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

President:
Dr. Roberto Fernández-Prini
CNEA
Av. Libertador 8250
Buenos Aires-1429
Argentina

Executive Secretary:
Dr. R.B. Dooley
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California, 94304-1395, USA

This release replaces the corresponding release of 1991 and contains 7 numbered pages.

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the data have been converted to the ITS-90 Temperature Scale, and the equation of state in the previous release has been replaced by the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use [2].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	$\rho^* = 1000 \text{ kg} \cdot \text{m}^{-3}$
Reference wavelength	$\lambda^* = 0.589 \ \mu\text{m}$

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]

$$\frac{n^2-1}{n^2+2}\left(1/\bar{\rho}\right) = a_0 + a_1\bar{\rho} + a_2\bar{T} + a_3\bar{\lambda}^2\bar{T} + a_4/\bar{\lambda}^2 + \frac{a_5}{\bar{\lambda}^2-\bar{\lambda}_{\mathrm{UV}}^2} + \frac{a_6}{\bar{\lambda}^2-\bar{\lambda}_{\mathrm{IR}}^2} + a_7\bar{\rho}^2 \qquad (1)$$

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

Table 1. Coefficients of the formulation, Eq. (1)

$a_0 = 0.244\ 257\ 733$	$a_4 = 1.589\ 205\ 70 \cdot 10^{-3}$
$a_1 = 9.746\ 344\ 76 \cdot 10^{-3}$	$a_5 = 2.459\ 342\ 59 \cdot 10^{-3}$
$a_2 = -3.732\ 349\ 96 \cdot 10^{-3}$	$a_6 = 0.900\ 704\ 920$
$a_3 = 2.686\ 784\ 72 \cdot 10^{-4}$	$a_7 = -1.666\ 262\ 19 \cdot 10^{-2}$
$\bar{\lambda}_{\mathrm{UV}} = 0.229\ 202\ 0$	$\bar{\lambda}_{\mathrm{IR}} = 5.432\ 937$

3. Equation of State of Water and Steam

In the conversion of the input independent variable pressure to density, preceding the optimization of Eq. (1), the "IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use" [2] has been used. In employing Eq. (1), 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	$-12\ °\mathrm{C} \leq t \leq 500\ °\mathrm{C}$
Density	$0\ \mathrm{kg \cdot m^{-3}} \leq \rho \leq 1060\ \mathrm{kg \cdot m^{-3}}$
Wavelength	$0.2\ \mu\mathrm{m} \leq \lambda \leq 1.1\ \mu\mathrm{m}$

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 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	$< 6 \cdot 10^{-5}$
0.40 to 0.70	5 to 60	ambient	liquid	$1.5 \cdot 10^{-5}$
0.40 to 0.60	60 to 100	ambient	liquid	$< 3 \cdot 10^{-4}$
0.47 to 0.67	0 to 60	up to 150	liquid	$2 \cdot 10^{-4}$
0.63	100 to 225	0 to 2	vapor	$5 \cdot 10^{-6}$
0.70 to 1.1	ambient	ambient	liquid	$1 \cdot 10^{-3}$
0.21 to 0.40	0 to 100	ambient	liquid	$5 \cdot 10^{-4}$
In the following ranges there are no supporting data.				
0.40 to 0.70	0 to 374	0 to 0.1 P_{sat}	vapor	$5 \cdot 10^{-6}$
0.40 to 0.70	225 to 374	0.1 P_{sat} to P_{sat}	vapor	$1 \cdot 10^{-4}$
0.40 to 0.70	60 to 374	P_{sat} to 200	liquid	$1 \cdot 10^{-3}$
0.40 to 0.70	> 374	$< P(\rho_c/3)$	low dens.	$1 \cdot 10^{-5}$
0.40 to 0.70	> 374	$> P(\rho_c)$	high dens.	$2 \cdot 10^{-3}$

6. Values for Program Verification

Table 3 contains refractive index values calculated from the formulation, Eq. (1). If the densities are calculated from the 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.

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

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, Erratum, J. Phys. Chem. Ref. Data 19, 1617, (1990).

[4] IAPWS releases prepared up to 1994 have been published in Proc. 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, USA.

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