Experimental Data for the Viscosity and Thermal Conductivity of Water and Steam

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Experimental Data for the Viscosity and Thermal Conductivity of Water and Steam

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As part of a joint project between the International Association for the Properties of Water and Steam and the Subcommittee on Transport Properties of the International Union of Pure and Applied Chemistry Commission I.2 on Thermodynamics, all available and reliable experimental data on the viscosity and thermal conductivity of ordinary water and steam have been collected and converted to the current temperature scale (ITS-90) and a common set of units. The data are grouped according to state into four regions: the liquid phase (excluding data near 0.101 325 MPa), the steam (vapor) phase, the supercritical region ($T > T_c$ for any pressure), and liquid water at ambient pressure (near 0.101 325 MPa) between the triple-point temperature and the normal boiling-point temperature. For each point with measured temperature and pressure (or at specified saturation conditions), a density has been computed with the current scientific standard thermodynamic formulation (IAPWS-95), and each experimental datum has been compared with the viscosity or thermal conductivity calculated from the current standard formulations for these properties. The total data collection contains 4090 points for viscosity in the range of temperatures from 238 to 1346 K with pressures to 346 MPa and 5107 points for thermal conductivity in the range of temperatures from 256 to 1191 K with pressures to 785 MPa. The current standard IAPWS formulations for the transport properties of water are based on correlations adopted in 1984 which considered experimental data available through 1980. The present study considers all data available in the earlier work, data collected in bibliographic efforts within IAPWS and documented in unpublished reports through 1988, and additional data published subsequent to the earlier reports or, in some cases, older data which were not considered in the previous compilations. Thus, this study has identified new data which were not available for the previous reviews of the transport properties of water, has identified regions in which the current standard transport property formulations can now be improved, and is intended to facilitate the development of new, more accurate, international formulations for the viscosity and thermal conductivity of water and steam. © *2000 American Institute of Physics.* [S0047-2689(00)00202-]

Key words: data, evaluation, liquid, steam, thermal conductivity, vapor, viscosity, water.

Contents

1. Introduction

The study of the transport properties of water certainly dates back to the earliest contemplations concerning the nature of fluids, with scientific systematization perhaps beginning with the 17th century work of Newton, or the mid-19th century viscometry of Poiseuille. Water is the vital working fluid in myriad systems, and the 19th century development of fluid dynamics rests, in part, on an understanding of the viscosity and thermal conductivity of water. Today's designs using water and steam in electric power generation and in other technological applications for transfer of heat or of momentum also require knowledge of the transport properties of the fluid, with design innovation and optimization based, in part, on very precise values for these quantities. Other fluid-based applications also require the transport properties of water, as these can serve as calibration points in commercial or scientific instruments for viscometry and thermal conductivity measurements, or as the basis of relative measurements of these properties in a variety of fluid systems.

Measurements of the viscosity and thermal conductivity of water by a variety of methods have been made throughout the 20th century: the earliest viscosity data considered in this project are from 1914, and the earliest thermal conductivity data are from 1932. The process of collecting and evaluating data for the transport properties of water, with the goal of generating the most accurate tables, charts, or formulations is also not new. The need to develop internationally agreed-upon values for properties of water was recognized by the power industry, and the initial efforts in this area are associated with the first International Steam Conference held in London in 1929. It was not until the fourth meeting of this series, held in Philadelphia in 1954, that transport properties of steam were considered explicitly, and this Fourth International Conference on the Properties of Steam provides the root of the current project.

The first internationally accepted formulations for the transport properties of water substance were completed in 1964 [Kestin and Whitelaw (1966)]. The International Association for the Properties of Water and Steam (IAPWS), as the standing organization for international cooperation on properties of steam is currently named, has continued the tradition of developing standardized tables or formulations for the viscosity and thermal conductivity of water and steam as part of its ongoing efforts on water and aqueous systems. The independently constituted Subcommittee on Transport Properties of the International Union of Pure and Applied Chemistry (IUPAC) Commission I.2 on Thermodynamics began work in 1981 and has met annually since then to study transport properties of fluids, with an emphasis on fluids of industrial importance. It is in the context of a joint project between IAPWS and the Subcommittee, representing a common interest in and responsibility for these subjects, that the current study has progressed.

The current standard formulations for calculating the viscosity and thermal conductivity of water and steam are de-

scribed in Releases issued by IAPWS; the basic correlations were adopted in 1984, although there have been minor revisions and documentary material promulgated since that time. The discussion by Sengers and Kamgar-Parsi (1984) describes the formulation for viscosity which serves as the basis for the current standard. They noted that the equation is based mainly on the experimental database which was established as international input and which included measurements published through 1973 [Scheffler *et al.* (1974)]; this database was supplemented by additional data which had become available when Watson *et al.* (1980) revised an earlier equation. This viscosity formulation is valid in the following range of pressures p and temperatures t:

$$p \leqslant 500 \text{ MPa}, \quad 273.15 \text{ K} \leqslant t \leqslant 423.15 \text{ K}$$

$$p \leqslant 350 \text{ MPa}, \quad 423.15 \text{ K} < t \leqslant 873.15 \text{ K}$$

$$p \leqslant 300 \text{ MPa}, \quad 873.15 \text{ K} < t \leqslant 1173.15 \text{ K}.$$

Additional information concerning the data and genesis of this formulation can be found in the literature [Hendricks *et al.* (1977); Scheffler *et al.* (1978); Alexandrov *et al.* (1975); Nagashima (1977), (1983)].

The formulation for the thermal conductivity of water is discussed by Sengers *et al.* (1984). There are, in fact, two standard formulations for the thermal conductivity: one simpler equation which is adequate for most industrial purposes and a scientific formulation which provides the best representation over the broad range of temperature and pressure state variables; in the present paper, we are considering only the scientific formulation. The experimental data for the thermal conductivity of water considered in the current standard formulation were compiled by Scheffler and his co-workers and include sources through 1976 [Scheffler *et al.* (1977)]. A study by Tarzimanov (1975) provides a review of the data situation through the early 1970s. The IAPWS thermal conductivity formulation is valid in the following range of pressures p and temperatures t:

$$p \leqslant 100 \text{ MPa for } 273.15 \text{ K} \leqslant t \leqslant 773.15 \text{ K}$$

$$p \leqslant 70 \text{ MPa for } 773.15 \text{ K} < t \leqslant 923.15 \text{ K}$$

$$p \leqslant 40 \text{ MPa for } 923.15 \text{ K} < t \leqslant 1073.15 \text{ K}.$$

An article by Sengers and Watson (1986) provides some additional information concerning the IAPS Formulation 1985 for the Viscosity of Ordinary Water Substance and the IAPS Formulation 1985 for the Thermal Conductivity of Ordinary Water Substance, and provides the full text of the releases on these formulations which were adopted in Moscow in 1984. The document by Matsunaga *et al.* (1988) provides the most recent set of international input for both properties, although this report is not easily available. There are also other representations for the transport properties of water in the literature. For instance, the report by Theiss and

Thodos (1963) provides an earlier set of correlations, and the study of the thermal conductivity of saturated liquid water, published under the auspices of the IUPAC Subcommittee, by Ramires *et al.* (1995), provides an important standard for the saturated liquid.

Since the adoption of the IAPWS viscosity and thermal conductivity standard formulations in 1984, there have been several significant developments which impact the study of the transport properties of water. A new formulation for the thermodynamic properties of water and steam, IAPWS-95 [IAPWS (1995)], was adopted, which slightly altered the calculated relationships among temperature, pressure, and density which must be used to analyze and correlate the experimental viscosity and thermal conductivity data. One of the reasons for the development of IAPWS-95 was the introduction of the new temperature scale, ITS-90 [Mangum (1990) and Preston-Thomas (1990)], which supersedes the IPTS-68 temperature scale upon which the older analyses of the thermodynamic and transport properties of water were based. IAPWS has considered these changes, and in 1997 and 1998 issued slightly revised releases for the transport properties of water which simply account for the change in the thermodynamic formulation and the change in temperature scale. Current implementations of the IAPWS water-property standards, such as the NIST Steam Properties Program [NIST/ASME (1996)], generally incorporate the slight revisions of the transport property formulations described in the more recent releases for viscosity [IAPWS (1997)] and thermal conductivity [IAPWS (1998)].

In addition to the relatively minor effects on our knowledge of the transport properties of water caused by the change in temperature scale and the IAPWS-95 thermodynamic formulation, the existence of new experimental data obtained in the intervening years may allow a substantial improvement in our ability to describe the viscosity and thermal conductivity of water. For these reasons, we have again collected the data which were used as input in the development of the current IAPWS standards, examined documents which may provide additional data from the earlier measurements, and emphasized the compilation of new experimental measurements which were not available when the 1985 formulations were developed. For each such point collected, we have converted the reported temperature to the ITS-90 scale, as appropriate, and calculated the density according to the IAPWS-95 thermodynamic formulation.

The temperature conversions were applied directly to the reported temperature; i.e., when the state point to which a measurement was associated was given on the IPTS-68 scale, a conversion algorithm [a linear interpolation of the temperature differences tabulated in the report by Preston-Thomas (1990)] was applied to find the equivalent temperature on the ITS-90 scale. Analogous conversions were made for data reported on earlier temperature scales, and if a temperature scale was not explicitly stated in a publication, the year of publication was used to determine which temperature scale was appropriate to the data. No attempts were made to convert any platinum–resistance–thermometer calibrations

TABLE 1. Four regions of the water measurements

Region	State
1	Liquid water at ambient pressure (typically at 0.101 325 MPa), but between the triple point temperature and the normal boiling point temperature.
2	Liquid phase (excluding data near 0.101 325 MPa).
3	Steam (vapor) phase.
4	Supercritical region ($T > T_c$ for any pressure, $T_c = 647.096$ K).

reported in the publications to the ITS-90 scale, and higher order effects of the change in temperature scale, such as the effect of the derivative $d(T_{90} - T_{68})/d T_{68}$ on the temperature gradient used in the measurement of the thermal conductiv-ity, were not considered. Following the arguments of Rusby (1991), we note that the temperature scale difference is generally not a strong function of temperature, and that few experimental values are of sufficient accuracy to necessitate incorporating these higher order corrections. We have also not explicitly considered other possible revisions to the experimental transport properties, such as those associated with improved working equations for an instrument subsequent to the original measurements or those associated with changes in reference values for relative measurements or instrument calibrations. The tables in this manuscript provide key information for all of the important data on the viscosity and thermal conductivity of water, and the accompanying figures show deviations between the data and the current standard formulations.

TABLE 2. Viscosity of liquid water at ambient pressure (0.101 325 MPa) between the triple-point temperature and the normal boiling-point temperature

First author	Year	Method[a]	Uncertainty[b] (%)	Temperature range (K)	Number of data	Av. abs. deviation (%)
White	1914	CAP	0.5	273–293	5	0.19
Coe	1944	CAP	0.3	298–313	3	0.01
Swindells	1952	CAP	0.1	293	1	0.01
Weber	1955	CAP	0.3	273–313	9	0.04
Roscoe	1958	OSV	0.1	293	1	0.07
Malyarov	1959	CAP	0.1	293	1	0.17
Whitelaw	1960	CAP	2	294–330	7	1.55
Hallett	1963	CAP	0.5	273	1	0.09
Tanaka	1965	CAP	1	285–300	9	0.98
Agaev	1967	CAP	1	273–348	31	0.35
Korosi	1968	CAP	0.3	298–373	5	0.06
Kerimov	1969	CAP	1	373	1	0.41
Korson	1969	CUb	0.3	273–373	21	0.17
Dumas	1970	OSD	1	289–294	4	0.88
Eicher	1971	CAP	0.3	273–313	9	0.04
Mashovets	1971	CAP	2	365	1	0.08
Kingham	1974	CUb	0.01	274–283	20	0.01
Kudish	1974	CUb	0.05	288–308	5	0.04
Kestin	1977	OSD	0.3	284–312	11	0.18
Kestin	1978	OSD	0.7	312–363	8	0.17
Kubota	1979	CAP	2	283–348	4	0.16
Agaev	1980	CAP	1.5	273–373	19	0.24
Gonçalves	1980	CAP	n.a.	293–333	6	0.01
Kestin	1981	OSD	0.3	299–364	6	0.12
Baldauf	1983	CAP	1	283–303	3	1.34
Collings	1983	CAP	0.2	274–343	12	0.04
James	1984	CAP	1	273–333	8	0.06
Kozlov	1985	NMR	n.a.	283–338	6	5.38
Tanaka	1987	FBd	2	283–348	4	0.11
Berstad	1988	OSC	0.05	293–299	18	0.14
Melzer	1989	CAP	1	283–303	3	2.01
Ramkumar	1989	CUb	0.1	303–343	5	0.43
Mazurkiewicz	1990	ROT	1	298	1	0.03
Lee	1992	FBd	1	303–323	3	0.43
Rosenberger	1992	CAP	1	297	1	0.81
Assael	1993	VbW	0.5	293–328	8	0.14
Olive	1994	CUb	0.5	303	1	0.17
Wode	1994	CUb	0.5	293–313	5	0.06
Lee	1995	FBd	1.5	303–313	2	0.32
					Total 268	

[a]CAP - capillary; CUb - Cannon–Ubbelhode; FBd - falling body; NMR - NMR method; OSC - oscillating cylinder; OSD - oscillating disc; OSV - oscillating vessel; ROT - rotary; VbW - vibrating wire.
[b]n.a.-no uncertainty given in source reference.

TABLE 3. Viscosity of water in the liquid phase (excluding data near 0.101 325 MPa)

First author	Year	Method[a]	Uncertainty[b] (%)	Temperature range (K)	Pressure range (MPa)	Number of data	Av. abs. deviation (%)
White	1914	CAP	0.5	264–271	0.0003–0.0005	6	0.42
Hardy	1949	CAP	0.25	278–398	0.34	10	0.33
Moszynski	1961	OSS	2	293–459	0.4–35	41	1.31
Mayinger	1962	CAP	1.5	352–573	6–77	28	0.68
Hallett	1963	CAP	0.5	254–272	0.0001–0.0006	19	0.49
Tanaka	1965	CAP	1	289–645	9.4–98	48	0.94
Dudziak	1966	OSD	5	433–623	100–346	34	5.27
Rivkin	1966	CAP	1.5	323–473	5.0	16	0.51
Agaev	1967	CAP	1	273–373	1–118	567	0.32
Korosi	1968	CAP	0.3	398–423	0.23–0.48	4	0.34
Kerimov	1969	CAP	1	373–548	0.12–118	223	0.32
Nagashima	1969	CAP	1.5	323–646	6–100	107	2.49
Rivkin	1970b	CAP	1	496–647	2.5–50	87	0.29
Eicher	1971	CAP	0.3	265–272	0.0003–0.0006	4	0.08
Mashovets	1971	CAP	2	386–548	0.16–5.9	10	0.44
Penkina	1971	RIV	n.a.	373–523	14.71	7	1.42
Rivkin	1972a	CAP	1	523–623	40–100	32	0.26
Rivkin	1972b	CAP	1	497–647	2.5–22	51	0.41
Rivkin	1975a	CAP	1	647	22	5	1.86
Rivkin	1975b	CAP	1	497–647	2.5–22	51	0.39
Kestin	1977	OSD	0.3	284–312	1.6–31	59	0.08
Osipov[c]	1977	CAP	3	238–273	1	28	1.48
Kestin	1978	OSD	0.5	313–423	0.6–31	103	0.19
Kubota	1979	CAP	2	283–348	10–69	28	0.20
Agaev	1980	CAP	1.5	263–473	2.1–196	146	0.63
Kestin	1981	OSD	0.3	395–424	0.2–0.5	2	0.32
Naake	1984	OSD	1	291–479	10–100	18	0.01
Kestin	1985	OSD	0.5	298–492	0.003–30	74	0.16
Tanaka	1987	FBd	2	283–348	9.9–118	43	0.06
Assael	1993	VbW	0.5	298–313	5–32	11	0.25
						Total 1862	

[a]CAP - capillary; OSD - oscillating disc; OSS - oscillating sphere; RIV - radioisotope; VbW - vibrating wire.
[b]n.a.-no uncertainty given in source reference.
[c]16 points from this source are below the lower temperature limit of the IAPWS correlation; these points are not included in the statistics or in the figures.

2. Data Analysis

The data collection contains 4090 points for viscosity in the range of temperatures from 238 to 1346 K with pressures to 346 MPa, and 5107 points for thermal conductivity in the range of temperatures from 256 to 1191 K with pressures to 785 MPa. This collection includes all data considered for the current IAPWS formulations as well as some additional historical data and results published since the earlier compilations discussed above. However, this collection is not meant to be exhaustive, and some of the very early data are not included. The compilation by Nagashima (1977) includes references to additional data of historical interest for viscosity, and the study by Sengers *et al.* (1984) gives additional information for thermal conductivity; the compilation of Scheffler *et al.* (1977), the evaluation of Tarzimanov (1975),

and the status report of Alexandrov *et al.* (1991) can also be consulted. These publications and, in particular the development of the international input resources by Scheffler *et al.* (1974), (1977), involved evaluation of the data available at that time. Although some of the older experiments cited in these sources may represent excellent work, these data were determined to be inadequate for developing transport property correlations, and we have generally concurred and omitted them from the current database. We have also not included sources that only give graphical results and have eliminated most references with only smoothed results or references that report duplicate information. We have also omitted several sources such as those that cover very high pressures, such as shock-tube measurements for viscosity, and measurements of related properties, such as the thermal

TABLE 4. Viscosity of water in the vapor phase

First author	Year	Method[a]	Uncertainty (%)	Temperature range (K)	Pressure range (MPa)	Number of data	Av. abs. deviation (%)
Shifrin	1959	CAP	2	422–647	0.101	42	1.74
Kestin	1960	OSD	0.5	411–511	0.102–2.0	19	0.47
Whitelaw	1960	CAP	2	641–643	19.6	2	5.98
Moszynski	1961	OSS	2	411–540	0.16–4.2	25	1.31
Kestin	1963	OSD	0.8	421–548	0.11–5.23	39	0.50
Latto	1965	CAP	3	383–641	0.101	176	1.11
Tanaka	1965	CAP	1	620–645	10–20	3	1.99
Rivkin	1966	CAP	1.5	448–573	0.3–4.4	25	0.37
Rivkin	1968	CAP	1	548–623	0.6–14	64	0.46
Sato	1968	CAP	0.2	430–473	0.23–0.96	17	0.31
Nagashima	1969	CAP	1.5	619	7–14	2	2.93
Rivkin	1970a	CAP	1	585–647	10–22	37	0.64
Sato	1970	CAP	1	433–633	0.2–2.5	66	0.37
Yasumoto	1970	CAP	0.5	280–302	0.0008–0.003	15	2.07
Rivkin	1972b	CAP	1	585–647	10–22	37	0.84
Timrot	1973	OSD	0.3	326–618	0.001–0.14	36	0.16
Nagashima	1974	CAP	1.5	523–624	0.49–15	18	1.22
Rivkin	1975b	CAP	1	585–647	10–22	37	0.84
Oltermann	1977	OSD	1.6	614–647	0.1–22	62	0.88
						Total 722	

[a]CAP - capillary; OSD - oscillating disc; OSS - oscillating sphere.

TABLE 5. Viscosity of water in the supercritical region ($T > T_c$ for any pressure)

First author	Year	Method[a]	Uncertainty (%)	Temperature range (K)	Pressure range (MPa)	Number of data	Av. abs. deviation (%)
Shifrin	1959	CAP	2	648–1140	0.101	72	1.44
Whitelaw	1960	CAP	2	651–927	25–78	47	2.36
Mayinger	1962	CAP	1.5	659–980	18–61	56	4.38
Latto	1965	CAP	3	665–1346	0.101	379	1.08
Tanaka	1965	CAP	1	655–1181	9.5–98	92	2.73
Dudziak	1966	OSD	5	673–823	100–336	57	3.94
Rivkin	1968	CAP	1	648–723	2–35	63	0.90
Nagashima	1969	CAP	1.5–3	648–1179	9–100	142	1.42
Rivkin	1970a	CAP	1	647–673	10–22	31	0.44
Rivkin	1970b	CAP	1	648	22–50	7	0.60
Sato	1970	CAP	1	673–778	0.3–0.9	13	0.30
Rivkin	1972a	CAP	1	648	50–100	6	0.24
Rivkin	1972b	CAP	1	647–668	10–22	31	0.45
Rivkin	1973	CAP	1	649–773	23–50	59	0.72
Timrot	1973	OSD	0.3	669–772	0.007–0.14	10	0.13
Nagashima	1974	CAP	1.5	650–874	0.7–21	35	1.38
Rivkin	1975a	CAP	1	647–663	22–30	73	2.69
Rivkin	1975b	CAP	1	647–668	10–22	31	0.45
Oltermann	1977	OSD	4	648–656	10–24	34	1.62
						Total 1238	

[a]CAP - capillary; OSD - oscillating disc.

TABLE 6. Thermal conductivity of liquid water at ambient pressure (0.101 325 MPa) between the triple-point temperature and the normal boiling-point temperature

First author	Year	Method[a]	Uncertainty[b] (%)	Temperature range (K)	Number of data	Av. abs. deviation (%)
Schmidt	1932	CC	3	282–346	4	0.35
Riedel	1951	CS	1	293	1	0.56
Schmidt	1955	CC	0.3	293–357	8	0.54
Challoner	1956	PP	1	273–353	5	0.40
Lawson	1959	CC	2	303–363	4	1.24
Vargaftik	1959b	HW	2	294–351	14	0.65
Bach	1970	Opt	1	294–363	374	0.61
Rastorguev	1970	CC	1.6	295–363	3	0.88
Stupak	1970	CC	2	316–352	4	0.25
Gazdiev	1971	CC	1.5	313–373	4	0.46
Papadopoulos	1971	ThB	3	298	1	3.16
Turnbull	1971	THW	1.5	298	1	0.95
Potienko	1972	THW	3	292	1	0.95
Shurygin	1974	RD	5	293	1	6.43
Amirkhanov	1975	PP	2	298–348	3	0.45
Takizawa	1975	THW	2	273–323	4	1.22
Rastorguev	1977	CC	2	296–371	22	0.35
Takizawa	1978	THW	1.5	273–353	9	1.55
Varchenko	1978	HW	3	303	16	0.77
Filippov	1979	THW	4	293	1	1.93
Venart	1980	THW	0.5	273–368	22	0.46
Dietz	1981	PHW	1	373	1	0.13
Nagasaka	1981	THW	1	274–319	4	0.10
Nagasaka	1984	THW	0.5	274–354	5	0.23
Guseinov	1987	PP	1.8	293–368	10	0.45
Wakeham	1987	THW	0.5	298	2	0.08
Assael	1988	THW	0.5	304–333	12	0.20
Zalaf	1988	THW	0.5	303–342	5	0.22
Venkateshan	1990	TH	n.a.	298	1	2.34
Gross	1992	THS	2	293	1	0.72
Assael	1993	THW	0.5	285–328	4	0.18
Ramires	1993	THW	0.5	299–364	38	0.37
Watanabe	1994	SpH	n.a.	296	2	0.97
Mensah-Brown	1996	THW	0.5	304–338	6	0.39
					Total 593	

[a]CC-concentric cylinders; CS-concentric spheres; HW-heated wire; Opt-optical; PHW-pulsed-heated wire; PP-parallel plates; RD-rotating disc; SpH-spot-heating; TH-transient heated foil; ThB-thermistor bead; THS-transient hot-strip; THW-transient hot-wire.
[b]n.a.-no uncertainty given in source reference.

diffusivity. The ''Supplementary References'' Appendix provides a reference to thermal conductivity and viscosity sources not incorporated in the current database.

The data are grouped according to state into four regions, shown in Table 1. For each point with measured temperature and pressure (or at specified saturation conditions), the temperature was converted to ITS-90 either according to information given by the authors or according to the year of publication of the data. Following that, the density was computed with the current scientific standard thermodynamic formulation (IAPWS-95), and each experimental datum was compared with the viscosity or thermal conductivity calculated from the current standard formulations for these properties.

Tables 2–5 and 6–9 show the data sets collected for the viscosity and the thermal conductivity, respectively, of water according to the four regions. In each table, the first author and the year published are given together with the method employed, the uncertainty indicated by the authors, the temperature and pressure ranges, and the number of data reported. The average absolute percentage deviation of each data set for the viscosity and thermal conductivity from the values calculated by the current IAPWS standard formulation is also shown in these tables.

A thorough discussion of the experimental methods which have been developed for measuring viscosity and thermal conductivity can be found in an IUPAC monograph [Wakeham *et al*. (1991)]; the methods used for the water measure-

TABLE 7. Thermal conductivity of water in the liquid phase (excluding data near 0.101 325 MPa)

First author	Year	Method[a]	Uncertainty[b] (%)	Temperature range (K)	Pressure range (MPa)	Number of data	Av. abs. deviation (%)
Schmidt	1932	CC	3	348–542	0.7–7.4	20	0.36
Lawson	1959	CC	2	303–403	98–785	30	1.26
Vargaftik	1959b	SHW	2	359–623	0.4–21	21	2.43
Venart	1964	CC	1.5	370–526	0.4–30	80	0.95
Tarzimanov	1968	SHW	1	302–428	3–98	19	0.70
Cherneeva	1970	CC	4.3	373–623	10–100	59	0.76
Rastorguev	1970	CC	1.6	294–454	0.14–196	51	3.16
Cherneeva	1971	CC	4.2	373–623	10–100	59	0.75
Gazdiev	1971	CC	1.5	393–433	0.20–0.62	3	0.39
Le Neindre	1973	CC	2	612–643	20–51	15	1.83
Castelli	1974	CC	1	275–305	1–140	62	1.01
Amirkhanov	1975	PP	2	298–623	9–245	348	1.17
Sirota	1975	PP	n.a.	481–647	20–30	70	1.07
Takizawa	1975	THW	2	273–373	1–49	25	1.33
Le Neindre	1976	CC	1.5	310–643	0.2–51	215	0.69
Rastorguev	1977	CC	2	374–393	0.25	7	0.36
Amirkhanov	1979	PP	3	298–473	200–456	57	0.88
Yata	1979a	CC	1.4	304–473	10–147	179	0.57
Yata	1979b	CC	1.7	377–633	10–147	206	0.68
Dietz	1981	PHW	1	303–523	0.004–350	53	1.73
Sirota	1981	PP	3	622–647	23–35	9	1.06
Amirkhanov	1982	PP	4	298–573	392–687	84	7.33
Nagasaka	1984	THW	0.5	274–354	10–40	20	0.31
Tufeu	1986	CC	0.5	256–294	100–200	12	0.84
Tufeu	1987	CC	2	630–635	20–51	7	0.79
Zalaf	1988	THW	0.5	302–342	0.105–286	73	0.33
Mensah–Brown	1996	THW	0.5	304–339	13–140	32	0.50
						Total 1816	

[a]CC-concentric cylinders; PHW-pulsed-heated wire; PP-parallel plates; SHW-steady-state heated wire; THW-transient hot-wire.
[b]n.a.-no uncertainty given in source reference.

ments and listed in the tables are included in this monograph. In certain cases, the measurements summarized in Tables 2–9 yielded relative properties, with the results dependent on an assumed value for a property of water at a standard condition or on absolute measurements for a different fluid. In some cases, the theory of the instrument has been advanced since the experimental data were obtained, and corrections could be applied to the original data. In all cases, only the original reported data were considered in the current compilation.

The temperature and pressure ranges covered by all the data sets included in the data bank are shown, in the case of viscosity in Fig. 1(a), and in the case of thermal conductivity in Fig. 1(c). In the three-dimensional plots of Figs. 1(b) and 1(d), we show the experimental viscosity and thermal conductivity, respectively, as functions of temperature and density.

2.1. Viscosity

The deviations of the experimental data for the viscosity from the values calculated from the current standard formulation are shown in Figs. 2–5. To put these figures in per-

spective, we summarize the uncertainty of the IAPWS formulation for viscosity. The uncertainty is expressed in the IAPWS release [IAPWS (1997)] in terms of assigned tolerances associated with each of about 640 evenly spaced points in the range 273.15–1073.15 K from 0.1 to 100 MPa which were tabulated in the release. In general these tolerances are about 1% for the liquid phase below 573 K; 2% for the vapor, for the liquid at 573 K, and for supercritical states below 773 K and below about 40 MPa; and 3% for the remainder of the points in the tabulated region. Watson *et al.* (1980) provide additional information concerning the uncertainty of the formulation; for pressures above 100 MPa, they estimate an uncertainty of 3% for temperatures below 423 K and 5% for higher temperatures, where the limits of the formulation were given above.

The atmospheric pressure region is shown in two figures due to the very large number of data sets. The data sets are arranged chronologically. Figure 2(a) shows data sets from 1914 to 1974. These are in essence the data employed in the IAPWS formulation. Hence, they agree very well within their mutual uncertainty. It should be noted that for most of this region the uncertainty quoted by the IAPWS formulation

TABLE 8. Thermal conductivity of water in the vapor phase

First Author	Year	Method[a]	Uncertainty[b] (%)	Temperature range (K)	Pressure range (MPa)	Number of data	Av. abs. deviation (%)
Milverton	1935	SHW	2	345–368	0.006–0.048	77	1.18
Timrot	1935	SHW	3	342–526	0.03–0.10	10	2.04
Vargaftik	1935	SHW	3	562–632	0.101	7	0.73
Vargaftik	1937	SHW	3	523–628	0.5–3	14	1.42
Timrot	1940	SHW	3	529–623	2–5.9	8	2.25
Vargaftik	1956	CC	2	504–581	0.101	2	1.59
Vargaftik	1959a	SHW	2	623–639	0.5–14.7	8	2.00
Vargaftik	1960	SHW	2	593–625	0.6–15	8	3.26
Vines	1960	CC	2	543	0.101	1	0.34
Tarzimanov	1962	SHW	2	505–624	0.2–14.7	31	3.39
Vukalovich	1963	CC	5	583–643	10	7	2.51
Baker	1964	SHW	n.a.	381–526	0.101	4	1.81
Keyes	1964	CC	3	412–644	0.1–17	46	2.38
Vargaftik	1964	SHW	2	611–623	0.101	2	0.84
Venart	1964	CC	1.5	406–528	0.1–4	83	3.32
Brain	1967	CC	1.5	416–432	0.101	3	1.01
Le Neindre	1968	CC	2	383–603	0.1–12.5	65	1.67
Brain	1969	CC	2	443–602	0.101	23	1.88
Cherneeva	1970	CC	4.3	623	10	1	1.34
Cherneeva	1971	CC	4.3	623	10	1	1.34
Dijkema	1972	CC	0.5	298–333	0.003–0.02	2	1.26
Mustafaev	1972	TCC	n.a.	423–636	0.101	11	1.90
Le Neindre	1973	CC	2	646	0.1–10	4	4.00
Tarzimanov	1973	CC	3	440–646	0.1–21	25	3.25
Vargaftik	1973	SHW	1.5	430–646	0.1	6	1.22
Bury	1975	CC	2	377–646	0.1–17.5	62	3.96
Sirota	1975	PP	n.a.	640–646	20–21.6	17	2.95
Sirota	1976	PP	1.5–3	534–640	0.1–20	7	3.11
Popov	1977	CC	4	597	0.1	1	2.23
Sirota	1978	PP	3	534–626	0.1–2.5	6	3.01
Curtiss	1979	SHW	2	358–386	0.01–0.13	54	1.15
Frohn	1980	CC	n.a.	300–600	0.003	7	2.22
Sirota	1981	PP	3	647	20	1	1.19
Tufeu	1987	CC	2	623–628	0.9–17.4	11	5.79
Tarzimanov	1989	THW	1.3	573–629	1–12.5	19	3.21
						Total 634	

[a]CC-concentric cylinders; PP-parallel plates; SHW-steady-state heated wire; TCC-transient concentric cylinders; THW-transient hot-wire.
[b]n.a.-no uncertainty given in source reference.

Table 9. Thermal conductivity of water in supercritical region ($T > T_c$ for any pressure)

First author	Year	Method[a]	Uncertainty[b] (%)	Temperature range (K)	Pressure range (MPa)	Number of data	Av. abs. deviation (%)
Vargaftik	1935	SHW	3	680–750	0.101	4	1.77
Timrot	1940	SHW	3	647–797	0.1–29	25	5.36
Vargaftik	1956	CC	2	667–715	0.101	2	2.08
Vargaftik	1959a	SHW	2	716–997	1–34	53	2.64
Vargaftik	1960	SHW	2	657–841	0.5–49	33	1.84
Vines	1960	CC	2	833	0.101	1	4.16
Vukalovich	1963	CC	5	653–933	10–147	128	8.61
Vargaftik	1964	SHW	2	760–1191	0.101	19	1.27
Brain	1969	CC	2	661–877	0.101	10	1.91
Cherneeva	1970	CC	4.3	673–974	10–100	70	5.54
Cherneeva	1971	CC	4.3	673–974	10–40	28	2.88
Mustafaev	1972	TCC	n.a.	653–677	0.101	3	1.29
Le Neindre	1973	CC	2	647–788	0.1–50	126	8.71
Tarzimanov	1973	CC	3	649–773	0.1–100	61	2.17
Vargaftik	1973	SHW	1.5	686–998	0.1	5	0.68
Bury	1975	CC	2	647–790	0.1–50	45	2.65
Sirota	1975	PP	n.a.	648–679	20–30	191	4.18
Sirota	1976	PP	3	654–672	20–28	8	3.55
Tsederberg	1976	CC	2	706–1072	10–98	147	2.26
Popov	1977	CC	4	655–1074	0.1–98	74	3.43
Amirkhanov	1978	PP	2.2	649–875	0.1–250	136	3.06
Popov	1979	PP	4	773–1072	10–98	240	2.87
Tufeu	1979	CC	3	680–748	0.02–13	16	3.36
Yata	1979b	CC	2.5	653–693	39–147	35	0.65
Frohn	1980	CC	n.a.	650	0.004	1	0.14
Popov	1980a	CC	6	713–1073	10–100	50	2.28
Popov	1980b	CC	4	707–1072	10–98	148	2.11
Sirota	1981	PP	3	648–702	20–35	129	8.02
Tufeu	1987	CC	2	651–786	0.9–95	191	2.04
Tarzimanov	1989	THW	1.3	648–978	1–30	85	3.43
						Total 2064	

[a]CC-concentric cylinders; PP-parallel plates; SHW-steady-state heated wire; THW-transient hot-wire; TCC-transient concentric cylinders.
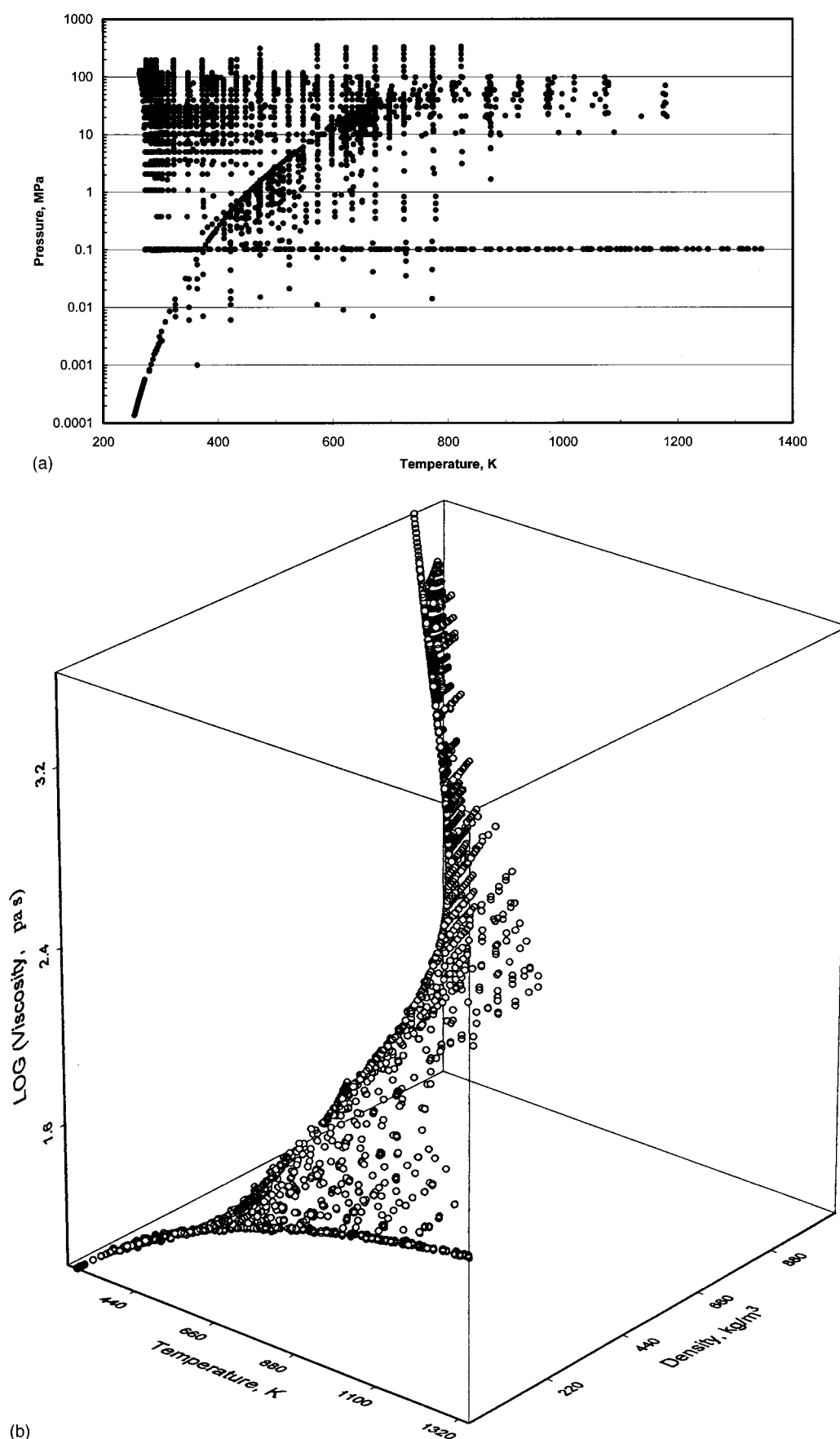[b]n.a.-no uncertainty given in source reference.

FIG. 1. (a) Temperature and pressure ranges of viscosity measurements considered; (b) Experimental viscosity as function of temperature and density; (c) Temperature and pressure ranges of thermal-conductivity measurements considered; (d) Experimental thermal conductivity as function of temperature and density.
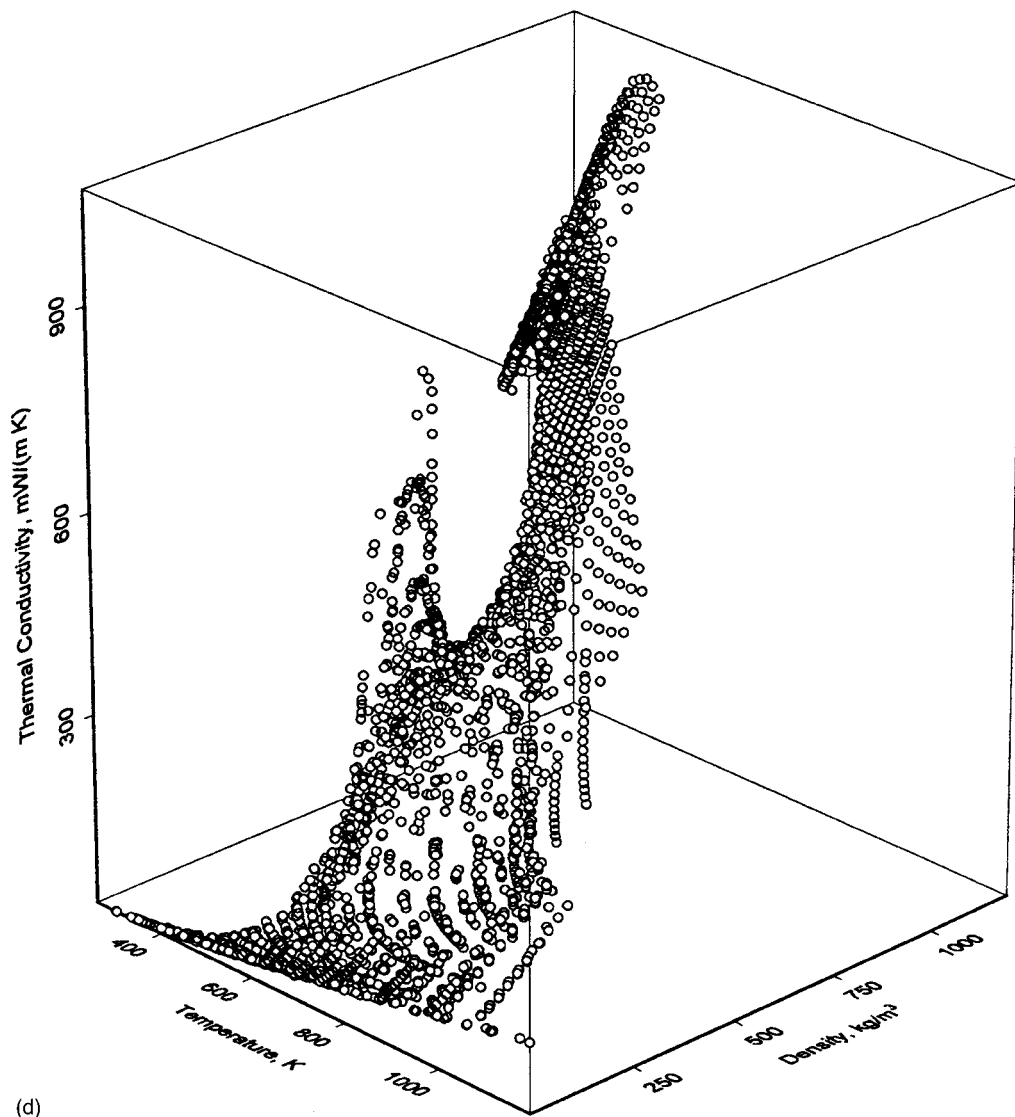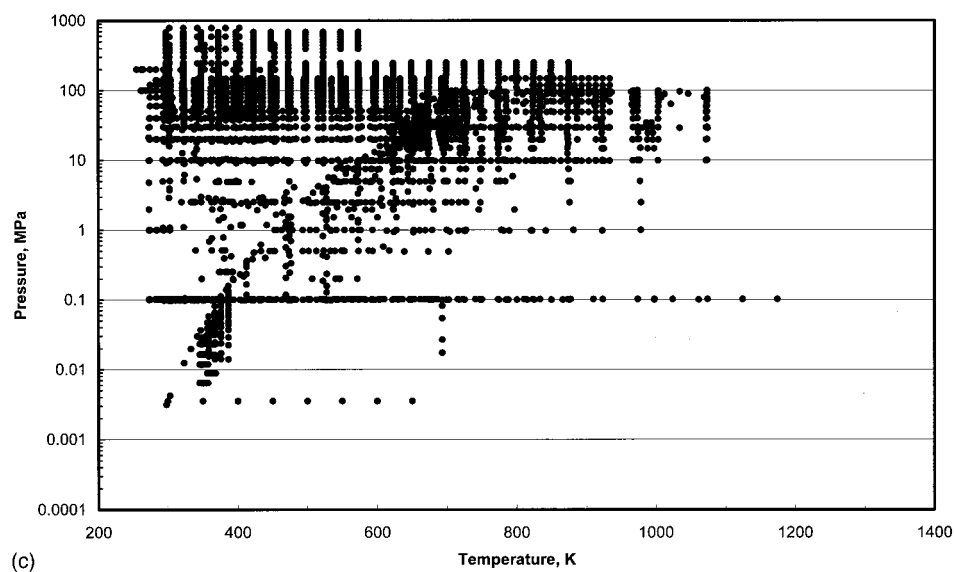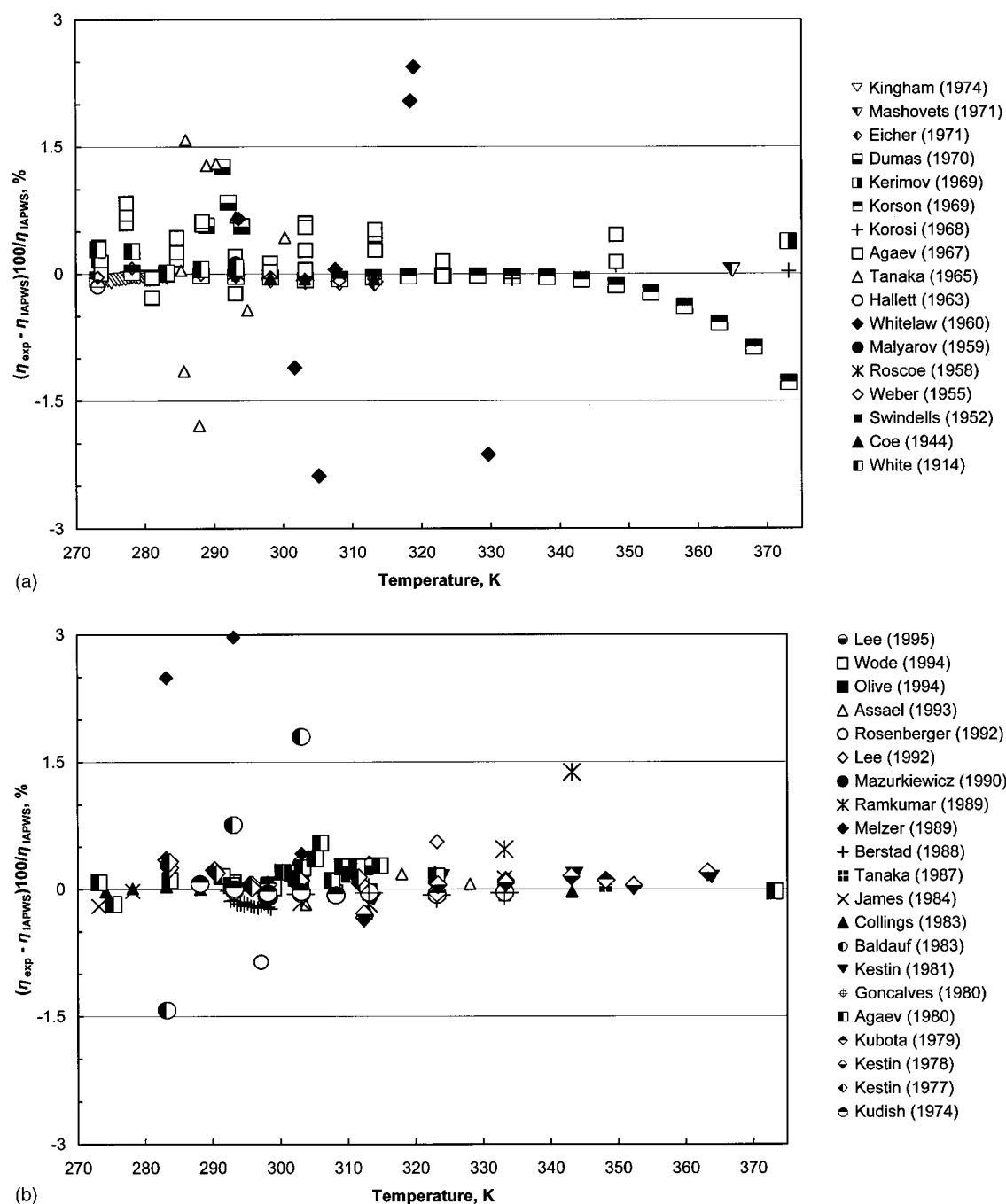
(c)

(d)

Fig. 1. (*Continued.*)

FIG. 2. (a) and (b) Deviations of viscosity measurements of liquid water at ambient pressure between 273.15 and 373.12 K from the IAPWS correlation.
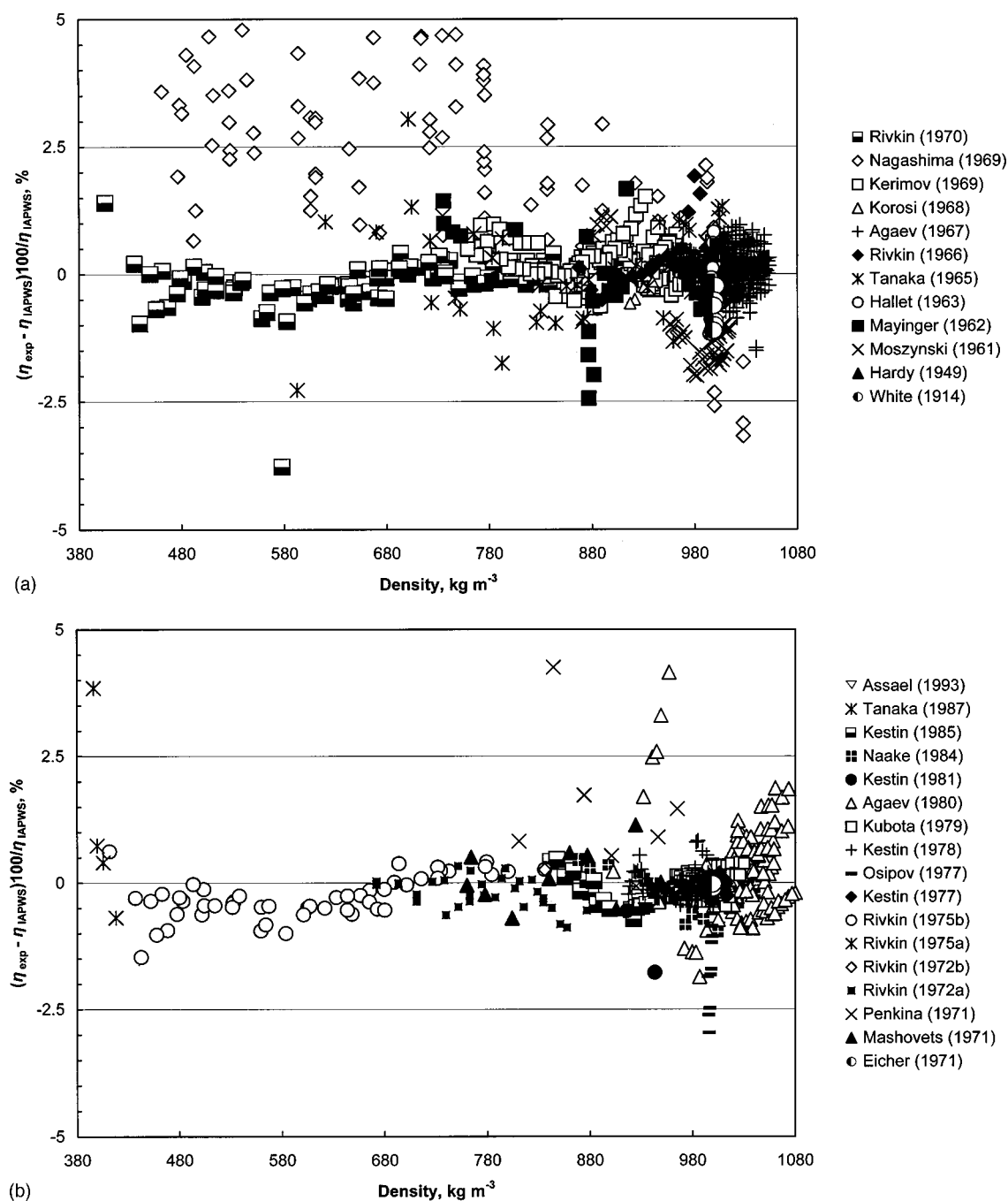
FIG. 3. (a) and (b) Deviations of viscosity measurements of water in the liquid phase (excluding data near 0.101 325 MPa) from the IAPWS correlation.
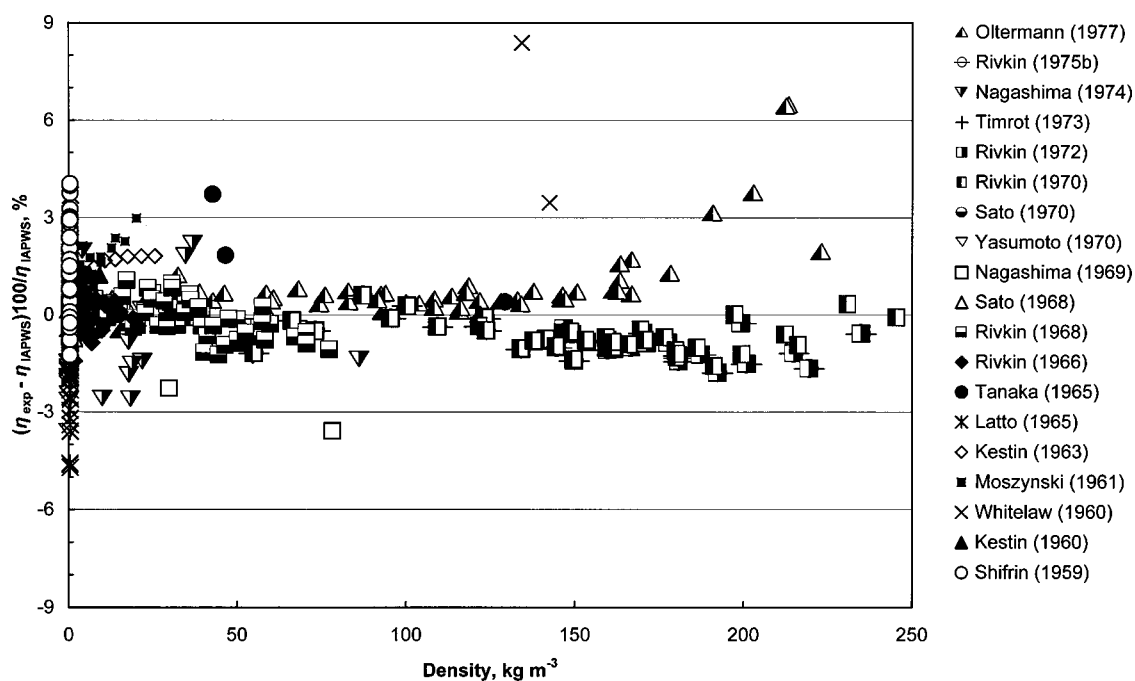
FIG. 4. Deviations of viscosity measurements of water in the vapor phase from the IAPWS correlation.
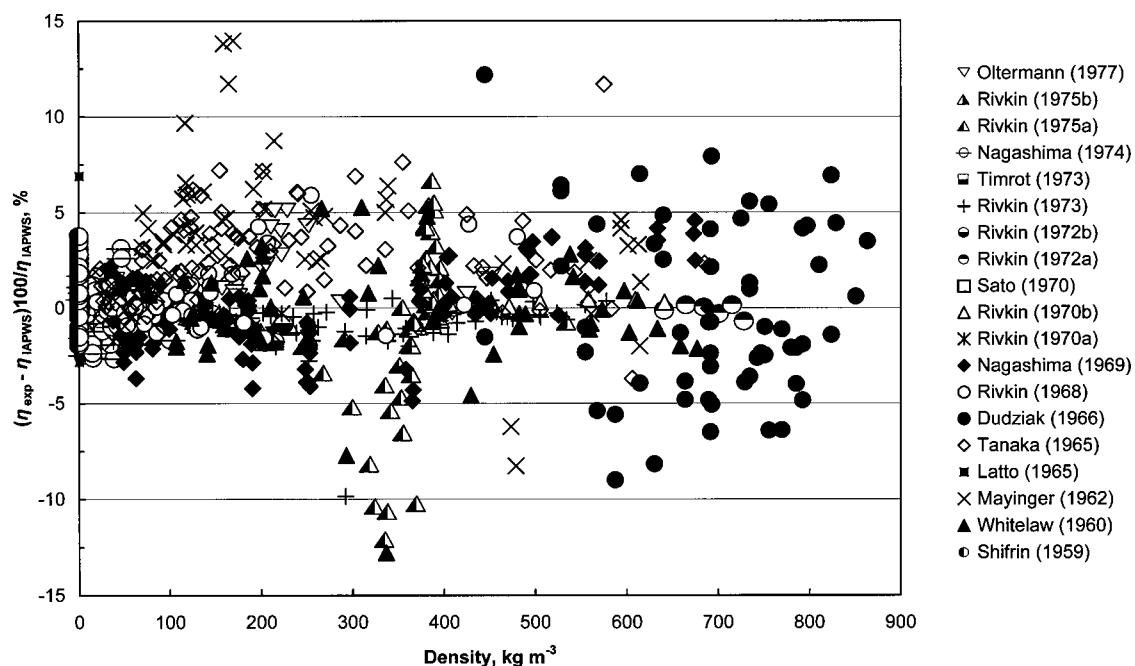
FIG. 5. Deviations of viscosity measurements of water in the supercritical region ($T>T_c$ for any pressure) from the IAPWS correlation.
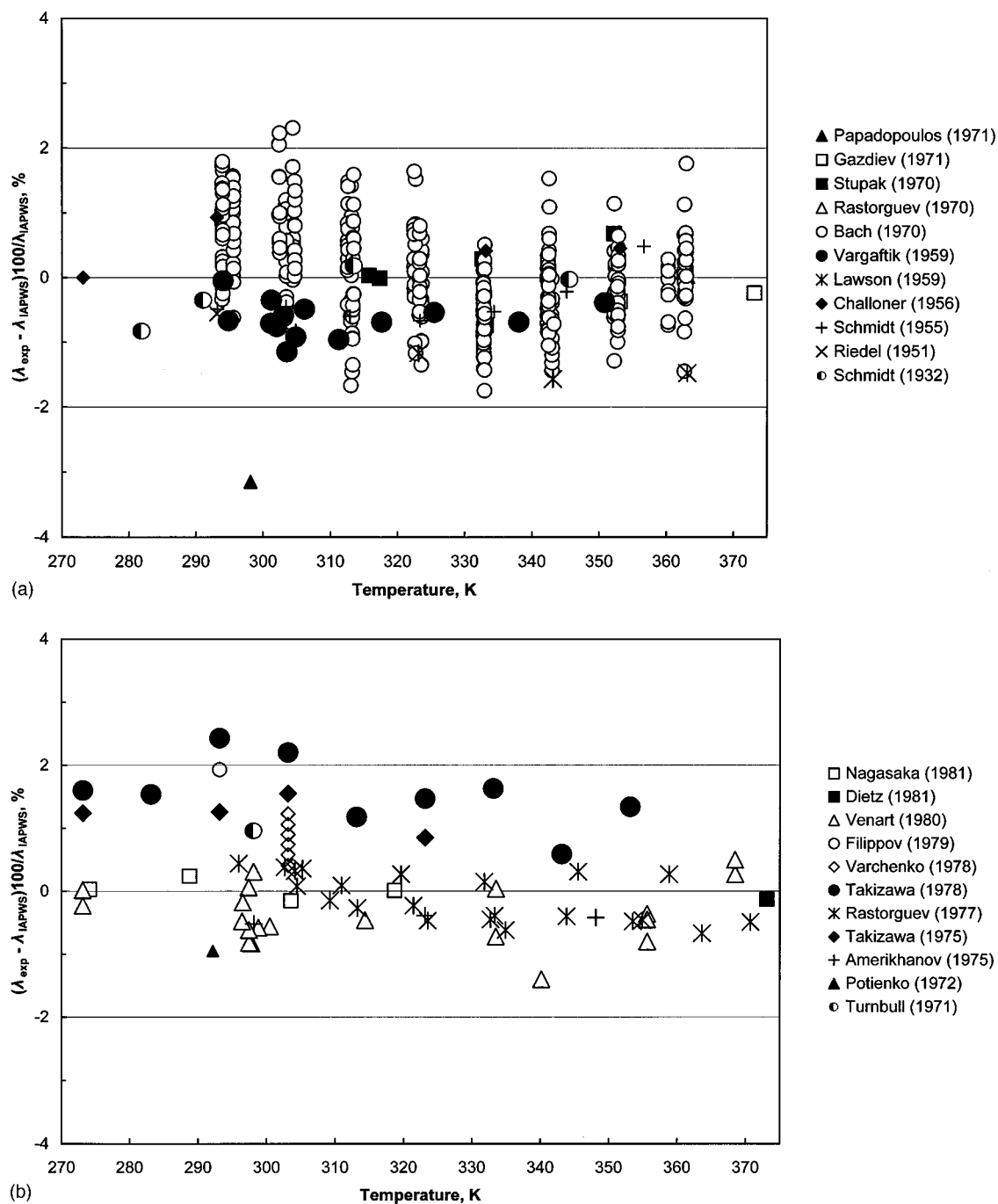
FIG. 6. (a), (b), (c) Deviations of thermal conductivity measurements of liquid water at ambient pressure between 273.15 and 373.12 K from the IAPWS correlation.
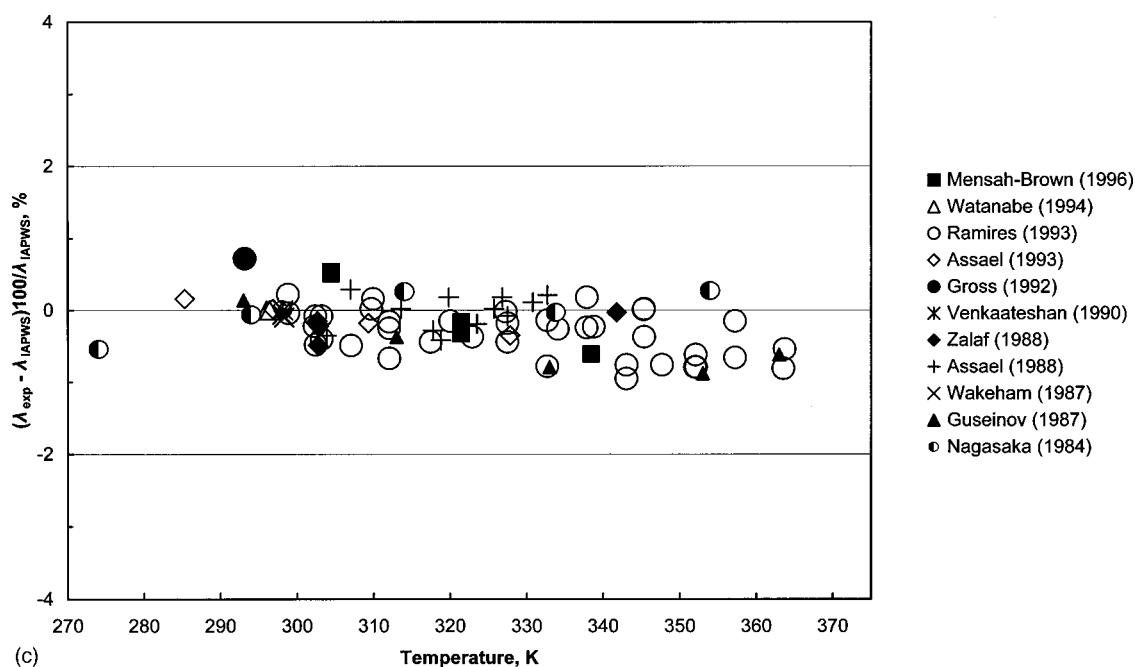
Fig. 6. (*Continued.*)

is less than about 1%. Figure 2(b) shows data sets from 1974 to 1995. The data sets after 1980 were not used in the original formulation. With the exception of those of Melzer *et al.* (1989), whose measurements seem to be higher than all other sets, the new measurements also agree very well with the IAPWS formulation. Finally, the measurements of Kozlov (1985) performed with a NMR technique with unquoted uncertainty, show a 12% deviation from all present sets and were not included in the figures. In Sec. 2.1.1, we provide additional discussion concerning the viscosity of liquid water at atmospheric pressure and 20 °C, because this is an important calibration standard.

The deviations of the data sets in the liquid phase (excluding liquid data near 0.101 325 MPa) presented in Table 3, are shown in Figs. 3(a) and 3(b). Only the data of Dudziak and Franck (1966) performed in an oscillating-disk viscometer with an uncertainty specified as 5% and a reproducibility which is considerably larger for some state points, have been excluded from the figures, because they show some deviations of up to about 12%. In both figures, the data sets agree with the viscosity values obtained from the IAPWS formulation within their mutual uncertainty. The low-pressure data below 273 K of White and Twining (1914), Hallett (1963), and Eicher and Zwolinski (1971) agree with the extrapolation of the formulation within ±1%. The three liquid data sets reported after 1980 also agree well with the formulation.

The data sets in the vapor phase reported in Table 4 are shown in Fig. 4. These are the data used in the original formulation. More recent measurements have not yet been reported. Some data of Whitelaw (1960) and Oltermann (1977), which show larger deviations, were obtained very near the critical point.

In Fig. 5, the deviations of the data sets of Table 5, in the supercritical region ($T > T_c$ for any pressure) are shown. No measurements after 1986 have been reported. Here, the data of Dudziak and Franck (1966) are shown although their uncertainty and reproducibility are worse than most other investigators. Only about 70 points, from the 1238 shown, deviate by more than ±5%.

2.1.1. Viscosity of Liquid Water at Atmospheric Pressure and 20 °C

The viscosity of liquid water at the standard condition of 0.101 325 MPa and 293.15 K is an important calibration standard and is the subject of a recently revised report from the International Organization for Standardization [ISO (1998)]. This ISO Technical Report was based on an analysis of the available data by Bauer *et al.* (1995) as well as input from various sources, including unpublished comments prepared by the IUPAC Subcommittee on Transport Properties (STP). The data considered in the development of the ISO standard, as well as their evaluation, are of considerable interest in the current compilation.

The sources considered by Bauer *et al.* in determining the temperature dependence of the viscosity of liquid water near 293.15 K represent a subset of Table 2. In particular, the work of Assael *et al.* (1993b), (1994), Berstad *et al.* (1988), James *et al.* (1984), Kestin and Shankland (1981), Korosi and Fabuss (1968), Weber (1955), Hardy and Cottington (1949) (at lower pressures, so in Table 3), and Coe and Godfrey (1944) were assigned a weight of 1.0 in the regression of a description of the temperature dependence by Bauer *et al.*, and the data of Eicher and Zwolinski (1971) and of Korson *et al.* (1969) were assigned lower weights in that regression.
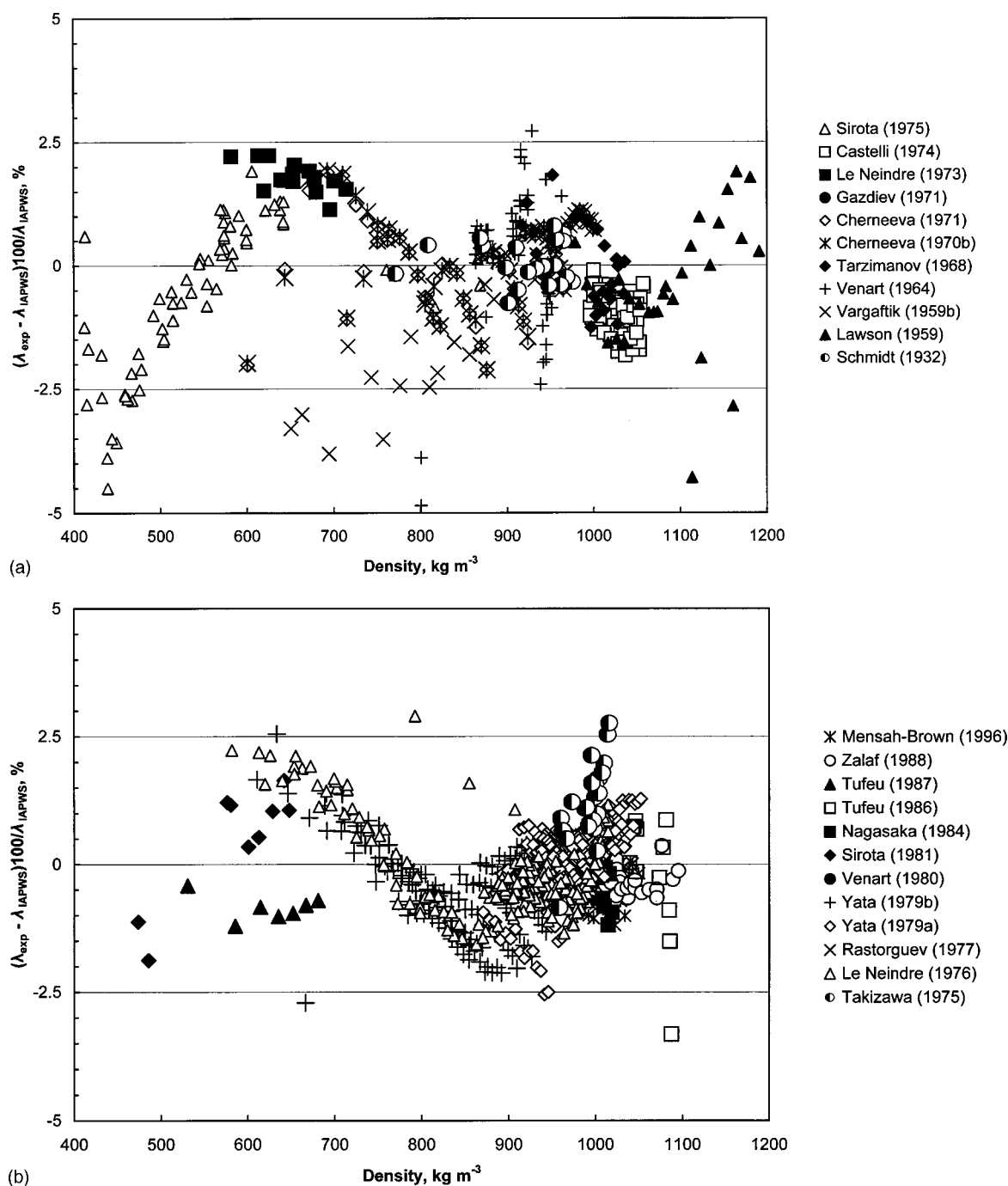
(a)

(b)

FIG. 7. (a), (b), (c) Deviations of thermal conductivity measurements of water in the liquid phase (excluding data near 0.101 325 MPa) from the IAPWS correlation.

Five important studies were used by Bauer *et al.* (1995) to establish the absolute viscosity at 20 °C and atmospheric pressure and are also included in our Table 2; these are the work by Swindells *et al.* (1952), Malyarov (1959), Roscoe and Bainbridge (1958), Kestin and Shankland (1981), and Berstad *et al.* (1988). After converting the data to 293.15 K on the IPTS-90 temperature scale, Bauer *et al.* assigned these five measurement results an equal weight in the determination of a recommended calibration standard. Subsequent to the publication of the report by Bauer *et al.*, the STP per-

formed an independent evaluation of the relevant data and concluded that only the measurements of Swindells *et al.* (1952) and of Berstad *et al.* (1988) should be accepted as being of quality sufficient to develop the calibration standard at 293.15 K and 0.101 325 MPa; unfortunately, these data are not mutually consistent within their reported uncertainties. After deliberation, the ISO has accepted a value for this reference standard of 1.0016 mPa s with an estimated uncertainty of 0.17% [ISO (1998)]. The current IAPWS formulation for viscosity also gives a value of 1.0016 mPa s for this
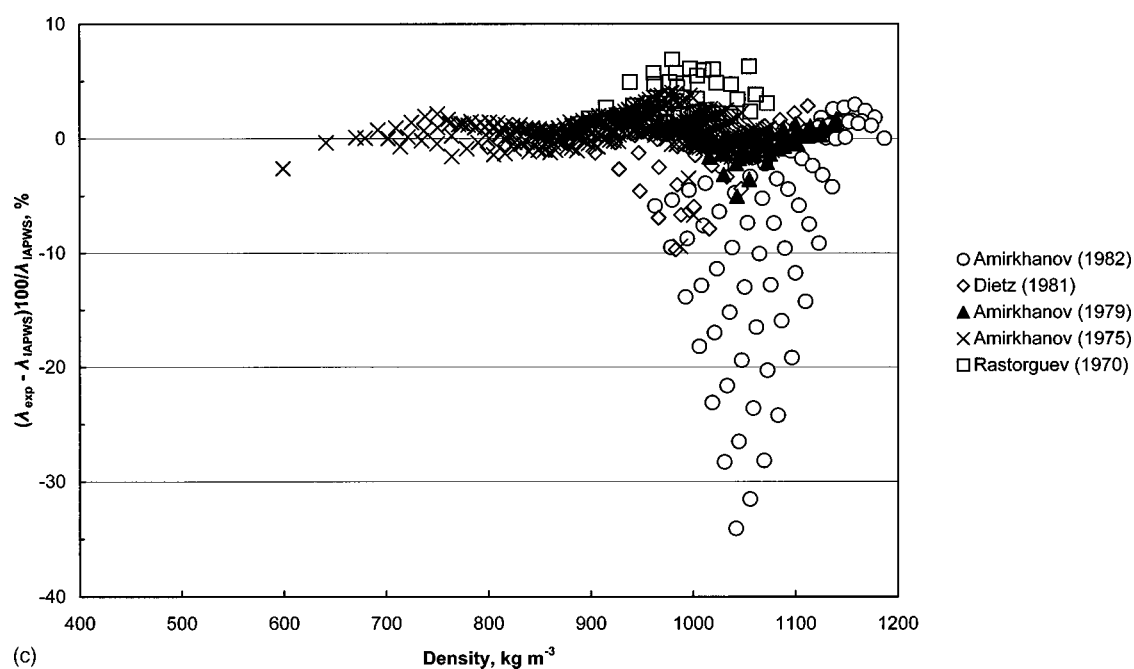
FIG. 7. (*Continued.*)

point with an assigned tolerance of 1% [IAPWS (1997)]. Deviations between the experimental data and the IAPWS formulation can be seen in Figs. 2(a) and 2(b).

2.2. Thermal Conductivity

The deviations of the experimental data for the thermal conductivity from the values calculated from the current standard formulation are shown in Figs. 6–9. The uncertainty of the IAPWS thermal conductivity formulation was again expressed by means of assigned tolerances associated with each of about 640 evenly spaced points in the range 273–1073 K from 0.1 MPa pressure to 100 MPa and about 40 points each along the saturated vapor and saturated liquid lines [IAPWS (1998)]. In general for the single phase region, the tolerances range from 1.5% to 4% depending on the state point below 50 MPa, and can rise considerably at higher pressures and near the critical point. The tabulated thermal conductivity of the saturated liquid has a tolerance of about 2% for temperatures up to 553 K, but this rises to about 10% close to the critical temperature. The tabulated thermal conductivity of the saturated vapor has a tolerance of about 3%–4% for temperatures up to 553 K; above 553 K, the tolerance increases to up to about 30% close to the critical temperature.

The atmospheric pressure region is shown in three figures due to the very large number of data sets also summarized in Table 6. The data sets are arranged chronologically. The point of Shurygin *et al.* (1974), performed in a rotating-disk instrument with an uncertainty of 5%, is excluded from the figures, because it lies 6.4% below all other data. In the last figure, Fig. 6(c), which includes data sets published after

1980, the deviations are much smaller, possibly indicating a general improvement in experimental capabilities.

The deviations of the thermal conductivity data in the liquid phase (excluding data near 0.101 325 MPa) from the IAPWS formulation, are shown in Figs. 7(a), 7(b), and 7(c) and are summarized in Table 7. Data are arranged chronologically in the first two figures, while in the third figure, Fig. 7(c), five of the data sets obtained at very high pressures are shown. In Figs. 7(a) and 7(b), the deviations are in general within ±3%. However, we note the systematic ''S'' shape of the deviations in all figures with a minimum in the deviation at about 850 kg m^{-3}. In Fig. 7(c), some very high-pressure measurements are shown. The measurements of Amirkhanov *et al.* (1982) were not considered in the original formulation. The deviations in this figure are very large, and a careful reconsideration of this range might be appropriate.

The vapor phase deviations of the thermal conductivity are shown in the next two figures. The data sets in Figs. 8(a) and 8(b) are arranged chronologically. Because most of these older data were obtained at low densities, the first figure is more restricted in density. Most of the deviations are within 5%, while only a few deviations, especially near 100 kg m^{-3}, rise to 10%. The more recent measurements of Tufeu and Le Neindre (1987), performed in a concentric cylinder instrument with a 2% uncertainty, show deviations up to 10% with a maximum deviation at a density of about 100 kg m^{-3}.

Finally, deviations in the supercritical region ($T > T_c$ for any pressure) are shown in Figs. 9(a) and 9(b). Most of these measurements were considered in the original formulation. Nevertheless, deviations show a maximum up to 30% near the critical temperature at different densities, indicating a possible area of improvement of the formulation.
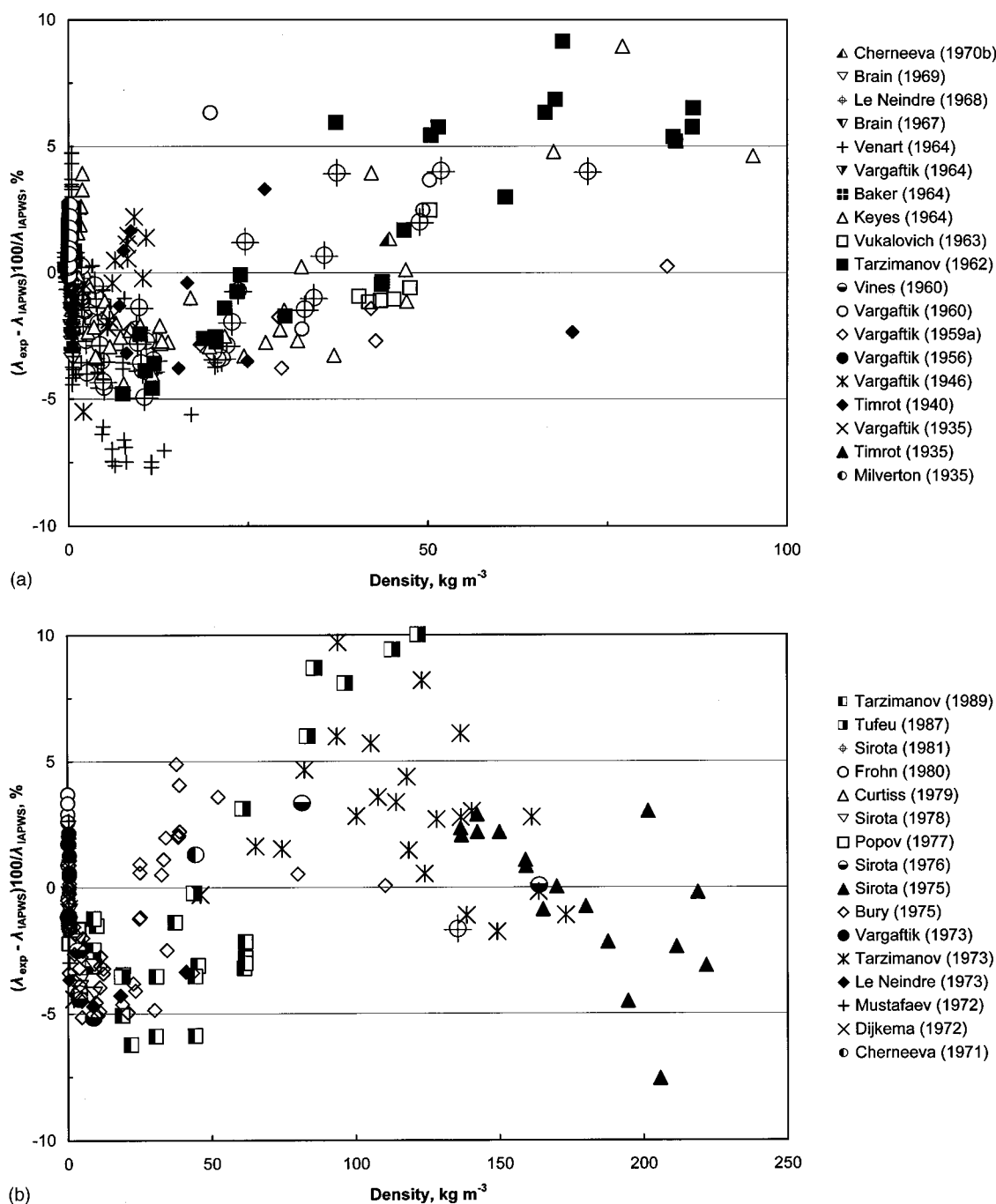
FIG. 8. (a) and (b) Deviations of thermal conductivity measurements of water in the vapor phase from the IAPWS correlation.

3. Conclusions

For the viscosity, the only measurements made after the development of the IAPWS formulation are in the liquid phase. Some of these data have slightly smaller uncertainties than the data considered in the development of the earlier IAPWS formulation. These data may be employed to develop a new standard formulation that will improve the representation of the viscosity of water in this region.

The behavior of the deviations of the thermal conductivity is, however, slightly different. At atmospheric pressure, the

new measurements may help to improve the formulation. In the liquid phase, the high-pressure region needs to be re-examined. Also, the vapor-phase region can probably be improved in view of more recent measurements. Finally, it might be worthwhile to re-examine the critical region taking into account the new data and progress in the theoretical understanding of properties in this region.

This data collection represents the initial stage of a project to develop new standard formulations for the viscosity and thermal conductivity of water which are consistent with the IAPWS-95 thermodynamic surface. The project involves
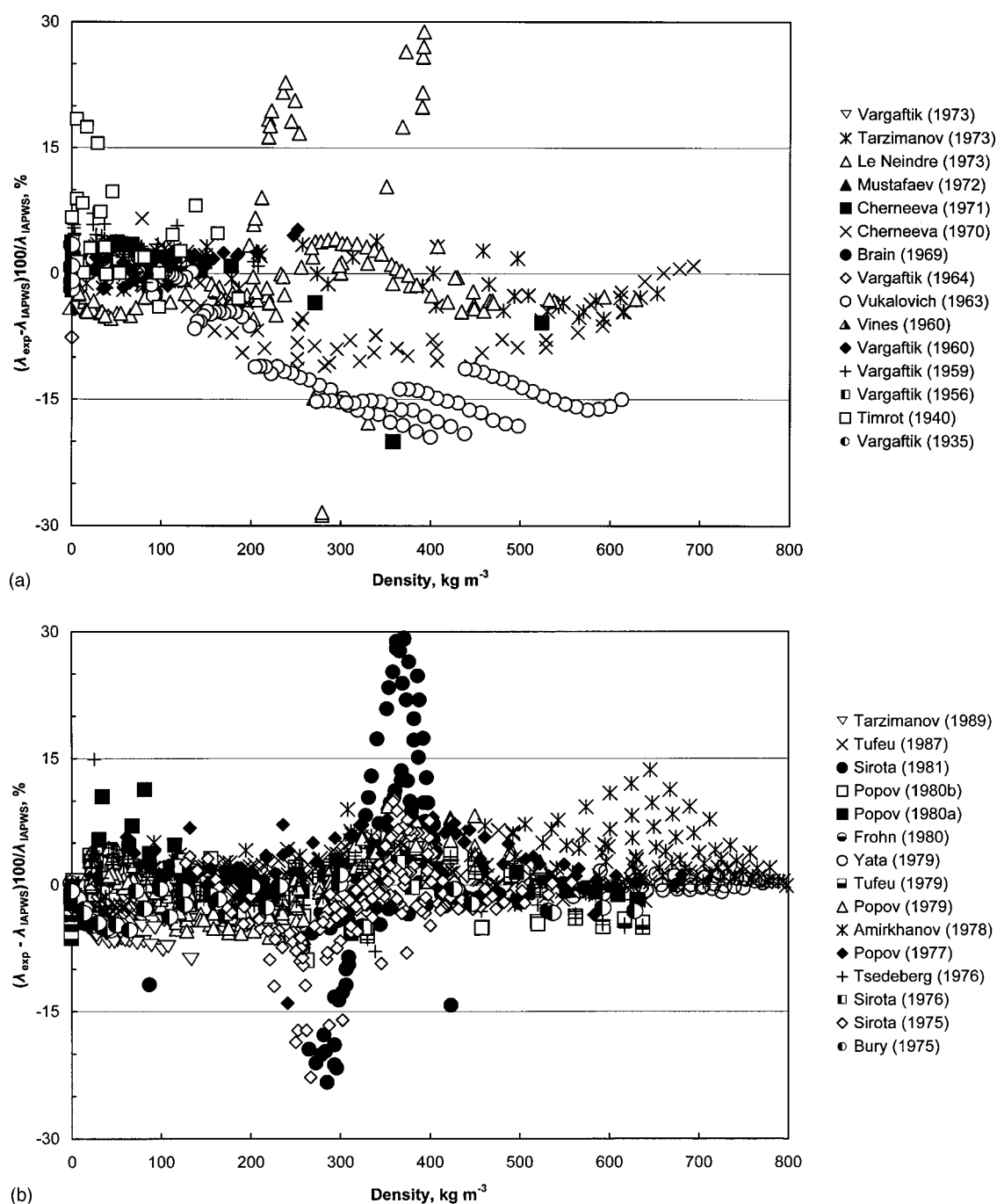
FIG. 9. (a) and (b) Deviations of thermal conductivity measurements of water in the supercritical region ($T > T_c$ for any pressure) from the IAPWS correlation.

continued evaluation of these data, selection of primary data to be used for regression, establishment of the structural form of the terms which contribute to the transport properties, and regression, optimization, and validation of the resulting correlating equations.

4. Acknowledgments

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