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Revised Formulation for the Refractive Index of Water and Steam as a Function of Wavelength, Temperature and Density

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Schiebener *et al.* published a formulation for the refractive index of water and steam in 1990 [J. Phys. Chem. Ref. Data **19**, 677 (1990)]. It covered the ranges 0.2 to 2.5 μm in wavelength, -12 to 500 °C in temperature, and 0 to 1045 $\mathrm{kg\,m^{-3}}$ in density. The formulation was adopted by the International Association for the Properties of Water and Steam (IAPWS) in 1991. In the present article, the data, after conversion to ITS-90, have been refitted to the same functional form, but based on an improved equation of state for water adopted by IAPWS in 1995. The revised coefficients are reported, and some tabular material is provided. The revised refractive-index formulation was adopted by IAPWS in 1997 and is available as part of a National Institute of Standards and Technology Standard Reference Database. For most conditions, the revised formulation does not differ significantly from the previous one. A substantial improvement has been obtained in supercooled water at ambient pressure, where the previous formulation was defective. Special attention has been paid to the behavior of the refractive index in the near infrared, where strongly oscillating data were reported after the correlation of Schiebener *et al.* had appeared, leading to subsequent curtailing of the range of validity of the formulation. Newer results do not show these oscillations. They are compared with the revised formulation.
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Key words: formulation; infrared; ITS-90; molar refraction; refractive index; steam; supercooled water; supercritical steam; ultraviolet; visible; water

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1. Introduction

Schiebener *et al.*,[1] in 1990, published a formulation for the refractive index of water and steam. It extended over the ranges of 0.2 to 2.5 μm in wavelength, -12 to 500 °C in temperature, and 0 to 1045 kg m^{-3} in density. It made use of a comprehensive data collection by Thormählen *et al.*,[2] completed in 1985, from which the most reliable sources were selected. Some additional vapor-phase data[3,4] were also used. The formulation was based on the assumption that the Lorentz–Lorenz function

$$LL=\frac{n^2-1}{(n^2+2)\rho_m}, \tag{1}$$

where n is the refractive index, is a smooth, slowly varying function of molar density ρ_m and temperature. This assumption was validated on the basis of the existing data. In particular, for fixed wavelength, LL does not vary more than 1% between the liquid at ambient temperatures and the vapor above the normal boiling point. The wavelength dependence of LL is pronounced. Strong variations occur near the first major infrared resonance, at around 2.9 μm in wavelength, and near the ultraviolet resonance at around 0.18 μm. The original correlation was limited to a region between these two resonances.

Since most of the data were obtained as a function of pressure and temperature, an equation of state was needed to convert measured pressures to densities. For this purpose, the NBS/NRC Steam Tables[5] were used; these had been adopted by the International Association for the Properties of Steam [now the International Association for the Properties of Water and Steam (IAPWS)] in 1984. The formulation of Schiebener *et al.*[1] represented most of the selected data to near their experimental uncertainty, which, in some cases, was within 10^{-6} in n. A notable exception was the substantial departure from the precise data available in supercooled water. This departure was due to extrapolation of the equation of state and was therefore not curable within the chosen framework.

Just after the publication of Ref. 1, the international practical temperature scale (IPTS-68) was replaced by ITS-90.[6] The differences between the scales are significant for the refractive index formulation only in those regions where highly accurate data are available, that is, for liquid water at ambient pressure and temperatures between −12 and 60 °C.

Furthermore, in 1995, IAPWS adopted a new formulation for the equation of state of water and steam, which was of improved accuracy and had been fitted to the available density data in supercooled water, representing them well.[7,8]

Shortly after Ref. 1 appeared in print, some reported refractive indices in the near infrared[9] were brought to the authors' attention; these data showed strong oscillations in n as a function of wavelength at 1.2 μm and up. Schiebener *et al.* then published an Erratum,[10] recommending that the correlation not be used beyond 1.1 μm. Further investigation, however, strongly suggests that these oscillations are not real; this will be discussed in Sec. 5.

The purpose of the present work is the following: (1) to base the refractive index formulation on the new temperature scale, ITS-90; (2) to base it on the newly adopted equation of state, in the hope of obtaining better performance in supercooled water; and (3) to clarify some issues related to the behavior of the refractive index in the near infrared.

2. Data and Method

The selected database of Ref. 1, with temperatures transformed to the ITS-90 temperature scale according to the method given by Rusby,[11] was used for the revised correlation. The data of highest accuracy and internal consistency, thus anchoring the correlation, are those of Tilton and Taylor[12,13] at ambient pressure and at temperatures up to 60 °C, and the data of Saubade[14] in low-temperature and supercooled water down to −12 °C, both with claimed uncertainty of 10^{-6} in n; the data for pressurized water from 2 to 54 °C by Waxler *et al.*,[15,16] with claimed uncertainty of 10^{-4}; and the data for pressurized steam from 100 to 225 °C by Achtermann,[3,4] with claimed uncertainty of 2×10^{-7}.

The method of correlation was to write LL as a function of density, temperature, and wavelength, with as few adjustable parameters as possible, so as to control unwanted oscillations in the large regions where no data are available (liquid at temperatures above the normal boiling point; vapor below the boiling point; supercritical steam). The functional dependence on the wavelength was dominated by the customary mathematical poles near the resonances. The correlating equation, of the same form as that used in Ref. 1, is Eq. (A1) in Appendix 1. The densities of the experimental data were calculated from the new IAPWS formulation of 1995.[8,17] The wavelength range of the fit was from 0.2 to 1.1 μm.

3. Revised Formulation

3.1. Description and Tabulation

The optimized coefficients from the new fit of the data to Eq. (A1) in Appendix 1 are listed in Appendix 1, Table 1. Table 2, which gives the estimated uncertainty in various ranges of temperature, pressure, and wavelength, remains nearly unchanged from the previous formulation, except for the supercooled liquid, where substantial improvement has been obtained. In Table 3 of Appendix 1, values of the refractive index are listed for three wavelengths, four temperatures, and four pressures, with more digits than the uncertainty of the formulation warrants, for the purpose of checking computer codes.

In Appendix 2, the refractive index as calculated by the formulation is tabulated as a function of temperature and pressure for four widely used wavelengths in the visible spectrum (Tables 4–7). The upper temperature and pressure limits in these tables are 500 °C and 100 MPa; we must emphasize that the data do not cover this entire region, so portions of these tables are extrapolations (Table 2 in Appendix 1 gives the regions in which data do exist). The wavelengths used are the argon-ion laser wavelengths of 0.488 and 0.5145 μm, the sodium-D line wavelength (intensity-weighted mean of the doublet) of 0.589 26 μm, and the helium-neon laser wavelength of 0.6328 μm. For these four wavelengths, the refractive index is also tabulated for the

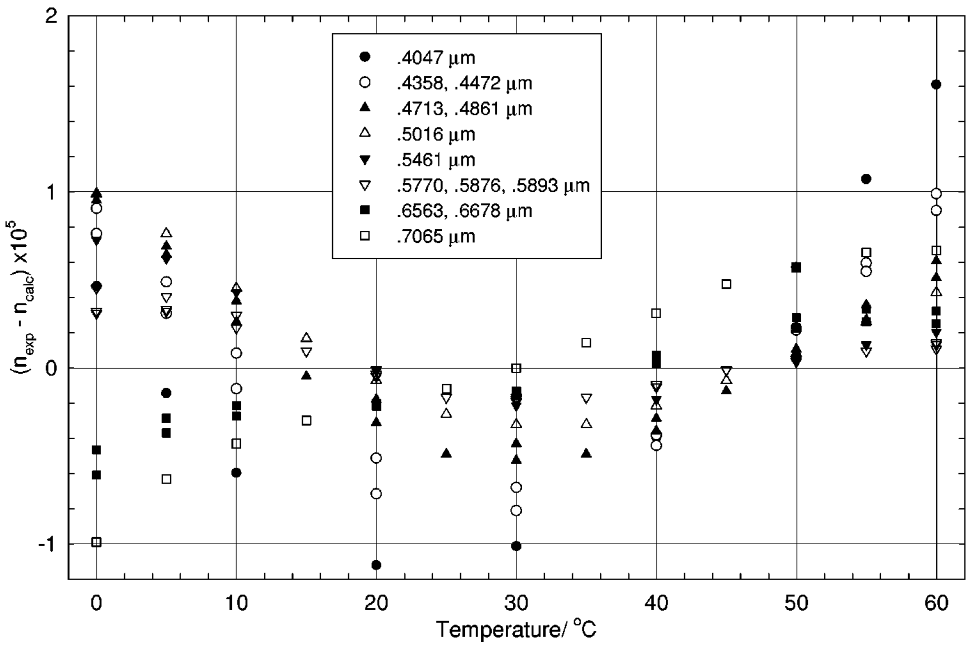

FIG. 1. Deviations of Tilton and Taylor data (Refs. 12 and 13) from the revised formulation vs temperature.

saturated liquid and vapor (Table 8). In Tables 4–8, the number of digits given is sometimes more than that justified by the uncertainty in the formulation; consult Table 2 to estimate the uncertainty at any given state point.

3.2. Comparison with Data

For data of moderate accuracy, the revised formulation is not significantly different from the previous one. We therefore refrain from comparing it with the complete database. We make exceptions for the highly accurate data of Tilton and Taylor,[12,13] Achtermann,[3,4] and Saubade.[14] The deviations of the data of Tilton and Taylor from the new fit are shown in Fig. 1 (with temperature as the x axis) and Fig. 2 (with wavelength as the x axis). The deviations are very similar to those from the previous fit (within 10^{-5}), except that the present fit shows substantial improvement at 0 and 5 °C for reasons to be discussed in Sec. 4. The fit to the data of Achtermann[3,4] is insignificantly, less than 10^{-6}, different from that of the correlation by Schiebener *et al.* A marginal change is observed at the highest temperature (Fig. 3).

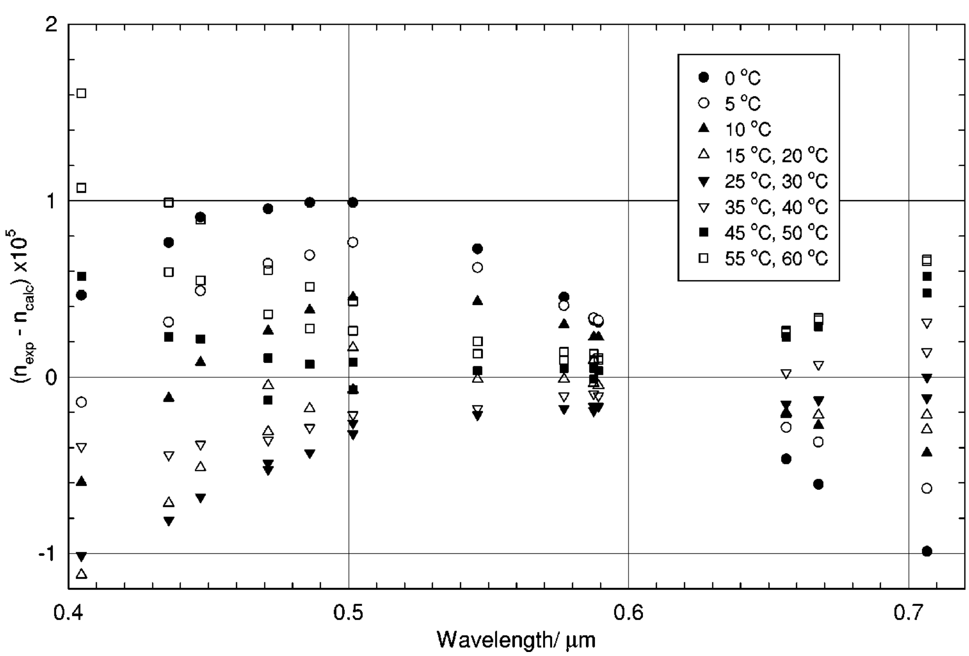

FIG. 2. Deviations of Tilton and Taylor data (Refs. 12 and 13) from the revised formulation vs wavelength.

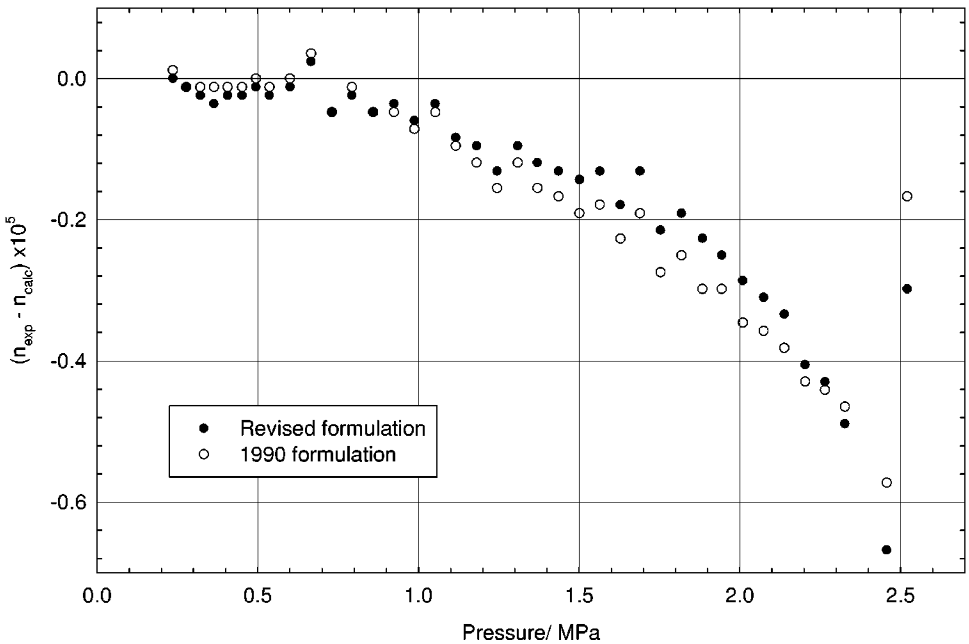

FIG. 3. Deviations of Achtermann data (Refs. 3 and 4) at 225 °C from the revised and 1990 formulations.

4. Refractive Index and Density of Supercooled Water

Figure 11 of Ref. 1 showed that the high-quality Saubade data[14] increasingly and systematically departed from the original formulation as the temperature decreased below 5 °C. At −12 °C the departure had increased to 2×10^{-4}, two orders of magnitude beyond the claimed uncertainty of the data. At that time it was concluded that the departure was due to the extrapolation of the NBS/NRC equation of state,[5] which had not been fitted to any data in supercooled water. The IAPWS-1995 equation of state[7,8] was fitted to data in supercooled water, and also benefited from density data now available[18] for liquid water from 0 to 85 °C with a relative accuracy near 10^{-6}.

In Fig. 4, we show the departures of the Saubade data (and also the low-temperature data of Tilton and Taylor at the same wavelength) from both the present formulation and the previous one. The low-temperature systematic errors have been reduced by a factor of 3. The remaining systematic

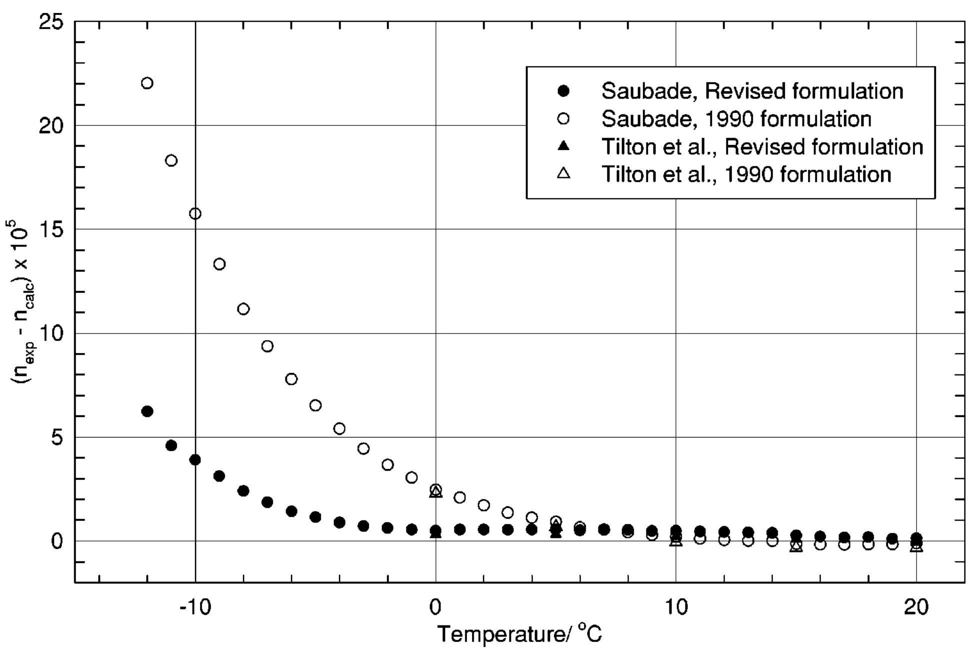

FIG. 4. Deviations of low-temperature data (Refs. 12–14) from the revised and 1990 formulations.

errors are most likely still due to the equation of state, since the experimental liquid density data below 0 °C are less accurate than the data now available in the range 0 to 85 °C.

5. Refractive Index in the Near Infrared

5.1. Previous Concerns

The previous formulation[1] was fitted to a few selected data points for the refractive index of liquid water in the near infrared at wavelengths up to 2.5 μm. However, after that work was completed, its authors were made aware of new data by Ichikawa[9] which exhibited strong oscillations in the refractive index associated with the known weak absorption peaks at roughly 1.46 and 1.93 μm. Since the refractive index from the formulation varied smoothly through this region, it could not represent these oscillations. Therefore, an Erratum was issued[10] in which the upper wavelength limit of the formulation was restricted to 1.1 μm. The same upper limit was used to restrict the data used in the refit reported here.

5.2. Obtaining Refractive Indices from Absorption

While water is essentially transparent at visible wavelengths, it contains strong absorption bands in the infrared. The first such peak is near 2.9 μm, but there is significant absorption at all wavelengths beyond about 1 μm. This can introduce significant errors if experiments are performed under the assumption of complete transparency.

In absorbing fluids, one must treat the refractive index as a complex number, where the imaginary part describes the absorption. The real and imaginary parts, denoted $n(\lambda)$ and $k(\lambda)$, are connected by the Kramers-Kronig relations, which give the real part as an integral over the imaginary spectrum, and vice versa. For determining the real part from the absorption, the Kramers-Kronig relation is

$$n(\lambda)=1+\frac{2\lambda^2}{\pi}\int_0^\infty \frac{k(\lambda')d\lambda'}{\lambda'(\lambda^2-\lambda'^2)}. \qquad (2)$$

Two aspects of Eq. (2) are worth noting. First, while absorption at all wavelengths contributes to $n(\lambda)$, that at wavelengths close to λ is weighted more heavily. Therefore, if one is concerned with $n(\lambda)$ in a specific wavelength range, it is important to know $k(\lambda)$ accurately in that range, but the absorption need only be known approximately at distant wavelengths. Second, the integrand in Eq. (2) is positive for $\lambda>\lambda'$ and negative for $\lambda<\lambda'$. Therefore, in the neighborhood of a strong absorption, $n(\lambda)$ will decrease as the absorption is approached from a shorter wavelength, increase sharply at the absorption, and then decline again as λ increases further.

If accurate absorption data are available, Kramers-Kronig analysis provides a rigorous tool for obtaining accurately changes of n with wavelength; it is particularly useful in regions where absorption renders direct measurement unworkable.

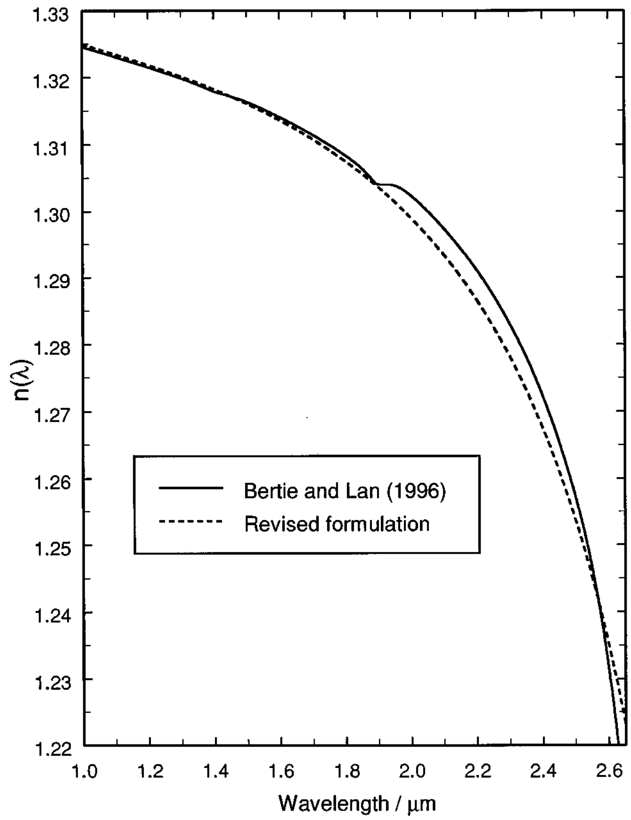

FIG. 5. Refractive index in the near infrared at 25 °C.

5.3. Critique of Data in the Near Infrared

Direct measurement of water's refractive index in the near infrared is impractical due to absorption. However, the absorption spectrum $k(\lambda)$ can be measured more easily; there have been several such studies including the recent precise work of Kou *et al.*[19] in liquid water from 0.65 to 2.5 μm. The available absorption data were collected by Bertie and Lan,[20] who performed a Kramers-Kronig analysis to obtain $n(\lambda)$ for liquid water at 25 °C. For the region of interest here (near-infrared wavelengths shorter than that of the strong resonance near 2.9 μm), their analysis is estimated to be accurate within 0.001 in $n(\lambda)$.[21] Their refractive indices in this region are in good agreement with the earlier analysis of Hale and Querry,[22] who worked from a more limited set of absorption data.

The important aspect for our purposes of the results from Kramers-Kronig analysis is that they do *not* show the severe oscillations exhibited by Ichikawa's[9] data. The weak absorption peak at 1.46 μm produces only a barely perceptible change in the slope of $n(\lambda)$, while the slightly stronger peak at 1.93 μm produces a small shoulder in the spectrum. Figure 5 shows $n(\lambda)$ in the region of interest here, along with the extrapolation of our formulation. The data of Ichikawa[9] are not shown, but their oscillations would be well off the scale of Fig. 5.

We think that Ichikawa's measurements in this region do not give correct values for $n(\lambda)$. We come to this conclusion not only because they disagree with rigorous Kramers-

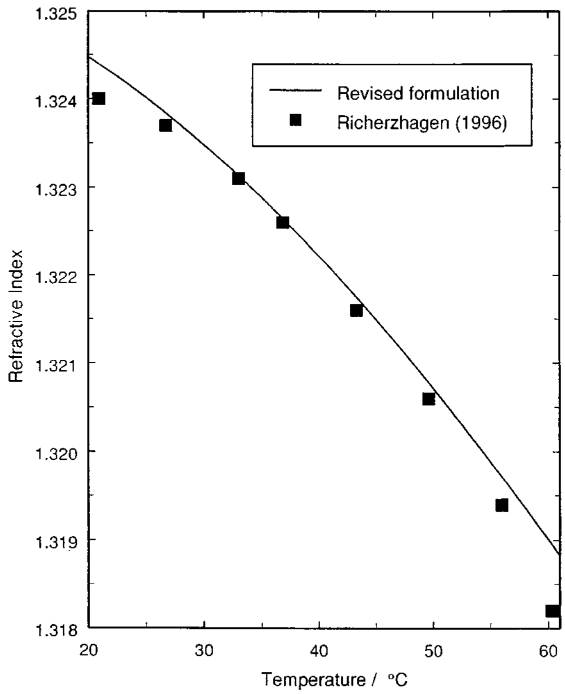

FIG. 6. Temperature dependence of refractive index at 1.064 μm.

Kronig analysis, but also because they show a steady increase of $n(\lambda)$ as the strong absorption near 2.9 μm is approached. As mentioned above, physics demands that $n(\lambda)$ decrease prior to such a strong absorption. In addition, it has been pointed out to us that Ichikawa's experimental technique in this region, which involved counting interference fringes generated by water in a small gap, is prone to errors when there is absorption.[21]

5.4. Temperature Dependence in the Near Infrared

When this formulation was developed, the only available data covering a significant range of temperatures were at visible and ultraviolet wavelengths. These data therefore determined the temperature dependence of the formulation at infrared (IR) wavelengths.

Recently, Richerzhagen[23] measured the refractive index of liquid water at a wavelength of 1.064 μm from 20 to 60 °C. These data provide a test of our implicit assumption that the temperature dependence of the refractive index can be extrapolated from visible wavelengths into the near infrared. Figure 6 compares these data to the new formulation. The reported uncertainty in these data is approximately 2×10^{-4}. While the formulation is consistent with Richerzhagen's data in the middle of the temperature range, the highest and lowest temperature points are clearly in disagreement, suggesting that the temperature dependence of the formulation in the IR in this region is not quantitatively correct.

5.5. Recommendations

The new formulation is officially endorsed by IAPWS only for the wavelength region in which data were fitted, which extends to 1.1 μm. However, we can judge its performance at longer wavelengths by comparing it to the results of Bertie and Lan.[20] As shown in Fig. 5, the extrapolation is accurate up to the shoulder associated with the absorption at 1.93 μm. It is therefore our judgment that this formulation can be extrapolated safely for liquid water at ambient temperature up to a wavelength of 1.9 μm. In addition, the comparison to the data of Richerzhagen[23] in Fig. 6 suggests that the accuracy of the formulation is diminished at higher and lower temperatures in the near infrared.

6. Summary

The formulation of the refractive index of water and steam as a function of temperature, density, and wavelength by Schiebener *et al.*[1] has been revised. The same database has been used as in the previous work. The data were transformed to the new ITS-90 temperature scale, and conversions from experimental pressure to density were made with the IAPWS-1995 formulation for water's equation of state. The data were fitted in the wavelength range from 0.2 to 1.1 μm.

The fit shows substantial improvement in the range from $-$ 12 to 5 °C, reflecting the improvement of the equation of state for supercooled water. The remaining offset below 0 °C likely arises because the equation of state is based on data of limited accuracy in this region.

Strong oscillations in the refractive index had been reported in one study in the near infrared; this report led to a cutoff of the range of the formulation. Further examination, particularly by Kramers-Kronig analysis, does not support the existence of these oscillations. Extrapolation of the present formulation beyond 1.1 μm gives results that are consistent with the best estimates from Kramers-Kronig analysis up to 1.9 μm at ambient temperature. The database of Schiebener *et al.* contains very limited information on the temperature dependence of the refractive index in the near infrared. Recent data at 1.064 μm from 20 to 60 °C suggest that the formulation does not quite produce the correct temperature dependence in the near infrared. The estimated uncertainty in this range given in the IAPWS release (Table 2, Appendix 1) may therefore be overly optimistic. A change in the form of the fitting equation would probably be required to accommodate these new data.

There are no data on the temperature dependence of the refractive index above 225 °C in the vapor and above the normal boiling point in the liquid. All results of this formulation should be viewed with caution in regions where data are not available.

This formulation is available in the form of computer code as part of a NIST Standard Reference Database.[17]

7. Acknowledgments

The Working Group for Thermophysical Properties of Water and Steam of the International Association for the Properties of Water and Steam provided a framework and part of the information needed for this revision. The authors are grateful to Professor J. Bertie for clarifying issues regarding the refractive index in the near infrared and for providing his results plotted in Fig. 5. They also acknowledge helpful correspondence with Professor M. Querry and Professor M. Ichikawa, and they thank Dr. B. Richerzhagen for providing the coordinates of his data plotted in Fig. 6.

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9. Appendix A. Text of IAPWS Release

This Appendix contains the text of the release as accepted by the International Association for the Properties of Water and Steam.[24] Section 1 contains the nomenclature, Sec. 2 the formulation and table of coefficients. Section 3 gives the information on the equation of state used. Section 4 defines the range of the formulation. Section 5 gives the estimates of uncertainty. For the purpose of checking computer code, Sec. 6 presents a short table of values, with more significant digits than the uncertainty of the formulation warrants. Section 7 gives the references associated with the release.

Minor formatting changes have been made in the original IAPWS release for clarity within the context of this article.

The International Association for the Properties of Water and Steam

Erlangen, Germany September 1997

Release on the Refractive Index of Ordinary Water Substance as a Function of Wavelength, Temperature and Pressure

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Executive Secretary:
Dr. R. B. Dooley
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Palo Alto, California 94304-1395

This release replaces the corresponding release of 1991.

This release has been authorized by the International Association for the Properties of Water and Steam (IAPWS) at its meeting in Erlangen, Germany, September 1997, for issue by its Secretariat. The members of IAPWS are Argentina, Canada, the Czech Republic, Denmark, Germany, France, Italy, Japan, Russia, the United Kingdom, and the United States of America.

Details about the original formulation, the data sources and their evaluation are given in the paper ''Refractive Index of Water and Steam as Function of Wavelength, Temperature and Density,'' by P. Schiebener, J. Straub, J. M. H. Levelt Sengers and J. S. Gallagher [1]. In the present formulation, the data have been converted to the ITS-90 Temperature Scale, and the equation of state in the previous release has been replaced by the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use [2]. The refractive index data have been refitted to the original functional form, but in a reduced wavelength range, see [3].

Further information about this release and other releases issued by IAPWS can be obtained from the Executive Secretary of IAPWS [4].

Release on the Refractive Index of Ordinary Water Substance as a Function of Wavelength, Temperature and Pressure

1. Nomenclature

n	refractive index with respect to vacuum
P_{sat}	saturation pressure
T	absolute temperature, ITS-90
t	temperature in degrees Celsius
λ	wavelength of light
ρ	mass density

Reference constants

Reference temperature	$T^* = 273.15$ K
Reference density	$\rho^* = 1000$ kg m^{-3}
Reference wavelength	$\lambda^* = 0.589\ \mu$m

Dimensionless variables

Temperature	$\overline{T} = T/T^*$
Density	$\overline{\rho} = \rho/\rho^*$
Wavelength	$\overline{\lambda} = \lambda/\lambda^*$

2. Formulation

The refractive index is represented by the following equation [1]:

$$\frac{n^2-1}{n^2+2}(1/\overline{\rho}) = a_0 + a_1\overline{\rho} + a_2\overline{T} + a_3\overline{\lambda}^2\overline{T} + a_4/\overline{\lambda}^2 + \frac{a_5}{\overline{\lambda}^2-\overline{\lambda}_{UV}^2} + \frac{a_6}{\overline{\lambda}^2-\overline{\lambda}_{IR}^2} + a_7\overline{\rho}^2. \quad \text{(A1)}$$

The coefficients a_0–a_7, and the constants $\overline{\lambda}_{UV}, \overline{\lambda}_{IR}$ are given in Table 1.

3. Equation of State of Water and Steam

In the conversion of the input independent variable pressure to density, preceding the optimization of Eq. (A1), the ''IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific

TABLE 1. Coefficients of the formulation, Eq. (A1)

$a_0 = 0.244\,257\,733$	$a_4 = 1.589\,205\,70\times10^{-3}$
$a_1 = 9.746\,344\,76\times10^{-3}$	$a_5 = 2.459\,342\,59\times10^{-3}$
$a_2 = -3.732\,349\,96\times10^{-3}$	$a_6 = 0.900\,704\,920$
$a_3 = 2.686\,784\,72\times10^{-4}$	$a_7 = -1.666\,262\,19\times10^{-2}$
$\overline{\lambda}_{UV} = 0.229\,202\,0$	$\overline{\lambda}_{IR} = 5.432\,937$

TABLE 2. Estimated uncertainty of the refractive-index formulation

Wavelength (μm)	Temperature range (°C)	Pressure range (MPa)	Phase	Absolute uncertainty of refractive index
0.40 to 0.70	−12 to 5	ambient	liquid	$<6\times10^{-5}$
0.40 to 0.70	5 to 60	ambient	liquid	1.5×10^{-5}
0.40 to 0.60	60 to 100	ambient	liquid	$<3\times10^{-4}$
0.47 to 0.67	0 to 60	up to 150	liquid	2×10^{-4}
0.63	100 to 225	0 to 2	vapor	5×10^{-6}
0.70 to 1.1	ambient	ambient	liquid	1×10^{-3}
0.21 to 0.40	0 to 100	ambient	liquid	5×10^{-4}
In the following ranges there are no supporting data				
0.40 to 0.70	0 to 374	0 to 0.1 P_{sat}	vapor	5×10^{-6}
0.40 to 0.70	225 to 374	0.1 P_{sat} to P_{sat}	vapor	1×10^{-4}
0.40 to 0.70	60 to 374	P_{sat} to 200	liquid	1×10^{-3}
0.40 to 0.70	>374	$<P(\rho_c/3)$	low density	1×10^{-5}
0.40 to 0.70	>374	$>P(\rho_c)$	high density	2×10^{-3}

Use'' [2] has been used. In employing Eq. (A1), with the constants in Table 1, for calculating the refractive index as a function of pressure, the IAPWS Formulation 1995 should be used.

4. Range of the Formulation

IAPWS endorses the formulation of the refractive index in the following range [1,3]:

Temperature	$-12\ °C \leqslant t \leqslant 500\ °C$
Density	$0\ kg\ m^{-3} \leqslant \rho \leqslant 1060\ kg\ m^{-3}$
Wavelength	$0.2\ \mu m \leqslant \lambda \leqslant 1.1\ \mu m$.

Extrapolation of the formulation to longer wavelengths has been tested. The formulation is in good agreement with recent results [5] in liquid water at wavelengths up to 1.9 μm.

5. Estimates of Uncertainty

The estimated uncertainty of the representation of the refractive index, in the absence of error in the independent variables, is given in Table 2. In the range where data exist, the estimate represents the largest departure of the most reliable, validated data from the formulation. Note that above 225 °C there are no data supporting the estimate. In the absence of data, the estimate is based on the assumption [1] that the Lorentz-Lorenz function will vary smoothly and uneventfully with temperature and density throughout the range represented in this release.

TABLE 3. Refractive index values from the formulation

Wavelength (μm)	Temperature (°C)	Pressure/MPa 0.1	1	10	100
0.226 50	0	1.394 527	1.394 711	1.396 526	1.412 733
	100	1.000 216 8	1.375 622	1.377 286	1.391 983
	200	1.000 168 3	1.001 775 4	1.338 299	1.359 330
	500	1.000 100 8	1.001 015 5	1.010 990 6	1.198 312
0.589 00	0	1.334 344	1.334 494	1.335 969	1.349 101
	100	1.000 187 6	1.318 725	1.320 084	1.332 057
	200	1.000 145 6	1.001 535 9	1.287 891	1.305 191
	500	1.000 087 1	1.000 877 3	1.009 493 9	1.170 231
1.013 98	0	1.326 135	1.326 279	1.327 710	1.340 435
	100	1.000 183 7	1.311 257	1.312 577	1.324 202
	200	1.000 142 7	1.001 505 2	1.281 529	1.298 369
	500	1.000 085 6	1.000 861 9	1.009 326 7	1.167 119

6. Values for Program Verification

Table 3 contains refractive index values calculated from the formulation, Eq. (A1). If the densities are calculated from IAPWS Formulation 1995 [2] to one part in 10^6, and the coefficients in Table 2 are carried to the number of significant digits stated, the formulation should produce the values listed in Table 3 to within one unit in the least significant digit.

7. References

[1] P. Schiebener, J. Straub, J. M. H. Levelt Sengers, and J. S. Gallagher, J. Phys. Chem. Ref. Data **19**, 677 (1990).

[2] Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use, Fredericia, Denmark, September 1996.

[3] P. Schiebener, J. Straub, J. M. H. Levelt Sengers, and J. S. Gallagher, J. Phys. Chem. Ref. Data **19**, 1617 (1990).

[4] IAPWS releases prepared up to 1994 have been published in *Proceedings of the 12th ICPWS*, Orlando, FL, 1994, H. J. White, Jr., J. V. Sengers, D. B. Neumann, and J. C. Bellows (Eds.), Begell House, New York (1995). Up-to-date versions can be obtained from the Executive Secretary of IAPWS, Dr. R. B. Dooley, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94304-1395.

[5] J. E. Bertie and Z. Lan, Appl. Spectrosc. **50**, 1047 (1996).

10. Appendix 2. Tables of Refractive Index Values

The following five tables (Tables 4–8) contain values of the refractive index computed from the revised formulation given in Appendix 1.

The number of digits printed in these tables should not be considered indicative of the formulation's accuracy; estimates of the uncertainty are given in Table 2 of Appendix 1. Table 2 also shows the regions in which no data are available (and therefore no uncertainty estimates are possible); in these regions the numbers in Tables 4–8 are extrapolations. Finally, we note that, in Tables 4–7, some of the low-temperature state points listed are for the metastable liquid; the thermodynamic equilibrium state for these points would be a solid. These points are indicated by italicizing their refractive index values.

TABLE 4. Refractive index for water for wavelength 0.488 μm

	p/MPa									
T/°C	0.1	0.2	0.5	1	2	5	10	20	50	100
−10	*1.338 06*[a]	*1.338 08*	*1.338 14*	*1.338 23*	*1.338 41*	*1.338 96*	*1.339 87*	*1.341 64*	*1.346 68*	*1.354 20*
0	*1.338 40*	1.338 42	1.338 47	1.338 55	1.338 72	1.339 22	1.340 05	1.341 68	1.346 33	1.353 38
10	1.338 12	1.338 14	1.338 18	1.338 26	1.338 42	1.338 89	1.339 67	1.341 20	1.345 59	1.352 31
20	1.337 39	1.337 41	1.337 45	1.337 53	1.337 68	1.338 13	1.338 88	1.340 35	1.344 56	1.351 04
30	1.336 32	1.336 33	1.336 37	1.336 45	1.336 59	1.337 03	1.337 76	1.339 19	1.343 29	1.349 61
40	1.334 95	1.334 96	1.335 01	1.335 08	1.335 22	1.335 66	1.336 37	1.337 78	1.341 81	1.348 03
50	1.333 34	1.333 35	1.333 39	1.333 47	1.333 61	1.334 04	1.334 75	1.336 14	1.340 15	1.346 31
60	1.331 51	1.331 52	1.331 56	1.331 64	1.331 78	1.332 21	1.332 92	1.334 32	1.338 33	1.344 48
70	1.329 48	1.329 50	1.329 54	1.329 61	1.329 76	1.330 19	1.330 91	1.332 32	1.336 35	1.342 53
80	1.327 28	1.327 29	1.327 34	1.327 41	1.327 56	1.328 00	1.328 73	1.330 16	1.334 24	1.340 47
90	1.324 91	1.324 92	1.324 97	1.325 05	1.325 20	1.325 65	1.326 39	1.327 85	1.332 00	1.338 31
100	1.000 190	1.322 40	1.322 44	1.322 52	1.322 68	1.323 14	1.323 90	1.325 39	1.329 63	1.336 05
120	1.000 179	1.316 89	1.316 94	1.317 02	1.317 19	1.317 68	1.318 49	1.320 08	1.324 55	1.331 26
140	1.000 170	1.000 343	1.310 85	1.310 94	1.311 12	1.311 66	1.312 53	1.314 24	1.319 03	1.326 12
160	1.000 161	1.000 326	1.000 835	1.304 27	1.304 47	1.305 06	1.306 02	1.307 89	1.313 08	1.320 65
180	1.000 154	1.000 310	1.000 791	1.001 647	1.297 20	1.297 86	1.298 94	1.301 01	1.306 70	1.314 86
200	1.000 147	1.000 296	1.000 752	1.001 552	1.289 24	1.290 00	1.291 23	1.293 57	1.299 89	1.308 77
220	1.000 141	1.000 283	1.000 717	1.001 472	1.003 127	1.281 37	1.282 80	1.285 49	1.292 62	1.302 36
240	1.000 135	1.000 271	1.000 686	1.001 402	1.002 941	1.271 81	1.273 51	1.276 68	1.284 84	1.295 63
260	1.000 130	1.000 261	1.000 658	1.001 339	1.002 786	1.261 04	1.263 15	1.266 99	1.276 51	1.288 57
280	1.000 125	1.000 251	1.000 632	1.001 283	1.002 651	1.007 541	1.251 32	1.256 17	1.267 54	1.281 17
300	1.000 120	1.000 241	1.000 608	1.001 232	1.002 533	1.007 020	1.237 30	1.243 83	1.257 82	1.273 41
320	1.000 116	1.000 233	1.000 586	1.001 185	1.002 427	1.006 605	1.016 546	1.229 19	1.247 22	1.265 26
340	1.000 112	1.000 225	1.000 565	1.001 142	1.002 331	1.006 259	1.014 813	1.210 47	1.235 50	1.256 70
360	1.000 108	1.000 217	1.000 546	1.001 102	1.002 244	1.005 961	1.013 625	1.180 22	1.222 37	1.247 70
380	1.000 105	1.000 210	1.000 528	1.001 065	1.002 163	1.005 700	1.012 718	1.038 70	1.207 35	1.238 23
400	1.000 102	1.000 204	1.000 512	1.001 030	1.002 089	1.005 468	1.011 986	1.032 03	1.189 74	1.228 28
420	1.000 099	1.000 198	1.000 496	1.000 998	1.002 020	1.005 258	1.011 371	1.028 39	1.168 57	1.217 83
440	1.000 096	1.000 192	1.000 481	1.000 967	1.001 956	1.005 067	1.010 842	1.025 91	1.143 70	1.206 90
460	1.000 093	1.000 186	1.000 467	1.000 939	1.001 896	1.004 892	1.010 377	1.024 05	1.117 94	1.195 54
480	1.000 090	1.000 181	1.000 454	1.000 912	1.001 840	1.004 731	1.009 963	1.022 57	1.097 06	1.183 85
500	1.000 088	1.000 176	1.000 441	1.000 886	1.001 787	1.004 581	1.009 591	1.021 35	1.082 45	1.172 04

[a]Values in italics indicate points where the thermodynamic equilibrium state would be a solid; the computed values are for the metastable liquid.

TABLE 5. Refractive index for water for wavelength 0.5145 μm

	p/MPa									
T/°C	0.1	0.2	0.5	1	2	5	10	20	50	100
−10	*1.336 79*[a]	*1.336 81*	*1.336 86*	*1.336 95*	*1.337 14*	*1.337 68*	*1.338 59*	*1.340 35*	*1.345 36*	*1.352 85*
0	*1.337 12*	1.337 14	1.337 19	1.337 27	1.337 44	1.337 94	1.338 77	1.340 38	1.345 01	1.352 04
10	1.336 85	1.336 86	1.336 91	1.336 99	1.337 15	1.337 61	1.338 39	1.339 91	1.344 28	1.350 97
20	1.336 12	1.336 14	1.336 18	1.336 26	1.336 41	1.336 86	1.337 60	1.339 06	1.343 26	1.349 71
30	1.335 05	1.335 07	1.335 11	1.335 18	1.335 33	1.335 77	1.336 49	1.337 91	1.342 00	1.348 28
40	1.333 69	1.333 71	1.333 75	1.333 82	1.333 97	1.334 40	1.335 11	1.336 50	1.340 52	1.346 71
50	1.332 09	1.332 10	1.332 14	1.332 22	1.332 36	1.332 79	1.333 49	1.334 88	1.338 87	1.345 00
60	1.330 27	1.330 28	1.330 32	1.330 39	1.330 54	1.330 97	1.331 68	1.333 07	1.337 06	1.343 18
70	1.328 25	1.328 27	1.328 31	1.328 38	1.328 53	1.328 96	1.329 67	1.331 08	1.335 09	1.341 24
80	1.326 06	1.326 07	1.326 12	1.326 19	1.326 34	1.326 78	1.327 50	1.328 92	1.332 99	1.339 19
90	1.323 70	1.323 71	1.323 76	1.323 84	1.323 99	1.324 43	1.325 17	1.326 62	1.330 76	1.337 04
100	1.000 189	1.321 20	1.321 25	1.321 32	1.321 48	1.321 94	1.322 70	1.324 18	1.328 40	1.334 79
120	1.000 179	1.315 72	1.315 77	1.315 85	1.316 02	1.316 51	1.317 31	1.318 89	1.323 34	1.330 02
140	1.000 169	1.000 342	1.309 71	1.309 80	1.309 98	1.310 51	1.311 38	1.313 08	1.317 85	1.324 90
160	1.000 161	1.000 324	1.000 833	1.303 16	1.303 36	1.303 94	1.304 90	1.306 76	1.311 93	1.319 46
180	1.000 153	1.000 309	1.000 788	1.001 641	1.296 12	1.296 78	1.297 85	1.299 92	1.305 58	1.313 70
200	1.000 147	1.000 295	1.000 750	1.001 547	1.288 20	1.288 95	1.290 17	1.292 50	1.298 80	1.307 63
220	1.000 140	1.000 282	1.000 715	1.001 467	1.003 117	1.280 36	1.281 78	1.284 46	1.291 56	1.301 26
240	1.000 135	1.000 270	1.000 684	1.001 397	1.002 931	1.270 84	1.272 53	1.275 69	1.283 82	1.294 56
260	1.000 129	1.000 260	1.000 656	1.001 335	1.002 776	1.260 12	1.262 21	1.266 04	1.275 52	1.287 53
280	1.000 125	1.000 250	1.000 630	1.001 279	1.002 643	1.007 516	1.250 44	1.255 27	1.266 59	1.280 16
300	1.000 120	1.000 241	1.000 606	1.001 228	1.002 525	1.006 997	1.236 47	1.242 97	1.256 91	1.272 43
320	1.000 116	1.000 232	1.000 584	1.001 181	1.002 419	1.006 584	1.016 493	1.228 39	1.246 35	1.264 32
340	1.000 112	1.000 224	1.000 563	1.001 138	1.002 324	1.006 239	1.014 765	1.209 75	1.234 68	1.255 79
360	1.000 108	1.000 217	1.000 544	1.001 098	1.002 236	1.005 942	1.013 580	1.179 61	1.221 60	1.246 83
380	1.000 105	1.000 210	1.000 527	1.001 061	1.002 156	1.005 682	1.012 677	1.038 57	1.206 64	1.237 40
400	1.000 101	1.000 203	1.000 510	1.001 027	1.002 082	1.005 450	1.011 947	1.031 92	1.189 09	1.227 49
420	1.000 098	1.000 197	1.000 494	1.000 994	1.002 014	1.005 241	1.011 334	1.028 30	1.168 00	1.217 08
440	1.000 095	1.000 191	1.000 479	1.000 964	1.001 950	1.005 051	1.010 807	1.025 83	1.143 22	1.206 19
460	1.000 093	1.000 186	1.000 466	1.000 936	1.001 890	1.004 876	1.010 344	1.023 98	1.117 55	1.194 87
480	1.000 090	1.000 180	1.000 452	1.000 909	1.001 834	1.004 716	1.009 931	1.022 50	1.096 74	1.183 23
500	1.000 088	1.000 176	1.000 440	1.000 883	1.001 781	1.004 567	1.009 560	1.021 28	1.082 18	1.171 46

[a]Values in italics indicate points where the thermodynamic equilibrium state would be a solid; the computed values are for the metastable liquid.

TABLE 6. Refractive index for water for wavelength 0.589 26 μm

T/°C	p/MPa 0.1	0.2	0.5	1	2	5	10	20	50	100
−10	*1.334 00*[a]	*1.334 02*	*1.334 07*	*1.334 17*	*1.334 35*	*1.334 89*	*1.335 78*	*1.337 53*	*1.342 48*	*1.349 90*
0	*1.334 34*	1.334 35	1.334 40	1.334 49	1.334 65	1.335 15	1.335 96	1.337 56	1.342 14	1.349 09
10	1.334 06	1.334 08	1.334 13	1.334 20	1.334 36	1.334 82	1.335 59	1.337 10	1.341 42	1.348 04
20	1.333 35	1.333 37	1.333 41	1.333 48	1.333 63	1.334 08	1.334 81	1.336 26	1.340 41	1.346 79
30	1.332 29	1.332 31	1.332 35	1.332 42	1.332 57	1.333 00	1.333 71	1.335 12	1.339 16	1.345 38
40	1.330 95	1.330 96	1.331 00	1.331 08	1.331 22	1.331 64	1.332 35	1.333 73	1.337 71	1.343 83
50	1.329 36	1.329 37	1.329 42	1.329 49	1.329 63	1.330 05	1.330 75	1.332 13	1.336 08	1.342 15
60	1.327 56	1.327 57	1.327 62	1.327 69	1.327 83	1.328 26	1.328 96	1.330 33	1.334 28	1.340 34
70	1.325 57	1.325 58	1.325 63	1.325 70	1.325 84	1.326 27	1.326 98	1.328 37	1.332 34	1.338 42
80	1.323 40	1.323 42	1.323 46	1.323 53	1.323 68	1.324 11	1.324 83	1.326 24	1.330 26	1.336 40
90	1.321 07	1.321 08	1.321 13	1.321 20	1.321 35	1.321 80	1.322 53	1.323 96	1.328 05	1.334 27
100	1.000 188	1.318 59	1.318 64	1.318 72	1.318 87	1.319 33	1.320 08	1.321 55	1.325 72	1.332 05
120	1.000 177	1.313 17	1.313 22	1.313 30	1.313 47	1.313 95	1.314 75	1.316 31	1.320 72	1.327 33
140	1.000 168	1.000 339	1.307 22	1.307 31	1.307 49	1.308 02	1.308 88	1.310 57	1.315 28	1.322 27
160	1.000 160	1.000 322	1.000 827	1.300 74	1.300 94	1.301 52	1.302 47	1.304 31	1.309 42	1.316 89
180	1.000 152	1.000 307	1.000 783	1.001 629	1.293 77	1.294 42	1.295 49	1.297 53	1.303 14	1.311 19
200	1.000 146	1.000 293	1.000 744	1.001 536	1.285 93	1.286 68	1.287 88	1.290 20	1.296 43	1.305 18
220	1.000 139	1.000 280	1.000 710	1.001 457	1.003 095	1.278 17	1.279 57	1.282 23	1.289 26	1.298 87
240	1.000 134	1.000 268	1.000 679	1.001 387	1.002 911	1.268 74	1.270 42	1.273 55	1.281 60	1.292 24
260	1.000 128	1.000 258	1.000 651	1.001 325	1.002 757	1.258 12	1.260 19	1.263 99	1.273 38	1.285 28
280	1.000 124	1.000 248	1.000 625	1.001 270	1.002 624	1.007 463	1.248 53	1.253 31	1.264 53	1.277 99
300	1.000 119	1.000 239	1.000 602	1.001 219	1.002 507	1.006 948	1.234 68	1.241 13	1.254 95	1.270 33
320	1.000 115	1.000 230	1.000 580	1.001 173	1.002 402	1.006 537	1.016 376	1.226 68	1.244 48	1.262 29
340	1.000 111	1.000 222	1.000 559	1.001 130	1.002 307	1.006 195	1.014 661	1.208 19	1.232 91	1.253 84
360	1.000 107	1.000 215	1.000 541	1.001 090	1.002 221	1.005 900	1.013 485	1.178 30	1.219 95	1.244 96
380	1.000 104	1.000 208	1.000 523	1.001 054	1.002 141	1.005 642	1.012 588	1.038 30	1.205 11	1.235 62
400	1.000 101	1.000 202	1.000 506	1.001 019	1.002 068	1.005 412	1.011 863	1.031 70	1.187 71	1.225 79
420	1.000 098	1.000 196	1.000 491	1.000 987	1.002 000	1.005 204	1.011 255	1.028 10	1.166 78	1.215 48
440	1.000 095	1.000 190	1.000 476	1.000 957	1.001 936	1.005 016	1.010 731	1.025 65	1.142 19	1.204 68
460	1.000 092	1.000 184	1.000 462	1.000 929	1.001 877	1.004 843	1.010 272	1.023 81	1.116 72	1.193 45
480	1.000 090	1.000 179	1.000 449	1.000 902	1.001 821	1.004 683	1.009 862	1.022 34	1.096 06	1.181 90
500	1.000 087	1.000 174	1.000 437	1.000 877	1.001 769	1.004 535	1.009 494	1.021 13	1.081 60	1.170 23

[a]Values in italics indicate points where the thermodynamic equilibrium state would be a solid; the computed values are for the metastable liquid.

TABLE 7. Refractive index for water for wavelength 0.6328 μm

	p/MPa									
T/°C	0.1	0.2	0.5	1	2	5	10	20	50	100
−10	*1.332 75*[a]	*1.332 77*	*1.332 82*	*1.332 91*	*1.333 09*	*1.333 63*	*1.334 52*	*1.336 26*	*1.341 19*	*1.348 57*
0	*1.333 08*	1.333 10	1.333 15	1.333 23	1.333 40	1.333 89	1.334 70	1.336 30	1.340 86	1.347 77
10	1.332 82	1.332 83	1.332 88	1.332 95	1.333 11	1.333 57	1.334 33	1.335 84	1.340 14	1.346 72
20	1.332 11	1.332 12	1.332 17	1.332 24	1.332 39	1.332 83	1.333 56	1.335 00	1.339 14	1.345 49
30	1.331 05	1.331 07	1.331 11	1.331 18	1.331 33	1.331 76	1.332 47	1.333 87	1.337 90	1.344 08
40	1.329 72	1.329 73	1.329 78	1.329 85	1.329 99	1.330 41	1.331 11	1.332 49	1.336 45	1.342 54
50	1.328 14	1.328 16	1.328 20	1.328 27	1.328 41	1.328 83	1.329 53	1.330 90	1.334 83	1.340 87
60	1.326 35	1.326 37	1.326 41	1.326 48	1.326 62	1.327 04	1.327 74	1.329 11	1.333 04	1.339 07
70	1.324 37	1.324 38	1.324 43	1.324 50	1.324 64	1.325 07	1.325 77	1.327 15	1.331 11	1.337 16
80	1.322 21	1.322 23	1.322 27	1.322 34	1.322 49	1.322 92	1.323 64	1.325 04	1.329 04	1.335 15
90	1.319 89	1.319 91	1.319 95	1.320 03	1.320 17	1.320 62	1.321 35	1.322 77	1.326 85	1.333 04
100	1.000 187	1.317 43	1.317 48	1.317 55	1.317 71	1.318 16	1.318 91	1.320 37	1.324 53	1.330 83
120	1.000 177	1.312 04	1.312 09	1.312 17	1.312 33	1.312 81	1.313 61	1.315 16	1.319 55	1.326 13
140	1.000 167	1.000 338	1.306 12	1.306 21	1.306 38	1.306 91	1.307 77	1.309 45	1.314 14	1.321 10
160	1.000 159	1.000 321	1.000 824	1.299 67	1.299 86	1.300 44	1.301 39	1.303 22	1.308 31	1.315 74
180	1.000 152	1.000 306	1.000 780	1.001 624	1.292 73	1.293 38	1.294 44	1.296 48	1.302 06	1.310 07
200	1.000 145	1.000 292	1.000 742	1.001 531	1.284 93	1.285 67	1.286 87	1.289 17	1.295 38	1.304 10
220	1.000 139	1.000 279	1.000 708	1.001 452	1.003 085	1.277 20	1.278 60	1.281 25	1.288 25	1.297 81
240	1.000 133	1.000 268	1.000 677	1.001 383	1.002 901	1.267 81	1.269 48	1.272 60	1.280 62	1.291 22
260	1.000 128	1.000 257	1.000 649	1.001 321	1.002 748	1.257 23	1.259 30	1.263 08	1.272 44	1.284 29
280	1.000 123	1.000 247	1.000 623	1.001 266	1.002 616	1.007 439	1.247 68	1.252 45	1.263 63	1.277 03
300	1.000 119	1.000 238	1.000 600	1.001 215	1.002 499	1.006 926	1.233 90	1.240 32	1.254 08	1.269 40
320	1.000 115	1.000 230	1.000 578	1.001 169	1.002 395	1.006 517	1.016 325	1.225 92	1.243 66	1.261 40
340	1.000 111	1.000 222	1.000 558	1.001 126	1.002 300	1.006 175	1.014 615	1.207 50	1.232 14	1.252 99
360	1.000 107	1.000 214	1.000 539	1.001 087	1.002 214	1.005 882	1.013 443	1.177 72	1.219 22	1.244 14
380	1.000 104	1.000 208	1.000 521	1.001 050	1.002 135	1.005 625	1.012 549	1.038 18	1.204 45	1.234 84
400	1.000 100	1.000 201	1.000 505	1.001 016	1.002 061	1.005 395	1.011 827	1.031 60	1.187 10	1.225 05
420	1.000 097	1.000 195	1.000 489	1.000 984	1.001 994	1.005 188	1.011 221	1.028 01	1.166 25	1.214 77
440	1.000 095	1.000 189	1.000 475	1.000 954	1.001 930	1.005 000	1.010 698	1.025 57	1.141 74	1.204 02
460	1.000 092	1.000 184	1.000 461	1.000 926	1.001 871	1.004 828	1.010 240	1.023 74	1.116 36	1.192 83
480	1.000 089	1.000 179	1.000 448	1.000 900	1.001 816	1.004 669	1.009 832	1.022 28	1.095 77	1.181 33
500	1.000 087	1.000 174	1.000 436	1.000 875	1.001 763	1.004 521	1.009 465	1.021 07	1.081 35	1.169 69

[a]Values in italics indicate points where the thermodynamic equilibrium state would be a solid; the computed values are for the metastable liquid.

TABLE 8. Refractive index for water and steam at vapor-liquid saturation

T (°C)	p (MPa)	λ = 0.488 μm n^{liq}	λ = 0.488 μm n^{vap}	λ = 0.5145 μm n^{liq}	λ = 0.5145 μm n^{vap}	λ = 0.589 26 μm n^{liq}	λ = 0.589 26 μm n^{vap}	λ = 0.6328 μm n^{liq}	λ = 0.6328 μm n^{vap}
0.01	0.0006	1.338 38	1.000 002	1.337 11	1.000 002	1.334 32	1.000 002	1.333 07	1.000 002
5	0.0009	1.338 31	1.000 002	1.337 03	1.000 002	1.334 25	1.000 002	1.333 00	1.000 002
10	0.0012	1.338 10	1.000 003	1.336 83	1.000 003	1.334 05	1.000 003	1.332 80	1.000 003
15	0.0017	1.337 79	1.000 004	1.336 52	1.000 004	1.333 74	1.000 004	1.332 49	1.000 004
20	0.0023	1.337 38	1.000 006	1.336 11	1.000 006	1.333 34	1.000 006	1.332 09	1.000 006
25	0.0032	1.336 88	1.000 007	1.335 61	1.000 007	1.332 85	1.000 007	1.331 60	1.000 007
30	0.0042	1.336 30	1.000 010	1.335 04	1.000 010	1.332 28	1.000 010	1.331 04	1.000 010
35	0.0056	1.335 65	1.000 013	1.334 39	1.000 013	1.331 64	1.000 013	1.330 41	1.000 013
40	0.0074	1.334 94	1.000 017	1.333 68	1.000 016	1.330 93	1.000 016	1.329 71	1.000 016
45	0.0096	1.334 16	1.000 021	1.332 90	1.000 021	1.330 17	1.000 021	1.328 95	1.000 021
50	0.0124	1.333 32	1.000 027	1.332 07	1.000 027	1.329 35	1.000 027	1.328 13	1.000 026
55	0.0158	1.332 43	1.000 034	1.331 19	1.000 034	1.328 47	1.000 033	1.327 26	1.000 033
60	0.0199	1.331 49	1.000 042	1.330 25	1.000 042	1.327 55	1.000 042	1.326 34	1.000 041
65	0.0250	1.330 51	1.000 052	1.329 27	1.000 052	1.326 58	1.000 051	1.325 37	1.000 051
70	0.0312	1.329 47	1.000 064	1.328 24	1.000 064	1.325 56	1.000 063	1.324 36	1.000 063
75	0.0386	1.328 39	1.000 078	1.327 17	1.000 078	1.324 50	1.000 077	1.323 30	1.000 077
80	0.0474	1.327 27	1.000 095	1.326 05	1.000 094	1.323 39	1.000 094	1.322 21	1.000 093
85	0.0579	1.326 11	1.000 114	1.324 89	1.000 114	1.322 25	1.000 113	1.321 07	1.000 112
90	0.0702	1.324 90	1.000 136	1.323 70	1.000 136	1.321 06	1.000 135	1.319 89	1.000 135
95	0.0846	1.323 66	1.000 162	1.322 46	1.000 162	1.319 84	1.000 161	1.318 67	1.000 160
100	0.1014	1.322 38	1.000 192	1.321 18	1.000 192	1.318 58	1.000 190	1.317 42	1.000 190
110	0.1434	1.319 71	1.000 266	1.318 52	1.000 265	1.315 95	1.000 263	1.314 80	1.000 262
120	0.1987	1.316 89	1.000 360	1.315 72	1.000 359	1.313 17	1.000 357	1.312 04	1.000 355
130	0.2703	1.313 93	1.000 481	1.312 77	1.000 479	1.310 26	1.000 476	1.309 14	1.000 474
140	0.3615	1.310 83	1.000 631	1.309 68	1.000 629	1.307 20	1.000 624	1.306 09	1.000 622
150	0.4762	1.307 58	1.000 817	1.306 45	1.000 814	1.304 00	1.000 809	1.302 91	1.000 806
160	0.6182	1.304 20	1.001 045	1.303 08	1.001 041	1.300 67	1.001 034	1.299 59	1.001 030
170	0.7922	1.300 66	1.001 320	1.299 56	1.001 316	1.297 18	1.001 307	1.296 13	1.001 302
180	1.0028	1.296 98	1.001 652	1.295 90	1.001 646	1.293 55	1.001 634	1.292 51	1.001 629
190	1.2552	1.293 14	1.002 046	1.292 07	1.002 040	1.289 77	1.002 025	1.288 75	1.002 019
200	1.5549	1.289 13	1.002 514	1.288 08	1.002 506	1.285 82	1.002 488	1.284 81	1.002 480
210	1.9077	1.284 95	1.003 065	1.283 92	1.003 055	1.281 70	1.003 034	1.280 71	1.003 024
220	2.3196	1.280 58	1.003 712	1.279 57	1.003 700	1.277 39	1.003 674	1.276 42	1.003 662
230	2.7971	1.276 02	1.004 468	1.275 03	1.004 453	1.272 89	1.004 421	1.271 94	1.004 407
240	3.3469	1.271 23	1.005 349	1.270 26	1.005 331	1.268 16	1.005 293	1.267 24	1.005 277
250	3.9762	1.266 20	1.006 374	1.265 25	1.006 354	1.263 21	1.006 308	1.262 30	1.006 289
260	4.6923	1.260 91	1.007 568	1.259 98	1.007 543	1.257 98	1.007 490	1.257 10	1.007 466
270	5.5030	1.255 31	1.008 958	1.254 41	1.008 929	1.252 46	1.008 866	1.251 60	1.008 838
280	6.4166	1.249 38	1.010 58	1.248 50	1.010 55	1.246 60	1.010 47	1.245 77	1.010 44
290	7.4418	1.243 04	1.012 49	1.242 19	1.012 44	1.240 35	1.012 36	1.239 54	1.012 32
300	8.5879	1.236 24	1.014 73	1.235 42	1.014 68	1.233 64	1.014 58	1.232 86	1.014 53
310	9.8651	1.228 87	1.017 41	1.228 08	1.017 35	1.226 36	1.017 23	1.225 61	1.017 17
320	11.2843	1.220 80	1.020 63	1.220 03	1.020 57	1.218 38	1.020 42	1.217 66	1.020 36
330	12.8581	1.211 80	1.024 61	1.211 07	1.024 53	1.209 50	1.024 36	1.208 81	1.024 28
340	14.6007	1.201 54	1.029 65	1.200 85	1.029 55	1.199 36	1.029 35	1.198 71	1.029 25
350	16.5294	1.189 32	1.036 36	1.188 67	1.036 24	1.187 28	1.035 98	1.186 67	1.035 87
360	18.6660	1.173 36	1.046 15	1.172 78	1.045 99	1.171 52	1.045 67	1.170 97	1.045 53
370	21.0436	1.147 72	1.064 99	1.147 23	1.064 78	1.146 16	1.064 32	1.145 70	1.064 12