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A survey of the available experimental data and the existing equations for the refractive index of water is given. The dependence of the molar refraction on wavelength, temperature, and density is shown over an extended range. Based upon the electromagnetic theory of light an equation for the refractive index of water with wavelength, temperature, and density as independent variables is constructed. Its coefficients are directly deduced from all available experimental data by least-squares fit. The range of validity of wavelength is restricted by the theory for normal dispersion to 182 nm$\leqslant\lambda\leqslant$2770 nm. The range of temperature and density is given by the available experimental data. Interpolations between the single measured points are possible and the following range of validity can be recommended: for temperature $-10\,°\mathrm{C}\leqslant T\leqslant 500\,°\mathrm{C}$ and for density 0.0028 kg/m^3 $\leqslant\rho\leqslant$ 1045 kg/m^3. Good agreement exists between the new relation, the available experimental data, and several existing equations.

Key words: data collection; equation of state; molar refraction; refractive index; steam; water.

1. Introduction

The importance of optical measurement methods in various technologies is increasing. The advantage of these methods is that physical quantities can be measured without disturbing the system. The dependence of the refractive index of liquids on the influencing parameters is an old problem which has received much attention because experimental results vary significantly from the values inferred from the usual Lorentz–Lorenz formula. For this reason it is felt that the dependence of the refractive index of water on the influential parameters should be investigated further.

This work was initiated by Working Group III of the International Association for the Properties of Steam (IAPS), whose significant task is to formulate and standardize data on the thermophysical properties of water and steam for scientific and industrial use. The object of this work was to review the experimental data and existing equations and to formulate a representative equation for the refractive index of water and steam.

2. Available Data Sources

The refractive index of liquid water under atmospheric pressure has been measured repeatedly since the middle of the last century. All available data on the refractive index of water have been collected and presented to Working Group III of the IAPS at a meeting in Kyoto, Japan (1976).[54] This so-called "available input of data" is updated in the present work by adding all new measurements available (see Table 1).

This updated data collection includes about 3100 measured points by 55 different authors, where the new measurements by Scheffler[57] for pressures up to 700 bar and on the saturation line, as well as the measurements of Achtermann[1] for vapor, should be mentioned. As can be seen in Fig. 1 most of the measurements were made at atmospheric pressure. Very few measurements have been done at wavelengths beyond the wavelengths of visible light (see Table 1). Measurements for the refractive index of subcooled water are available from four different authors. The temperature scale employed in this work is the 1968 International Practical Temperature Scale.[71] All temperatures measured before 1968 are transformed to this scale. For those authors who have not measured densities, the "1967 IFC Formulation for Industrial Use" (IFC67)[72] and for pressures above 1000 bar the equation of state by Juza[32] were used to calculate the specific volume.

A precise indication of the quality of the experimental data is not possible, because the measurements had been taken at various wavelengths in various regions of the thermodynamic surface. Therefore the scatter Δn of the refractive index in the different experimental data may give an estimation of the quality. This scatter Δn at one grid point is for liquid water from 0.0001 up to 0.001 at atmospheric pressure, up to 0.01 in the region near the critical point, and in the high pressure region. For vapor the tolerance of the experimental data is about 0.000 05 connected with a diminishing accuracy for pressures lower than 2 bar.

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Table 1. Experimental data sources (compare Fig.1)

First Author	Year	Experimental Range			Density Measurement	Reference
		T (°C)	p (bar)	λ (nm)		
Achtermann	(1981)	100.0 - 225.0	0.0737 - 25.21	632.99	-	1
Baxter	(1911)	20.0 - 30.0	1.0133	589.32	-	3
Bender	(1899)	9.0 - 42.5	1.0133	410.1 - 653.3	-	4
Born	(1959)	15.0	1.0133	589.3	yes	6
Brühl	(1891)	19.9 - 27.0	1.0133	410.1 - 770.0	-	7
Centeno	(1941)	20.0	1.0133	182.0 - 18000	-	8
Cohen	(1965)	25.0	1.0133	436.0 - 546.0	-	9
Conroy	(1895)	0.0 - 9.0	1.0133	589.32	-	10
Dale	(1858)	0.0 - 80.0	1.0133	396.85 - 760.82	-	11
Damien	(1881)	-8.0 - 8.0	1.0133	317.0 - 656.3	-	12
Duclaux	(1921)	20.0	1.0133	182.9 - 568.0	-	15
Dufet	(1885)	16.52 - 21.06	1.0133	410.1 - 718.5	-	17
Flatow	(1903)	0.0 - 80.0	1.0133	214.45 - 589.31	-	19
Fouqué	(1867)	0.4 - 93.0	1.0133	434.0 - 656.3	-	21
Fraunhofer	(1817)	18.75	1.0133	396.8 - 686.7	-	22
Gifford	(1907)	15.0	1.0133	193.35 - 795.0	-	23
Gladstone	(1870)	20.0	1.0133	317.0 - 397.0	-	24
Gregg-Wilson	(1931)	-5.0 - 10.0	1.0133	589.32	-	25
Hale	(1973)	25.0	1.0133	200 - 200000	-	26
Hall	(1922)	16.0 - 98.4	1.0133	589.32	-	27
Ingersoll	(1922)	23.0	1.0133	600.0 - 1250.0	-	28
Int. Critical Tables	(1926)	-10.0 - 90.0	1.0133	182.9 - 81100	-	29
Jasse	(1934)	0.03 - 93.53	1.0133	436.0 - 579.0	-	31
Kanonnikoff	(1885)	20.0	1.0133	486.14 - 656.29	-	33
Ketteler	(1888)	20.9 - 94.2	1.0133	535.05 - 670.82	-	34
Landolt	(1862)	15.0 - 30.0	1.0133	433.9 - 653.3	-	36
Lorenz	(1875)	7.62 - 16.55	1.0133	486.1 - 671.26	-	37
Lorenz	(1880)	10.0 - 100.0	1.0133	589.37 - 671.26	-	38
Müttrich	(1864)	0.9 - 65.0	1.0133	258.7 - 589.32	-	40
Osborn	(1913)	2.59 - 37.5	1.0133	546.1	-	41
Pinkley	(1977)	1.0 - 50.0	1.0133	406.0 - 25000	-	42
Poindexter	(1934)	25.0	1.0133 - 1823.9	406.0 - 579.0	-	43
Pulfrich	(1888)	-10.0 - 10.0	1.0133	589.32	-	44
Quincke	(1883)	17.5 - 20.42	1.0133	430.7 - 656.2	-	45
Raman	(1939)	23.1	1.0133	589.3	-	46
Roberts	(1930)	20.0	1.0133	237.8 - 706.5	-	47
Röntgen	(1891)	19.4	0.9933	589.32	-	48
Rosen	(1947)	25.0	1.0133 - 1519.9	406.0 - 579.0	yes	49
Rouss	(1893)	22.9	1.0133	589.32	-	50
Rubens	(1892)	12.0	1.0133	434.0 - 1250.0	-	51
Rubens	(1909)	18.0	1.0133	1000 - 18000	-	52
Rühlmann	(1867)	0.0 - 77.3	1.0133	535.05 - 670.82	-	53
Scheffler	(1981)	16.07 - 374.04	1.0133 - 698.0	546.1	-	57
Schütt	(1890)	18.0	1.0133	434.07 - 768.24	-	58
Simon	(1894)	21.7	1.0133	223.9 - 768.0	-	59
Tilton	(1938)	0.0 - 60.0	1.0133	404.66 - 706.52	-	61
Verschaffelt	(1894)	18.0 - 30.0	1.0133	589.32	-	62
Walter	(1892)	0.0 - 30.0	1.0133	589.32	-	63
Waxler	(1964)	1.56 - 54.34	1.0133 - 1127.7	467.82 - 667.92	yes	64
Wiedemann	(1876)	13.0 - 25.0	1.0133	535.05 - 670.82	-	65
Van der Willigen	(1864)	16.58 - 22.37	1.0133	396.8 - 759.3	-	66
Van der Willigen	(1869)	17.15 - 32.0	1.0133	396.8 - 759.3	-	67
Wüllner	(1868)	11.7 - 36.5	1.0133	434.07 - 656.29	-	68
Yadev	(1973)	25.0	180.0 - 8200.0	589.32	yes	69
Zeldovich	(1961)	185.0 - 875.0	39520 - 145900	589.32	yes	70

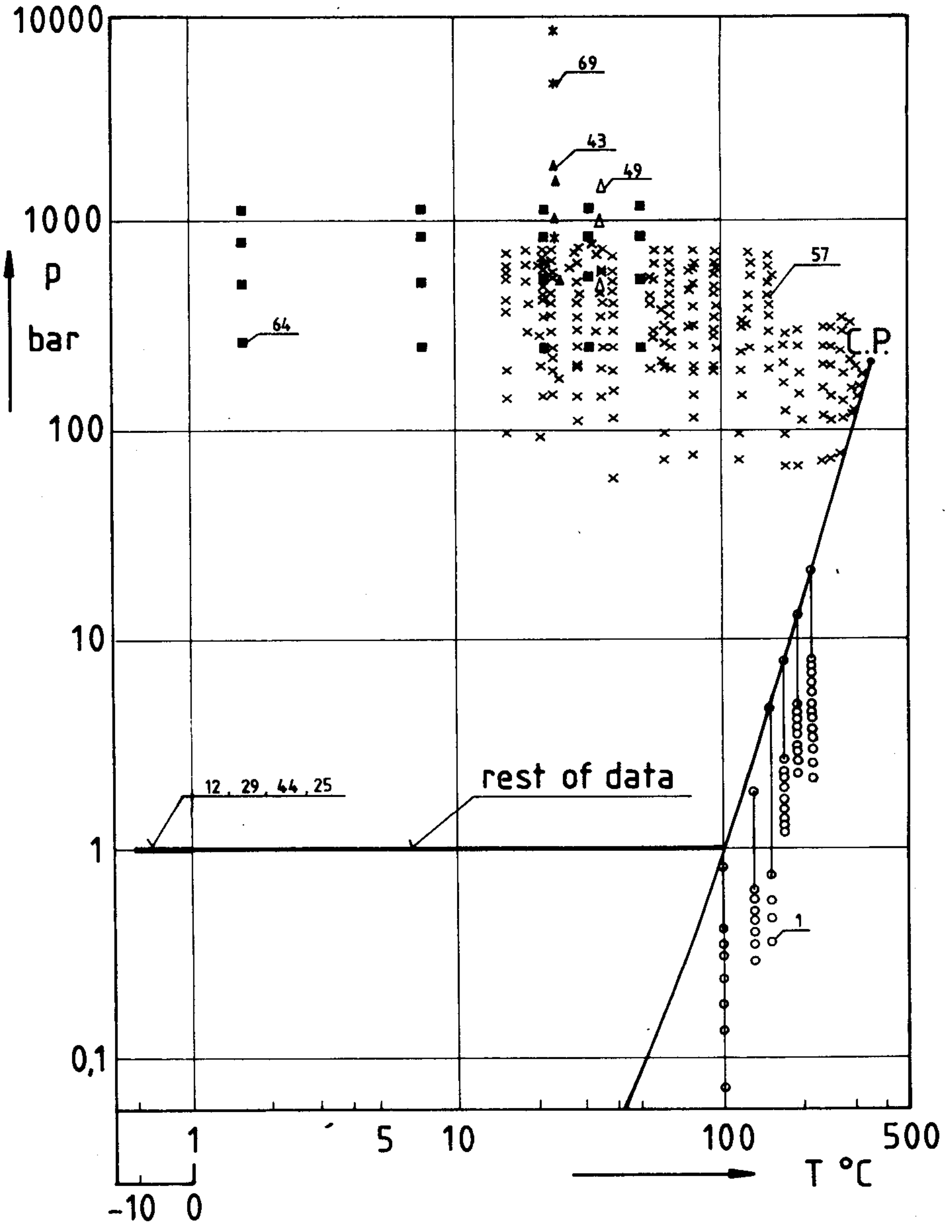

FIG. 1. Available experimental data of the refractive index of water in p-T space (authors are marked by their reference, C.P. means "critical point").

3. Existing Equations

The available input of data by Scheffler[54] was followed by a bibliography of several existing equations and a comparison of these equations between each other and with the experimental data.[55,56]

A survey of the existing equations is given in Table 2. Regarding this tabulation, it is significant that none of these formulations considers the influence of wavelength, temperature, density, or pressure on the refractive index of water at the same time. The share of each influencing quantity is shown in Figs. 2–4. In addition, the equations are restricted in range of temperature and only valid for the liquid phase. Therefore, it becomes obvious that a new formulation is necessary.

In 1979 the following equation for the refractive index of liquid water as a function of wavelength, temperature, and pressure was presented at the 9th International Conference

Table 2. Existing Equations for the Refractive Index of Water

First Author	Year	Type	Range of Validity			Reference
			λ(nm)	T (°C)	p (bar)	
Andreasson	(1971)	n(T)	632.8	16.0 - 24.0	1.0133	2
Bender	(1899)	n(T)	$\lambda_{1,2,3}$ = const	9.0 - 43.0	-	4
Beysens	(1977)	n(ρ)	638.0	23.0	1.0133	5
Dale	(1858)	n(ρ)	$\lambda_{1,2,3}$ = const	0.0 - 80.0	-	11
Dobbins	(1973)	n(T)	632.9	20.0 - 35.0	-	13
Dorsey	(1957)	n(λ)	182.9 - 589.3	20.0	-	14
Duclaux	(1924)	n(λ)	182.9 - 589.3	20.0	-	16
Dufet 1	(1885)	n(λ)	410.1 - 718.5	20.0	-	17
Dufet 2	(1885)	n(T)	589.3	0.0 - 50.0	-	17
Eisenberg	(1965)	n(ρ,T)	$\lambda_{1,2,3,4,5}$=const	0.0 - 60.0	-	18
Flatow 1	(1903)	n(λ)	214.5 - 589.3	$T_{1,2,3,4,5}$ = const	-	19
Flatow 2	(1923)	n(T)	589.3	0.0 - 80.0	-	20
Hale	(1973)	n(λ)	200 - 200000	25.0	1.0133	26
Hall	(1922)	n(T)	589.3	15.0 - 100.0	-	27
Jamin	(1856)	n(T)	589.3	0.0 - 30.0	-	30
Kettoler 1	(1888)	n(λ,T)	$\lambda_{1,2,3}$ = const	20.0 - 95.0	-	34
Ketteler 2	(1887)	n(ρ)	589.3	0.0 - 80.0	-	35
Lorenz	(1875)	n(ρ)	-	-	-	37
Lorenz	(1880)	n(T)	$\lambda_{1,2}$ = const	0.0 - 34.0	-	38
Martens	(1901)	n(λ)	224.0 - 1256.0	21.7	-	39
Müttrich	(1864)	n(T)	589.3	15.0 - 65.0	-	40
Osborn	(1913)	n(T)	564.1	1.0 -38.0	-	41
Poindexter	(1934)	n(p)	$\lambda_{1,2,3,4}$ = const	25.0	1.0133 - 1823.9	43
Pulfrich	(1888)	n(T)	589.3	-10.0 - 10.0	-	44
Rühlmann 1	(1867)	n(λ,T)	535.0 - 670.8	0.0 - 80.0	1.00658	53
Rühlmann 2	(1867)	n(T)	$\lambda_{1,2,3}$ = const	0.0 - 80.0	1.00658	53
Tilton	(1938)	n(λ,T)	404.66 - 706.52	0.0 - 60.0	1.0133	61
Walter	(1892)	n(T)	589.3	0.0 - 30.0	-	63
Wüllner	(1868)	n(T)	$\lambda_{1,2,3}$ = const	11.0 - 37.0	-	68
Yadev	(1973)	n(ρ)	-	-	less 10000	69
Zeldovich	(1961)	n(ρ,T)	-	185.0 - 875.0	39516.8 - 158590.8	70

on the Properties of Steam, 1979, held in Munich.[60]

$$\begin{aligned} n(\lambda,T,p) &= \sqrt{\frac{a_1}{\lambda^2-\lambda_a^2}+a_2+a_3\cdot\lambda^2+a_4\cdot\lambda^4+a_5\cdot\lambda^6} \\ &\quad+(b_1+b_2\cdot\lambda^2+b_3\cdot\lambda^4)\cdot(T-T_b) \\ &\quad+(b_4+b_5\cdot\lambda^2+b_6\cdot\lambda^4)\cdot(T-T_b)^2 \\ &\quad+(b_7+b_8\cdot\lambda^2+b_9\cdot\lambda^4)\cdot(T-T_b)^3 \\ &\quad+[c_1+c_2\cdot\lambda^2+(c_3+c_4\cdot\lambda^2)\cdot T]\cdot(p-p_b) \\ &\quad+(c_5+c_6\cdot\lambda^2)\cdot(p-p_b)^2, \end{aligned} \tag{1}$$

with the range of validity of

$$0.182\,\mu\text{m}\leqslant\lambda\leqslant2.770\,\mu\text{m},$$

$$-10\,^\circ\text{C}\leqslant T<100\,^\circ\text{C},$$

$$1\text{ bar}\leqslant p\leqslant1200\text{ bar}.$$

The numerical values of the coefficients in Eq. (1) determined with a least-squares method are listed in Table 3. As reference temperature $T_{b48}=20\,^\circ\text{C}$ was chosen, which according to the 1968 International Practical Temperature Scale corresponds to a temperature of $T_b = 19.993\,^\circ\text{C}$ and a reference pressure of $p_b = 1\text{ atm} = 1.013\,25$ bar, since most measurements were carried out under these conditions. Using Eq. (1), the wavelength λ, the temperature T, and the pressure p must be expressed in μm, °C, and bar, respectively.

Compared with the other equations, this equation for the refractive index of water, depending on wavelength, temperature, and pressure, has the advantage of being more exact with a wider range of validity. But in comparison with the new measurements by Achtermann[1] and Scheffler,[57] it must be remarked that this equation is applicable for liquid water only and the range of validity as a function of temperature cannot be enlarged.

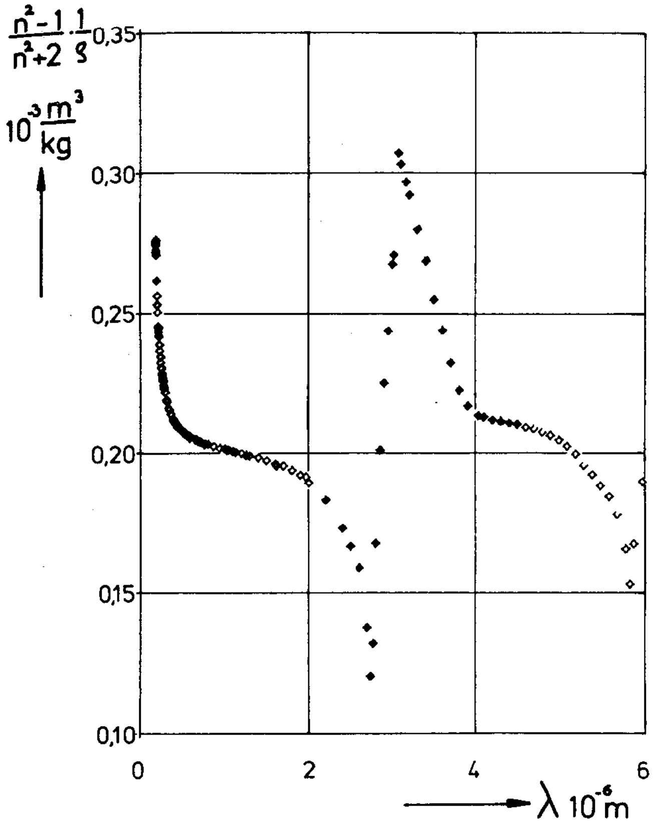

FIG. 2. Dependence of the molar refraction on the wavelength for $T = 20$ °C and $p = 1.013\ 25$ bar.

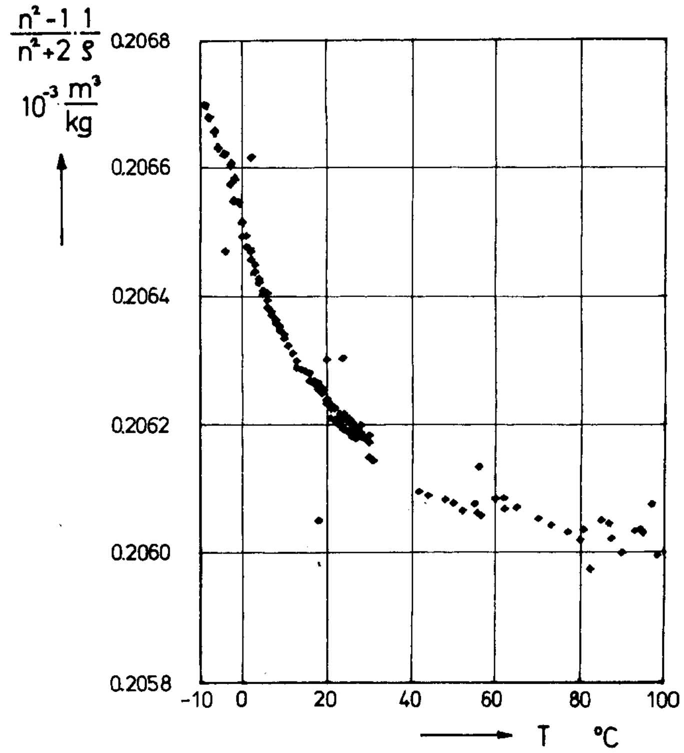

FIG. 3. Dependence of the molar refraction on the temperature for $\lambda = 589.32$ nm and $p = 1.013\ 25$ bar.

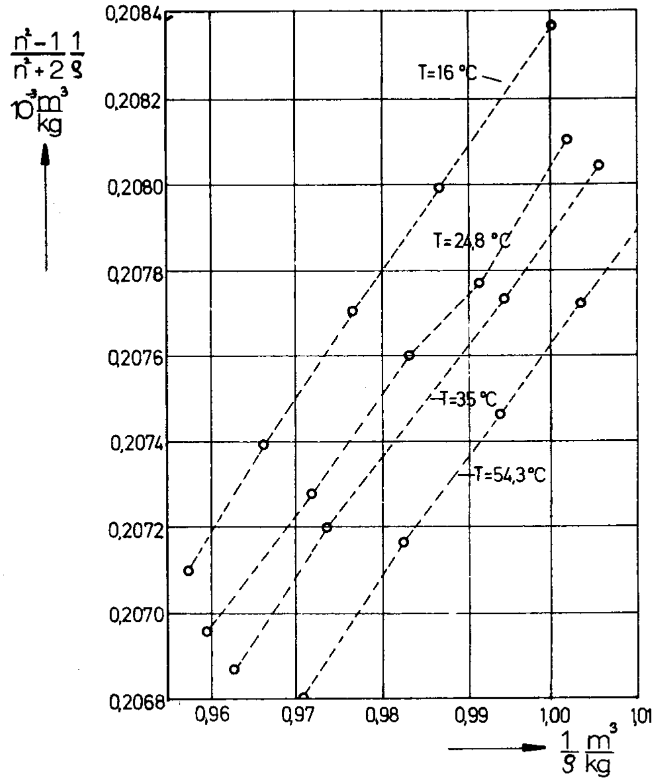

FIG. 4. Dependence of the molar refraction on the reciprocal density for $\lambda = 501.57$ nm.

TABLE 3. Numerical values of the coefficients of Eq. (1)

$\lambda_a^2 = 0.018\,085$	$b_1 = -8.454\,823\times 10^{-5}$	$c_1 = 8.419\,632\times 10^{-6}$
$a_1 = 5.743\,534\times 10^{-3}$	$b_2 = -2.787\,742\times 10^{-5}$	$c_2 = 1.941\,681\times 10^{-5}$
$a_2 = 1.769\,238$	$b_3 = 2.608\,176\times 10^{-6}$	$c_3 = -7.762\,524\times 10^{-8}$
$a_3 = -2.797\,222\times 10^{-2}$	$b_4 = -2.050\,671\times 10^{-6}$	$c_4 = 4.371\,257\times 10^{-8}$
$a_4 = 8.715\,348\times 10^{-3}$	$b_5 = 1.019\,989\times 10^{-6}$	$c_5 = 7.089\,664\times 10^{-9}$
$a_5 = -1.413\,942\times 10^{-3}$	$b_6 = -2.611\,919\times 10^{-6}$	$c_6 = -2.240\,384\times 10^{-8}$
	$b_7 = 8.194\,989\times 10^{-9}$	
	$b_8 = -8.107\,707\times 10^{-9}$	
	$b_9 = 4.877\,274\times 10^{-8}$	

4. New Formulation

For setting up the new equation we begin by examining the Lorentz–Lorenz formulation. This equation for the refractive index is based on the principle that for an infinitely long wavelength the right-hand side of the Eq. (2) is constant, called the molar refraction R_m:

$$\frac{n^2-1}{n^2+2}\cdot\frac{M_n}{\rho}=R_m. \tag{2}$$

Since in reality only finite wavelengths exist, the following restriction is valid here: this equation can only be used for substances where the refractive index shows little dependency on the wavelength. For the substance water the refractive index is a quantity which depends on the wavelength, as can be seen in Fig. 2.

The properties of light, the interactions of the waves penetrating the body, and the matter present were taken into account. Based on the electromagnetic theory of light the following relation is valid for the refractive index n (see Born[6]):

$$\frac{n^2-1}{n^2+2}\cdot\frac{M_n}{\rho}=\frac{1}{3\cdot\epsilon}\cdot\alpha\cdot N_A, \tag{3}$$

where M_n = molecular weight, ρ = density, ϵ = dielectric constant, α = polarizability, and N_A = number of molecules per mole (Avogadro constant). If one considers the dipole moment arising from the oscillation of the negative planetary electrons against the positive nucleus and neglecting the damping forces, Eq. (3) can be simplified after some transformations to

$$\frac{n^2-1}{n^2+2}\cdot\frac{M_n}{\rho}=\sum_i\frac{a_i\cdot\lambda^2}{\lambda^2-\lambda_i^2}, \tag{4}$$

where λ = wavelength and λ_i = wavelength at the eigenfrequency. This relation is valid only in the region of normal dispersion. The normal dispersion comprises those ranges in which the refractive index increases with increasing frequency; the anomalous dispersion comprises those ranges in which the refractive index decreases with increasing frequency (see Fig. 2).

Examining the data (see Figs. 3 and 4) it can be seen that the molar refraction R_m not only depends on the wavelength but also on temperature and density. The influence of the temperature and density has been taken into account by empirical terms.

By combining the theoretical term incorporating the wavelength with empirical terms for the influence of temperature and density, the following dimensionless equation for the refractive index of water is obtained:

$$\begin{aligned}\frac{n^2-1}{n^2+1}\cdot\frac{1}{\rho^*}&=\frac{a_1}{\lambda^{*2}-a_2}+a_3\\&\quad+(a_4+a_5\cdot\lambda^*+a_6\cdot\lambda^{*2}+a_7\cdot\lambda^{*3}+a_8\cdot\lambda^{*4})\\&\quad\cdot\lambda^{*2}+a_9\frac{1}{\rho^*}+(a_{10}+a_{11}\cdot\lambda^*+a_{12}\cdot\lambda^{*2})\\&\quad\cdot\lambda^{*2}\cdot T^*+(a_{13}+a_{14}\cdot\lambda^*)\cdot\lambda^*\cdot T^{*2}\end{aligned} \tag{5}$$

in a range of validity of

$$182\text{ nm}\leqslant\lambda\leqslant 2770\text{ nm},$$

where

$$\rho^*=\rho/\rho_0 \qquad \rho_0=1000\text{ kg/m}^3,$$
$$\lambda^*=\lambda/\lambda_{N_A} \qquad \lambda_{N_A}=589.0\text{ nm},$$
$$T^*=T/T_0 \qquad T_0=273.15\text{ K}.$$

The numerical values of the coefficients a_i in Eq. (5) are determined with a least-squares method and are listed in Table 4.

This equation has been proved wherever measurements are available (see Fig. 1). Since the dependence of this equation on the wavelength is well-founded on the theory of light, interpolations between the single measured points are physi-

TABLE 4. Numerical values of the coefficients and constants of Eq. (5)

$a_1 = 3.036\,167\times 10^{-3}$	$a_6 = -1.918\,429\times 10^{-2}$	$a_{11} = -4.008\,264\times 10^{-2}$
$a_2 = 0.052\,421$	$a_1 = 2.582\,351\times 10^{-3}$	$a_{12} = 8.339\,681\times 10^{-3}$
$a_3 = 2.117\,579\times 10^{-1}$	$a_8 = -2.352\,054\times 10^{-4}$	$a_{13} = -1.054\,741\times 10^{-2}$
$a_4 = -5.195\,756\times 10^{-2}$	$a_9 = 3.964\,628\times 10^{-5}$	$a_{14} = 9.491\,575\times 10^{-3}$
$a_5 = 5.922\,248\times 10^{-2}$	$a_{10} = 3.336\,153\times 10^{-2}$	

TABLE 5. Numerical values of the coefficients of Eq. (6) for $\lambda = 546.07$ nm.

$b_1 = 2.054\,998 \times 10^{-1}$	$b_3 = 2.895\,491 \times 10^{-3}$
$b_2 = 3.964\,628 \times 10^{-5}$	$b_4 = -1.620\,261 \times 10^{-3}$

cally possible and the following range of validity can be recommended:

$$-10\,^\circ\mathrm{C} \leqslant T \leqslant 500\,^\circ\mathrm{C},$$

$$0.0028\ \mathrm{kg/m^3} \leqslant \rho \leqslant 1045\ \mathrm{kg/m^3}.$$

For a constant wavelength the number of coefficients is reduced and Eq. (5) simplifies to

$$\frac{n^2-1}{n^2+1} \cdot \frac{1}{\rho^*} = b_1 + b_2 \cdot \frac{1}{\rho^*} + b_3 \cdot T^* + b_4 \cdot T^{*2}. \quad (6)$$

For instance the coefficients b_i for the wavelength $\lambda_{\mathrm{Hg}} = 546.07$ nm can be determined from Eq. (5) to the values as listed in Table 5.

For computing the refractive index n, Eqs. (5) or (6) can be placed in the following form, where R is the abbreviation for the right-hand side of Eqs. (5) or (6):

$$n = \sqrt{\frac{1 + 2 \cdot R \cdot \rho^*}{1 - R \cdot \rho^*}}\,. \quad (7)$$

In a p,T-diagram, curves of constant refractive index computed by Eq. (6) are shown for the wavelength $\lambda = 546.07$ nm in Fig. 5. Tables 6–8 contain values of the refractive index of water and steam at selected grid points of temperature and pressure for the following common wavelengths calculated with Eq. (5):

Table no.	Wavelength	Element
6	404.66 nm	Hg
7	589.32 nm	Na
8	706.52 nm	He

The effect of computing the density by another internationally accepted equation of state, such as the IFC67, was examined. The “1968 IFC Formulation for Scientific Use,”[73] the equation of state by Haar, Gallagher, and Kell (HGK),[74] and the equation of state by Pollak[75] were selected. The values obtained for the refractive index had been compared with those values from the IFC67 and the experimental data, with the conclusion that the deviation from computing the density with another internationally accepted equation of state is so small that it can be neglected.

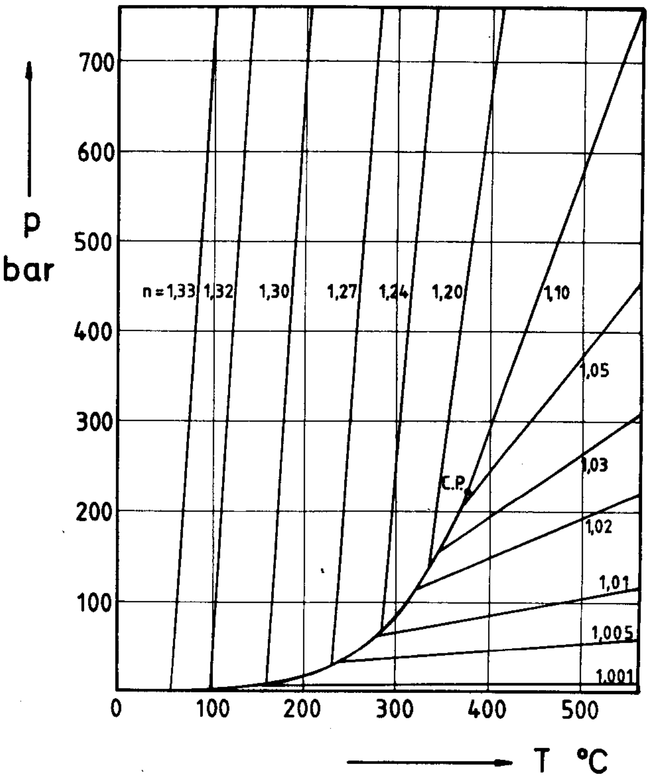

FIG. 5. Curves of constant refractive index for the wavelength $\lambda = 546.07$ nm.

The new relation for the refractive index, Eq. (5), is advantageous because it can be solved for the density explicitly. This makes it possible to calculate the density from a given refractive index, wavelength, and temperature:

$$\rho^* = \left[\frac{n^2-1}{n^2+1} - a_9\right] \Big/ \left[\frac{a_1}{\lambda^{*2} - a_2} + a_3 + (a_4 + a_5 \cdot \lambda^* + a_6 \cdot \lambda^{*2} + a_7 \cdot \lambda^{*3} + a_8 \cdot \lambda^{*4}) \cdot \lambda^{*2} + (a_{10} + a_{11} \cdot \lambda^* + a_{12} \cdot \lambda^{*2}) \cdot \lambda^{*2} \cdot T^* + (a_{13} + a_{14} \cdot \lambda^*) \cdot \lambda^* \cdot T^{*2}\right], \quad (8)$$

in the range of validity of

$$182\ \mathrm{nm} \leqslant \lambda \leqslant 2770\ \mathrm{nm},$$

$$-10\,^\circ\mathrm{C} \leqslant T \leqslant 500\,^\circ\mathrm{C},$$

$$1.000\,06 \leqslant n \leqslant 1.494,$$

and with the same values of the constants as listed in Table 4.

Table 6. Refractive index of water for λ = 404.66 nm (p in bar, T in °C)

T\P	0.1	0.5	1.0	2.0	3.0	5.0	10.0	20.0	30.0	50.0	100.0	200.0	300.0	500.0	1000.0
0	1.34358	1.34358	1.34359	1.34361	1.34363	1.34367	1.34376	1.34396	1.34415	1.34452	1.34547	1.34734	1.34918	1.35277	1.36106
10	1.34350	1.34350	1.34351	1.34353	1.34355	1.34359	1.34368	1.34385	1.34403	1.34439	1.34528	1.34703	1.34876	1.35213	1.36008
20	1.34286	1.34287	1.34287	1.34289	1.34291	1.34294	1.34303	1.34320	1.34337	1.34372	1.34457	1.34625	1.34790	1.35111	1.35874
30	1.34179	1.34180	1.34180	1.34182	1.34184	1.34187	1.34196	1.34212	1.34229	1.34263	1.34345	1.34509	1.34669	1.34981	1.35719
40	1.34037	1.34038	1.34039	1.34040	1.34042	1.34045	1.34054	1.34070	1.34087	1.34120	1.34201	1.34362	1.34520	1.34826	1.35549
50	1.00008	1.33866	1.33867	1.33868	1.33870	1.33873	1.33882	1.33898	1.33915	1.33940	1.34029	1.34189	1.34346	1.34650	1.35364
60	1.00008	1.33668	1.33669	1.33670	1.33672	1.33675	1.33684	1.33700	1.33717	1.33750	1.33832	1.33993	1.34150	1.34454	1.35166
70	1.00008	1.33446	1.33447	1.33449	1.33451	1.33454	1.33462	1.33479	1.33496	1.33530	1.33613	1.33775	1.33934	1.34240	1.34954
80	1.00008	1.33204	1.33204	1.33206	1.33208	1.33211	1.33220	1.33237	1.33254	1.33288	1.33373	1.33538	1.33698	1.34008	1.34729
90	1.00008	1.00015	1.32942	1.32944	1.32946	1.32949	1.32958	1.32976	1.32993	1.33028	1.33114	1.33282	1.33446	1.33761	1.34491
100	1.00008	1.00015	1.00025	1.32664	1.32665	1.32669	1.32678	1.32696	1.32714	1.32750	1.32838	1.33010	1.33178	1.33499	1.34241
120	1.00008	1.00015	1.00024	1.32052	1.32054	1.32057	1.32067	1.32086	1.32105	1.32143	1.32237	1.32420	1.32596	1.32933	1.33706
140	1.00008	1.00014	1.00023	1.00040	1.00057	1.31381	1.31392	1.31412	1.31433	1.31474	1.31575	1.31770	1.31958	1.32316	1.33128
160	1.00008	1.00014	1.00022	1.00038	1.00054	1.00088	1.30652	1.30675	1.30697	1.30742	1.30852	1.31064	1.31267	1.31650	1.32509
180	1.00007	1.00013	1.00021	1.00036	1.00052	1.00084	1.00168	1.29871	1.29896	1.29946	1.30067	1.30300	1.30521	1.30936	1.31852
200	1.00007	1.00013	1.00020	1.00035	1.00050	1.00080	1.00159	1.28996	1.29024	1.29080	1.29216	1.29475	1.29720	1.30173	1.31157
220	1.00007	1.00013	1.00020	1.00034	1.00048	1.00076	1.00151	1.00313	1.28069	1.28134	1.28290	1.28584	1.28859	1.29361	1.30426
240	1.00007	1.00013	1.00019	1.00033	1.00046	1.00073	1.00144	1.00295	1.00465	1.27092	1.27275	1.27618	1.27932	1.28496	1.29660
260	1.00007	1.00012	1.00019	1.00031	1.00044	1.00070	1.00137	1.00279	1.00435	1.25927	1.26151	1.26561	1.26929	1.27574	1.28860
280	1.00007	1.00012	1.00018	1.00030	1.00043	1.00068	1.00132	1.00266	1.00410	1.00745	1.24879	1.25391	1.25836	1.26589	1.28025
300	1.00007	1.00012	1.00018	1.00030	1.00041	1.00065	1.00126	1.00254	1.00389	1.00693	1.23386	1.24067	1.24627	1.25530	1.27156
320	1.00007	1.00012	1.00017	1.00029	1.00040	1.00063	1.00122	1.00243	1.00371	1.00651	1.01621	1.22514	1.23263	1.24383	1.26248
340	1.00007	1.00011	1.00017	1.00028	1.00039	1.00061	1.00117	1.00233	1.00355	1.00617	1.01450	1.20563	1.21675	1.23122	1.25290
360	1.00007	1.00011	1.00017	1.00027	1.00038	1.00059	1.00113	1.00225	1.00340	1.00587	1.01332	1.17497	1.19734	1.21727	1.24275
380	1.00007	1.00011	1.00016	1.00026	1.00037	1.00057	1.00110	1.00216	1.00327	1.00560	1.01242	1.03758	1.16989	1.20186	1.23259
400	1.00007	1.00011	1.00016	1.00026	1.00036	1.00056	1.00106	1.00209	1.00315	1.00537	1.01169	1.03104	1.11065	1.18413	1.22216
420	1.00007	1.00011	1.00016	1.00025	1.00035	1.00054	1.00103	1.00202	1.00303	1.00515	1.01107	1.02747	1.06284	1.16295	1.21137
440	1.00007	1.00011	1.00015	1.00024	1.00034	1.00052	1.00099	1.00195	1.00293	1.00496	1.01054	1.02505	1.04937	1.13791	1.20008
460	1.00007	1.00010	1.00015	1.00024	1.00033	1.00051	1.00096	1.00189	1.00283	1.00478	1.01007	1.02321	1.04257	1.11289	1.18831
480	1.00007	1.00010	1.00015	1.00023	1.00032	1.00050	1.00094	1.00183	1.00274	1.00461	1.00964	1.02174	1.03816	1.09300	1.17631
500	1.00007	1.00010	1.00014	1.00023	1.00031	1.00048	1.00091	1.00177	1.00265	1.00446	1.00926	1.02051	1.03494	1.07871	1.16437

Table 7. Refractive index of water for λ= 589.32 nm (p in bar, T in °C)

T\P	0.1	0.5	1.0	2.0	3.0	5.0	10.0	20.0	30.0	50.0	100.0	200.0	300.0	500.0	1000.0
0	1.33344	1.33345	1.33346	1.33347	1.33349	1.33353	1.33362	1.33381	1.33399	1.33436	1.33527	1.33707	1.33885	1.34232	1.35034
10	1.33339	1.33340	1.33341	1.33343	1.33344	1.33348	1.33357	1.33374	1.33391	1.33426	1.33512	1.33681	1.33848	1.34174	1.34943
20	1.33281	1.33282	1.33283	1.33285	1.33286	1.33290	1.33298	1.33315	1.33331	1.33364	1.33447	1.33609	1.33768	1.34079	1.34817
30	1.33183	1.33183	1.33184	1.33186	1.33187	1.33191	1.33199	1.33215	1.33231	1.33263	1.33344	1.33502	1.33656	1.33958	1.34672
40	1.33051	1.33051	1.33052	1.33054	1.33055	1.33059	1.33067	1.33083	1.33099	1.33131	1.33210	1.33365	1.33518	1.33814	1.34513
50	1.00008	1.32891	1.32892	1.32894	1.32895	1.32899	1.32907	1.32923	1.32939	1.32970	1.33049	1.33204	1.33356	1.33650	1.34341
60	1.00008	1.32707	1.32707	1.32709	1.32711	1.32714	1.32722	1.32738	1.32754	1.32786	1.32865	1.33021	1.33173	1.33467	1.34156
70	1.00008	1.32500	1.32500	1.32502	1.32504	1.32507	1.32515	1.32532	1.32548	1.32580	1.32661	1.32818	1.32971	1.33267	1.33959
80	1.00008	1.32273	1.32274	1.32275	1.32277	1.32280	1.32289	1.32305	1.32322	1.32355	1.32437	1.32596	1.32752	1.33052	1.33750
90	1.00008	1.00015	1.32029	1.32030	1.32032	1.32035	1.32044	1.32061	1.32078	1.32112	1.32195	1.32358	1.32517	1.32822	1.33529
100	1.00008	1.00015	1.00024	1.31768	1.31770	1.31773	1.31782	1.31800	1.31817	1.31852	1.31937	1.32104	1.32267	1.32578	1.33297
120	1.00008	1.00014	1.00023	1.31196	1.31198	1.31202	1.31211	1.31230	1.31248	1.31285	1.31376	1.31553	1.31724	1.32051	1.32801
140	1.00008	1.00014	1.00022	1.00039	1.00056	1.30569	1.30579	1.30599	1.30619	1.30659	1.30757	1.30947	1.31130	1.31477	1.32265
160	1.00007	1.00014	1.00021	1.00037	1.00053	1.00086	1.29887	1.29909	1.29931	1.29974	1.30081	1.30287	1.30484	1.30857	1.31692
180	1.00007	1.00013	1.00021	1.00036	1.00051	1.00082	1.00164	1.29155	1.29180	1.29228	1.29346	1.29572	1.29788	1.30191	1.31083
200	1.00007	1.00013	1.00020	1.00034	1.00049	1.00078	1.00155	1.28332	1.28360	1.28414	1.28547	1.28800	1.29038	1.29480	1.30439
220	1.00007	1.00013	1.00020	1.00033	1.00047	1.00075	1.00148	1.00307	1.27461	1.27523	1.27676	1.27963	1.28231	1.28721	1.29761
240	1.00007	1.00012	1.00019	1.00032	1.00045	1.00072	1.00141	1.00289	1.00457	1.26539	1.26719	1.27053	1.27360	1.27912	1.29050
260	1.00007	1.00012	1.00018	1.00031	1.00044	1.00069	1.00135	1.00274	1.00427	1.25433	1.25654	1.26055	1.26415	1.27046	1.28305
280	1.00007	1.00012	1.00018	1.00030	1.00042	1.00067	1.00130	1.00261	1.00404	1.00733	1.24442	1.24944	1.25380	1.26119	1.27527
300	1.00007	1.00012	1.00018	1.00029	1.00041	1.00065	1.00125	1.00250	1.00383	1.00683	1.23012	1.23682	1.24232	1.25119	1.26716
320	1.00007	1.00012	1.00017	1.00028	1.00040	1.00062	1.00120	1.00240	1.00366	1.00643	1.01599	1.22191	1.22928	1.24031	1.25866
340	1.00007	1.00011	1.00017	1.00028	1.00039	1.00060	1.00116	1.00231	1.00351	1.00609	1.01433	1.20303	1.21401	1.22828	1.24967
360	1.00007	1.00011	1.00016	1.00027	1.00037	1.00059	1.00112	1.00222	1.00337	1.00581	1.01318	1.17310	1.19520	1.21491	1.24008
380	1.00007	1.00011	1.00016	1.00026	1.00036	1.00057	1.00109	1.00215	1.00324	1.00556	1.01231	1.03726	1.16838	1.20005	1.23049
400	1.00007	1.00011	1.00016	1.00026	1.00035	1.00055	1.00105	1.00207	1.00313	1.00533	1.01161	1.03083	1.10990	1.18285	1.22060
420	1.00007	1.00011	1.00015	1.00025	1.00035	1.00054	1.00102	1.00201	1.00302	1.00513	1.01102	1.02734	1.06254	1.16216	1.21034
440	1.00007	1.00011	1.00015	1.00024	1.00034	1.00052	1.00099	1.00195	1.00292	1.00495	1.01051	1.02498	1.04925	1.13754	1.19954
460	1.00007	1.00010	1.00015	1.00024	1.00033	1.00051	1.00096	1.00189	1.00283	1.00478	1.01006	1.02320	1.04255	1.11285	1.18824
480	1.00007	1.00010	1.00015	1.00023	1.00032	1.00050	1.00094	1.00183	1.00275	1.00462	1.00966	1.02178	1.03823	1.09318	1.17667
500	1.00007	1.00010	1.00014	1.00023	1.00031	1.00048	1.00091	1.00178	1.00266	1.00448	1.00930	1.02060	1.03510	1.07905	1.16511

Table 8. Refractive index of water for λ = 706.52 nm (p in bar, T in °C)

T\P	0.1	0.5	1.0	2.0	3.0	5.0	10.0	20.0	30.0	50.0	100.0	200.0	300.0	500.0	1000.0
0	1.33084	1.33085	1.33086	1.33088	1.33090	1.33093	1.33102	1.33121	1.33139	1.33175	1.33266	1.33445	1.33621	1.33965	1.34760
10	1.33071	1.33072	1.33073	1.33074	1.33076	1.33080	1.33088	1.33105	1.33122	1.33157	1.33242	1.33410	1.33575	1.33898	1.34660
20	1.33006	1.33007	1.33007	1.33009	1.33011	1.33014	1.33022	1.33039	1.33055	1.33088	1.33170	1.33330	1.33488	1.33797	1.34527
30	1.32901	1.32902	1.32903	1.32904	1.32906	1.32909	1.32917	1.32933	1.32950	1.32982	1.33061	1.33217	1.33371	1.33669	1.34377
40	1.32765	1.32766	1.32766	1.32768	1.32770	1.32773	1.32781	1.32797	1.32813	1.32844	1.32923	1.33077	1.33228	1.33521	1.34213
50	1.00008	1.32602	1.32603	1.32605	1.32606	1.32610	1.32618	1.32633	1.32645	1.32681	1.32759	1.32912	1.33062	1.33353	1.34038
60	1.00008	1.32416	1.32417	1.32418	1.32420	1.32423	1.32431	1.32447	1.32463	1.32495	1.32573	1.32727	1.32878	1.33169	1.33851
70	1.00008	1.32208	1.32209	1.32211	1.32212	1.32216	1.32224	1.32240	1.32256	1.32288	1.32368	1.32523	1.32675	1.32968	1.33653
80	1.00008	1.31982	1.31983	1.31984	1.31986	1.31989	1.31998	1.32014	1.32030	1.32063	1.32144	1.32302	1.32456	1.32753	1.33444
90	1.00008	1.00015	1.31739	1.31741	1.31743	1.31746	1.31754	1.31771	1.31788	1.31821	1.31904	1.32066	1.32223	1.32524	1.33224
100	1.00008	1.00015	1.00024	1.31482	1.31483	1.31487	1.31495	1.31513	1.31530	1.31564	1.31649	1.31814	1.31975	1.32283	1.32995
120	1.00008	1.00014	1.00023	1.30918	1.30920	1.30924	1.30933	1.30951	1.30970	1.31006	1.31096	1.31271	1.31441	1.31765	1.32507
140	1.00008	1.00014	1.00022	1.00039	1.00056	1.30304	1.30314	1.30334	1.30353	1.30393	1.30490	1.30678	1.30859	1.31203	1.31983
160	1.00007	1.00014	1.00021	1.00037	1.00053	1.00086	1.29638	1.29659	1.29681	1.29724	1.29830	1.30034	1.30230	1.30599	1.31426
180	1.00007	1.00013	1.00021	1.00036	1.00051	1.00081	1.00163	1.28926	1.28950	1.28998	1.29114	1.29339	1.29553	1.29953	1.30836
200	1.00007	1.00013	1.00020	1.00034	1.00049	1.00078	1.00154	1.28126	1.28153	1.28207	1.28338	1.28589	1.28826	1.29264	1.30215
220	1.00007	1.00013	1.00019	1.00033	1.00047	1.00075	1.00147	1.00305	1.27279	1.27342	1.27493	1.27778	1.28044	1.28531	1.29563
240	1.00007	1.00012	1.00019	1.00032	1.00045	1.00072	1.00140	1.00288	1.00454	1.26385	1.26564	1.26896	1.27201	1.27749	1.28880
260	1.00007	1.00012	1.00018	1.00031	1.00044	1.00069	1.00134	1.00273	1.00426	1.25309	1.25528	1.25928	1.26286	1.26914	1.28166
280	1.00007	1.00012	1.00018	1.00030	1.00042	1.00067	1.00129	1.00260	1.00402	1.00730	1.24348	1.24848	1.25282	1.26018	1.27420
300	1.00007	1.00012	1.00018	1.00029	1.00041	1.00064	1.00124	1.00249	1.00383	1.00681	1.22949	1.23617	1.24166	1.25051	1.26642
320	1.00007	1.00012	1.00017	1.00028	1.00040	1.00062	1.00120	1.00240	1.00366	1.00642	1.01597	1.22158	1.22895	1.23995	1.25828
340	1.00007	1.00011	1.00017	1.00028	1.00039	1.00060	1.00116	1.00231	1.00351	1.00609	1.01433	1.20301	1.21399	1.22825	1.24964
360	1.00007	1.00011	1.00016	1.00027	1.00037	1.00059	1.00112	1.00223	1.00337	1.00581	1.01320	1.17333	1.19547	1.21520	1.24041
380	1.00007	1.00011	1.00016	1.00026	1.00037	1.00057	1.00109	1.00215	1.00325	1.00557	1.01235	1.03737	1.16887	1.20064	1.23117
400	1.00007	1.00011	1.00016	1.00026	1.00036	1.00056	1.00106	1.00208	1.00314	1.00536	1.01166	1.03097	1.11039	1.18369	1.22163
420	1.00007	1.00011	1.00016	1.00025	1.00035	1.00054	1.00103	1.00202	1.00304	1.00516	1.01109	1.02751	1.06293	1.16320	1.21170
440	1.00007	1.00011	1.00015	1.00025	1.00034	1.00053	1.00100	1.00196	1.00295	1.00499	1.01059	1.02518	1.04964	1.13867	1.20121
460	1.00007	1.00010	1.00015	1.00024	1.00033	1.00051	1.00097	1.00191	1.00286	1.00482	1.01016	1.02343	1.04298	1.11399	1.19020
480	1.00007	1.00010	1.00015	1.00024	1.00032	1.00050	1.00095	1.00185	1.00278	1.00468	1.00978	1.02204	1.03869	1.09432	1.17888
500	1.00007	1.00010	1.00015	1.00023	1.00032	1.00049	1.00093	1.00181	1.00270	1.00454	1.00943	1.02089	1.03560	1.08019	1.16755

5. Comparison of the New Equation with Experimental Data and Other Equations

The new equation was deduced directly from the experimental data. On account of the small number of measurements a selection for a first data set was not possible and unreasonable. For the adaption of the coefficients all data were examined and some experimental data[11,12,21,24,40,53] which obviously differ from the others were excluded. When the refractive index n of water is computed with this equation and compared with the measured data, good agreement is obtained in the definition range. The equation fits the data within their anticipated errors. For demonstration, the deviations of all data available for the refractive index from the calculated values are shown in Figs. 6–8. A possible uncertainty of the equation cannot be assigned because of the small number and the variation in wavelength, temperature, and pressure of the experimental data. The mean scatter of 0.001 is indicated in Figs. 6–8 by dashed lines.

Figure 6 shows that the new equation for the refractive index of water reflects the influence of the wavelength well. Most of the data deviate less than 0.1% from the computed values. A small number of measurements lie outside the range of the scatter of the measurements. Only for wavelengths greater than 2500 nm do the deviations rise significantly; however, very few measurements have been done at wavelengths beyond the wavelength of visible light. The increase of the deviation at a wavelength of 546.1 nm is reduc-

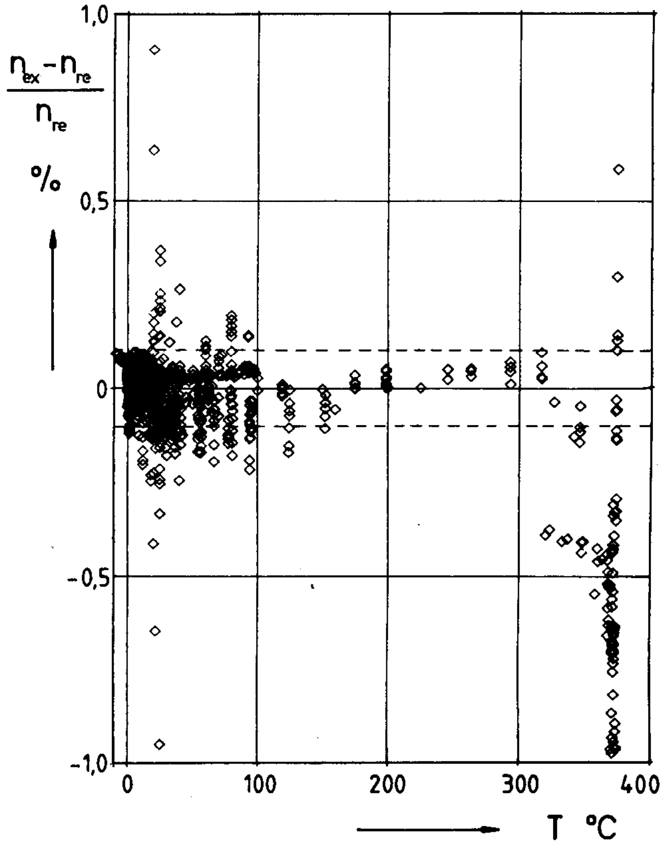

FIG. 7. Deviation of all data from Eq. (5) as a function of temperature.

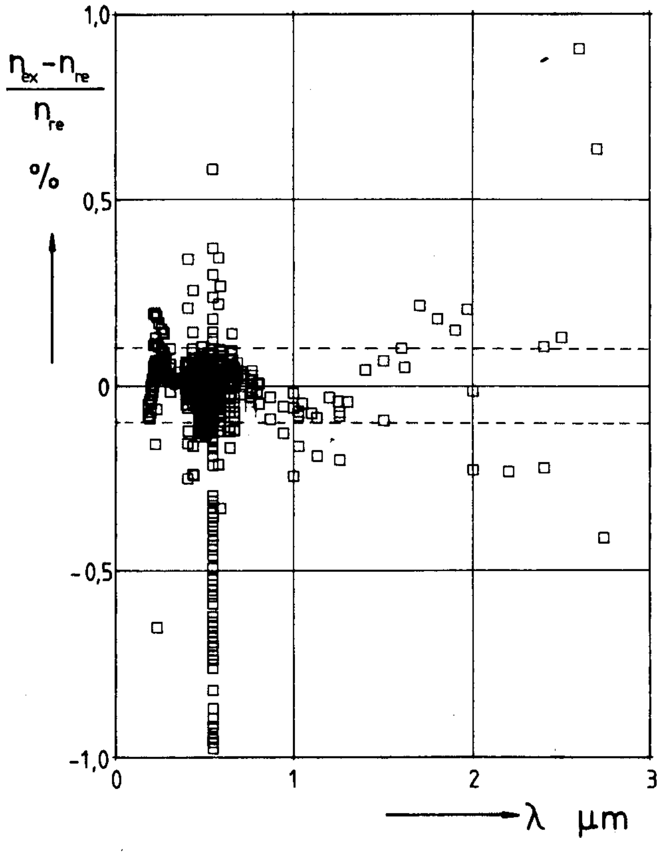

FIG. 6. Deviation of all data from Eq. (5) as a function of wavelength.

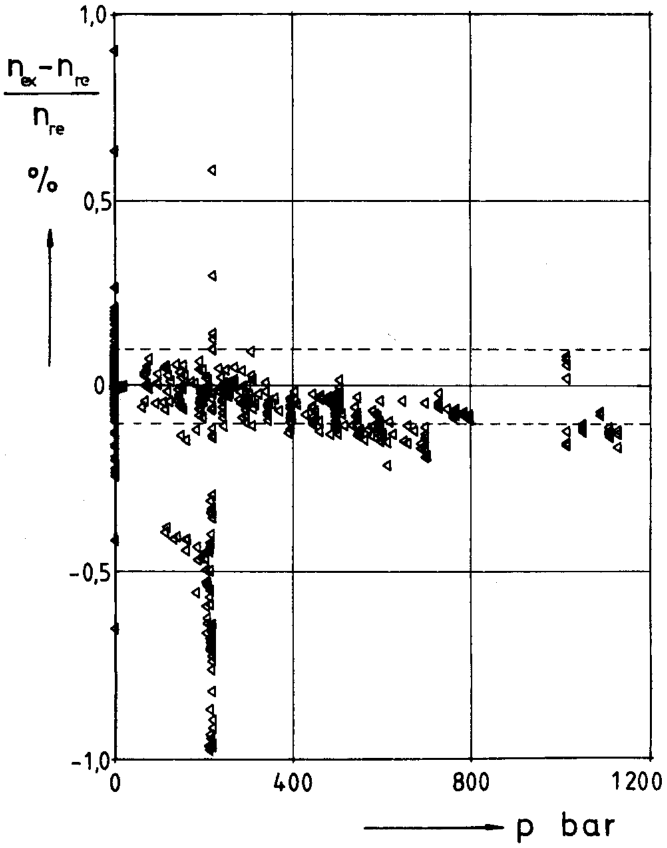

FIG. 8. Deviation of all data from Eq. (5) as a function of pressure.

TABLE 9. Standard deviation of the densities calculated by Eq. (8), IFC67, and equation of state by Haar, Gallagher, and Kell (HGK)

IFC67 ($p < 1000$ bar)	HGK	Eq. (8)
0.010	0.010	0.039

ible to measurements near the critical point (compare Table 1). The discrepancy near the temperature of 374.15 °C reflects the difficulty of measuring the refractive index of water near the critical point.

Considering Fig. 7, the equation coincides with the data of both liquid water and water vapor. The deviations at 20 °C correspond to the measurements done for greater wavelengths. These deviations at greater wavelengths as well as the deviation at the critical point are demonstrated in Fig. 8. This diagram shows that the new equation for the reflective index of water approximates well the whole pressure region.

As a result of the comparison of Eq. (5) with all available measurements, as made in Figs. 6–8, it can be concluded that good agreement in the definition range of the new equation is obtained. About 97% of all available experimental data deviate from the computed values by an amount less than the mean scatter of the measurements of 0.001. For liquid water at atmospheric pressure and wavelengths smaller than 1500 nm the scatter of the data from the new equation is less than 0.0004. For vapor the scatter between the experimental data and the computed values is smaller than the tolerance of the measurements.

A comparison of the new Eq. (5) with several existing equations has also been carried out. For this task, besides Eq. (1), the formula of Eisenberg[18] and the relation of Tilton and Taylor[61] are of special interest, since in the comparison of equations,[55,56] these equations turned out to be the ones which most accurately reflect the refractive index. In the range of validity of the Eisenberg equation all equations show the same standard deviation. In the area covered by the Tilton and Taylor equation the same improvement as with Eq. (1) is reached with the new Eq. (5). The formulations for the refractive index of water presented here are as good as the others in their range of validity. The improvement must be seen in the fact that both equations cover a wider range of validity. Compared with Eq. (1) the new Eq. (5) has a smaller number of constants and at the same time an enlarged range of validity, especially in the dependence on temperature. Moreover, the advantage is that the refractive index of liquid water, as well as of steam can be computed by the formulation presented here.

An uncertainty of the new equation should be mentioned. The temperatures have been surveyed only up to the critical point and measurements of wavelengths greater than those of visible light are available only at atmospheric pressure. The range of validity for the wavelength dependence is limited by the theory for normal dispersion, but there is no theoretical restriction for the validity of the temperature and density dependence of the new Eq. (5). As far as measurements are available the equation has been tested and good agreement is achieved. Extrapolations out of the recommended range of validity seem to be possible, because the measurements for the refractive index of water of Yadev[69] up to 8200 bar can be reproduced by this equation within an accuracy of 0.3% and the measurements of Zeldovich[70] up to 145 900 bar (not included in Fig. 1) within an accuracy of 3%.

A comparison of the densities calculated by Eq. (8) from measured wavelength, temperature, and refractive index with the experimental data and values of densities computed with the IFC67[72] and the equation of state by Haar, Gallagher, and Kell[74] from the measured temperature and pressure has been carried out. As can be seen in Table 1 density measurements were executed only by Born,[6] Rosen,[49] Waxler,[64] Yadev,[69] and Zeldovich.[70] The standard deviation of the densities computed by Eq. (8) is somewhat higher than those calculated by the equations of state as indicated in Table 9. Therefore the simple Eq. (8) can be recommended for computing the density whenever only measurements of temperature, wavelength, and refractive index are available.

6. Summary

For the refractive index of water a survey of the available experimental data sources is given followed by a summary of the existing equations. Since none of these formulations considered the influence of wavelength, temperature, density, or pressure on the refractive index at the same time, a new equation for the refractive index of water was established. Considering the electromagnetic theory of light an equation with variable wavelength, temperature, and density was adapted. The range of validity of wavelength is restricted by the theory for normal dispersion; the range of temperature and density is given by the available experimental data, where interpolations between the single measured points are physically possible. This new equation for the refractive index of water, whose coefficients have been directly deduced from the experimental data by least-squares fit, describes with great accuracy the dependence of the refractive index on the wavelength, temperature, and density for liquid water as well as for steam in the range of its validity. Good agreement with all available experimental data is obtained. The deviation from computing the density with another international accepted equation of state, such as the IFC67, is so small compared with the scatter of the experimental data that it can be neglected. Compared with other existing equations the new formulation presented here is as good as the others in their range of validity. The improvement must be seen in the fact that this formulation covers a wider range of validity in the liquid and vapor state. In addition, the equation presented here has the advantage that it can be solved for the density as an explicit parameter. In the opinion of the authors new measurements are still desirable to improve the formulation.

7. Acknowledgments

As a result of this work, which was largely stimulated by the activities of Working Group III of the International

Association for the Properties of Steam, a new International Formulation for the refractive index of water and steam was adapted. The final recommendation is presented in an official document entitled "Release on Refractive Index of Water and Steam" and will be available from the secretary of IAPS, Dr. Howard J. White, Office of Standard Reference Data, National Bureau of Standards, Gaithersburg, MD 20899, USA. This recommended equation has officially acquired the status of an international standard. The authors would like to express their gratitude to the Bundesministerium für Forschung und Technologie (BMFT) of the Federal Republic of Germany for the financial support which made this work possible.

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