

ADVANCE PROGRAM



**SAN
DIEGO** **2015**

IDA World Congress on Desalination and Water Reuse
Renewable Water Resources to Meet Global Needs

August 30 - September 4, 2015

San Diego Convention Center
San Diego, California, USA



ADVANCE PROGRAM

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THE INTERNATIONAL IAPWS STANDARD FOR THE THERMODYNAMIC PROPERTIES OF SEAWATER FOR DESALINATION PROCESSES

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Abstract

Development and operation of desalination plants require knowledge of accurate thermodynamic properties of seawater and their fast calculation. Therefore, the International Association for the Properties of Water and Steam (IAPWS) adopted the "Advisory Note No. 5: Industrial Calculation of the Thermodynamic Properties of Seawater" (IAPWS-2013) as an international standard for the calculation of the thermodynamic properties of seawater for industrial use. This standard contains an equation of state in the form of the Gibbs free energy for seawater which consists of one part for pure liquid water and one part for dissolved sea salt. The water part is calculated from the "IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam" (IAPWS-IF97) and the saline part from the "IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater" (IAPWS-08) which represents the scientific standard for seawater. The purpose of this paper is to introduce the new IAPWS industrial standard for the thermodynamic properties of seawater to the community of desalination plant developers and operators to enable more accurate and efficient calculations in their daily work.

The Industrial Formulation IAPWS-2013 is valid for seawater with sea salt of the reference composition at temperatures from -12°C to 80°C , pressures from 0.3 kPa to 100 MPa, and salinities from 0 (pure water) to 120 g kg^{-1} , with some restrictions in certain regions. All thermodynamic properties such as density, specific volume, specific enthalpy, specific entropy, specific isobaric heat capacity, cubic isobaric expansion coefficient, isothermal compressibility, and thermodynamic derivatives can be calculated from this Gibbs free energy equation for seawater. In addition, boiling temperature, freezing temperature, osmotic pressure, and properties of brine-vapor mixtures and brine-ice mixtures are calculable.

When using the industrial formulation IAPWS-2013, the uncertainties of the calculated seawater properties are slightly greater than those of the scientific formulation IAPWS-08. The difference results from the use of the industrial formulation IAPWS-IF97 for the pure-water part in IAPWS-2013 and the use of the scientific formulation IAPWS-95 for the pure-water part in IAPWS-08. In comparison with the use of the scientific formulation IAPWS-08, the computing speed of the industrial formulation IAPWS-2013 for seawater is increased by a factor of 100 to 200 depending on the requested property function.

The industrial formulation IAPWS-2013 for seawater may be applied in calculations for analyzing, designing, simulating, operating, and optimizing desalination processes and for calculating cooling processes with seawater in power plants.



I. INTRODUCTION

In 2008, IAPWS adopted the IAPWS Formulation 2008 for the Thermodynamic Properties of Seawater (IAPWS-08) [1, 2], the so-called scientific formulation, where the thermodynamic properties of seawater are calculated from an equation of state, consisting of a water part and a saline part. The water part is computed from the Helmholtz free energy equation in terms of temperature and density of the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use (IAPWS-95) [3, 4]. The saline part is formulated as a Gibbs free energy equation in terms of pressure and temperature.

However, the iterative calculation of required properties for given pressure and temperature from the IAPWS-95 Helmholtz free energy equation is computationally intensive and thus time-consuming, making its use less desirable in applications where computational speed is important. In modeling industrial desalination and cooling processes, it is more reasonable to use the Gibbs free energy equation of Region 1 of the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam (IAPWS-IF97) [5-8] for the water part of the seawater formulation instead of IAPWS-95. In addition, the IAPWS-IF97 Industrial Formulation is already being used by industry for calculating properties of pure steam and water for power plants and their components and for industrial applications in general.

Therefore, the International Association for the Properties of Water and Steam (IAPWS) adopted the "Advisory Note No. 5: Industrial Calculation of the Thermodynamic Properties of Seawater" (IAPWS-2013) [9, 10] as an international standard for the calculation of the thermodynamic properties of seawater for industrial use.

II. THERMODYNAMIC PROPERTIES OF SEAWATER

The IAPWS-2013 equation of state for the liquid mixture "seawater" [9, 10] is in the form of the specific Gibbs free energy as a function of pressure p , temperature T , and salinity S , and reads

$$g(p, T, S) = g^w(p, T) + g^s(p, T, S). \quad (1)$$

The water part $g^w(p, T)$ is computed from the Gibbs free energy equation of Region 1 of the industrial formulation IAPWS-IF97 [5-8], and the saline part $g^s(p, T, S)$ from the IAPWS-08 scientific seawater formulation [1, 2]. The salinity S is the mass fraction of sea salt in seawater

$$S = \frac{m_s}{m}, \quad (2)$$

where m_s is the mass of sea salt and m is the mass of the mixture seawater. The composition of sea salt is assumed to be the Reference Composition of Standard Seawater [11]. Note that the mass fraction (2) may deviate from Practical Salinity (PSS-78) and from Total Dissolved Solute (TDS) reported by many commercial salinometers.

All thermodynamic properties for seawater can be calculated from Eq. (1) by using the appropriate combinations of the Gibbs free energy equation and its derivatives with respect to p , T , and S . Table 1 shows the formulas for calculating relevant properties.



Table 1: Formulas for calculating relevant thermodynamic properties of seawater from the Gibbs free energy equation $g(p, T, S)$, Eq. (1), and its derivatives

Property	Relation
Density $\rho = \frac{1}{v}$	$\rho(p, T, S) = \frac{1}{g_p}$
Specific volume v	$v(p, T, S) = g_p$
Specific enthalpy h	$h(p, T, S) = g - T g_T$
Specific internal energy $u = h - p v$	$u(p, T, S) = g - p g_p - T g_T$
Specific entropy s	$s(p, T, S) = -g_T$
Specific Helmholtz free energy $f = u - T s$	$f(p, T, S) = g - p g_p$
Specific isochoric heat capacity $c_v = \left(\frac{\partial u}{\partial T} \right)_{v, S}$	$c_v(p, T, S) = T \left(\frac{g_{pT}^2}{g_{pp}} - g_{TT} \right)$
Specific isobaric heat capacity $c_p = \left(\frac{\partial h}{\partial T} \right)_{p, S}$	$c_p(p, T, S) = -T g_{TT}$
Isothermal compressibility $\kappa_T = -\frac{1}{v} \left(\frac{\partial v}{\partial p} \right)_{T, S}$	$\kappa_T(p, T, S) = -\frac{g_{pp}}{g_p}$
Cubic isobaric expansion coefficient $\alpha_v = \frac{1}{v} \left(\frac{\partial v}{\partial T} \right)_{p, S}$	$\alpha_v(p, T, S) = \frac{g_{pT}}{g_p}$
Isentropic exponent $\kappa = -\frac{v}{p} \left(\frac{\partial p}{\partial v} \right)_{s, S}$	$\kappa(p, T, S) = \frac{1}{p} \frac{g_p g_{TT}}{g_{pT}^2 - g_{pp} g_{TT}}$
Speed of sound $w = v \sqrt{-\left(\frac{\partial p}{\partial v} \right)_{s, S}}$	$w(p, T, S) = g_p \sqrt{\frac{g_{TT}}{g_{pT}^2 - g_{pp} g_{TT}}}$
Relative chemical potential $\mu = \left(\frac{\partial g}{\partial S} \right)_{p, T}$	$\mu(p, T, S) = g_S$
Chemical potential of water $\mu_W = g - S \mu$	$\mu_W(p, T, S) = g - S g_S$

Definitions of the used derivatives

$$g_p = \left(\frac{\partial g}{\partial p} \right)_{T, S} = \left(\frac{\partial g^W}{\partial p} \right)_T + \left(\frac{\partial g^S}{\partial p} \right)_{T, S}, \quad g_{pp} = \left(\frac{\partial^2 g}{\partial p^2} \right)_{T, S} = \left(\frac{\partial^2 g^W}{\partial p^2} \right)_T + \left(\frac{\partial^2 g^S}{\partial p^2} \right)_{T, S},$$

$$g_T = \left(\frac{\partial g}{\partial T} \right)_{p, S} = \left(\frac{\partial g^W}{\partial T} \right)_p + \left(\frac{\partial g^S}{\partial T} \right)_{p, S}, \quad g_{TT} = \left(\frac{\partial^2 g}{\partial T^2} \right)_{p, S} = \left(\frac{\partial^2 g^W}{\partial T^2} \right)_p + \left(\frac{\partial^2 g^S}{\partial T^2} \right)_{p, S},$$



$$g_{pT} = \left(\frac{\partial^2 g}{\partial p \partial T} \right)_S = \left(\frac{\partial^2 g^W}{\partial p \partial T} \right) + \left(\frac{\partial^2 g^S}{\partial p \partial T} \right)_S, \quad g_S = \left(\frac{\partial g}{\partial S} \right)_{p,T} = \left(\frac{\partial g^S}{\partial S} \right)_{p,T},$$

In addition any thermodynamic derivative can be calculated as described in detail in the IAPWS Advisory Note No. 3 [12] and in [8].

Backward functions are calculated by iteration from equations listed in Table 1. For example, temperature T is calculated by iteration from the equation for $h(p, T, S)$ for given pressure p , specific enthalpy h , and salinity S .

III. COLLIGATIVE PROPERTIES

3.1 Phase Equilibrium between Seawater and Water Vapor

For computing the equilibrium between seawater and water vapor, the required thermodynamic condition is the equality of the chemical potential of H_2O in seawater μ_W with the specific Gibbs energy of water vapor g^{vap}

$$\mu_W(p, T, S) = g^{\text{vap}}(p, T), \quad (3)$$

where $\mu_W(p, T, S)$ is calculated using the formula given in Table 1 and $g^{\text{vap}}(p, T)$ from the Gibbs free energy equation of the IAPWS-IF97 region 2 [5-8]. Using Eq. (3), the boiling temperature can be calculated by iteration for pressure p and salinity S , or boiling pressure for temperature T and salinity S , or brine salinity for p and T . Table 2 shows selected boiling temperatures for given pressures and salinities.

Table 2: Boiling temperatures t_b in °C of seawater for selected pressures and salinities calculated by iteration from Eq. (3)

Salinity S in g kg^{-1}	Pressure p in MPa								
	0.001	0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.040
0	6.97	32.88	45.81	53.97	60.06	64.96	69.10	72.68	75.86
10	7.05	32.97	45.91	54.08	60.17	65.08	69.22	72.80	75.98
20	7.12	33.06	46.01	54.19	60.29	65.20	69.34	72.93	76.11
30	7.20	33.16	46.12	54.30	60.41	65.32	69.46	73.06	76.24
40	7.28	33.26	46.23	54.42	60.53	65.45	69.60	73.19	76.38
50	7.37	33.37	46.35	54.55	60.66	65.58	69.73	73.33	76.52
60	7.46	33.48	46.47	54.68	60.80	65.73	69.88	73.48	76.68



70	7.55	33.60	46.60	54.81	60.94	65.87	70.03	73.64	76.84
80	7.65	33.72	46.74	54.96	61.09	66.03	70.19	73.80	77.00
90	7.75	33.85	46.88	55.11	61.25	66.20	70.36	73.98	77.18
100	7.86	33.99	47.04	55.27	61.42	66.37	70.54	74.16	77.37
110	7.98	34.14	47.20	55.45	61.60	66.56	70.74	74.36	77.57
120	8.10	34.29	47.37	55.63	61.79	66.76	70.94	74.57	77.79

3.2 Phase Equilibrium between Seawater and Ice

For the phase equilibrium between seawater and ice Ih, the following condition has to be fulfilled:

$$\mu_W(p, T, S) = g^{\text{Ih}}(p, T) \quad (4)$$

with the chemical potential of H₂O in seawater $\mu_W(p, T, S)$ given in Table 1 and the Gibbs free energy $g^{\text{Ih}}(p, T)$ of ice Ih calculated from the corresponding IAPWS Release [13, 14].

Using Eq. (4), the freezing temperature can be calculated by iteration for pressure p and salinity S or the freezing pressure for T and S , or brine salinity for p and T . Table 3 shows selected freezing temperatures for given pressures and salinities.

Table 3: Freezing temperatures t_f in °C of seawater for selected pressures and salinities calculated by iteration from Eq. (4)

Salinity S in g kg ⁻¹	Pressure p in MPa									
	0.001	0.005	0.01	0.05	0.1	1	10	20	50	100
0	0.01	0.01	0.01	0.01	0.00	-0.06	-0.75	-1.54	-4.09	-8.94
10	-0.53	-0.53	-0.53	-0.53	-0.54	-0.60	-1.29	-2.08	-4.63	-9.50
20	-1.07	-1.07	-1.07	-1.07	-1.08	-1.14	-1.83	-2.62	-5.18	-10.06
30	-1.62	-1.62	-1.62	-1.62	-1.63	-1.69	-2.38	-3.18	-5.74	-10.63
40	-2.19	-2.19	-2.19	-2.19	-2.20	-2.26	-2.95	-3.75	-6.33	-11.23
50	-2.78	-2.78	-2.78	-2.78	-2.78	- ^a	- ^a	- ^a	- ^a	- ^a
60	-3.39	-3.39	-3.39	-3.39	-3.40	- ^a	- ^a	- ^a	- ^a	- ^a
70	-4.02	-4.02	-4.03	-4.03	-4.03	- ^a	- ^a	- ^a	- ^a	- ^a
80	-4.69	-4.69	-4.69	-4.69	-4.70	- ^a	- ^a	- ^a	- ^a	- ^a
90	-5.38	-5.38	-5.38	-5.39	-5.39	- ^a	- ^a	- ^a	- ^a	- ^a
100	-6.11	-6.11	-6.11	-6.11	-6.12	- ^a	- ^a	- ^a	- ^a	- ^a
110	-6.87	-6.87	-6.87	-6.87	-6.88	- ^a	- ^a	- ^a	- ^a	- ^a
120	-7.66	-7.66	-7.66	-7.66	-7.67	- ^a	- ^a	- ^a	- ^a	- ^a

^a This state point is out of range of validity of Eq. (1).



3.3 Triple-Point Temperatures and Pressures

The triple-point temperature and triple-point pressure of seawater are calculated for given salinity S by iteration from both Eqs. (3) and (4). Table 4 contains selected triple-point temperatures and pressures for given salinities.

Table 4: Triple-point temperatures and related triple-point pressures of seawater for selected salinities S

Salinity S in g kg^{-1}	Triple-point temperature t_t in $^{\circ}\text{C}$	Triple-point pressure p_t in kPa
0	0.01	0.61168
10	-0.53	0.58509
20	-1.07	0.55953
30	-1.62	0.53441
40	-2.19	0.50961
50	-2.78	0.48507
60	-3.39	0.46073
70	-4.02	0.43656
80	-4.69	0.41257
90	-5.38	0.38877
100	-6.11	0.36524
110	-6.87	0.34205
120	-7.66	0.31932

3.4 Osmotic Pressure

The osmotic pressure p_{osm} is computed from the condition

$$\mu_{\text{W}}(p + p_{\text{osm}}, T, S) = g^{\text{W}}(p, T), \quad (5)$$

with the chemical potential of H_2O in seawater μ_{W} determined from Table 1 and g^{W} calculated from the Gibbs free energy equation of Region 1 of the industrial formulation IAPWS-IF97 [5-8]. Using Eq. (5), the osmotic pressure p_{osm} is calculated by iteration for pressure p , temperature T , and salinity S .

3.5 Properties of Brine-Vapor Mixture

The properties for the mixture of brine and water vapor, termed brine-vapor mixture (BV), are computed from the combined Gibbs free energy equation

$$g^{\text{BV}}(p, T, S) = (1 - x)g(p, T, S_{\text{b}}) + xg^{\text{vap}}(p, T), \quad (6)$$



where p is the given pressure, T is the given temperature, and S is the given salinity of the seawater mixture including water vapor. The boiling-brine salinity $S_b = S_b(p, T)$ is calculated for pressure p and temperature T using Eq. (3) by iteration. The mass fraction of water vapor in the seawater mixture (vapor fraction) x is determined from the equation

$$x = 1 - \frac{S}{S_b(p, T)}. \quad (7)$$

The Gibbs free energy of the brine $g(p, T, S_b)$ is calculated from Eq. (1) and the Gibbs free energy of water vapor $g^{\text{vap}}(p, T)$ from the Gibbs free energy equation of the IAPWS-IF97 region 2 [5-8].

Brine-vapor properties can be computed from the equation $g^{\text{BV}}(p, T, S)$, Eq. (6), and its derivatives in analogy to Table 1. As an example, the specific enthalpy of brine-vapor mixtures is calculated from the equation

$$h^{\text{BV}}(p, T, S) = (1 - x)h(p, T, S_b) + xh^{\text{vap}}(p, T) \quad (8)$$

where the determination of $h(p, T, S_b)$ is given in Table 1 and of $h^{\text{vap}}(p, T)$ in [5-8]. Further properties such as specific volume $v^{\text{BV}}(p, T, S)$, specific internal energy $u^{\text{BV}}(p, T, S)$, and specific entropy $s^{\text{BV}}(p, T, S)$ are computed analogously.

3.6 Properties of Brine-Ice Mixture

The properties for the mixture of brine and ice Ih, termed brine-ice mixture or sea ice (BI), are computed from the combined Gibbs free energy equation

$$g^{\text{BI}}(p, T, S) = (1 - y)g(p, T, S_f) + yg^{\text{Ih}}(p, T), \quad (9)$$

where p is the given pressure, T is the given temperature, and S is the given salinity. The freezing-brine salinity $S_f = S_f(p, T)$ is calculated for pressure p and temperature T using Eq. (4) by iteration. The mass fraction of ice Ih in the seawater mixture (ice fraction) y is determined from the equation

$$y = 1 - \frac{S}{S_f(p, T)}. \quad (10)$$

The Gibbs free energy of the brine $g(p, T, S_f)$ is calculated from Eq. (1) and the Gibbs free energy of ice Ih $g^{\text{Ih}}(p, T)$ from the IAPWS Formulation [13, 14].

Brine-ice mixture properties are computed from the equation $g^{\text{BI}}(p, T, S)$, Eq. (9), and its derivatives in analogy to Table 1. The derivatives of the included equation $g^{\text{Ih}}(p, T)$ for ice Ih is taken from [13, 14]. As an example, the specific volume of brine-ice mixtures is calculated from the equation

$$v^{\text{BI}}(p, T, S) = (1 - y)v(p, T, S_f) + yv^{\text{Ih}}(p, T), \quad (11)$$

where the determination of $v(p, T, S_f)$ is given in Table 1 and of $v^{\text{Ih}}(p, T)$ in [13, 14].

Further properties such as the specific enthalpy $h^{\text{BI}}(p, T, S)$, specific internal energy $u^{\text{BI}}(p, T, S)$, and specific entropy $s^{\text{BI}}(p, T, S)$ are computed analogously.



IV. REFERENCE STATES

According to the IAPWS Formulation 2008 for Seawater [1, 2], the specific enthalpy and the specific entropy of seawater calculated from Eq. (1) have been set to zero, $h = 0$ and $s = 0$, at

$$p = 0.101325 \text{ MPa}, T = 273.15 \text{ K}, \text{ and } S = S_n = 35.16504 \text{ g kg}^{-1},$$

where S_n is the normal salinity of seawater [11].

The reference state of Eq. (1) for water corresponds to the following values. The specific internal energy and the specific entropy of saturated liquid water are set $u = 0$ and $s = 0$ at the triple point $T = 273.16 \text{ K}$, $p = 0.611657 \text{ kPa}$, and $S = 0$.

From $u = 0$ it follows for the specific enthalpy $h = u + pv$:

$$h = 0.000611783 \text{ kJ kg}^{-1}$$

at this state point. These values correspond to the reference state of IAPWS-IF97.

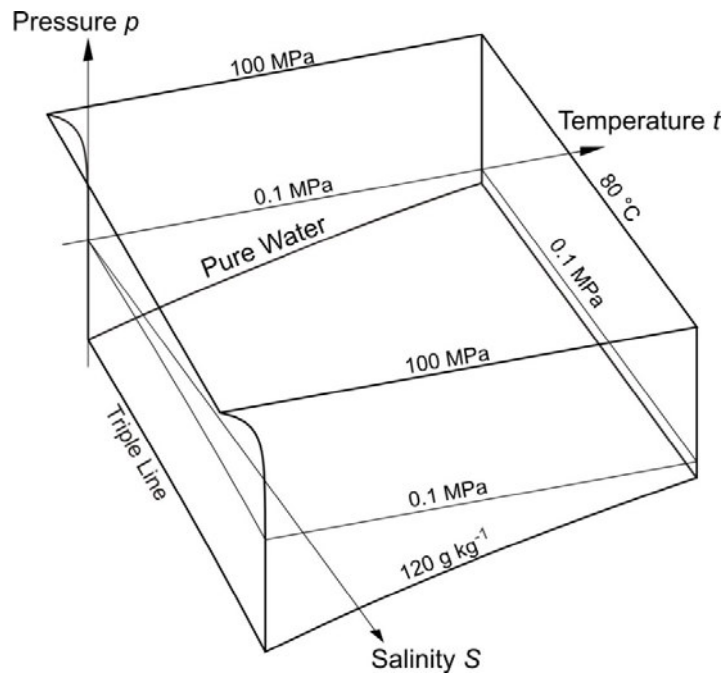
V. RANGE OF VALIDITY

The equation of state for Standard Seawater with sea salt of the Reference Composition, Eq. (1), is valid inside the following pressure, temperature, and salinity ranges

$$0.3 \text{ kPa} \leq p \leq 100 \text{ MPa}, -12^\circ\text{C} \leq t \leq 80^\circ\text{C}, \text{ and } 0 \leq S \leq 120 \text{ g kg}^{-1}$$

with some restrictions, described in [9, 10]. Figure 1 shows a p - T - S plot containing a graphical representation of this range of validity.

Figure 1: Range of validity of the industrial formulation IAPWS-2013 for seawater in a p - T - S diagram



VI. UNCERTAINTY

The deviations between properties calculated from the industrial formulation IAPWS-2013 and calculated from the scientific formulation IAPWS-08 caused by the use of IAPWS-IF97 instead of IAPWS-95 are small compared to the uncertainties of IAPWS-08. Therefore, the total uncertainties of the industrial seawater formulation IAPWS-2013 are generally equivalent to those of the IAPWS-08 formulation. Table 5 contains uncertainties of selected quantities in certain regions for salinity S , temperature t , and pressure p for the industrial formulation IAPWS-2013.

Table 5: Uncertainties of selected quantities in certain regions for salinity, temperature, and pressure for Eq. (1)

Quantity	S interval g kg^{-1}	t interval $^{\circ}\text{C}$	p interval MPa	Uncertainty u
Density	0-40	0-40	0.1	5×10^{-6}
$\left \frac{\Delta \rho}{\rho} \right $	40-50	15-30	0.1	1×10^{-5}
	5-40	0-40	0.1-10	1×10^{-5}
	5-40	0-40	10-100	2×10^{-5}
	40-120	20-40	0.1	3×10^{-4}
	0-40	40-60	0.1	4×10^{-4}
	40-80	40-60	0.1	9×10^{-4}
	0-40	60-80	0.1	1.4×10^{-3}
	80-120	40-60	0.1	3×10^{-3}
	40-80	60-80	0.1	4×10^{-3}
	80-120	60-80	0.1	1.3×10^{-2}
Specific isobaric heat capacity	0-120	0-80	0.1	$4.2 \text{ J kg}^{-1} \text{ K}^{-1}$
$ \Delta c_p $				
Isobaric cubic expansion coefficient	10-30	-6-1	0.7-33	$1 \times 10^{-6} \text{ K}^{-1}$
$ \Delta \alpha_v $				
Boiling temperature	6-70	60-80	0.02-0.05	2.3 mK
$ \Delta t_b $				
Freezing Temperature	4-40	-2-0	0.1	2 mK
$ \Delta t_f $				



VII. COMPUTING TIMES FOR THE IAPWS SEAWATER FUNCTIONS

As mentioned above, one important reason to use IAPWS-IF97 instead of IAPWS-95 for calculating the water contribution of the IAPWS seawater functions is the computing speed difference, which is particularly important in computer-intensive process modeling calculations. A comparison of the computing speed of the seawater functions of the IAPWS-08 seawater scientific formulation, which uses IAPWS-95, with that of the industrial formulation IAPWS-2013, which uses IAPWS-IF97, was reported in [15]. The measured computing times were used to calculate computing-time ratios (CTR) between the scientific formulation IAPWS-08 and the industrial formulation IAPWS-2013:

$$\text{CTR} = \frac{\text{computing time for a quantity calculated from IAPWS-08}}{\text{computing time for this quantity calculated from IAPWS-2013}} \quad (12)$$

Table 6 shows the results of these calculations. The tests were performed using the same code as for the evaluation of IAPWS-IF97, so-called NIFBENCH [16], on a PC using an Intel Core i7 920 with 2.64 GHz as CPU in combination with a 32-bit Windows 7 operating system.

Table 6: Computing time ratios CTR of important properties between the scientific formulation IAPWS-08 and the industrial formulation IAPWS-2013 calculated from Eq. (12) [15]

Property	CTR
Density ρ	243
Specific enthalpy h	236
Specific entropy s	220
Specific isobaric heat capacity c_p	430
Chemical potential of water in seawater μ_W	134
Boiling temperature of seawater t_b	206
Freezing temperature of seawater t_f	32

In summary, the calculation of seawater properties using the industrial seawater formulation IAPWS-2013 is approximately 200 times faster than the calculation using the IAPWS-08 scientific formulation. It should also be noted that the observed improvement depends on the efficiency with which IAPWS-95 is programmed (and also on the machine and compiler used). Nevertheless, the use of IAPWS-IF97 clearly produces a significant reduction in computing time.

VIII. PROPERTY LIBRARY FOR THE INDUSTRIAL FORMULATION OF SEAWATER

The algorithms for the calculation of the thermodynamic and colligative properties of seawater of IAPWS-2013 in combination with an enlargement of the range of validity using algorithms described by Hömig in the Fichtner Handbook [17] have been implemented into the property library LibSeaWa [18]. Its range of validity is as follows:



$$0.209 \text{ kPa} \leq p \leq 100 \text{ MPa}, -12^{\circ}\text{C} \leq t \leq 220^{\circ}\text{C}, \text{ and } 0 \leq S \leq 200 \text{ g kg}^{-1}.$$

Selected seawater properties using this property library can be calculated online [19].

IX. SUMMARY

In this paper, the industrial formulation IAPWS-2013 for seawater properties using the algorithms of IAPWS-IF97 for pure water has been described. This was a requirement by industry which routinely uses the industrial formulation IAPWS-IF97 for process calculations that are often demanding in the sense of computing time. The main advantage of using the algorithms of IAPWS-IF97 instead of IAPWS-95 is to avoid iterative calculations from the IAPWS-95 Helmholtz free energy equation which is computationally intensive and therefore less desirable in applications where processing speed is important.

To verify the accuracy of the industrial formulation of seawater, comparison calculations were carried out. The results showed that the differences between the two seawater formulations are very small. Consequently, the accuracy of the industrial formulation IAPWS-2013 is nearly the same as that of the scientific formulation IAPWS-08.

The range of validity of the industrial formulation of seawater is the same as that given for IAPWS-08.

The computing time comparison leads to the conclusion that the calculation of seawater properties using the industrial seawater formulation IAPWS-2013 is approximately 200 times faster than calculation using the IAPWS-08 scientific Formulation. In conclusion, the industrial formulation presented here is recommended for use in desalination and cooling processes.

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XI. ACKNOWLEDGEMENTS

The authors thank the further members of the IAPWS Task Group Industrial Formulation for Seawater Properties:

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the IAPWS Working Groups:
Thermophysical Properties of Water and Steam (TPWS),
Industrial Requirements and Solutions (IRS),
and the
the IAPWS Subcommittee on Seawater (SCSW)
for their collaboration.

