



## Thermophysical properties of seawater: a review of existing correlations and data

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### ABSTRACT

Correlations and data for the thermophysical properties of seawater are reviewed. Properties examined include density, specific heat capacity, thermal conductivity, dynamic viscosity, surface tension, vapor pressure, boiling point elevation, latent heat of vaporization, specific enthalpy, specific entropy and osmotic coefficient. These properties include those needed for design of thermal and membrane desalination processes. Results are presented in terms of regression equations as functions of temperature and salinity. The available correlations for each property are summarized with their range of validity and accuracy. Best-fitted new correlations are obtained from available data for density, dynamic viscosity, surface tension, boiling point elevation, specific enthalpy, specific entropy and osmotic coefficient after appropriate conversion of temperature and salinity scales to the most recent standards. In addition, a model for latent heat of vaporization is suggested. Comparisons are carried out among these correlations, and recommendations are provided for each property, particularly over the ranges of temperature and salinity common in thermal and/or reverse osmosis seawater desalination applications.

**Keywords:** Seawater; Thermophysical properties; Density; Specific heat; Thermal conductivity; Viscosity; Surface tension; Vapor pressure; Boiling point elevation; Latent heat; Enthalpy; Entropy; Osmotic coefficient

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### 1. Introduction

The knowledge of seawater properties is important in the development and design of desalination systems. Literature contain many data for the properties of seawater, but only a few sources provide full coverage for all of these properties [1–5]. The data are mainly based on experimental measurements carried out in and before the 1970s, and usually span a limited temperature and salinity range. Most of the data are presented as tabulated data, which require interpolation and extrapolation to conditions of interest, and not all desirable properties

are given in any single source, particularly transport properties such as viscosity and thermal conductivity. The researcher, as well as the design engineer, is typically faced with the problem of searching the literature, and perhaps interpolating tabulated data, in order to obtain necessary property values.

As a first approximation, most physical properties of seawater are similar to those of pure water, which can be described by functions of temperature and pressure. However, because seawater is a mixture of pure water and sea salts, salinity (which is the mass of dissolved salts per unit mass of seawater) should be known as a third independent property in addition to temperature and pressure. Differences between pure water and seawater properties, even if only in the range of 5 to 10%, can

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have important effects in system level design: density, specific heat capacity, and boiling point elevation are all examples of properties whose variation affects distillation system performance in significant ways. Therefore, it is necessary to identify accurately the physical and thermal properties of seawater for modeling, analysis, and design of various desalination processes.

The original papers giving correlations of seawater properties develop best fit (regression) equations to experimental data. These correlations are valid only within the range of the experimental parameters. On the other hand, in some cases, liquid or electrolyte theories such as the Debye-Huckel and Pitzer theories are used to correlate the experimental data. In this case, the obtained correlations may have extended ranges of temperature and salinity. A large fraction of experimental measurements have been carried out on “synthetic” seawater (prepared by dissolving appropriate salts in distilled water and omitting sometimes calcium sulphate as would be necessary for evaporation at higher temperatures [2]). However, some measurements have been carried out on natural seawater. In this regard, seawater samples at higher salinity were concentrated by evaporation while seawater at lower salinity was prepared by dilution.

Temperature and salinity are the most important intensive properties for desalination systems, and they determine the other physical and thermal properties associated with seawater at near-atmospheric pressures. In the past, different salinity and temperature scales have been used. Previous salinity scales are the Knudsen salinity,  $S_K$  (Knudsen [6]), Chlorinity,  $Cl$  (Jacobsen and Knudsen [7]), and the Practical Salinity Scale,  $S_p$  (PSS-78, Lewis and Perkin [8]). The most recent salinity scale is the reference-composition salinity,  $S_R$  defined by Millero et al. [9] which is currently the best estimate for the absolute salinity of IAPSO Standard Seawater. The relationships between these different salinity scales are given by equations 1–3 in Table 1.

Previous temperature scales are the International Temperature Scale of 1927,  $T_{27}$  (ITS-27, [10]), the International Practical Temperature Scale,  $T_{48}$  (IPTS-48, [11]) and the International Practical Temperature Scale of 1968,  $T_{68}$  (IPTS-68, [12]). The most recent temperature scale is The

International Temperature Scale of 1990,  $T_{90}$  (ITS-90, [13]). The conversion between IPTS-68 and ITS-90 temperature scales is given by Rusby [14] which is described by Eq. (4) in Table 1 for the temperature range of 260 K to 400 K and with an accuracy of  $\pm 0.001$  K. In the present work, different scales that were used early with any seawater property equation will be distinguished by  $T_{27}$ ,  $T_{48}$ ,  $T_{68}$  and  $T_{90}$  for the temperature scales and by  $S_K$ ,  $Cl$ ,  $S_p$  and  $S_R$  for the salinity scales. However, for comparison between equations, recommending or development of new equations the ITS-90 temperature scale (will be referred by simply  $T$  for Kelvin and  $t$  for degree Celsius) and the reference-composition salinity scale (referred by  $S$ ) will be used after appropriate conversions.

Most seawater properties measurements have been carried out within the oceanographic range ( $S = 0\text{--}40$  g/kg and  $t = 0\text{--}40^\circ\text{C}$ ). The salinity of enclosed seas and areas that receive a high drainage rate of saline water may reach higher values. For example, the salinity of the Arabian Gulf water near the shores lines of Kuwait and Saudi Arabia may reach 50 g/kg [4], tropical estuaries like the Australian Shark Bay show salinities up to 70 g/kg [15], while desiccating seas like the Dead Sea have salinity even approach saturation concentrations [16]. Similarly, in desalination systems the temperature and salinity of the brine may reach values much higher than the oceanographic range. For instance, in thermal desalination systems, the top brine temperature is typically between  $60^\circ\text{C}$  and  $120^\circ\text{C}$  depending on the particular technology. In typical seawater reverse osmosis systems (SWRO), the temperature is in the order of the ambient temperature however; a brine discharge can be expected to have a salinity that is between 1.5 and two times greater than the feed seawater. Therefore the temperature and salinity ranges that are of interest for desalination processes are  $0\text{--}120^\circ\text{C}$  and  $0\text{--}120$  g/kg.

Measurements of seawater properties at pressures higher or lower than atmospheric pressure are very limited in the literature. However, the effect of pressure on the thermophysical properties may be neglected in desalination applications. In thermal desalination systems for instance, the pressure does not exceed atmospheric pressure by more than 10%. In RO systems, the pressure may reach 10 MPa but the thermodynamic properties can be well approximated by assuming saturated liquid at the corresponding temperature since the effect of pressure is very small. In addition, equations that model seawater properties at temperatures higher than normal boiling temperature are assumed to be at the saturation pressure.

Significant efforts have been made to obtain an accurate thermodynamic fundamental equation for seawater, similar to those available for pure water [17,18]. The fundamental equation (e.g., the Gibbs potential) is

Table 1  
Relationship between different salinity and temperature scales.

Equation		Ref.
$S_R = 1.00557 \times S_K - 0.03016$	(1)	[26]
$S_R = 1.815068 \times Cl$	(2)	[26]
$S_R = 1.00472 \times S_p$	(3)	[9]
$T_{90} = T_{68} - 0.00025 \times (T_{68} - 273.15)$	(4)	[14]

developed by fitting theoretically-based equations to experimental data. By considering appropriate mathematical manipulations of the fundamental equation, other thermodynamic properties, can be calculated. The first internationally accepted fundamental equation for seawater is the 1980 International Equation of State of Seawater (EOS-80) that has been established by empirical fitting to the experimental data of many researchers. It was released by the Joint Panel on Oceanographic Tables and Standards (JPOTS) and published by Millero et al. [19]. This equation of state is based on the IPTS-68 temperature scale and on the PSS-78 Practical Salinity Scale valid between 2 and 42 g/kg and  $-2$  to  $35^{\circ}\text{C}$  which is too low for desalination applications.

A more recent equation of state for seawater was given by Feistel [20] to compensate the inconsistencies of the EOS-80 equation of state. He proposed a polynomial-like function for the specific Gibbs energy as a function of salinity, temperature and pressure which has the same range of temperature and salinity of that for EOS-80 but with extended range of pressure. This equation has been readjusted by Feistel and Hagen [21] to replace the high-pressure density and high pressure heat capacity by new values extracted from the sound speed equation of Chen and Millero [22]. Subsequently, Feistel [23] provided a new Gibbs potential function for seawater which was compiled from experimental data, rather than being derived from the EOS-80 equation. Again this equation is valid for the same EOS-80 range of temperature and salinity but with pressures up to 100 MPa. However, it was consistent with the 1996 International Scientific Pure Water Standard (IAPWS-95 [24]), and the 1990 International Temperature Scale (ITS-90, [13]). Feistel and Marion [25] extended the salinity range of the Feistel [23] Gibbs function up to 110 g/kg using Pitzer model for the sea salt components. Consequently, Feistel [26] provided a new saline part of the seawater specific Gibbs energy function that has an extended range of temperature and salinity ( $t = -6$  to  $80^{\circ}\text{C}$  and  $S = 0$  to 120 g/kg) but at atmospheric pressure. It was expressed in terms of the temperature scale ITS-90 and the Reference-Composition absolute salinity scale of 2008.

Finally, a recent formulation for the thermodynamic properties of seawater has been released and authorized by the International Association for the Properties of Water and Steam [27]. In this formulation, the equation of state for seawater is the fundamental equation for the Gibbs energy given by Feistel [26] as a function of salinity, temperature and pressure. The range of validity and accuracy of this equation differs from region to region on the temperature-salinity-pressure diagram and some extrapolations were carried out to cover higher salinities and higher pressure regions. However, it is important to note that the equation of state does not provide transport

properties such as viscosity and thermal conductivity, and that these liquid-state equations are not structured to provide multiphase properties such as surface tension. In addition, mathematical manipulation of thermodynamic relations to obtain thermodynamic properties may be more cumbersome than using available best-fit correlations of comparable accuracy to the experimental data. For this reason, Sun et al. [28] derived best fit polynomial equations for some thermodynamic properties of seawater (density, specific heat and specific entropy) calculated from Feistel [23] Gibbs energy function and some other measured data (discussed later).

The objective of this paper is to carry out a state-of-the-art review on the thermophysical properties of seawater needed in design and performance evaluation of desalination systems. This work collects the available correlations of seawater properties, compares them, and recommends an equation to be used for each property. These comparisons and recommendations are carried out after converting different salinity and temperature scales to the absolute salinity scale [9] and to the International Temperature Scale (ITS-90, [13]). In addition, the equations are checked to be consistent at the limit of zero salinity with the most recent properties of pure water standard (IAPWS-95 [24]). The properties considered are: density, specific heat, thermal conductivity, dynamic viscosity, surface tension, vapor pressure, boiling point elevation, latent heat of vaporization, specific enthalpy, specific entropy and osmotic coefficient.

## 2. Density

In general, the density of seawater can be found with sufficient accuracy in the literature, as there is much published data [29–40] in the oceanographic range, although data are more limited at higher salinities and temperatures. A recent review and measurements of seawater density is given by Safarov et al. [41] where the density of seawater is measured at  $T = 273$  to  $468$  K, pressures up to 140 MPa and a salinity of  $S = 35$  g/kg with an estimated experimental uncertainty of  $\pm 0.006\%$ . Available equations of seawater density are given in Table 2 with its range of validity, units and accuracy. Equation (5) is given by Isdale and Morris [36] based on their experimental measurements that were carried out at the National Engineering Laboratory, the data of Fabuss and Korosi [34], and the data of Hara et al. [29]. The density measurements were carried out on synthetic seawater (calcium free seawater) and have an accuracy of  $\pm 0.1\%$ .

Equation (6) is given by Millero and Poisson [42] based on the measurements carried out by Millero et al. [37] and Poisson et al. [39]. The pure water density used with Eq. (6) was given by Bigg [43] which is valid up to

Table 2  
Seawater density correlations.

Correlation	Ref.
$\rho_{sw} = 10^3 (A_1 F_1 + A_2 F_2 + A_3 F_3 + A_4 F_4)$ <p>where</p> $B = (2S_p - 150)/150, G_1 = 0.5, G_2 = B, G_3 = 2B^2 - 1$ $A_1 = 4.032G_1 + 0.115G_2 + 3.26 \times 10^{-4}G_3$ $A_2 = -0.108G_1 + 1.571 \times 10^{-3}G_2 - 4.23 \times 10^{-4}G_3$ $A_3 = -0.012G_1 + 1.74 \times 10^{-3}G_2 - 9 \times 10^{-6}G_3$ $A_4 = 6.92 \times 10^{-4}G_1 - 8.7 \times 10^{-5}G_2 - 5.3 \times 10^{-5}G_3$ $A = (2t_{68} - 200)/160, F_1 = 0.5, F_2 = A, F_3 = 2A^2 - 1, F_4 = 4A^3 - 3A$ <p>Validity: <math>\rho_{sw}</math> in (kg/m<sup>3</sup>); <math>20 &lt; t_{68} &lt; 180</math> °C; <math>10 &lt; S_p &lt; 160</math> g/kg Accuracy: <math>\pm 0.1</math> %</p>	(5) [36]
$\rho_{sw} = \rho_w + A S_p + B S_p^{3/2} + C S_p$ <p>where</p> $A = 0.824493 - 4.0899 \times 10^{-3}t_{68} + 7.6438 \times 10^{-5}t_{68}^2 - 8.2467 \times 10^{-7}t_{68}^3 + 5.3875 \times 10^{-9}t_{68}^4$ $B = -5.72466 \times 10^{-3} + 1.0227 \times 10^{-4}t_{68} - 1.6546 \times 10^{-6}t_{68}^2, C = 4.8314 \times 10^{-4}$ $\rho_w = 999.842594 + 6.793952 \times 10^{-2}t_{68} - 9.09529 \times 10^{-3}t_{68}^2 + 1.001685 \times 10^{-4}t_{68}^3 - 1.120083 \times 10^{-6}t_{68}^4 + 6.536336 \times 10^{-9}t_{68}^5$ <p>Validity: <math>\rho_{sw}</math> and <math>\rho_w</math> in (kg/m<sup>3</sup>); <math>-2 &lt; t_{68} &lt; 40</math> °C; <math>0 &lt; S_p &lt; 42</math> g/kg Accuracy: <math>\pm 0.01</math> %</p>	(6) [42]
$\rho_{sw} = \left( \begin{aligned} &a_1 + a_2t + a_3t^2 + a_4t^3 + a_5t^4 + a_6p + a_7pt^2 + a_8pt^3 + a_9pt^4 + a_{10}p^2 \\ &+ a_{11}p^2t + a_{12}p^2t^2 + a_{13}p^2t^3 + a_{14}p^3 + a_{15}p^3t + a_{16}p^3t^2 + a_{17}p^3t^3 + a_{18}p^3t^4 \end{aligned} \right) - (b_1S + b_2St + b_3St^2 + b_4St^3 + b_5Sp + b_6Sp^2)$ <p>where</p> $a_1 = 9.992 \times 10^2, a_2 = 9.539 \times 10^{-2}, a_3 = -2.581 \times 10^{-5}, a_4 = 3.131 \times 10^{-5}, a_5 = -6.174 \times 10^{-8},$ $a_6 = 4.337 \times 10^{-1}, a_7 = 2.549 \times 10^{-5}, a_8 = -2.899 \times 10^{-7}, a_9 = 9.578 \times 10^{-10}, a_{10} = 1.763 \times 10^{-3},$ $a_{11} = -1.231 \times 10^{-4}, a_{12} = 1.366 \times 10^{-6}, a_{13} = 4.045 \times 10^{-9}, a_{14} = -1.467 \times 10^{-5}, a_{15} = 8.839 \times 10^{-7}$ $a_{16} = -1.102 \times 10^{-9}, a_{17} = 4.247 \times 10^{-11}, a_{18} = -3.959 \times 10^{-14}, b_1 = -7.999 \times 10^{-1}, b_2 = 2.409 \times 10^{-3}$ $b_3 = -2.581 \times 10^{-5}, b_4 = 6.856 \times 10^{-8}, b_5 = 6.298 \times 10^{-4}, b_6 = -9.363 \times 10^{-7}$ <p>Validity: <math>\rho_{sw}</math> in (kg/m<sup>3</sup>); <math>0 &lt; t &lt; 180</math> °C; <math>0 &lt; S &lt; 80</math> g/kg; <math>0.1 &lt; p &lt; 100</math> MPa Accuracy: <math>\pm 2.5</math> %</p>	(7) [28]
$\rho_{sw} = (a_1 + a_2t + a_3t^2 + a_4t^3 + a_5t^4) + (b_1S + b_2St + b_3St^2 + b_4St^3 + b_5S^2t^2)$ <p>where</p> $a_1 = 9.999 \times 10^2, a_2 = 2.034 \times 10^{-2}, a_3 = -6.162 \times 10^{-3}, a_4 = 2.261 \times 10^{-5}, a_5 = -4.657 \times 10^{-8},$ $b_1 = 8.020 \times 10^2, b_2 = -2.001, b_3 = 1.677 \times 10^{-2}, b_4 = -3.060 \times 10^{-5}, b_5 = -1.613 \times 10^{-5}$ <p>Validity: <math>\rho_{sw}</math> in (kg/m<sup>3</sup>); <math>0 &lt; t &lt; 180</math> °C; <math>0 &lt; S &lt; 0.16</math> kg/kg Accuracy: <math>\pm 0.1</math> %</p>	(8)

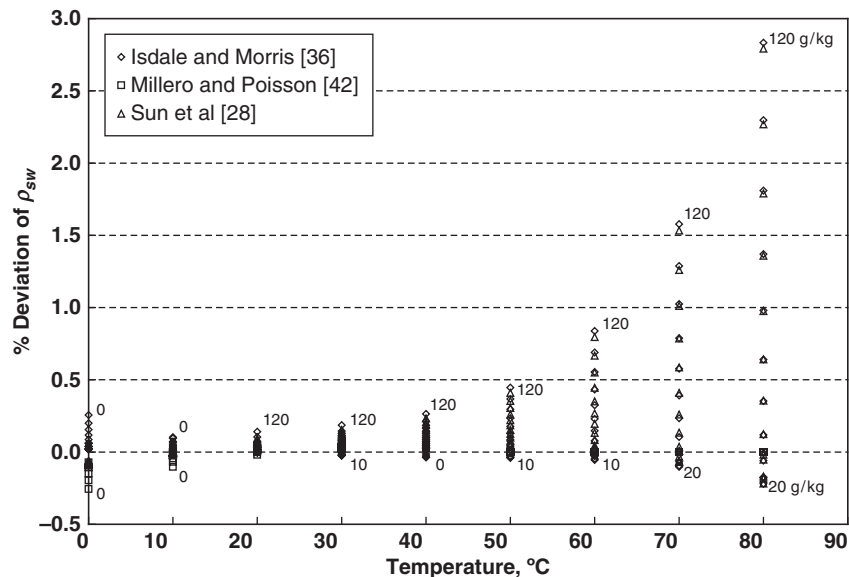


Fig. 1. Deviation of seawater density calculated using Eqs (5–7) from that calculated using IAPWS-2008 formulation for salinity 0–120 g/kg (numbers in the figure refer to salinity in g/kg).

70°C and has a maximum deviation of  $\pm 0.1\%$  from the IAPWS-95 density values of pure water. Sun et al. [28] provided a polynomial equation (Eq. 7) based on the calculated seawater density from the Feistel [23] Gibbs energy function. The Gibbs function of Feistel is limited in its validity to salinities up to 42 g/kg and temperatures up to 40°C. However, Sun et al. [28] extended the calculations and compared the calculated density at higher temperature and salinity to that measured by Isdale and Morris [36]. There is a difference of about  $\pm 2.5\%$  at  $S = 120$  g/kg and  $t = 80^\circ\text{C}$ .

The percentage deviation of the seawater density calculated using equations (5–7) from that calculated using the recent IAPWS 2008 release [27] of seawater thermodynamic properties is given in Figure 1. It is shown in this figure that the deviation increases with temperature reaching a maximum of  $\pm 2.8\%$  for Eq. 5 of Isdale and Morris [36] and about the same value for Eq. 7 of Sun et al. [28] at temperature of  $80^\circ\text{C}$  and salinity of 120 g/kg. The deviation is about  $\pm 0.04\%$  for Eq. 6 of Millero and Poisson [42] which is valid only up to  $40^\circ\text{C}$ .

It is important to mention that the density values calculated from the IAPWS 2008 seawater formulation at salinity higher than 40 g/kg and temperature higher than  $40^\circ\text{C}$  are based on the extrapolation of Gibbs energy function outside its range of validity. However, the maximum deviation from the calculated density value from the best available experimental data in that range (Isdale and Morris [36]) is  $\pm 2.44\%$  (given in Table 11 of Feistel [26] at  $t = 80^\circ\text{C}$  and  $S = 120$  g/kg). Therefore, we consider that using Eq. (5) is better to calculate the density of seawater because it fits the experimental data to an accuracy

of  $\pm 0.1\%$  and has wide temperature and salinity ranges. However, the temperature and salinity should be converted to the International Temperature Scale (ITS-90) and the reference-composition salinity respectively. In addition, the density value at zero salinity should be matched with the pure water value (IAPWS-95).

For calculations of seawater density at atmospheric pressure (0.1 MPa), a polynomial correlation (Eq. 8) is designed to best fit the data of Isdale and Morris [36] and that of Millero and Poisson [42]. The pure water density values were generated from the IAPWS-95 formulation of liquid water at 0.1 MPa at 1 K intervals (values at temperature higher than the normal boiling temperature are calculated at the saturation pressure). The performance of Eq. (8) in reproducing the measured values of seawater density at  $p = 0.1$  MPa is shown in Figure 2 where there is a maximum deviation of  $\pm 0.1\%$ . Also the maximum deviation of the pure water part is  $\pm 0.01\%$  from that calculated using the IAPWS-95 formulation. Equation (8) is in a simpler format with only 10 coefficients than that of Eq. (5) (Chebyshev polynomial) and Eq. (6) (24 coefficients). Moreover, the temperature and salinity scales are the International Temperature Scale (ITS-90) and the reference-composition salinity respectively. Figure 3 shows the density of seawater calculated from Eq. (8) as it changes with temperature and salinity.

### 3. Specific heat

The specific heat of seawater has been measured by many researchers [44–48], and it is available over a wide



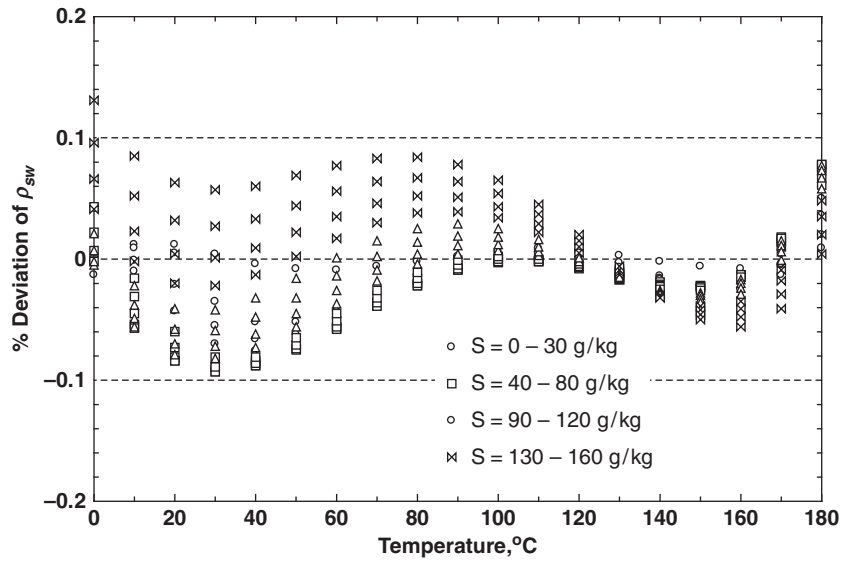


Fig. 2. Deviation of seawater density calculated using Eq. (8) from the data of [36] and [42] for salinity 0–160 g/kg.

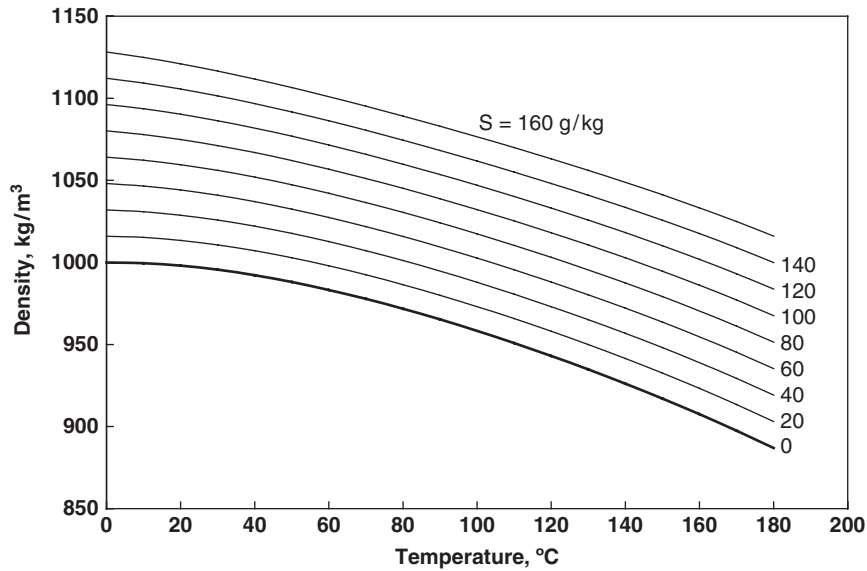


Fig. 3. Seawater density variations with temperature and salinity calculated using Eq. (8).

range of temperature (0–200°C) and salinity (0–120 g/kg). Correlations for these measurements are given in Table 3 with the range of validity, units and accuracy. Additional correlations for seawater specific heat have been fit to the extended Debye-Huckel equation (Bromley [49], Brandani et al. [50]) or Pitzer equation (Millero and Pierrot [51]). This kind of correlation requires knowledge of the molalities of various ions in seawater.

Equation (9) is given by Jamieson et al. [46] based on measurements of synthetic seawater for temperatures 0–180°C, salinities 0–180 g/kg, and has a maximum

deviation of  $\pm 0.28\%$ . Equation (10) is given by Bromley et al. [47] based on the measurements of heat capacities of samples from Pacific Ocean for temperatures 2–80°C, salinities 0–120 g/kg, and has a maximum deviation of  $\pm 0.004$  J/kg K. Equation (11) is given by Millero et al. [48] based on measurements of standard seawater for temperatures 0–35°C, salinities 0–40 g/kg, and with a maximum deviation of  $\pm 0.5$  J/kg K. Equation (12) is given by Sun et al. [28] valid for temperatures between 0 and 374°C, absolute salinities 0–40 g/kg, and pressure 0.1–100 MPa. Sun’s equation is a polynomial fitted to the

Table 3  
Seawater specific heat correlations.

Correlation	Ref.
$c_{sw} = A + B T_{68} + C T_{68}^2 + D T_{68}^3 \quad (9)$ <p>where</p> $A = 5.328 - 9.76 \times 10^{-2} S_p + 4.04 \times 10^{-4} S_p^2$ $B = -6.913 \times 10^{-3} + 7.351 \times 10^{-4} S_p - 3.15 \times 10^{-6} S_p^2$ $C = 9.6 \times 10^{-6} - 1.927 \times 10^{-6} S_p + 8.23 \times 10^{-9} S_p^2$ $D = 2.5 \times 10^{-9} + 1.666 \times 10^{-9} S_p - 7.125 \times 10^{-12} S_p^2$ <p>Validity: <math>c_{sw}</math> in (kJ/kg K); <math>273.15 &lt; T_{68} &lt; 453.15</math> K; <math>0 &lt; S_p &lt; 180</math> g/kg Accuracy: <math>\pm 0.28</math> %</p>	[46]
$c_{sw} = 1.0049 - 0.0162 S_K + 3.5261 \times 10^{-4} S_K^2 - (3.2506 - 1.4795 S_K + 0.0777 S_K^2) \times 10^{-4} t_{48} + (3.8013 - 1.2084 S_K + 0.0612 S_K^2) \times 10^{-6} t_{48}^2 \quad (10)$ <p>Validity: <math>c_{sw}</math> in (cal./g °C); <math>0 &lt; t_{48} &lt; 180</math> °C; <math>0 &lt; S_K &lt; 12</math> % Accuracy: <math>\pm 0.001</math> %</p>	[47]
$c_{sw} = c_w + A Cl + B Cl^{3/2} \quad (11)$ <p>where</p> $c_w = 4217.4 - 3.72 t_{68} + 0.141 t_{68}^2 - 2.654 \times 10^{-3} t_{68}^3 + 2.093 \times 10^{-5} t_{68}^4$ $A = -13.81 + 0.1938 t_{68} - 0.0025 t_{68}^2$ $B = 0.43 - 0.0099 t_{68} + 0.00013 t_{68}^2$ <p>Validity: <math>c_{sw}</math> in (J/kg K); <math>5 &lt; t_{68} &lt; 35</math> °C; <math>0 &lt; Cl &lt; 22</math> g/kg Accuracy: <math>\pm 0.01</math> %</p>	[48]
$c_{sw} = 10^3 (a_1 + a_2 t + a_3 t^2 + a_4 t^4 + a_5 p + a_6 p t + a_7 p t^3 + a_8 p^2 + a_9 p^2 t + a_{10} p^2 t^2) - (t + 273.15) \times (b_1 S + b_2 S^2 + b_3 S^3 + b_4 S t + b_5 S t^2 + b_6 S t^3 + b_7 S^2 t + b_8 S^3 t + b_9 S p + b_{10} S t p) \quad (12)$ <p>where</p> $a_1 = 4.193, a_2 = -2.273 \times 10^{-4}, a_3 = 2.369 \times 10^{-6}, a_4 = 1.670 \times 10^{-10},$ $a_5 = -3.978 \times 10^{-3}, a_6 = 3.229 \times 10^{-5}, a_7 = -1.073 \times 10^{-9}, a_8 = 1.913 \times 10^{-5},$ $a_9 = -4.176 \times 10^{-7}, a_{10} = 2.306 \times 10^{-9}, b_1 = 5.020 \times 10^{-3}, b_2 = -9.961 \times 10^{-6},$ $b_3 = 6.815 \times 10^{-8}, b_4 = -2.605 \times 10^{-5}, b_5 = 4.585 \times 10^{-8}, b_6 = 7.642 \times 10^{-10},$ $b_7 = -3.649 \times 10^{-8}, b_8 = 2.496 \times 10^{-10}, b_9 = 1.186 \times 10^{-6} \text{ and } b_{10} = 4.346 \times 10^{-9}$ <p>Validity: <math>c_{sw}</math> in (J/kg K); <math>0 &lt; t &lt; 374</math> °C; <math>0 &lt; S &lt; 40</math> g/kg; <math>0.1 &lt; p &lt; 100</math> MPa Accuracy: <math>\pm 4.62</math> %</p>	[28]

specific heat values calculated by differentiation of a seawater entropy function with respect to temperature; the seawater entropy function is derived from Gibbs energy function of Feistel [23].

The percentage deviation of the seawater specific heat calculated using equations (9)–(12) from that calculated using the IAPWS 2008 formulation [27] of seawater thermodynamic properties is given in Figure 4. Equation (9) of Jamieson et al. [46] gives a maximum deviation of  $\pm 0.4\%$ , Eq. (10) of Bromley et al. [47] gives a maximum deviation of  $\pm 4.8\%$ , Eq. (11) of Millero et al. [48] gives a

maximum deviation of  $\pm 1.9\%$ , and Eq. (12) of Sun et al. [28] gives a maximum deviation of  $\pm 4.6\%$ .

From the above comparison, it is clear that Eq. (9) of Jamieson et al. [46] has the minimum deviation from the IAPWS-2008 values and it also has a wider range of temperature and salinity. The maximum difference from the measured data is  $\pm 0.28\%$ . Therefore it is recommended to use Eq. (9) to calculate the specific heat of seawater within the range given in Table 3. However, the salinity should be converted to the absolute salinity scale using Eq. (3) and the temperature should be

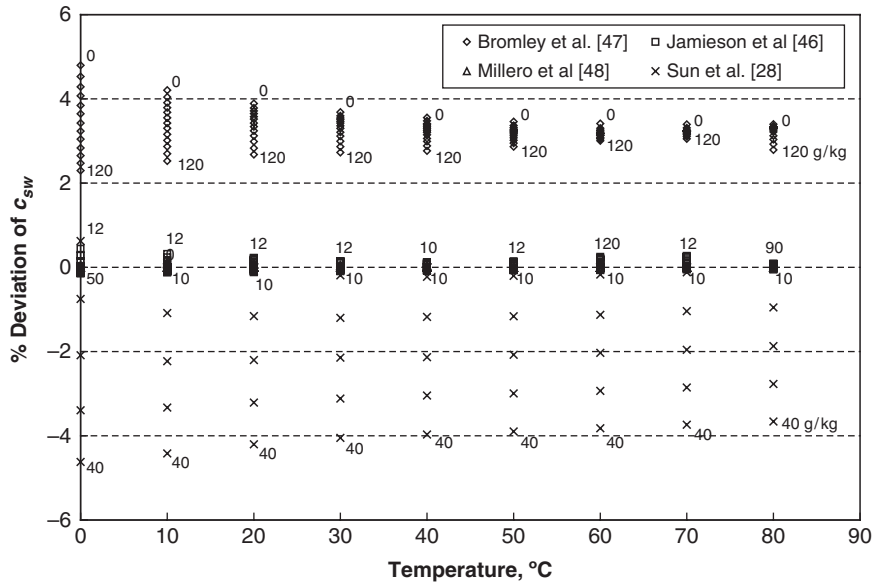


Fig. 4. Deviation of seawater specific heat calculated using Eqs (9)–(12) from that calculated using IAPWS (2008) formulation at salinity 0–120 g/kg (numbers in the figure refer to salinity in g/kg).

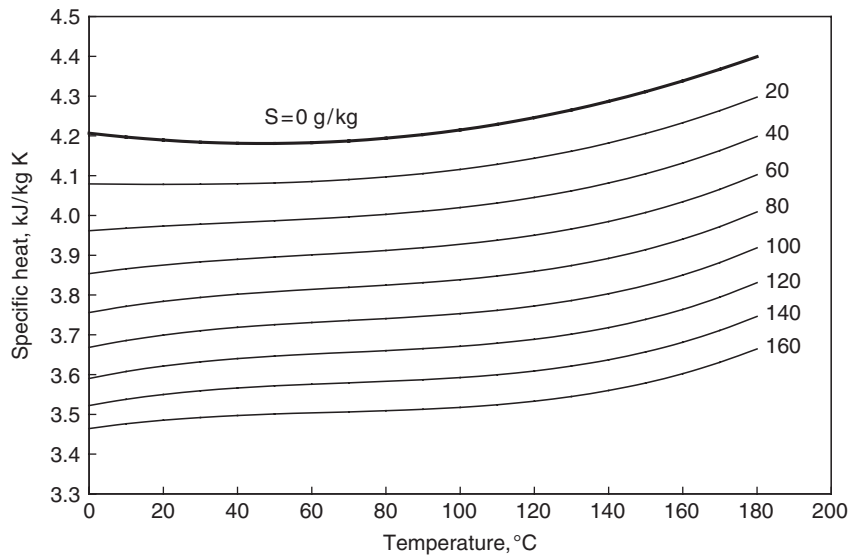


Fig. 5. Seawater specific heat variations with temperature and salinity calculated using Eq. (9).

converted to the International temperature scale, ITS-90 using Eq. (4).

As an alternative to Eq. (9), one could use the seawater Gibbs function of the IAPWS-2008 formulation for seawater, which has 64 coefficients to calculate the salt part of the specific heat and the Gibbs function of the IAPWS-95 formulation for pure water, which has 34 coefficients to calculate the specific heat of freshwater, then adding these to get the specific heat of seawater. This calculation will have temperature and salinity ranges less than Eq. (9) and of the same order of accuracy. Figure 5 shows the specific

heat of seawater calculated from Eq. (9) as it changes with temperature and salinity.

#### 4. Thermal conductivity

The thermal conductivity is one of the most difficult liquid properties to measure, and data on seawater thermal conductivity is consequently very limited. For aqueous solutions containing an electrolyte, such as seawater, the thermal conductivity usually decreases with an increase in the concentration of the dissolved salts



Table 4  
Seawater thermal conductivity correlations.

Correlation	Ref.
$\log_{10}(k_{sw}) = \log_{10}(240 + 0.0002 S_p) + 0.434 \left( 2.3 - \frac{343.5 + 0.037 S_p}{t_{68} + 273.15} \right) \left( 1 - \frac{t_{68} + 273.15}{647 + 0.03 S_p} \right)^{0.333}$	[58]
Validity: $k_{sw}$ in (mW/m K); $0 < t_{68} < 180$ °C; $0 < S_p < 160$ g/kg Accuracy: $\pm 3$ %	
$k_{sw} = 0.5715 (1 + 0.003 t_{68} - 1.025 \times 10^{-5} t_{68}^2 + 6.53 \times 10^{-3} p - 0.00029 S_p)$	[59]
Validity: $k_{sw}$ in (W/m K); $0 < t_{68} < 60$ °C; $0 < S_p < 60$ g/kg; $0.1 < p < 140$ MPa Accuracy: $\pm 0.5$ %	
$k_{sw} = 0.55286 + 3.4025 \times 10^{-4} p + 1.8364 \times 10^{-3} t_{68} - 3.3058 \times 10^{-7} t_{68}^3$	[60]
Validity: $k_{sw}$ in (W/m K); $0 < t_{68} < 30$ °C; $S_p = 35$ g/kg; $0.1 < p < 140$ MPa Accuracy: $\pm 0.4$ %	

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(Poling et al. [52]). To estimate the thermal conductivity of electrolyte mixtures, Jamieson and Tudhope [53] recommend an equation that involves the concentration of each electrolyte in the solution and a coefficient that is characterized for each ion. This equation predicts the thermal conductivity at a temperature of 293 K. However, for other temperatures and pressures, experimental measurements are needed.

The thermal conductivity of seawater has been measured by few researchers [54–60]. These measurements have been carried out for both natural and synthetic seawater. The best fit correlations for these experimental measurements are given in Table 4 with the range of

validity, units and accuracy. Equation (13) is given by Jamieson and Tudhope [58] based on measurements of synthetic seawater for temperatures 0–180°C, salinities 0–160 g/kg, and has an accuracy of  $\pm 3\%$ . Equation (14) is given by Caldwell [59] based on measurements of natural seawater for temperatures 0–60°C, salinities 0–60 g/kg, pressure 0.1–140 MPa, and has an accuracy of  $\pm 0.5\%$ . Equation (15) is given by Castelli et al. [60] based on measurements of standard seawater for temperatures 0–30°C, salinity of 35 g/kg, pressure 0.1–140 MPa, and has an accuracy of  $\pm 0.002$  W/m K.

Figure 6 shows the thermal conductivity values calculated from Eqs. (13)–(15), the data given in [54–57] at

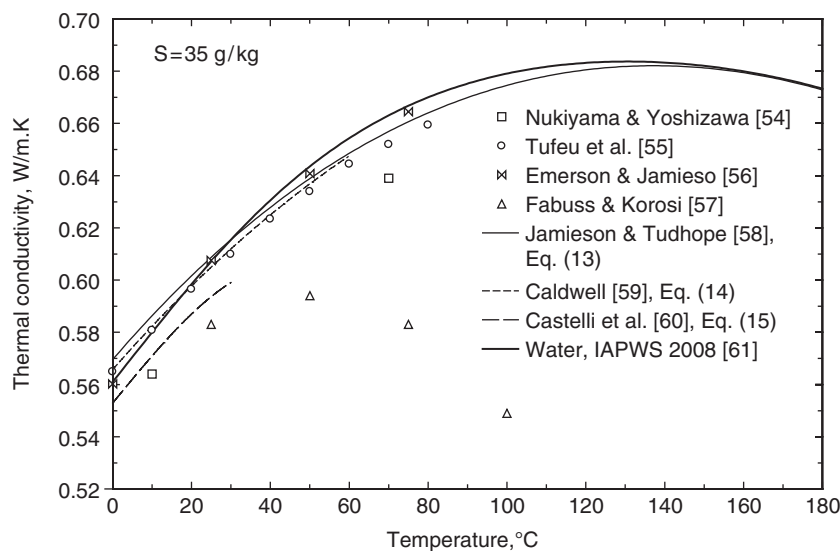


Fig. 6. Seawater thermal conductivity vs. temperature at a salinity of 35 g/kg.

salinity of 35 g/kg and the pure water thermal conductivity given by IAPWS 2008 [61]. The figure shows good agreement between equations (13,14) and less agreement of Eq. (15) and the data of [54,57]. However, Eqs. (13) and (14) give a thermal conductivity slightly higher than that of the pure water at lower temperature which is questionable on theoretical grounds. In addition, equations (13) and (14) give a difference of about  $\pm 2\%$  from the pure water thermal conductivity at zero salinity. Therefore, there is a need for further seawater measurements, particularly at higher salinities and lower temperatures. However, it is recommended to use Eq. (13) of Jamieson and Tudhope [58] for thermal conductivity calculations at temperatures above  $40^\circ\text{C}$  as the calculated values agree well (within  $\pm 1\%$ ) with other measurements [55,56,59].

### 5. Dynamic viscosity

Available data on seawater viscosity are those by Krummel [62] (for  $t = 0\text{--}30^\circ\text{C}$ ,  $S = 5\text{--}40$  g/kg), Miyake and Koizumi [63] (for  $t = 0\text{--}30^\circ\text{C}$ ,  $S = 5\text{--}40$  g/kg), Fabuss et al. [64] (for  $t = 25$  to  $150^\circ\text{C}$ ,  $S$  up to 110 g/kg and calcium-free synthetic seawater), Stanley and Butten [65] (for  $t = 0$  to  $30^\circ\text{C}$ ,  $p = 0.1\text{--}140$  MPa and  $S = 35$  g/kg), and Isdale et al. [66] (for  $t = 20\text{--}180^\circ\text{C}$ ,  $S = 0\text{--}150$  g/kg and synthetic seawater). The available correlations that best fit these experimental measurements are given in Table 5.

Equation (16) is given by Fabuss et al. [64] and is a fit to the measured data using Othmer's rule (Othmer and Yu [67]). According to this rule, the logarithm of the ratio of the viscosity of an aqueous solution of a given concentration to the viscosity of pure water is a linear function of the logarithm of water viscosity at the same temperature. The pure water viscosity used in their correlation was given by Dorsey [68] which has a maximum difference of  $\pm 1\%$  from IAPWS 2008 [73] (Eq. 23). Equation (16) requires the knowledge of the total ionic strength of the seawater which can be calculated from the practical salinity using Eq. (17). The accuracy of Eq. (16) is believed to be within  $\pm 0.4\%$  according to Fabuss et al. [64].

Equation (18), given by Millero [69], estimates the viscosity of seawater within the experimental error of the associated data, and is based on Young's Rule (the mixing of two binary solutions of the same ionic strength produces a ternary solution whose volume is the sum of the two binary solutions). This equation has a small range of temperature and salinity and requires the seawater density to convert from salinity to volume chlorinity. Also in this correlation, Millero used the equation given by Korson et al. [70] (Eq. 19) for the pure water viscosity. Equation (20) is given by Isdale et al. [66] based on measurements carried out on synthetic seawater, valid for temperatures

$10\text{--}180^\circ\text{C}$ , salinities  $0\text{--}150$  g/kg with an accuracy of  $\pm 1\%$ . The expression for pure water viscosity used in Eq. (20) was given by Korosi and Fabuss [72] (Eq. 21).

At zero salinity (pure water), the viscosity calculated using Eqs. (16), (18) and (20) limit to the pure water viscosity as given by Dorsey [68], Korson et al. [70] and Korosi and Fabuss [72] respectively. The most recent pure water viscosity correlation is that one given by IAPWS 2008 [73]. The pure water viscosity given by Dorsey, Korson et al. and Korosi and Fabuss differs from that calculated by IAPWS by a maximum difference of  $\pm 0.82\%$ ,  $\pm 0.16\%$  and  $\pm 2.14\%$  respectively. Therefore, the seawater viscosity data of Fabuss [64], Isdale et al. [66] and Millero [69] are normalized using the pure water viscosity data of IAPWS 2008 [73]. The normalized data is fit to Eq. (22) which has a correlation coefficient of 0.999, a maximum deviation of  $\pm 1.5\%$  from the measured data. In addition, the pure water viscosity data of IAPWS 2008 [73] is fit by Eq. (23) which has a maximum deviation of  $\pm 0.05\%$  and valid for  $t = 0\text{--}180^\circ\text{C}$ .

Figure 7 shows the percentage deviation of the seawater viscosity calculated by Eq. (22) and the data given by Fabuss [64], Isdale et al. [66] and Millero [69]. At salinity equal to zero, the viscosity calculated from Eq. (22) is equal to that of pure water given by IAPWS 2008 [73] with an error of  $\pm 0.05\%$ . Figure 8 shows the viscosity of seawater calculated using Eq. (22) as it changes with temperature and salinity. It is shown that the viscosity decreases with temperature and increases with salinity. The increase with salinity has a maximum of 40% at  $180^\circ\text{C}$  and 120 g/kg salinity.

### 6. Surface tension

Surface tension is a property of liquids arises from unbalanced molecular cohesive forces at or near the liquid surface. The general trend for liquid surface tension is that it decreases with an increase of temperature, reaching a value of zero at the critical point temperature. Solutes can have different effects on surface tension depending on their structure. Inorganic salts, which are the type of salts in seawater, increase the surface tension of the solution. Organic contamination in seawater may also have a considerable effect on the surface tension, particularly when surfactants are involved.

Measurements of seawater surface tension are very scarce in the literature and encompass only a limited range of temperature and salinity. The available correlations for seawater surface tension are listed in Table 6. An empirical correlation (Eq. 24) for seawater surface tension was given by Krummel [74] based on his measurements of the difference between distilled water and natural seawater surface tension using the bubble pressure method

Table 5  
Seawater dynamic viscosity correlations.

Correlation	Ref.
$\log_{10} \left( \frac{\mu_{sw}}{\mu_w} \right) = 0.0428I + 0.00123I^2 + 0.000131I^3 + (-0.03724I + 0.01859I^2 - 0.00271I^3) \log_{10} (10^3 \times \mu_w)$	[64]
<p>where</p> <p><math>\mu_w</math> is the pure water viscosity in (kg/m s) given by Dorsey [68]</p> <p><math>I</math> is the ionic strength given by <math>I = 19.915 S_p / (1 - 1.00487 S_p)</math></p> <p>Validity: <math>20 &lt; t &lt; 150^\circ\text{C}</math>; <math>15 &lt; S_p &lt; 130</math> g/kg</p> <p>Accuracy: <math>\pm 0.4\%</math></p>	
$\mu_{sw} = \mu_w (1 + A Cl^{1/2} + B Cl)$ <p><math>A = 5.185 \times 10^{-5} t_{68} + 1.0675 \times 10^{-4}</math> and <math>B = 3.300 \times 10^{-5} t_{68} + 2.591 \times 10^{-3}</math></p>	[69]
<p><math>Cl</math> is the volume chlorinity which is related to salinity by <math>Cl = \rho_{sw} S_p / 1806.55</math></p> <p><math>\mu_w</math> is the pure water viscosity in (kg/m s) given by Korson et al. [70]</p> $\log_{10} (\mu_w / \mu_{20}) = (1.1709 (20 - t_{68}) - 0.001827 (t_{68} - 20)^2) / (t_{68} + 89.93)$	[70]
<p><math>\mu_{20}</math> is the viscosity of distilled water at <math>20^\circ\text{C}</math> which is equal to <math>1.002 \times 10^{-3}</math> kg/m.s (Swindells et al. [71]).</p> <p>Validity: <math>\mu_{sw}</math> in (kg/m.s); <math>5 &lt; t_{68} &lt; 25^\circ\text{C}</math>; <math>0 &lt; S_p &lt; 40</math> g/kg</p> <p>Accuracy: <math>\pm 0.5\%</math></p>	
$\mu_{sw} = \mu_w (1 + A S_p + B S_p^2)$ <p><math>A = 1.474 \times 10^{-3} + 1.5 \times 10^{-5} t_{68} - 3.927 \times 10^{-8} t_{68}^2</math></p> <p><math>B = 1.073 \times 10^{-5} - 8.5 \times 10^{-8} t_{68} + 2.230 \times 10^{-10} t_{68}^2</math></p>	[66]
<p><math>\mu_w</math> is the pure water viscosity given by Korosi and Fabuss [72]</p> $\ln (\mu_w) = -0.00379418 + (0.604129/139.18 + t_{68})$	
<p>Validity: <math>\mu_{sw}</math> in (kg/m.s); <math>\mu_w</math> in (kg/m.s); <math>10 &lt; t_{68} &lt; 180^\circ\text{C}</math>; <math>0 &lt; S_p &lt; 150</math> g/kg</p> <p>Accuracy: <math>\pm 1\%</math></p>	
$\mu_{sw} = \mu_w (1 + A S + B S^2)$ <p><math>A = 1.541 + 1.998 \times 10^{-2} t - 9.52 \times 10^{-5} t^2</math></p> <p><math>B = 7.974 - 7.561 \times 10^{-2} t + 4.724 \times 10^{-4} t^2</math></p>	[22]
<p><math>\mu_w</math> is based on the IAPWS 2008 [73] data and given by</p> $\mu_w = 4.2844 \times 10^{-5} + (0.157 (t + 64.993)^2 - 91.296)^{-1}$	[23]
<p>Validity: <math>\mu_{sw}</math> and <math>\mu_w</math> in (kg/m.s); <math>0 &lt; t &lt; 180^\circ\text{C}</math>; <math>0 &lt; S &lt; 0.15</math> kg/kg</p> <p>Accuracy: <math>\pm 1.5\%</math></p>	

(Jaeger's method). The measurements were carried out in the temperature range  $0\text{--}40^\circ\text{C}$  and salinity range  $10\text{--}35$  g/kg. A modified form of Krummel's equation was given by Fleming and Revelle [75] (Eq. 25); they

modified the pure water surface tension component keeping the salinity contribution the same.

Guohua et al. [76] measured the surface tension of oceanic seawater in the temperature range  $15\text{--}35^\circ\text{C}$

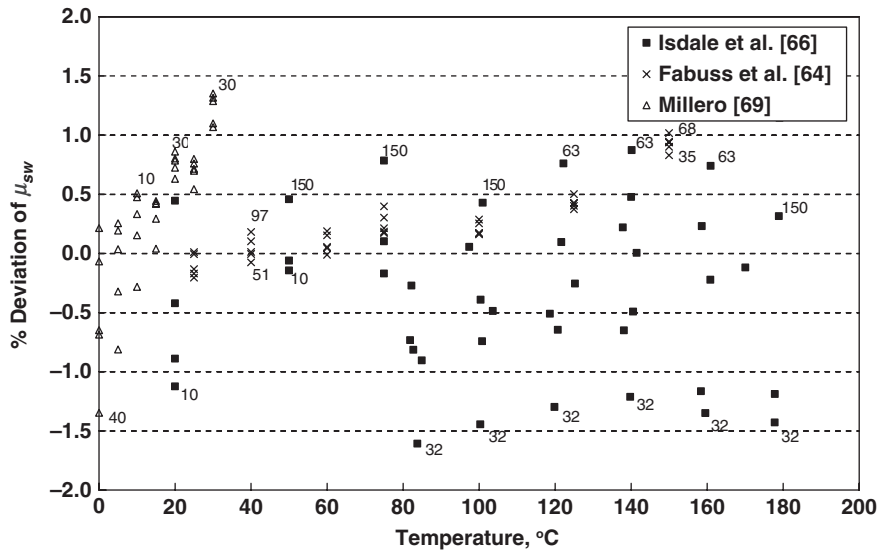


Fig. 7. Deviation of the seawater viscosity data from Eq. (22) for  $S = 0\text{--}150$  g/kg (numbers in the figure refer to salinity in g/kg).

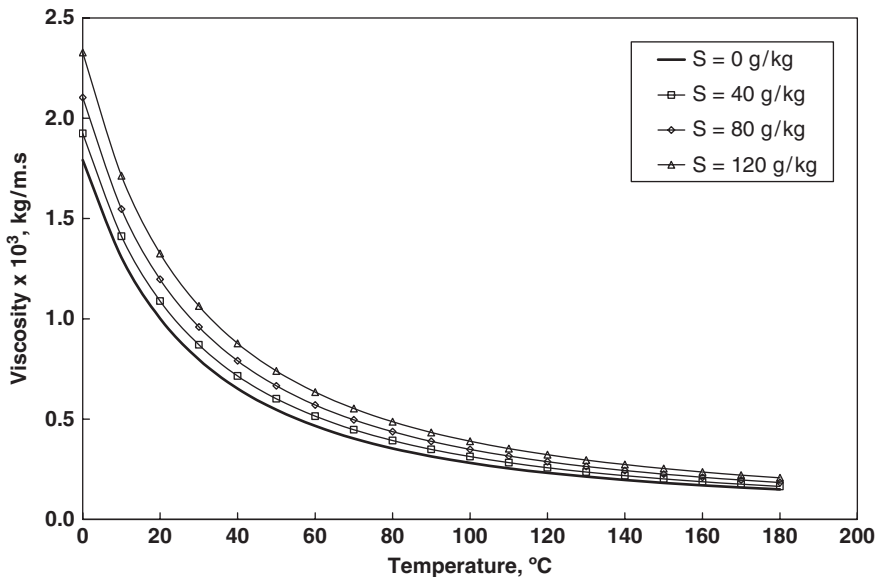


Fig. 8. Seawater viscosity variations with temperature and salinity calculated using Eq. (22).

and salinity range 5–35 g/kg by the maximum-bubble-pressure method. The uncertainty of the measurements is believed to be within  $\pm 0.07$  mN/m. A seawater sample with salinity of 34.5 g/kg was obtained from the North Pacific near Japan. Samples with salinity below 34.5 g/kg were prepared by dilution with pure water. An empirical correlation (Eq. 26) was obtained on the basis of these measurements; it gives the surface tension of seawater as a function of temperature and salinity with a correlation coefficient of 0.996.

At zero salinity (pure water), the surface tension calculated using equations 24, 25 and 26 differs from that

calculated using the 1994 IAPWS standard [77] (Eq. 27) by a maximum difference of  $\pm 0.5\%$ ,  $\pm 0.4\%$ , and  $\pm 0.9\%$  respectively. Also these equations are not consistent with the pure water formula in the limit of zero salinity. Therefore, the seawater surface tension data of Krummel [74] and Chen et al. [76] are fit to the modified Szyskowski equation given in Poling et al. [52] for the surface tension of aqueous solutions. The pure water surface tension calculated by Eq. (27) is used to normalize the measured seawater surface tension data; and a best fit correlation is obtained as Eq. (28), which has a correlation coefficient of 0.999 and a maximum deviation of  $\pm 0.13$  mN/m.

Table 6  
Seawater and pure water surface tension correlations.

Correlation	Ref.
$\sigma_{sw} = 77.09 - 0.1788 t_{27} + 0.0221 S_K \quad (24)$	[74]
Validity: $\sigma_{sw}$ in (mN/m); $0 < t_{27} < 40$ °C; $10 < S_K < 35$ g/kg Accuracy: not available in literature cited	
$\sigma_{sw} = 75.64 - 0.144 t_{27} + 0.0221 S_K \quad (25)$	[75]
Validity: $\sigma_{sw}$ in (mN/m); $0 < t_{27} < 40$ °C; $10 < S_K < 35$ g/kg Accuracy: not available in literature cited	
$\sigma_{sw} = 75.59 - 0.13476 t + 0.021352 S_p - 0.00029529 S_p t \quad (26)$	[76]
Validity: $\sigma_{sw}$ in (mN/m); $15 < t < 35$ °C; $5 < S_p < 35$ g/kg Accuracy: $\pm 0.1\%$	
$\sigma_w = 0.2358 \left( 1 - \frac{t + 273.15}{647.096} \right)^{1.256} \left[ 1 - 0.625 \left( 1 - \frac{t + 273.15}{647.096} \right) \right] \quad (27)$	[77]
Validity: $\sigma_w$ in (N/m); $0.01 < t < 370$ °C Accuracy: $\pm 0.08\%$	
$\frac{\sigma_{sw}}{\sigma_w} = 1 + (0.000226 \times t + 0.00946) \ln(1 + 0.0331 \times S) \quad (28)$	
Validity: $0 < t < 40$ °C; $0 < S < 40$ g/kg Accuracy: $\pm 0.18\%$	

Figure 9 shows the percentage difference between the seawater surface tension calculated by Eq. (28) and the data given by Krummel [74] and Guohua et al. [76]. The maximum deviation is  $\pm 0.28\%$  which is within the uncertainty of the experimental method used for determining the surface tension (not less than  $\pm 0.5\%$  for the bubble pressure method, Levitt [78]). At salinity equal to zero, the seawater surface tension calculated by Eq. (28) is equal to that of pure water calculated using Eq. (27) (IAPWS 1994 [77]). However, the applicable range of temperature and salinity is limited and more experimental measurements are needed. Further, the effects of organic contamination on surface tension may be considerably larger than the effects contained in these correlations, e.g., if a surfactant is present. Figure 10 shows the surface tension of seawater calculated using Eq. (28) as it changes with temperature and salinity. It is shown that the surface tension decreases with temperature and increases with salinity. The increase with salinity has a maximum of 1.5% at 40 °C and 40 g/kg salinity.

## 7. Vapor pressure and boiling point elevation

Increasing the salinity of seawater lowers the vapor pressure and hence the boiling temperature of seawater is higher than that of pure water at a given pressure by

an amount called the boiling point elevation (BPE). The vapor pressure and boiling temperature can be obtained from each other by inverting the boiling temperature function or the vapor pressure function respectively. In addition, seawater vapor pressure can be calculated from osmotic pressure data or freezing temperature data.

As a first approximation, Raoult's law can be used to estimate the vapor pressure of seawater assuming an ideal solution. According to this law, the vapor pressure of seawater ( $p_{v,sw}$ ) is equal to the product of the water mole fraction in seawater ( $x_w$ ) and water's vapor pressure in the pure state ( $p_{v,w}$ ). The mole fraction of water in seawater is a function of the salinity given, for example, by Bromley et al. [79]. Using these results, a simple equation for seawater vapor pressure based on Raoult's law is given by Eq. (29) in Table 7. However, the assumption of ideal seawater solution ignores the interactions between the various ions. The theories of these interactions have been worked out accurately only for dilute solutions, and it is therefore better to have experimental measurements.

Experimental measurements of seawater vapor pressure and boiling point have been carried out by many researchers [29,31,56,79–84]. Correlations of seawater vapor pressure and boiling point elevation are listed in Table 7. Equation (30) for seawater vapor pressure is

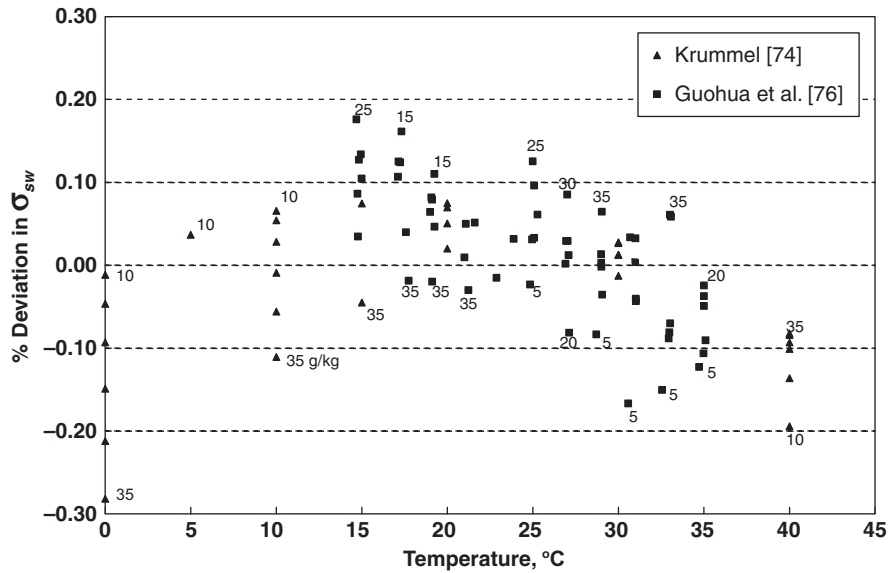


Fig. 9. Deviation of the seawater surface tension data from Eq. (28) for  $S = 0\text{--}35$  g/kg (numbers in the figure refer to salinity in g/kg).

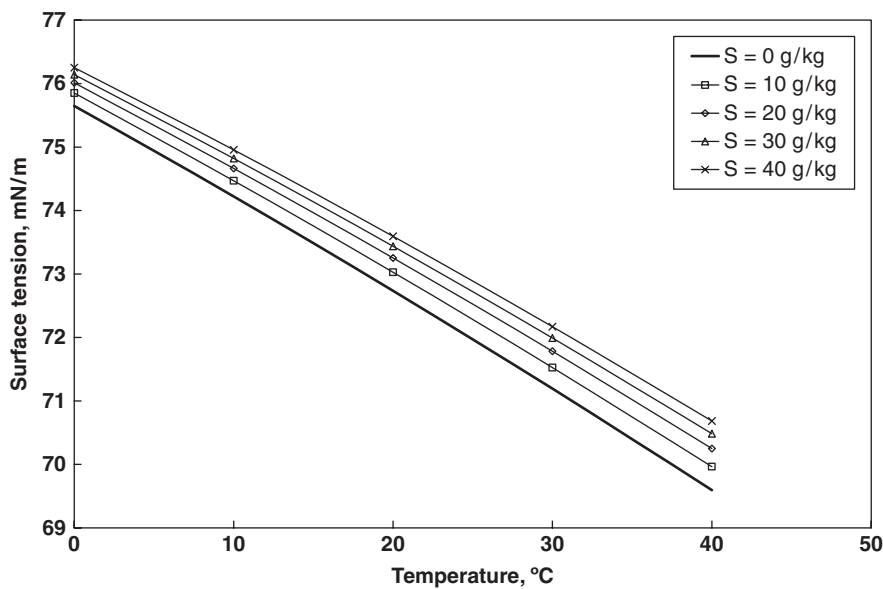


Fig. 10. Seawater surface tension variations with temperature and salinity calculated using Eq. (28).

given by Robinson [82] based on the measurements carried out on natural and synthetic seawater for chlorinities between 10 and 22 g/kg (salinity 18–40 g/kg) and at 25°C with an estimated accuracy of  $\pm 0.2\%$ . The vapor pressure of pure water at 25°C in Eq. (30) is given by Robinson [82] as 3167.2 Pa which differs from the IAPWS-95 [24] value by  $\pm 0.003\%$ . Equation (31) is given by Emerson and Jamieson [56] based on the measurements carried out on synthetic seawater in the temperature range 100–180°C and salinities 30–170 g/kg. The vapor pressure of

pure water is taken from NEL steam Tables [86] which has a maximum deviation of  $\pm 0.1\%$  from the IAPWS 1995 [24] values. Equation (32) is given by Weiss and Price [87] based on the measurements carried out by Robinson [82] at 25°C. However, Weiss and Price [87] mentioned that their equation (Eq. 32) may be used for temperature range 0–40°C and salinities 0–40 g/kg with an accuracy of  $\pm 0.015\%$ . Equation (33) is given by Millero [88] based on a model that fitted vapor pressure data which were derived from experimental osmotic coefficient data. This



Table 7  
Seawater vapor pressure and boiling point elevation correlations.

Correlation	Ref.
$p_{v,w}/p_{v,sw} = 1 + 0.57357 \times \left( \frac{S}{1000 - S} \right)$	(29)
<p>based on Raoult's law assumption, <math>S</math> in g/kg</p> $(p_{v,w} - p_{v,sw})/p_{v,w} = 9.206 \times 10^{-4} Cl + 2.360 \times 10^{-6} Cl^2$	[82]
<p>Validity: <math>p_{v,w} = 3167.2</math> Pa at <math>25</math> °C; <math>t_{48} = 25</math> °C; <math>10 &lt; Cl &lt; 22</math> % Accuracy: <math>\pm 0.2</math> %</p>	
$\log_{10} (p_{v,sw}/p_{v,w}) = -2.1609 \times 10^{-4} S_p - 3.5012 \times 10^{-7} S_p^2$	[56]
<p><math>p_{v,w}</math> data from NEL steam Tables [86] Validity: <math>100 &lt; t_{48} &lt; 180</math> °C; <math>35 &lt; S_p &lt; 170</math> g/kg Accuracy: <math>\pm 0.07</math> %</p>	
$\ln (p_{v,sw}) = 24.4543 - 67.4509 (100/T_{48}) - 4.8489 \ln (T_{48}/100) - 5.44 \times 10^{-4} S_p$	[87]
<p>Validity: <math>p_{v,sw}</math> in (atm); <math>273 &lt; T_{48} &lt; 313</math> K; <math>0 &lt; S_p &lt; 40</math> g/kg; Accuracy: <math>\pm 0.015</math> %</p>	
$p_{v,sw} = p_{v,w} + AS_p + BS_p^{3/2}$	[88]
$A = -2.3311 \times 10^{-3} - 1.4799 \times 10^{-4} t_{68} - 7.520 \times 10^{-6} t_{68}^2 - 5.5185 \times 10^{-8} t_{68}^3$	
$B = -1.1320 \times 10^{-5} - 8.7086 \times 10^{-6} t_{68} + 7.4936 \times 10^{-7} t_{68}^2 - 2.6327 \times 10^{-8} t_{68}^3$	
<p><math>p_{v,w}</math> data from Ambrose and Lawrenson [88] Validity: <math>p_{v,sw}</math> and <math>p_{v,w}</math> in (mm Hg); <math>0 &lt; t_{68} &lt; 40</math> °C; <math>0 &lt; S_p &lt; 40</math> g/kg; Accuracy: <math>\pm 0.02</math> %</p>	
$BPE = \frac{S_p T_{68}^2}{13832} \left[ 1 + 0.00137 T_{68} + 17.86 S_p - 0.00272 T_{68} \sqrt{S_p} - \frac{2.5835 (1 - S_p)}{T_{68}} - 0.0152 S_p T_{68} \left( \frac{T_{68} - 225.9}{T_{68} - 236} \right) \right]$	[79]
<p>Validity: <math>BPE</math> in (K); <math>273.15 \leq T_{68} \leq 473.15</math> K; <math>0 \leq S_p \leq 0.12</math> kg/kg; Accuracy: <math>\pm 0.1</math> %</p>	
$BPE = A (S_p / 34.46) + B (S_p / 34.46)^2$	[85]
$A = 0.2009 + 0.2867 \times 10^{-2} t_{48} + 0.002 \times 10^{-4} t_{48}^2$	
$B = 0.0257 + 0.0193 \times 10^{-2} t_{48} + 0.0001 \times 10^{-4} t_{48}^2$	
<p>Validity: <math>BPE</math> in (K); <math>20 \leq t_{48} \leq 180</math> °C; <math>35 \leq S_p \leq 100</math> g/kg; Accuracy: <math>\pm 0.7</math> %</p>	
$BPE = A S^2 + B S$	[86]
$A = -4.584 \times 10^{-4} t^2 + 2.823 \times 10^{-1} t + 17.95$	
$B = 1.536 \times 10^{-4} t^2 + 5.267 \times 10^{-2} t + 6.56$	
<p>Validity: <math>BPE</math> in (K); <math>0 \leq t \leq 200</math> °C; <math>0 \leq S \leq 0.12</math> kg/kg; Accuracy: <math>\pm 0.018</math> K</p>	

equation has a limited range of temperature and salinity and the vapor pressure of pure water is calculated from the best fit correlation given by Ambrose and Lawrenson [89] which has a maximum deviation of  $\pm 0.15\%$  from the IAPWS-95 [24] values.

For the boiling point elevation of seawater, Eq. (34) is given by Bromley et al. [79] based on measurements of the boiling point of natural seawater up to  $200^\circ\text{C}$  and  $120\text{ g/kg}$  salinity with an accuracy of  $\pm 2\%$ . Equation (35) is given by Fabuss and Korosi [85] based on vapor pressure data [29,81,84] and using the rule of additivity of molar vapor pressure depressions. Another correlation is given by Stoughton and Lietzke [90] using the extended Debye-Huckel theory and the osmotic coefficient data of Rush and Johnson [91] for sodium chloride solutions. This theoretically based equation has significant differences from the other reported values (as mentioned by Bromley et al. [79]) therefore it is not given in Table 7.

It is important to mention that the IAPWS 2008 formulation for seawater thermodynamic properties [27] did not give an explicit equation for the vapor pressure or boiling point of seawater as such an equation can not be derived from the Gibbs energy function explicitly. However, the vapor pressure and boiling point should satisfy the equilibrium requirement that the chemical potential of vapor is equal to the chemical potential of water in seawater which requires an iterative procedure. Therefore, the IAPWS 2008 Gibbs energy function used the vapor pressure data of Robinson [82] and the boiling point data of Bromley et al. [79] to satisfy this thermodynamic rule in its regression process.

From the above discussion, Eq. (31) given by Emerson and Jamieson [56] and Eq. (34) given by Bromley

et al. [79] are the best correlations for the seawater vapor pressure and boiling point elevation respectively because they are based on experimental measurements and have less deviation from the measured data. However, there is a need for temperature and salinity conversions. Therefore, based on the data of Bromley et al. [79] for boiling point elevation, a new best fit correlation is obtained (Eq. 36) that has a maximum deviation of  $\pm 0.018\text{ K}$  from that calculated using Eq. (34) of Bromley et al. [79]. Figure 11 shows the boiling point elevation calculated using Eq. (36) as it changes with temperature and salinity. The boiling point elevation increases with temperature and salinity. It has a maximum value of  $3.6\text{ K}$  at  $t = 200^\circ\text{C}$  and  $S = 120\text{ g/kg}$ .

## 8. Latent heat of vaporization

Latent heat of vaporization is the amount of heat required to transform a unit mass from the liquid to the gaseous state. For pure water, the latent heat of vaporization depends on temperature. For seawater, no formulae appear to be available for the change of latent heat with salinity and temperature [3].

When water evaporates from seawater, the latent heat of vaporization is the difference between the vapor's specific enthalpy, which is the same as that for pure water, and the partial specific enthalpy of water in the seawater solution (Glasstone [92]). As a first approximation, the partial specific enthalpy of water in seawater can be determined by treating seawater as an ideal solution. In this case, the partial specific enthalpy of water in the solution is equal to the specific enthalpy of

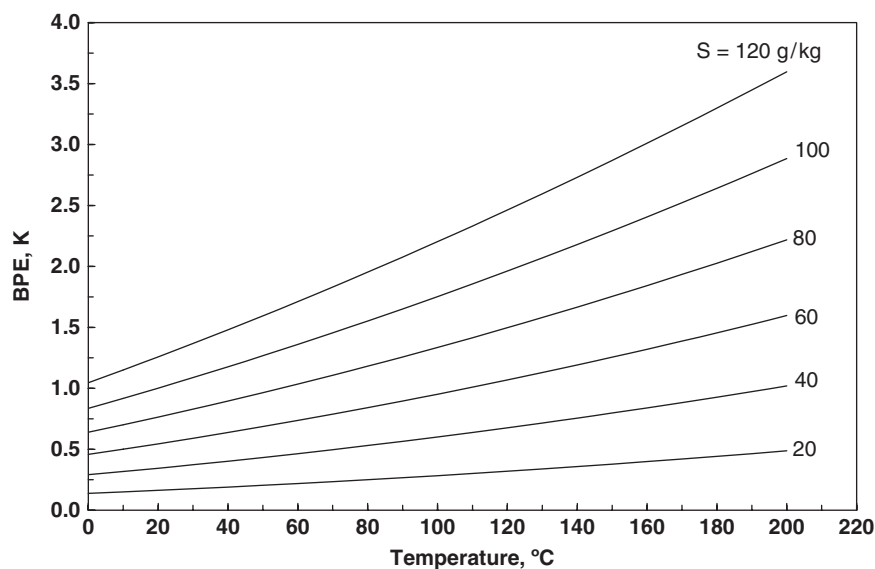


Fig. 11. Seawater BPE variations with temperature and salinity calculated using Eq. (36).

pure water. Therefore, the latent heat of vaporization of seawater is the enthalpy of vaporization of pure water. However, this quantity is per unit mass of water and it is required to convert to unit mass of seawater by using the salinity definition. Thus, a simple equation can be derived for the latent heat of seawater as a function of the latent heat of pure water and salinity:

$$h_{fg,sw} = h_{fg,w} \times (1 - S/1000) \quad (37)$$

On the other hand, if seawater is not treated as an ideal solution, the partial specific enthalpy of water in seawater solution is given by Bromley et al. [79]

$$\bar{h}_w = h_w + \frac{RT^2}{1000} \frac{\partial \phi}{\partial T} M \quad (38)$$

where  $\phi$  is the osmotic coefficient,  $\bar{h}_w$  is the partial specific enthalpy of water in seawater per unit mass of pure water,  $h_w$  is the specific enthalpy of pure water per unit mass of pure water and  $M$  is the total molality of all solutes. Hence the latent heat of vaporization of seawater can be written as;

$$h_{fg,sw} = (1 - S/1000) \left( h_{fg,w} - \frac{RT^2}{1000} \frac{\partial \phi}{\partial T} M \right) \quad (39)$$

Using the data of Bromley et al. [79] for the osmotic coefficient of seawater, the latent heat of vaporization of seawater can be calculated from Eq. (39). It is found that the second term in the second bracket of Eq. (39) is very small and that the deviation of the latent heat from the ideal seawater solution assumption is negligible. Therefore, Eq. (37) can be instead used to estimate the latent heat of seawater. Figure 12 shows the latent heat

of vaporization of seawater calculated from Eq. (37) as it changes with temperature and salinity.

## 9. Enthalpy

The enthalpy is always measured as a change of enthalpy relative to a specified datum. Seawater is modeled as a binary mixture of water and sea salts (the latter being held in a fixed proportion to one another). Therefore, the enthalpy of seawater at constant temperature and pressure, is given by [93]

$$h_{sw} = x_s \bar{h}_s + (1 - x_s) \bar{h}_w \quad (40)$$

where  $\bar{h}_s$  is the partial specific enthalpy of sea salt, J/kg salts;  $\bar{h}_w$  the partial specific enthalpy of water, J/kg water; and  $x_s$  is the mass fraction of salts in solution. Both partial enthalpies can be evaluated from calorimetric measurements of heat capacity and heat of mixing of sea salt solutions (Millero [94]).

As mentioned previously, experimental measurements of seawater specific heat are available over a wide range of temperature and salinity. Data on heat of mixing is also available, but with a limited range of temperature. Bromley [95] measured heats of dilution and concentration of seawater at 25°C and up to a salinity of 108 g/kg. Connors [96] published experimental data on mixing seawater samples with equal volumes for salinities up to 61 g/kg at temperatures from 2 to 25°C. Millero et al. [97] published experimental data of diluting seawater samples for a salinity range of 0–42 g/kg and a temperature range of 0–30°C. Singh and Bromley [93] evaluated the partial molar enthalpies of sea salts and water in seawater solutions, in the temperature range

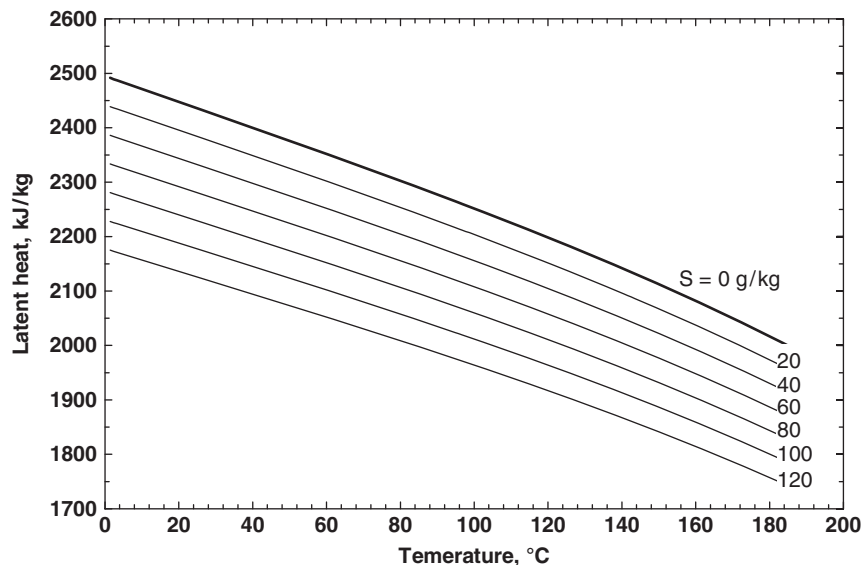


Fig. 12. Seawater latent heat variations with temperature and salinity calculated using Eq. (37).

0–75°C and salinity range 0–120 g/kg, from calorimetric measurements of heats of mixing of sea salt solutions.

Available correlations for seawater specific enthalpy are given in Table 8. Equation (41) is given by Connors [96] based on the heat capacity data of Cox and Smith [44], and his enthalpies of mixing within a temperature range of 0–30°C and salinities of 10–40 g/kg. Equation (42) is given by Millero [94] based on specific heat data within a temperature range of 0–40°C and salinities of 0–40 g/kg. Other data for the specific enthalpy of seawater is given in Fabuss [2] based on Bromley et al. [47] measurements. In addition, the enthalpy of seawater can be calculated using the IAPWS seawater Gibbs energy function [27] (with 64 coefficients) and using thermodynamic relationship between the enthalpy and Gibbs energy.

A new best fit equation (Eq. 43) is obtained in the present work to correlate the seawater specific enthalpy data calculated by the Gibbs energy function of IAPWS 2008 [27] for a temperature range of 10–120°C and salinity of 0–120 g/kg. The pure water specific enthalpy part in this equation is calculated from IAPWS 1995 [24] which can be obtained also from steam Tables. Equation (43) has a maximum deviation of ±0.5% and has a correlation coefficient of 0.9995. Figure 13 shows the percentage deviation of the seawater specific enthalpy calculated using Eqs. (41)–(43) and the data of Bromley et al. [47] from that calculated using the IAPWS 2008 formulation [27] taking the enthalpy value at zero

temperature and zero salinity as a datum value. Equation (41) of Connors [96] gives a maximum deviation of ±1.5%, Eq. (42) of Millero [94] gives a maximum deviation of ±6.8%, and Eq. (43) of the present work gives a maximum deviation of ±0.5%. Therefore, it is recommended to use Eq. (43) which is simple but accurately agrees well with the IAPWS 2008 release over wide range of temperature and salinity. Moreover, the temperature and salinity scales are the International Temperature Scale (ITS-90) and the reference-composition salinity respectively. Figure 14 shows the specific enthalpy of seawater calculated using Eq. (43) as it changes with temperature and salinity. It is shown that the enthalpy increases with temperature but decreases with salinity. The decrease with salinity has a maximum of 14% at 120°C and 120 g/kg salinity.

### 10. Entropy

There is scientific and technical interest in seawater entropy for energy analysis of desalination plants and for oceanographic applications such as thermohaline process studies. The entropy cannot be measured directly; however, it can be calculated if an equation of state is known. It can be derived by differentiating the Gibbs energy function with respect to temperature at constant pressure. There are few correlations that

Table 8  
Seawater specific enthalpy correlations.

Correlation	Ref.
$h_{sw} = 4.2044t_{68} - 0.00057t_{68}^2 - S_p (6.99t_{68} - 0.0343t_{68}^2) - S_p^2 (464 - 19.6t_{68} + 0.3t_{68}^2)$ <p>Validity: <math>h_{sw}</math> in (kJ/kg); <math>0 \leq t_{68} \leq 30</math> °C; <math>0.01 \leq S_p \leq 0.04</math> kg/kg; Accuracy: ±1.5 J/kg</p>	[96]
$h_{sw} = h_w + (AS_p + BS_p^{3/2} + CS_p^2)$ <p><math>A = 3.4086 \times 10^{-3} - 6.3798 \times 10^{-5}t_{68} + 1.3877 \times 10^{-6}t_{68}^2 - 1.0512 \times 10^{-8}t_{68}^3</math>  <math>B = 7.935 \times 10^{-4} + 1.076 \times 10^{-4}t_{68} - 6.3923 \times 10^{-7}t_{68}^2 + 8.6 \times 10^{-9}t_{68}^3</math>  <math>C = -4.7989 \times 10^{-4} + 6.3787 \times 10^{-6}t_{68} - 1.1647 \times 10^{-7}t_{68}^2 + 5.717 \times 10^{-10}t_{68}^3</math></p> <p>Validity: <math>h_{sw}</math> and <math>h_w</math> in (kJ/kg); <math>0 \leq t_{68} \leq 40</math> °C; <math>0 \leq S_p \leq 40</math> g/kg; Accuracy: ±20 J/kg</p>	[94]
$h_{sw} = h_w - S (a_1 + a_2S + a_3S^2 + a_4S^3 + a_5t + a_6t^2 + a_7t^3 + a_8St + a_9S^2t + a_{10}St^2)$ <p><math>a_1 = -2.348 \times 10^4, a_2 = 3.152 \times 10^5, a_3 = 2.803 \times 10^6, a_4 = -1.446 \times 10^7, a_5 = 7.826 \times 10^3</math>  <math>a_6 = -4.417 \times 10^1, a_7 = 2.139 \times 10^{-1}, a_8 = -1.991 \times 10^4, a_9 = 2.778 \times 10^4, a_{10} = 9.728 \times 10^1</math></p> <p>Validity: <math>h_{sw}</math> and <math>h_w</math> in (J/kg K); <math>10 \leq t \leq 120</math> °C; <math>0 \leq S \leq 0.12</math> kg/kg; Accuracy: ±0.5 % from IAPWS 2008 [27]</p>	[43]

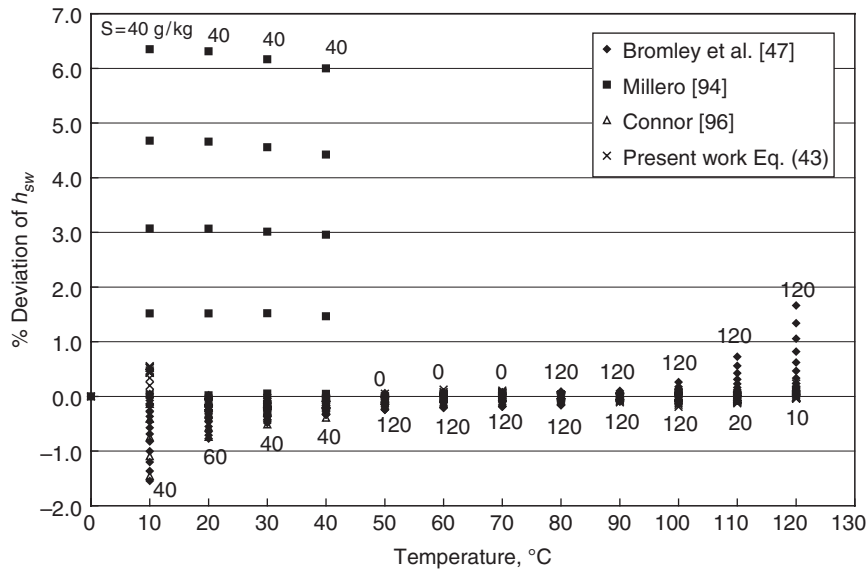


Fig. 13. Deviation of seawater enthalpy from that calculated using IAPWS (2008) formulation at salinity 0–120 g/kg (numbers in the figure refer to salinity in g/kg).

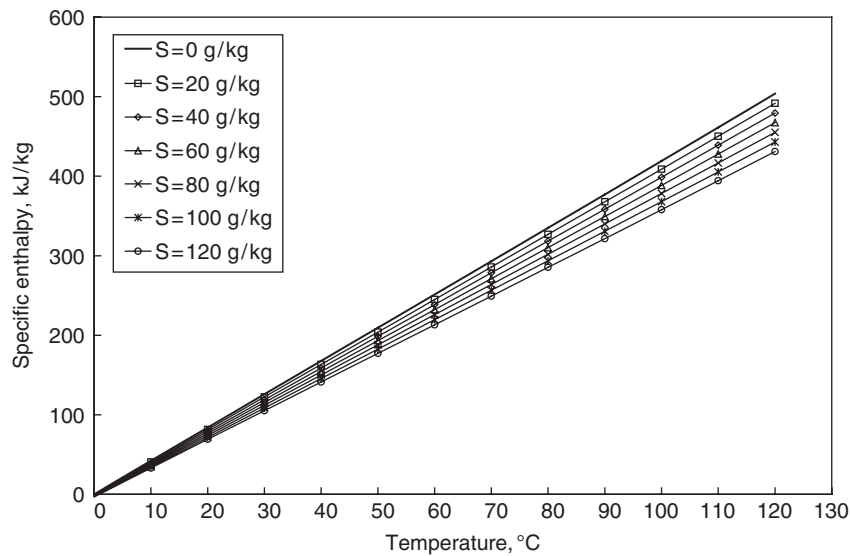


Fig. 14. Seawater specific enthalpy variations with temperature and salinity calculated using Eq. (43).

explicitly calculate the specific entropy of seawater. The available correlations for seawater specific entropy are listed in Table 9. Equation (44) is given by Millero [94] based on enthalpy and free energy data valid for temperature of 0–40°C and salinity of 0–40 g/kg. Equation (45) is given by Sun et al. [28] for a temperature range of 0–374°C, pressure range of 0.1–100 MPa and salinity range of 0–120 g/kg. The low temperature portion of this equation was derived based on the equation of state of Feistel [23] while high temperature portion was

calculated from numerical integration of the specific heat with temperature.

The IAPWS 2008 Gibbs energy function is used to calculate the seawater specific entropy and compare the results with that calculated using equations (44) and (45). It is found that there are large deviations, reaching  $\pm 8\%$  with Eq. (44) and about  $\pm 35\%$  with Eq. (45). Therefore, a new best fit equation (Eq. 46) is obtained in the present work to correlate the seawater specific entropy data calculated by the Gibbs energy function of IAPWS 2008 [27] for

Table 9  
Seawater specific entropy correlations.

Correlation	Ref.
$s_{sw} = s_w + (AS_p + BS_p^{3/2} + CS_p^2) \quad (44)$ $A = 1.4218 \times 10^{-3} - 3.1137 \times 10^{-7} t_{68} + 4.2446 \times 10^{-9} t_{68}^2$ $B = -2.1762 \times 10^{-4} + 4.1426 \times 10^{-7} t_{68} - 1.6285 \times 10^{-9} t_{68}^2$ $C = 1.0201 \times 10^{-5} + 1.5903 \times 10^{-8} t_{68} - 2.3525 \times 10^{-10} t_{68}^2$ <p>Validity: <math>s_{sw}</math> and <math>s_w</math> in (kJ/kg K); <math>0 \leq t_{68} \leq 40</math> °C; <math>0 \leq S_p \leq 40</math> g/kg; Accuracy: <math>\pm 8\%</math> from IAPWS 2008 [27]</p>	[94]
$s_{sw} = \left( \begin{aligned} &a_1 + a_2 t + a_3 t^2 + a_4 t^3 + a_5 t^4 + a_6 t^5 + a_7 P + a_8 p t + a_9 p t^2 + a_{10} p t^3 \\ &+ a_{11} p t^4 + a_{12} p^2 + a_{13} p^2 t + a_{14} p^2 t^2 + a_{15} p^2 t^3 + a_{16} p^3 + a_{17} p^3 t \\ &+ a_{18} p^3 t^2 + a_{19} p^3 t^3 + a_{20} p^4 + a_{21} p^4 t^2 + a_{22} p^4 t^3 + a_{23} p^5 + a_{24} p^5 t \end{aligned} \right) \quad (45)$ $- 0.001 \times \left( \begin{aligned} &b_1 S + b_2 S^2 + b_3 S^3 + b_4 S^4 + b_5 S t + b_6 S t^2 \\ &+ b_7 S t^3 + b_8 S^2 t + b_9 S^3 t + b_{10} S t p \end{aligned} \right)$ <p><math>a_1 = 7.712 \times 10^{-3}, a_2 = 1.501 \times 10^{-2}, a_3 = -2.374 \times 10^{-5}, a_4 = 3.754 \times 10^{-8}</math>  <math>a_5 = -1.522 \times 10^{-11}, a_6 = 6.072 \times 10^{-15}, a_7 = -1.439 \times 10^{-4}, a_8 = -5.019 \times 10^{-6}</math>  <math>a_9 = 2.54 \times 10^{-9}, a_{10} = -8.249 \times 10^{-11}, a_{11} = -5.017 \times 10^{-15}, a_{12} = -1.219 \times 10^{-6}</math>  <math>a_{13} = 1.071 \times 10^{-8}, a_{14} = 7.972 \times 10^{-11}, a_{15} = 1.335 \times 10^{-13}, a_{16} = 4.384 \times 10^{-9}</math>  <math>a_{17} = 4.709 \times 10^{-11}, a_{18} = -1.685 \times 10^{-13}, a_{19} = -6.161 \times 10^{-17}, a_{20} = -6.281 \times 10^{-12}</math>  <math>a_{21} = 8.182 \times 10^{-14}, a_{22} = 8.890 \times 10^{-17}, a_{23} = 2.941 \times 10^{-15}, a_{24} = -4.201 \times 10^{-17}</math>  <math>b_1 = -4.679 \times 10^{-4}, b_2 = 2.846 \times 10^{-5}, b_3 = -3.505 \times 10^{-7}, b_4 = 1.355 \times 10^{-9}</math>  <math>b_5 = 1.839 \times 10^{-5}, b_6 = -8.138 \times 10^{-8}, b_7 = 2.547 \times 10^{-10}, b_8 = -3.649 \times 10^{-8}</math>  <math>b_9 = 2.496 \times 10^{-10}, b_{10} = 4.346 \times 10^{-9}</math></p> <p>Validity: <math>s_{sw}</math> in (kJ/kg); <math>0 \leq t \leq 375</math> °C; <math>0 \leq S \leq 120</math> g/kg; <math>0.1 \leq p \leq 100</math> MPa Accuracy: <math>\pm 35\%</math> from IAPWS 2008 [27]</p>	[28]
$s_{sw} = s_w - S (a_1 + a_2 S + a_3 S^2 + a_4 S^3 + a_5 t + a_6 t^2 + a_7 t^3 + a_8 S t + a_9 S^2 t + a_{10} S t^2) \quad (46)$ <p><math>a_1 = -4.231 \times 10^2, a_2 = 1.463 \times 10^4, a_3 = -9.880 \times 10^4, a_4 = 3.095 \times 10^5, a_5 = 2.562 \times 10^1</math>  <math>a_6 = -1.443 \times 10^{-1}, a_7 = 5.879 \times 10^{-4}, a_8 = -6.111 \times 10^1, a_9 = 8.041 \times 10^1, a_{10} = 3.035 \times 10^{-1}</math></p> <p>Validity: <math>s_{sw}</math> and <math>s_w</math> in (J/kg K); <math>10 \leq t \leq 120</math> °C; <math>0 \leq S \leq 0.12</math> kg/kg Accuracy: <math>\pm 0.5\%</math> from IAPWS 2008 [27]</p>	

a temperature range of 10–120°C and salinity of 0–120g/kg. The pure water specific entropy part in this equation is calculated from IAPWS 1995 [24] which can be obtained also from steam Tables. The new equation has a maximum deviation of  $\pm 0.5\%$  and a correlation coefficient of 0.9998. Figure 15 shows the percentage deviation of the seawater specific entropy calculated using Eq. (46) and that calculated from the IAPWS 2008 seawater Gibbs function. Figure 16 shows the specific entropy of seawater calculated using Eq. (46) as it changes with temperature and salinity. It is shown that the entropy increases with temperature and decreases with salinity. The decrease with salinity reaches about 17% at 120°C and 120 g/kg salinity.

## 11. Osmotic coefficient

The osmotic coefficient characterizes the deviation of a solvent from its ideal behavior. The osmotic coefficient of a solution can be determined from vapor pressure, boiling point elevation, and freezing point measurements. Robinson [82] derived osmotic coefficient data from measurements of seawater vapor pressure at 25°C and salinity of 17–38 g/kg. Bromley et al.'s [79] data was derived from boiling point elevation measurements and the application of the extended Debye-Huckel theory up to a salinity of 120 g/kg. The osmotic coefficients data computed by Millero and Leung [97]



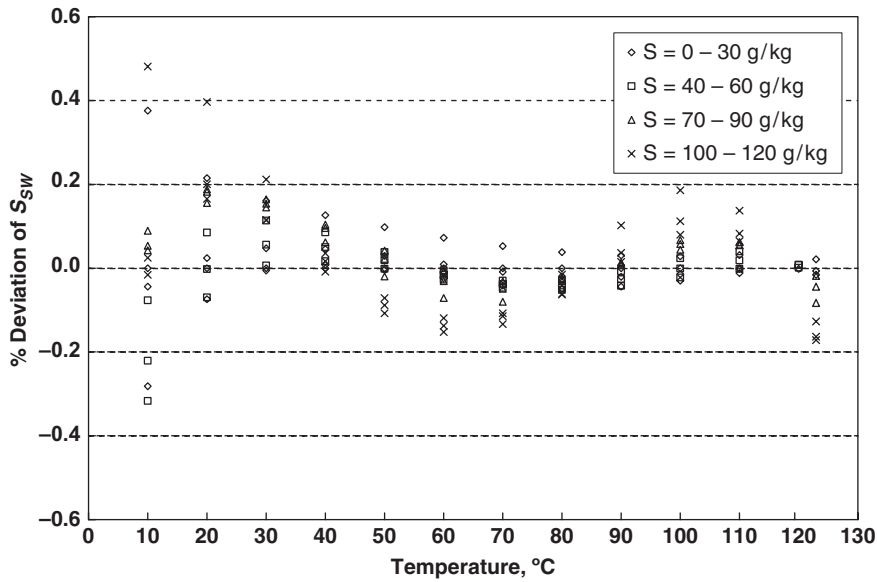


Fig. 15. Deviation of seawater entropy from that calculated using IAPWS (2008) formulation at salinity 0–120 g/kg.

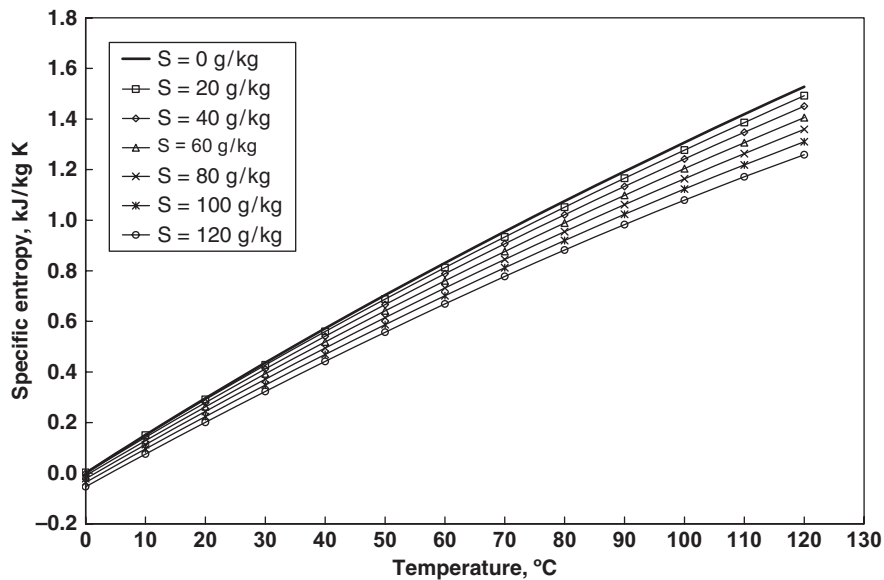


Fig. 16. Seawater specific entropy variations with temperature and salinity calculated using Eq. (46).

were based on the freezing point data of Doherty and Kester [98]. Other data are available for synthetic seawater solutions (Rush and Johnson [99], Gibbard and Scatchard [100]), and some additional estimates are based on multi-component electrolyte solution theories (Robinson and Wood [101], Whitfield [102], Brandani et al. [50]).

Among these osmotic coefficient data, only a few correlations are available as listed in Table 10. Equation (47) is given by Millero [69] as a fit of the seawater osmotic

coefficient data of Robinson [82] at temperature of 25°C and salinity 16–40 g/kg. Equation (48) is given by Millero and Leung [97] based on the freezing point data of Doherty and Kester [98] for temperature of 0–40°C and salinity 0–40 g/kg. A new equation (Eq. 49) that correlates the osmotic coefficient data of Bromley et al. [79] is obtained in the present work. It has a temperature range of 0–200°C and a salinity range of 0.01–120g/kg with a maximum deviation of  $\pm 1.4\%$  from the Bromley et al. [79] data and a correlation coefficient of 0.991.

Table 10  
Seawater osmotic coefficient correlations.

Correlation	Ref.
$\phi = 0.90799 - 0.07221I + 0.11904I^2 - 0.0383I^3 - 0.00092I^4$ <p>where</p> <p><math>I</math> is the ionic strength given by <math>I = 19.915 S_p / (1 - 1.00487 S_p)</math>  Validity: <math>t_{68} = 25</math> °C; <math>0.016 \leq S_p \leq 0.04</math> kg/kg  Accuracy: <math>\pm 0.1</math> %</p>	(47) [69]
$\phi = 1 - [A \times B \times I^{1/2} + C \times I + D \times I^{3/2} + E \times I^2]$ <p>where</p> <p><math>A = 20.661 - 432.579 / t_{68} - 3.712 \ln(t_{68}) + 8.638 \times 10^{-3} t_{68}</math>  <math>B = \frac{2.303}{I^{3/2}} [(1 + I^{1/2}) - 1 / (1 + I^{1/2}) - 2 \ln(1 + I^{1/2})]</math>  <math>C = -831.659 + 17022.399 / t_{68} + 157.653 \ln(t_{68}) - 0.493 t_{68} + 2.595 \times 10^{-4} t_{68}^2</math>  <math>D = 553.906 - 11200.445 / t_{68} - 105.239 \ln(t_{68}) + 0.333 t_{68} - 1.774 \times 10^{-4} t_{68}^2</math>  <math>E = -0.15112, I = 19.915 S_p / (1 - 1.00487 S_p)</math>  Validity: <math>0 \leq t_{68} \leq 40</math> °C; <math>0 \leq S_p \leq 0.04</math> kg/kg  Accuracy: <math>\pm 0.3</math> %</p>	(48) [97]
$\phi = a_1 + a_2 t + a_3 t^2 + a_4 t^4 + a_5 S + a_6 S t + a_7 S t^3 + a_8 S^2 + a_9 S^2 t + a_{10} S^2 t^2$ <p>Present work based on Bromley's et al. [79] data  where</p> <p><math>a_1 = 8.9453 \times 10^{-1}, a_2 = 4.1561 \times 10^{-4}, a_3 = -4.6262 \times 10^{-6}, a_4 = 2.2211 \times 10^{-11}</math>  <math>a_5 = -1.1445 \times 10^{-1}, a_6 = -1.4783 \times 10^{-3}, a_7 = -1.3526 \times 10^{-8}, a_8 = 7.0132</math>  <math>a_9 = 5.696 \times 10^{-2}, a_{10} = -2.8624 \times 10^{-4}</math>  Validity: <math>0 \leq t \leq 200</math> °C; <math>10 \leq S \leq 120</math> g/kg  Accuracy: <math>\pm 1.4</math> %</p>	(49)

The IAPWS 2008 [28] Gibbs energy function is used to calculate the seawater osmotic coefficient and compare the results with the data of Bromley et al. [79], and Millero and Leung [97]. There is a maximum deviation of  $\pm 3.8\%$  and  $\pm 0.4\%$  respectively. Fiestel [26] made a similar comparison at temperatures 0°C and 25°C. The deviation was less than  $\pm 0.5$  % at these low temperatures. However, at higher temperature the deviation is larger as shown in Figure 17. Therefore, the osmotic coefficient calculated from the IAPWS 2008 [28] Gibbs energy function has a limited temperature validity, (up to 25°C) and it is recommended to use Eq. (49) that best fit the data of Bromley et al. [79] (up to 200°C and 120g/kg salinity with  $\pm 1.4\%$  maximum deviation). Also it has a maximum deviation of  $\pm 0.3\%$  from the osmotic coefficient values calculated from the IAPWS 2008 Gibbs energy

function for temperature up to 25°C. Figure 18 shows the osmotic coefficient of seawater calculated using Eq. (49) as it changes with temperature and salinity.

## 12. Pure water properties

Correlations for pure water properties at atmospheric pressure are listed in Table 11. This includes density (Eq. 50), specific heat capacity (Eq. 51), thermal conductivity (Eq. 52), dynamic viscosity (Eq. 23), surface tension (Eq. 27), vapor pressure (Eq. 53), latent heat of vaporization (Eq. 54), specific enthalpy (Eq. 55), and specific entropy (Eq. 56). The source of each correlation, the range of validity, and the uncertainty are given also in Table 11. Correlations for which references are not given were developed by the present authors; these correlations

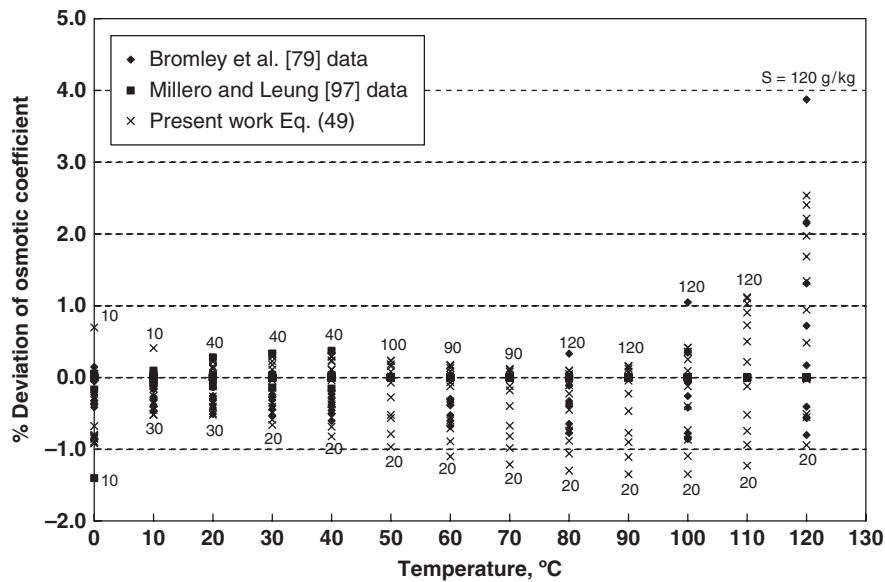


Fig. 17. Deviation of seawater osmotic coefficient from that calculated using IAPWS (2008) formulation at salinity 0–120 g/kg (numbers in the figure refer to salinity in g/kg).

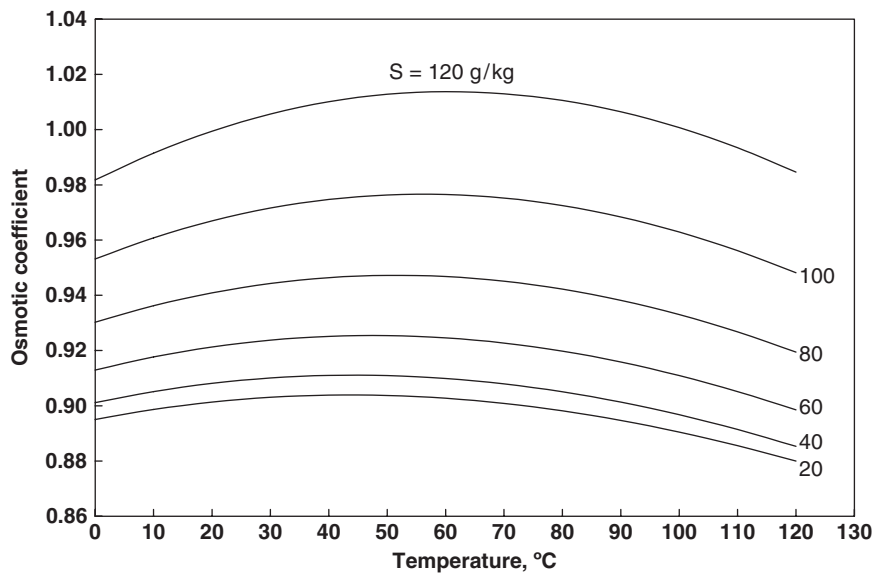


Fig. 18. Seawater osmotic coefficient variations with temperature and salinity calculated using Eq. (49).

are best fit equations for the IAPWS 1995 [24] formulation of liquid water at 0.1 MPa using data extracted at 1 K intervals, with values at temperature higher than the normal boiling temperature calculated at the saturation pressure. The accuracy of these equations is within  $\pm 0.1\%$ .

### 13. Concluding remarks

Existing correlations for the thermophysical properties of seawater are reviewed over ranges of interest

for both thermal and membrane desalination processes. Comparisons are provided among the correlations that are reported in the literature and recommendations are made for all the properties investigated in this study. In this regard temperature and salinity are the independent properties of these correlations and most of the properties examined are given in the temperature range of (0 to 120°C) and salinity range of (0 to 120 g/kg); however, the surface tension data and correlations are limited to oceanographic range (0–40°C and 0–40 g/kg salinity).

Table 11  
Pure water properties.

Correlation	Ref.
<p>Density:</p> $\rho_w = a_1 + a_2t + a_3t^2 + a_4t^3 + a_5t^4 \quad (50)$ <p>where</p> $a_1 = 9.999 \times 10^2, a_2 = 2.034 \times 10^{-2}, a_3 = -6.162 \times 10^{-3}, a_4 = 2.261 \times 10^{-5}, a_5 = -4.657 \times 10^{-8}$ <p>Validity: <math>\rho_w</math> in (kg/m<sup>3</sup>); <math>0 \leq t \leq 180</math> °C Accuracy: <math>\pm 0.01</math> % (best fit to IAPWS 1995 [24] data)</p>	
<p>Specific heat:</p> $c_w = a_1 + a_2t + a_3t^2 + a_4t^4 + a_5p + a_6pt + a_7pt^3 + a_8p^2 + a_9p^2t + a_{10}p^2t^2 \quad (51)$ <p>where</p> $a_1 = 4.193, a_2 = -2.273 \times 10^{-4}, a_3 = 2.369 \times 10^{-6}, a_4 = 1.670 \times 10^{-10},$ $a_5 = -3.978 \times 10^{-3}, a_6 = 3.229 \times 10^{-5}, a_7 = -1.073 \times 10^{-9}, a_8 = 1.913 \times 10^{-5},$ $a_9 = -4.176 \times 10^{-7}, a_{10} = 2.306 \times 10^{-9}$ <p>Validity: <math>c_w</math> in (kJ/kg K); <math>0 \leq t \leq 374</math> °C; <math>0.1 &lt; p &lt; 100</math> MPa Accuracy: <math>\pm 0.01</math> % (best fit to Wagner and Pruss [17] data)</p>	[28]
<p>Thermal conductivity:</p> $k_w = \sum_{i=1}^4 a_i (T/300)^{b_i} \quad (52)$ <p>where</p> $a_1 = 0.80201, a_2 = -0.25992, a_3 = 0.10024, a_4 = -0.032005$ $b_1 = -0.32, b_2 = -5.7, b_3 = -12.0, b_4 = -15.0$ <p>Validity: <math>k_w</math> in (W/m K); <math>273.15 \leq T \leq 383.15</math> K Accuracy: <math>\pm 2</math> % (best fit to IAPWS 2008 [61] data)</p>	[103]
<p>Dynamic viscosity:</p> $\mu_w = 4.2844 \times 10^{-5} + \left(0.157 (t + 64.993)^2 - 91.296\right)^{-1} \quad (23)$ <p>Validity: <math>\mu_w</math> in (kg/m.s); <math>0 \leq t \leq 180</math> °C; Accuracy: <math>\pm 0.05</math> % (best fit to IAPWS 2008 [73] data)</p>	
<p>Surface tension:</p> $\sigma_w = 0.2358 \left(1 - \frac{t + 273.15}{647.096}\right)^{1.256} \left[1 - 0.625 \left(1 - \frac{t + 273.15}{647.096}\right)\right] \quad (27)$ <p>Validity: <math>\sigma_w</math> in (N/m); <math>0.01 \leq t \leq 370</math> °C Accuracy: <math>\pm 0.08</math>%</p>	[77]
<p>Vapor pressure:</p> $\ln(p_{v,w}) = a_1/T + a_2 + a_3 T + a_4 T^2 + a_5 T^3 + a_6 \ln(T) \quad (53)$ <p>where</p> $a_1 = -5800, a_2 = 1.391, a_3 = -4.846 \times 10^{-2}, a_4 = 4.176 \times 10^{-5}, a_5 = -1.445 \times 10^{-8}, a_6 = 6.545$ <p>Validity: <math>p_{v,w}</math> in (Pa); <math>273.15 \leq T \leq 473.15</math> K Accuracy: <math>\pm 0.1</math> %</p>	[104]
<p>Latent heat of evaporation:</p> $h_{fg,w} = 2.501 \times 10^6 - 2.369 \times 10^3 \times t + 2.678 \times 10^{-1} \times t^2 - 8.103 \times 10^{-3} \times t^3 - 2.079 \times 10^{-5} \times t^4 \quad (54)$	

Table 11 (continued)

Validity:  $h_{fg,w}$  in (J/kg);  $0 \leq t \leq 200$  °C

Accuracy:  $\pm 0.01$  % (best fit to IAPWS 1995 [24] data)

**Specific saturated water enthalpy:**

$$h_w = 141.355 + 4202.07 \times t - 0.535 \times t^2 + 0.004 \times t^3 \quad (55)$$

Validity:  $h_w$  in (J/kg);  $5 \leq t \leq 200$  °C

Accuracy:  $\pm 0.02$ % (best fit to IAPWS 1995 [24] data)

**Specific saturated water entropy:**

$$s_w = 0.1543 + 15.383 \times t - 2.996 \times 10^{-2} \times t^2 + 8.193 \times 10^{-5} \times t^3 - 1.370 \times 10^{-7} \times t^4 \quad (56)$$

Validity:  $s_w$  in (J/kg K);  $5 \leq t \leq 200$ °C

Accuracy:  $\pm 0.1$  % (best fit to IAPWS 1995 [24] data)

It is therefore important to note that the surface tension data available in the literature has a limited range of utility for desalination processes. In addition we noticed that the results for thermal conductivity have significant disagreement. Further experimental investigation of those properties is warranted.

New correlations are obtained from available tabulated data for density, viscosity, surface tension, boiling point elevation, specific enthalpy, specific entropy, and osmotic coefficient. These new correlations have a maximum deviation of  $\pm 1.5\%$  from the data reported in the literature with temperature and salinity scales converted to the International Temperature Scale (ITS-90) and the reference-composition salinity respectively. In addition, a new simple model for seawater latent heat of vaporization is developed from first principles, which is presented as a function of salinity and pure water latent heat.

Tables of properties based on the present results and software that implements them are available at <http://web.mit.edu/seawater>

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**Nomenclature**

$BPE$	boiling point elevation, K
$Cl$	chlorinity, $g\ kg^{-1}$
$c$	specific heat at constant pressure, $J\ kg^{-1}\ K^{-1}$
$h$	specific enthalpy, $J\ kg^{-1}$
$h_{fg}$	latent heat of vaporization, $J\ kg^{-1}$

$\bar{h}_s$	partial specific enthalpy of sea salt per unit mass of sea salt in seawater, $J\ kg^{-1}$
$\bar{h}_w$	partial specific enthalpy of water per unit mass of water in seawater, $J\ kg^{-1}$
$I$	ionic strength
$k$	thermal conductivity, $W\ m^{-1}\ K^{-1}$
$m$	mass, kg
$M$	total molality
$p$	pressure, Pa
$p_v$	vapor pressure, Pa
$R$	universal gas constant, $J\ mol^{-1}\ K^{-1}$
$s$	specific entropy, $J\ kg^{-1}\ K^{-1}$
$S$	salinity, $g\ kg^{-1}$
$S_K$	knudsen salinity
$S_p$	practical salinity, $g\ kg^{-1}$
$S_R$	reference-composition salinity, $g\ kg^{-1}$
$T$	absolute temperature, ITS-90, K
$t$	celsius temperature, ITS-90, °C
$T_{27}$	absolute temperature, ITS-27, K
$T_{48}$	absolute temperature, IPTS-48, K
$t_{48}$	celsius temperature, IPTS-48, °C
$T_{68}$	absolute temperature, IPTS-68, K
$t_{68}$	celsius temperature, IPTS-68, °C
$T_{90}$	absolute temperature, ITS-90, K
$\lambda$	mass fraction

*Greek symbols*

$\phi$	osmotic coefficient
$\mu$	viscosity, $kg\ m^{-1}\ s^{-1}$
$\rho$	density, $kg\ m^{-3}$
$\sigma$	surface tension, $N\ m^{-1}$

*Subscripts*

$s$	sea salt
$sw$	seawater
$w$	pure water

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### A short note of correction

Paper:

M.H. Sharqawy, J.H. Lienhard V, S.M Zubair, "Thermophysical Properties of Sea Water: A Review of Existing Correlations and Data," *Desalination and Water Treatment* **16**, pp. 354 – 380, 2010.

An exponent is missing from Eq. (6) on pg. 357. The correct equation is

$$\rho_{sw} = \rho_w + A S_p + B S_p^{3/2} + C S_p^2 \quad (6)$$

All other results in the paper are unaffected by this typographical error.

## A short note of correction 2

Paper:

M.H. Sharqawy, J.H. Lienhard V, S.M Zubair, "Thermophysical Properties of Sea Water: A Review of Existing Correlations and Data," *Desalination and Water Treatment* **16**, pp. 354 – 380, 2010.

The unit of the salinity in Eq. (17) on pg. 364 should be kg/kg. The correct validity range of salinity for Eq. (17) is

Validity:  $0.015 < S_p < 0.13$  kg/kg

There is a unit conversion typo in Eq. (21) on pg. 364. The correct equation is

$$\ln(\mu_w) = -10.7019 + \frac{604.129}{139.18 + t_{68}} \quad (21)$$

All other results in the paper are unaffected by this typographical error.

### **A short note of correction 3**

Paper:

M.H. Sharqawy, J.H. Lienhard V, S.M Zubair, "Thermophysical Properties of Sea Water: A Review of Existing Correlations and Data," *Desalination and Water Treatment* **16**, pp. 354 – 380, 2010.

The coefficient  $a_3$  of Eq. (7) on pg. 357 is incorrect, the correct one should be  $a_3 = -7.619 \times 10^{-3}$

All other results in the paper are unaffected by this typographical error.

#### A short note of correction 4

Paper:

M.H. Sharqawy, J.H. Lienhard V, S.M Zubair, "Thermophysical Properties of Sea Water: A Review of Existing Correlations and Data," *Desalination and Water Treatment* **16**, pp. 354 – 380, 2010.

The pressure coefficient of Eq. (14) on pg. 362 is incorrect, the correct one should be  $6.53 \times 10^{-4}$  instead of  $6.53 \times 10^{-3}$

All other results in the paper are unaffected by this typographical error.

### A short note of correction 5

Paper:

M.H. Sharqawy, J.H. Lienhard V, S.M Zubair, "Thermophysical Properties of Sea Water: A Review of Existing Correlations and Data," *Desalination and Water Treatment* **16**, pp. 354 – 380, 2010.

Reference [88] should be:

F. J. Millero, W. H. Leung, "The Thermodynamics of Seawater at One Atmosphere," *American Journal of Science*, Vol 276, 1035-1077, 1976.

No results in the paper are affected by this citation error.