357.1	4 002	258
375.58	237.3	0.468 28	547.5	1 169	274	600.63	306.0	0.089 372	348.3	3 897	228
375.45	245.0	0.490 66	583.6	1 190	255	600.57	503.8	0.164 93	394.3	2 391	261
375.39	244.6	0.490 43	575.4	1 173	258	600.87	499.1	0.162 82	388.8	2 388	264
375.01	295.2	0.554 30	649.7	1 172	237	600.36	698.0	0.250 56	431.3	1 721	261
374.89	295.2	0.554 85	661.8	1 193	234	600.67	696.3	0.249 48	430.6	1 726	245
374.93	295.2	0.554 67	659.3	1 189	234	600.59	693.3	0.248 23	432.7	1 743	252
385.12	290.0	0.488 84	586.1	1 199	280	600.48	700.6	0.251 59	445.2	1 770	241
385.22	290.9	0.489 51	586.7	1 198	294	600.34	701.1	0.251 94	444.2	1 763	256
400.34	89.3	0.033 097	243.6	7 360	201	600.13	701.2	0.252 18	443.7	1 760	281
400.77	89.3	0.033 061	247.1	7 472	223	600.13	701.2	0.252 18	439.9	1 744	231
402.20	125.5	0.049 889	244.3	4 896	207	601.61	705.1	0.252 58	441.1	1 746	234
401.08	124.3	0.049 415	244.5	4 947	196	601.58	705.8	0.252 94	440.2	1 740	247
401.78	124.0	0.049 156	250.2	5 091	193	601.59	706.6	0.253 26	432.6	1 708	211
403.02	311.7	0.361 48	426.7	1 181	243	599.74	803.4	0.297 65	474.4	1 594	227
403.06	312.1	0.362 39	430.1	1 187	266	599.82	802.5	0.297 19	485.6	1 634	244
402.96	309.6	0.354 87	427.8	1 206	264	599.78	802.5	0.297 23	482.6	1 624	243
399.52	390.7	0.518 60	629.0	1 213	183	601.15	1 004.2	0.374 88	552.3	1 473	242
399.53	390.7	0.518 56	629.3	1 214	194	601.15	1 002.5	0.374 28	548.3	1 465	203
402.83	499.6	0.570 12	678.5	1 190	223	700.49	222.9	0.053 138	373.6	7 031	138
402.88	501.6	0.570 86	687.8	1 205	219	700.50	224.0	0.053 405	379.4	7 105	162
402.87	703.3	0.633 37	784.0	1 238	222	700.70	228.5	0.054 541	383.5	7 032	154
402.85	703.3	0.633 41	788.8	1 245	193	700.65	229.7	0.054 846	384.9	7 017	124
402.73	911.2	0.673 79	839.4	1 246	266	700.51	299.4	0.073 060	389.1	5 326	214
402.72	910.1	0.673 62	856.2	1 271	228	700.50	299.4	0.073 061	393.9	5 391	244
402.56	900.5	0.672 30	848.4	1 262	230	700.11	310.1	0.075 963	388.6	5 116	195
399.19	970.2	0.688 26	841.1	1 222	193	700.10	310.5	0.076 069	387.0	5 088	199
398.76	970.2	0.688 89	860.8	1 250	225	701.05	497.2	0.128 46	417.7	3 251	231
501.35	121.6	0.037 792	296.2	7 837	156	701.06	496.7	0.128 32	418.9	3 265	190
501.34	121.6	0.037 792	296.0	7 832	172	700.95	700.9	0.190 11	434.2	2 284	231
501.19	121.4	0.037 737	289.1	7 660	164	700.81	700.4	0.190 02	448.3	2 359	198
501.25	112.0	0.034 494	296.6	8 599	188	700.78	700.9	0.190 18	440.3	2 315	184
501.34	112.0	0.034 488	293.8	8 518	161	700.55	699.0	0.189 70	448.3	2 363	240
502.13	232.8	0.081 417	301.4	3 702	226	700.66	696.8	0.188 96	443.9	2 349	187
502.20	232.8	0.081 401	305.2	3 749	252	700.62	902.4	0.252 62	485.2	1 921	247
501.46	230.7	0.080 608	303.3	3 763	163	700.58	894.1	0.250 08	489.6	1 958	204
501.54	231.0	0.080 723	301.5	3 735	179	800.10	227.3	0.047 895	411.7	8 596	118
501.41	231.9	0.081 191	297.3	3 662	212	800.06	229.0	0.048 264	417.4	8 648	120
501.36	232.9	0.081 642	298.3	3 654	177	800.00	229.0	0.048 267	412.8	8 552	121
500.38	409.9	0.184 69	351.8	1 905	211	800.00	232.2	0.048 976	416.9	8 512	115
500.55	410.9	0.185 44	352.2	1 899	247	801.36	234.7	0.049 437	409.3	8 278	117
500.51	411.2	0.185 70	357.5	1 925	206	804.68	234.7	0.049 250	421.6	8 561	114
500.81	398.4	0.176 17	345.1	1 959	246	804.53	234.7	0.049 258	408.4	8 292	118
500.67	398.4	0.176 30	352.5	1 999	260	800.24	302.5	0.064 578	431.8	6 686	143
500.41	411.9	0.186 32	355.9	1 910	299	801.19	504.8	0.111 12	450.3	4 052	180
501.96	405.2	0.179 86	343.7	1 911	262	801.15	502.1	0.110 50	450.6	4 078	213
500.38	411.9	0.186 35	356.8	1 915	246	805.73	707.8	0.153 66	475.6	2 998	217
499.59	697.5	0.404 83	545.1	1 347	237	804.47	705.1	0.158 33	473.2	2 988	220
499.61	694.3	0.402 92	542.7	1 347	238	803.75	804.2	0.182 35	491.9	2 697	216
499.72	687.9	0.398 83	523.1	1 312	247	805.10	798.5	0.180 59	486.7	2 695	195
499.72	687.9	0.398 83	525.2	1 317	219	903.02	221.1	0.041 782	458.8	10 981	106
501.00	708.0	0.407 75	536.9	1 317	231	903.34	221.1	0.041 769	459.3	10 997	106
501.28	698.0	0.401 26	529.4	1 319	219	900.79	229.4	0.043 470	454.0	10 443	108
501.34	698.0	0.401 13	534.6	1 333	240	900.74	229.0	0.043 397	454.6	10 476	124
501.04	907.3	0.497 30	647.2	1 301	200	900.53	310.1	0.059 257	466.8	7 877	132
500.93	900.9	0.495 35	634.2	1 280	211	900.60	309.6	0.059 156	461.0	7 793	143
500.92	896.1	0.493 67	632.2	1 281	213	904.65	348.1	0.066 479	457.3	6 879	116
499.49	986.6	0.525 23	654.3	1 246	201	903.44	354.5	0.067 820	462.3	6 816	114
601.72	106.4	0.027 791	334.7	12 042	164	903.92	487.4	0.094 210	474.6	5 037	154
601.63	108.4	0.028 335	334.5	11 805	140	904.23	487.4	0.094 177	477.5	5 070	171
601.51	108.4	0.028 340	333.4	11 765	138	900.43	511.1	0.099 358	478.8	4 819	191
600.69	223.6	0.062 296	345.8	5 551	186	900.40	510.6	0.099 263	473.7	4 772	165
600.98	224.3	0.062 480	336.7	5 389	192	904.21	701.2	0.137 24	502.2	3 659	158
600.76	224.9	0.062 689	329.6	5 257	202	904.35	705.6	0.138 10	503.6	3 647	181

$$\zeta = 0.81 \frac{8\eta}{3} \sqrt{\frac{2}{\pi P \rho}} \dots \dots \dots (4)$$

6.2 Source of the density data

The density of water and steam at the capillary, and water density at the injector and at the manometer were calculated by the 1967 IFC Formulation for Industrial Use⁽⁶⁾. On 900°C isotherm, also IFC Formulation was used although the nominal upper limit of the Formulation was 800°C. Discrepancies between density values by IFC Formulation and by Vukalovich Table⁽⁸⁾ are about 0.1% at 900°C, 1 bar, and 2% at 900°C, 1000 bar.

The density of mercury at the manometer was calculated by the following equation which represents values of the International Critical Tables:

$$\begin{aligned} 1/\rho(\text{Hg}) = & 1/13.5951 [1 + 10^{-6} \{181.456t \\ & + 9.205 \times 10^{-3} t^2 + 6.608 \times 10^{-6} t^3 \\ & + 6.732 \times 10^{-8} t^4\}] [1 - 3.9517 \times 10^{-6} P] \dots \dots (5) \end{aligned}$$

Fig. 7 Comparison of the measured results with ICPS equation (I) Compressed water region below 300°C

Fig. 8 Comparison of the measured results with ICPS equation (II) Superheated steam region

6.3 Experimental results

Experimental results in the water and the steam region are shown in Tables 1 and 2, respectively.

Comparison with the Skeleton Table (1964) values is shown in Figs. 7 and 8. The biggest difference appears on isotherms of 375°C to 500°C, where measured results at lower pressures are lower than the Skeleton Table values by up to 10%. This trend confirms the results by Tanaka⁽³⁾, although their results are generally higher than those of this study. In this region Reynolds number quite easily climbs up to values higher than the critical because of low kinematic viscosity.

6.4 Estimation of errors

Since all measurements were performed under the condition that Reynolds number was below 300, measurement could not be made with a large pressure drop between both ends of the capillary. Then major portion of the error came from the measurement of the pressure drop. Actual height of the mercury column was about 0.7 to 3.5 cm and this caused an error of approximately 0.3 to 1.4% in viscosity values. Error caused from the flow rate measurement was about 0.3%. Errors from the measurement of the capillary length, the density of mercury, the uncertainty of kinetic energy correction factor m and the thermal expansion coefficient of platinum-rhodium alloy do not exceed 0.1%. Maximum calibration error of the capillary constant is estimated to be about 0.5%.

The finally estimated accuracy is about 1.5% in the most region and about 3% in the very narrow steam region close to the critical point.

7. Correlation and comparisons

In order to examine experimental results of many investigators and also to utilize them for industrial purposes, it is necessary to correlate them into a formula which has a simple form and is valid for a wide range of temperatures and pressures.

Over a range of temperatures and pressures up to 1000 °C and 1000 bar, the following

Table 3 Constants in Eq. (6)

a_1	= 80.4
a_2	= 0.407
a_3	= 276.67
a_4	= 866.67
a_5	= -2.3947×10^4
a_6	= 1.7544×10^{-8}
a_7	= 90.00
a_8	= 5.4483×10^8
a_9	= 4.6479×10^{-2}

equation of viscosity was correlated

$$\eta = \eta_1 + \eta_2 + \eta_3 + \eta_4$$

$$= a_1 + a_2 t + a_3 \rho + a_4 \rho^2 + \frac{a_5 \rho (1 - \rho)^4}{1 + t + a_6 t^4}$$

$$+ \frac{a_8 \rho}{(t + a_7)^3 \{(1 - \rho)^2 + a_9\}}; [\mu\text{P}] \dots\dots\dots (6)$$

The values of constant a_i are shown in Table 3.

The term $\eta_3 = \frac{a_5 \rho (1 - \rho)^4}{1 + t + a_6 t^4}$ works only in low pressure steam region and the term

$$\eta_4 = \frac{a_8 \rho}{(t + a_7)^3 \{(1 - \rho)^2 + a_9\}}$$

only in water region, and they may be neglected outside these regions. The calculated results are shown in Tables 4 and 5. The calculated results of kinematic viscosity ν are shown in Fig. 9.

This single equation represents experimental results of this investigation within about 2% deviations. In order to compare experimental viscosity values in other investigations, differences of density values should be taken into consideration. All values referred to hereafter are corrected with the density values by 1967 IFC Formulation for Industrial Use⁽⁶⁾. If the report gives the kinematic

Table 4 Calculated viscosity by Eq. (6)

$t \text{ } ^\circ\text{C}$ P bar	(0)	50	100	150	200	250	300	350	375	400	425
1	17 301	5 428	119.9	140.8	161.5	182.0	202.4	222.8	233.0	243.2	253.4
5	17 304	5 430	2 761	1 800	160.1	181.2	202.0	222.7	233.0	243.2	253.4
10	17 309	5 432	2 762	1 801	158.3	180.3	201.6	222.5	232.9	243.2	253.5
25	17 321	5 437	2 767	1 806	1 349	177.4	200.2	222.1	232.8	243.3	253.8
50	17 343	5 446	2 774	1 812	1 356	1 086	198.3	221.7	232.8	243.8	254.5
75	17 363	5 454	2 782	1 819	1 362	1 093	197.1	221.8	233.4	244.6	255.6
100	17 382	5 463	2 789	1 826	1 369	1 100	893	222.7	234.5	246.0	257.1
125	17 400	5 471	2 796	1 832	1 375	1 107	903	225.1	236.6	248.0	259.1
150	17 416	5 479	2 803	1 839	1 381	1 114	912	230.6	240.2	250.9	261.7
175	17 431	5 486	2 810	1 845	1 387	1 120	921	689	246.6	255.2	265.2
200	17 446	5 494	2 816	1 851	1 393	1 126	930	714	260.1	261.8	270.0
225	17 459	5 501	2 823	1 857	1 399	1 133	938	734	469.1	272.4	276.4
250	17 471	5 507	2 829	1 863	1 405	1 139	946	751	592.4	291.6	285.3
275	17 483	5 514	2 836	1 870	1 410	1 145	954	766	634.1	338.5	298.3
300	17 493	5 520	2 842	1 875	1 416	1 151	961	779	662.7	435.2	317.6
350	17 510	5 532	2 854	1 887	1 427	1 162	975	803	704.1	565.4	393.0
400	17 522	5 544	2 865	1 898	1 438	1 173	989	824	735.1	627.2	486.3
450	17 531	5 554	2 877	1 909	1 449	1 184	1 001	842	760.6	668.3	556.2
500	17 536	5 564	2 887	1 920	1 459	1 194	1 013	859	782.5	699.9	605.6
550	17 538	5 573	2 898	1 931	1 470	1 205	1 025	875	801.9	726.0	643.0
600	17 536	5 581	2 907	1 941	1 480	1 215	1 036	889	819.3	748.4	673.2
650	17 530	5 588	2 917	1 951	1 489	1 225	1 047	903	835.4	768.3	698.8
700	17 530	5 594	2 926	1 961	1 499	1 234	1 057	915	850.2	786.3	721.1
750	17 509	5 600	2 935	1 970	1 508	1 243	1 067	927	864.0	802.6	741.0
800	17 495	5 605	2 943	1 979	1 518	1 253	1 077	939	877.0	817.8	759.0
850	17 477	5 610	2 951	1 988	1 527	1 262	1 086	950	889.0	831.9	775.5
900	17 458	5 613	2 959	1 997	1 535	1 270	1 095	961	900.9	845.2	790.9
950	17 435	5 616	2 967	2 006	1 544	1 279	1 104	971	912.0	857.7	805.1
1 000	17 411	5 619	2 974	2 014	1 553	1 287	1 113	981	922.7	869.6	818.6

$t \text{ } ^\circ\text{C}$ P bar	450	475	500	550	600	650	700	750	800	900	1 000
1	263.6	273.8	283.9	304.3	324.7	345.0	365.4	385.7	406.1	446.8	487.4
5	263.7	273.9	284.1	304.5	324.8	345.2	365.6	385.9	406.3	446.9	487.6
10	263.8	274.0	284.3	304.7	325.1	345.5	365.8	386.2	406.5	447.2	487.9
25	264.2	274.6	284.9	305.4	325.9	346.3	366.6	387.0	407.3	447.9	488.5
50	265.2	275.7	286.1	306.8	327.3	347.7	368.0	388.3	408.6	449.2	489.7
75	266.4	277.0	287.5	308.3	328.8	349.2	369.5	389.8	410.0	450.5	490.9
100	268.0	278.6	289.2	310.0	330.5	350.9	371.1	391.3	411.5	451.9	492.2
125	269.9	280.6	291.2	311.9	332.3	352.6	372.8	392.9	413.1	453.3	493.5
150	272.4	283.0	293.4	314.0	334.4	354.5	374.6	394.6	414.7	454.7	494.8
175	275.5	285.8	296.1	316.4	336.5	356.6	376.5	396.4	416.4	456.2	496.2
200	279.4	289.2	299.1	319.0	338.9	358.7	378.5	398.3	418.1	457.8	497.6
225	284.3	293.3	302.7	322.0	341.5	361.0	380.6	400.3	419.9	459.4	499.1
250	290.4	298.1	306.8	325.2	344.3	363.5	382.9	402.3	421.8	461.1	500.6
275	298.3	304.0	311.6	328.9	347.3	366.1	385.2	404.4	423.8	462.8	502.1
300	308.4	311.0	317.1	332.9	350.5	368.9	387.7	406.7	425.9	464.6	503.7
350	338.9	329.8	330.8	342.2	357.8	375.0	393.0	411.4	430.2	468.3	506.9
400	389.0	356.9	349.1	353.5	366.2	381.9	398.9	416.6	434.8	472.2	510.3
450	450.0	394.1	372.9	367.0	375.9	389.5	405.3	422.2	439.8	476.3	513.9
500	507.0	437.4	402.1	383.0	386.8	397.9	412.2	428.2	445.0	480.6	517.6
550	554.8	480.9	435.4	401.5	399.0	407.2	419.8	434.5	450.6	485.1	521.4
600	594.0	521.3	469.3	422.1	412.6	417.3	427.8	441.3	456.5	489.8	525.4
650	626.5	557.4	502.3	444.2	427.4	428.1	436.5	448.5	462.7	494.8	529.5
700	654.2	589.2	533.6	467.1	443.3	439.7	445.6	456.1	469.2	499.9	533.8
750	678.3	617.1	562.5	490.1	460.0	452.1	455.3	464.1	476.0	505.2	538.2
800	699.7	641.8	589.0	512.8	477.2	465.0	465.4	472.4	483.1	510.6	542.7
850	719.0	663.9	613.0	535.2	494.6	478.5	475.9	481.0	490.4	516.3	547.3
900	736.7	683.9	634.9	556.8	512.1	491.7	486.9	489.9	497.9	522.1	552.1
950	752.9	702.1	654.8	577.6	529.4	506.3	498.2	499.1	505.7	528.0	556.9
1 000	768.0	718.9	673.1	597.2	546.7	520.4	509.8	508.5	513.6	534.1	561.8

viscosity ν too, the dynamic viscosity η is corrected by multiplying the density ratio. Without the kinematic viscosity data, the correction can be estimated from the density ratio and the given Reynolds number R_e . When neither ν nor R_e is shown in the report, the error caused from the correction by simply multiplying the density ratio can be estimated from the fraction of the kinetic energy correction

Table 5 Calculated viscosity of saturated water and steam by Eq. (6)

(μP)					
$t^\circ\text{C}$	Saturated water	Saturated steam	$t^\circ\text{C}$	Saturated water	Saturated steam
0	17 300	78.0	220	1 228	163.4
10	12 947	84.3	230	1 176	167.0
20	10 020	88.3	240	1 128	170.7
30	7 979	92.4	250	1 083	174.5
40	6 512	96.4	260	1 041	178.4
50	5 428	100.4	270	1 001	182.6
60	4 609	104.4	280	962.7	187.0
70	3 976	108.3	290	924.8	191.7
80	3 479	112.2	300	887.1	196.9
90	3 082	116.1	310	849.2	202.7
100	2 760	119.9	320	810.2	209.2
110	2 495	123.7	330	769.4	217.0
120	2 276	127.5	340	725.6	226.5
130	2 091	131.2	350	676.4	239.0
140	1 934	134.8	360	616.0	257.7
150	1 800	138.5	370	526.1	295.3
160	1 684	142.1	371	511.8	302.8
170	1 583	145.6	372	494.4	312.6
180	1 495	149.2	373	470.2	327.4
190	1 417	152.7	374	420.8	363.3
200	1 347	156.2			
210	1 284	159.8

Fig. 9 Kinematic viscosity calculated by Eq. (6)

term multiplied by the density ratio. The length of capillaries used in most of investigations is 30 to 50 cm and the diameter is 0.02 to 0.05 cm. For these capillaries the kinetic energy correction term of Eq. (3) does not exceed 10% of the total viscosity value in reasonable conditions. Then, if the correction is calculated by simply multiplying the density ratio, the difference of 2% in the density ratio corresponds to the maximum error of 0.2 % in the corrected dynamic viscosity.

7.1 Water region

In water region, comparison of Eq. (6) with the experimental results by the authors is made in Fig. 10. Both the experimental and the calculated values on the isotherms above 320°C fall rapidly with a decreasing pressure in the region very close to the saturation pressure. An example of 370°C isotherm is shown in Fig. 11. Equation (6) gives 526.1 μP for the viscosity of saturated water at 370°C, comparing with 540 μP by Miyabe⁽⁹⁾ and 600 μP by Bruges⁽¹⁰⁾. High value by Bruges seems to be caused by the procedure to estimate the value of saturated water from the values at higher pressures, as seen in Fig. 12.

Fig. 10 Comparison of the measured results with Eq.(6)
(I) Compressed water region

Fig. 11 Steam viscosity on 370°C isotherm (I)

Figure 13 shows comparisons with the experimental values by Timroth⁽¹¹⁾, Timroth and Flopkina⁽²⁾, Mayinger⁽⁴⁾ and Tanaka⁽³⁾. Values by the authors are generally lower than those by Timroth, higher than those by Mayinger and Tanaka, and close to Timroth and Flopkina.

7.2 Steam region

The comparisons of Eq. (6) with experimental values of steam region by authors and by other investigators are made in Fig. 14 and Fig. 15, respectively. Values by Timroth and Flopkina at around the critical temperature agree with Eq. (6). Values by Whitelaw⁽¹⁾ show fair agreement with Eq. (6), though their scattering seems to be larger. Whitelaw's measurements were performed with relatively lower R_e compared with Mayinger's. Ray⁽¹²⁾ used the viscometer which was originally constructed by Whitelaw, and got higher viscosity values in the region of $\rho < 0.4 \text{ g/cm}^3$. Experimental results by Tanaka show values lower than those by Mayinger and others in the moderate pressure steam region below 500°C where R_e is apt to go higher. Differences between the authors' and Tanaka's in the region of $\rho = 0.1 \sim 0.45 \text{ g/cm}^3$ are considered to be mainly caused from the difference of calibration methods. Calibrating data by Tanaka show that the critical Reynolds number for their capillary is about 200, and they used the capillary for R_e of up to about 1 660, determining the capillary constant as a function of R_e .

As seen from the comparisons discussed above, the experimental results of the present investigation reasonably agree with those by Whitelaw, who measured at comparatively lower R_e ,

Fig. 12 Steam viscosity on 370°C isotherm (II)

and with those by Tanaka, who used the capillary constant determined as a function of R_e , while values by Mayinger who measured at higher R_e show higher trends.

Fig. 13 Comparison of values in the literatures with Eq. (6)
(I) Compressed water region

Fig. 14 Comparison of the measured results with Eq. (6)
(II) Superheated steam region

Fig. 15 Comparison of values in the literatures with Eq. (6)
(II) Superheated steam region

In Eq. (6) η_1 , the viscosity at atmospheric pressure, is calculated by Shifrin's equation⁽¹³⁾. Because there exist discrepancies between η_1 by Shifrin, Latto⁽¹⁴⁾, Kestin et al.⁽¹⁵⁾ and Bonilla et al.⁽¹⁶⁾, above comparison may be slightly corrected in case of the future modification of η_1 equation.

7.3 Regions near the critical point and the saturation line

Equation (6) was correlated with experimental results of this investigation, especially to fit data in the critical region. In Tables 6 and 7 calculated results of Eq. (6) on 350°C and 375°C isotherms are compared with those in some other investigations. On 375°C isotherm, trend of this investigation at pressures from 200 to 300 bar is close to that of Tanaka, and much lower than Bruges and ICPS Skeleton Table (1964)⁽¹⁷⁾. For example the difference between this investigation and S.T. (1964) amounts to about 11% at 375°C and 200 bar, which exceeds the tolerance given in S.T. (1964).

Table 8 shows viscosity values of saturated water and steam by Eq. (6) and by other investigators. Above 320°C, considerable differences exist between values by Eq. (6) and by Bruges.

If it is assumed that there exist no peculiar behavior of the viscosity at the critical point, the critical viscosity is calculated as 386.47 μP .

8. Conclusions

This investigation was performed in order to get a consistent set of experimental viscosity data of water and steam over a wide range of tempera-

tures and pressures, and moreover to explain the large discrepancies among previous investigations. Measured data obtained at 151 points revealed some new facts, such as the behavior of the water viscosity in the vicinity of the saturation line.

Here confirmed is the importance of checking the variation of the capillary constant against Reynolds number. In the case of the rough walled capillary, such as metallic one, the critical Reynolds number is very likely to drop to the value considerably lower than 2300. In that case, if the same capillary constant obtained at low Reynolds number is applied also for measurements at higher Reynolds numbers, measured viscosity values will be much higher than true values. Precaution against this error is especially important in the steam region of pressures from 100 to 400 bar below 500°C, where the kinematic viscosity is low and Reynolds number tends to go higher. In this region, measured values of present investigation are much lower than those of ICPS Skeleton Table (1964).

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Table 6 Calculated viscosities on 350°C isotherm (μP)

P bar	Eq. (6)	Miyabe ⁽⁹⁾	Tanaka ⁽⁸⁾	Bruges ⁽¹⁰⁾	ICPS(1964) (Tolerance)
1	222.8	222.9	222.9	225	223(7)
100	222.7	234.1	228.7	237*	
150	230.6	249.0	238.0	255*	
175	689	692		728*	
200	714	717	706*	729*	735(29)*
300	779	778	765*	758*	785(31)*
500	859	855	837*	830*	850(34)*
800	939	928	910*	904*	915(37)*
1000	981		953.8	950*	

* Values obtained graphically

Table 7 Calculated viscosities on 375°C isotherm (μP)

P bar	Eq. (6)	Miyabe ⁽⁹⁾	Tanaka ⁽⁸⁾	Bruges ⁽¹⁰⁾	ICPS(1964) (Tolerance)
1	233.0	233	233.1	236	233(7)
100	234.5	247	240.6	249	249(10)
200	260.1	287	269.1	289	291(12)
225	469.1	492		485	491(20)
250	592.4	604	601.8	592	597(24)
300	662.7	667	659.0	651	657(26)
500	782.5	778	764*	760	762(30)
800	877.0	867	852*	844	846(34)
1000	922.7		896.2	885	

* Values obtained graphically

Table 8 Comparison of viscosities of saturated water and steam (μP)

Temperature	Saturated water				Saturated steam			
	Eq. (6)	Miyabe ⁽⁹⁾	Bruges ⁽¹⁰⁾	Tanaka ⁽⁸⁾	Eq. (6)	Miyabe ⁽⁹⁾	Bruges ⁽¹⁰⁾	Tanaka ⁽⁸⁾
200	1347	1357	1330	1331.5	156.2	156.4	157	156.55
300	887.1	887	896	895.1	196.9	199.6	200	199.75
320	810.2	809	837		209.2	217.8	222	213.75
340	725.6	727	768		226.5	243.2	251	232.71
350	676.4	680	728	668.59	239.0	260.3	272	
360	616.0	625	677	620.97	257.7	283.5	301	264.58
370	526.1	540	600	541.81	295.3	325.9	357	306.67
374.15	386.47	412.59		405.9	386.47	412.59		405.9

Addendum

Recently a new theoretical approach to the capillary viscometer theory was made by Kestin⁽¹⁸⁾. His theory suggests the value of the kinetic energy correction factor m in Eq. (3) as 0.97, comparing 1.12 used in this investigation. Recalculated values of measured results using $m=0.97$ are higher than those given in Tables 1 and 2 by about 0.15%, because the kinetic energy correction term in Eq. (3) is about 1% or less of the total viscosity value.

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