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Concise summary of existing correlations with thermophysical properties of seawater with applications: A recent review

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ABSTRACT

Physical and thermal specifications of seawater are used by researchers and engineers in different fields. Accordingly, a vast array of literature has been devoted to developing different correlation equations for calculating seawater characteristics. This review presents a concise investigation of various physical and thermal specifications of seawater including: density, boiling point and vapor pressure, osmotic coefficient and pressure, surface tension, thermal conductivity, viscosity, specific enthalpy, specific entropy, specific heat capacity, isothermal compressibility, isobaric expansivity and Gibbs energy. Further to this, apsects of temperature, salinity and pressure have a significant influence on these properties, and will also be considered here. The techniques for determining each property have been provided in this review, where the proposed correlations and their uncertainties are also discussed, along with aspects related to temperature, salinity and pressure range. Considering that thermodynamic basic equations of seawater have uncertain ranges and varied properties, this review provides new direction to researchers to get deep in the field of seawater correlations.

1. Introduction

Different methods can be applied to produce fresh water from seawater, from which desalination is the conventional technique. Various seawater desalination technologies have been used throughout the last few decades to produce fresh water. The desalination process mainly consists of separating salts from saline water to produce clean water for varied purposes. The most popular methods in this regard are: Multi-stage flash distillation (MSF), Multiple-effect distillation (MED), Vapor compression (VC), Membrane distillation (MD), Freezing distillation (FD), Electrolysis and Reverse osmosis (RO) [1]. The water produced through these methods is the major source of drinking water for millions of people around the world [2]. However, these methods are costly and involve high power consumption, where these systems are not easily installed in remote areas. Contrastingly, reverse osmosis is currently the most widely used desalination process around the world. Each desalination technology has certain operating conditions and therefore, additional properties of saltwater need to be investigated by researchers for effective separation techniques and operating conditions.

The properties of salt water should be known before application to any desalination process. These include physical as well as chemical properties of salt water, which play a vital role in respective areas of application. Physical properties of salt water can be determined by various methods, including the direct measurement method investigated by McManus et al. [3], who have presented expressions for salinity using this technique. Jellison et al. [4] have further measured density and conductivity for hyper saline brine using the direct measurement method. Additionally, Vollmer et al. [5] have measured the physical properties of water in a saline lake using this technique. The physical properties of saline water can also be determined using empirical or semi-empirical correlations, where Fisher and Lawrence [6] have measured the density of salt water using correlation of Millero and treated acid rock drainage in a pit lake. Direct numerical calculations using the chemical theory of composition have also been used to determine the physical properties of saline water. Wuest et al. [7] have examined the effects of dissolved solids and temperature on the density stratification of Lake Malawi, using quantified water column stability as a function of in-situ conductivity, temperature and silicic acid

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Nomenclature

Abbreviations

BGD	Borosilicate glass dilatometer
BPE	Boiling Point Elevation
BPT	Boiling Point Temperature
IM	Inorthodox method
IAPWS	International Association for the properties of water and steam
NEL	National engineering laboratory
OSP	Oscillating solderability preservative
LP	Lipkin pycnometer
TE	Temperature elevation
VP	Vapor Pressure
VT	Vibration tube densimeter

Subscripts

sw	Seawater
w	Water

Symbols

C	Molar index of solute
d	Density
I	Van't Hoff Index
K	Bulk modulus
P	Pressure
R	Ideal gas constant
S	Salinity
T	Temperature
U	Speed of sound

Greek Symbols

α	Isothermal expansivity
β	Isothermal compressibility
C_p	Specific heat
σ	Surface tension
ρ	density

concentration. Millero [8] determined the state equation for the lake using chemical theory, where this same technique has also been applied by Boehrer and Schultze [9]. Further, Chen and Millero [10] have investigated thermodynamic properties of natural water using chemical theory and provided different equations across a wide range of temperatures and salinities.

The properties of seawater mostly depend upon on temperature and salinity, which also assist in determining other thermal and physical properties near atmospheric pressure. For this purpose, different temperature and salinity scales of seawater properties have been investigated by researchers. Salinity has been proposed by Millero et al. [11] as expressed in g/kg. Further, the state equation of seawater has been investigated by many authors by curve fitting to the experimental data [12]. These equations describe the salinity of seawater in the range of 2 to 42 g/kg.

Many attempts have been proposed to determine properties of seawater like pure water, as proposed by Wagner and Prub [13], where the Gibbs equation has been applied as the basic equation of state as developed on theoretical bases by curve fitting into the experimental data. These equations were later used to determine various other thermo-physical properties of seawater. However, several thermodynamics equations of seawater have been developed in recent years based on the equation of state of seawater and its associated formula, namely IES-80 [14], which is the international equation of the state of seawater. In 2010, a new international equation of state of seawater, namely TEO-10, was developed to provide high quality estimates of the thermodynamics properties of seawater [15]. The most recent international formulation is IAPWS-14, represented by the international association for properties of water and steam, which has been developed by Kretzschmar et al. [16].

Although seawater properties have specific temperature and salinity ranges, at the same time the pressure dependence factor plays a vital role in determining/defining seawater properties. Most desalination plants operate at high pressure, such as ultra-filtration which operates at 0–0.5 MPa [17], nano filtration occuring between 0.035 and 4.0 MPa [18], as well as pressure retarded osmosis [19] and forward osmosis [20] at above 4.7 MPa and 0.6 MPa, respectively. Accordingly, for accurate correlation representation pressure property must be included, and its range considered, with regard to the thermophysical properties of seawater.

Generous et al. [21] has presented a comprehensive review of saline water correlation, with a specific focus on multi-ions concentration and high salinity, along with cosndierations of temperature and salinity. Their review not only accounts for saline water having sodium and chlorine components, but also considers brackish water, seawater and water from oil and gas hydraulic fracturing. The accuracy of most of different correlations were also highlighted in the review. Qasem et al. [22] have also included thermophysical properties of salt water that were not reviewed by Generous et al. [21], proposing the same comments with regard to the remaining thermophysical properties.

Ghafurian et al. [23] have measured the effect of sonication time on the evaporation rate of seawater, applying a nanocomposite made from a mixture of multi-walled carbon nanotubes and graphene nanoplates. Their indoor experiments were conducted using a solar simulator with results concluding that at 0.01 % wt. concentration, the rate of evaporation was the highest at 61.3 % during 120 min. Zeron et al. [24] have completed a molecular simulation of system with a composition very similar to standard seawater. They were able to predict related physical properties of seawater including density, viscosity, diffusion coefficient, and surface tension for temperature and salinity ranges.

The current study reviews the various correlations of different thermodynamics properties of seawater at a wide range of temperatures, pressures, and salinity. The properties considered in the current review are density, boiling point and vapor pressure, osmotic coefficient and osmotic pressure, surface tension, thermal conductivity, viscosity, specific enthalpy, specific entropy, specific heat capacity, isothermal compressibility, isobaric expansivity and Gibbs energy, where a roadmap of the current study is depicted in Fig. 1. The aim of this paper is to represent seawater properties in a systematic manner that can be used in the design and performance of desalination systems for researchers in future works. Further, important thermodynamic transport properties can be determined using thermodynamic relations or the equation of the state of seawater. The comparison of thermodynamic properties can also be done among various correlations of each property described in the literature. Thus, this review assists scholars in exploring new correlations of seawater based on existing correlations that consider a wide range of temperature and salinity ranges with additional applications.

2. Thermophysical properties of seawater

2.1. Density

The density of seawater is considered a vital factor in estimating the properties of a desalination system. Density of seawater in a temperature range of 20–35 °C has been measured by Hampel [25], applying an approach in which five samples were taken. The densities were

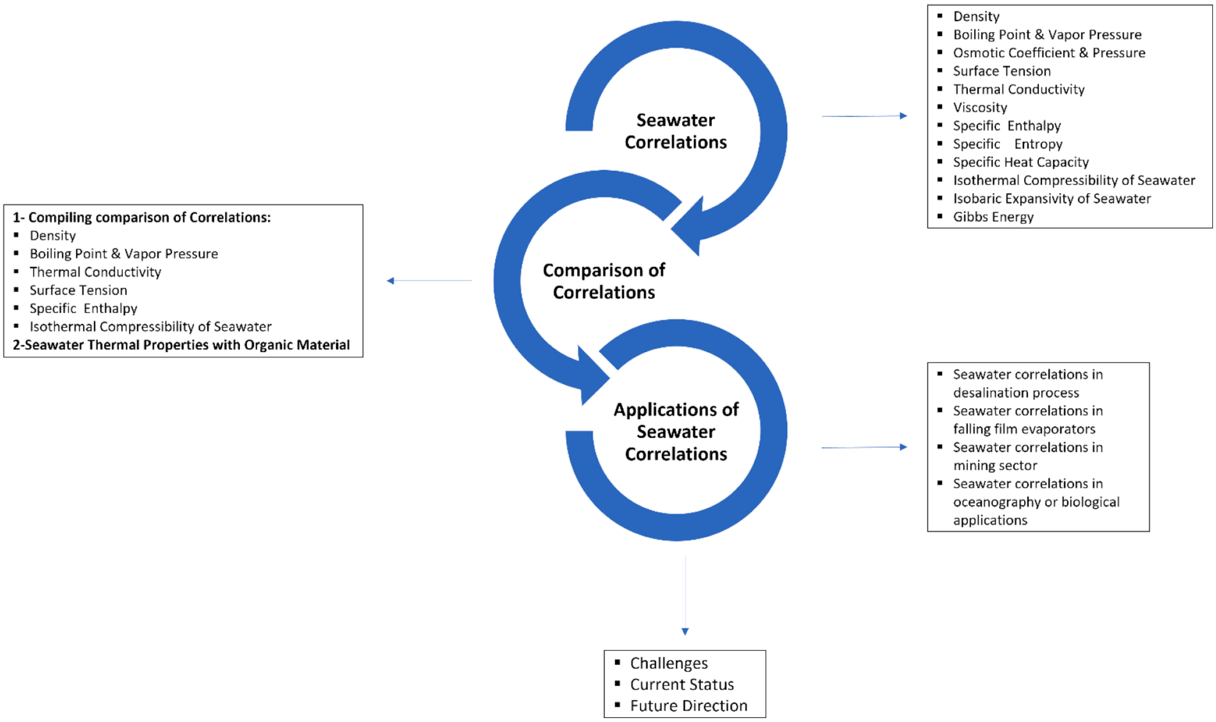

Fig. 1. Roadmap for seawater properties correlations.

measured with chlorinity of 17.69, 28.39, 38.16, 51.75 and 76.62 per milliliter, respectively. Fabuss et al. [26] have determined densities of aqueous solutions of NaCl, Na_2SO_4 and $MgSO_4$ in a temperature range of 25–130 °C with 0.05 °C accuracy. Isdale and Morris [27] have determined the density of seawater and its concentration within a temperature range of 70–180 °C using a borosilicate glass dilatometer. The dilatometer was calibrated before taking readings and soaked with potassium hydroxide in isopropanol, which is necessary for forming a good meniscus. The measurements of density were carried out on Ca-free seawater with ±0.1 % accuracy. The Gibbs energy of seawater was calculated in accordance with Rainer Feistel [28] for a temperature range of 0–40 °C, salinity range of 0–40 gr/kg and pressure range of 0.1–100 MPa. The author determined the temperatures of maximum density with their experimental uncertainty.

Feistel [29] also investigated the specific Gibbs energy for seawater for temperature in the range of −6 to 80 °C and absolute salinity 0–120 g/kg to obtain data on heat capacity, mixing heat, freezing point and vapor pressure near atmospheric pressure. A new Gibbs equation was developed combining properties of pure water and densities of Gibbs function proposed in 2003, in which the input variable was absolute salinity. A summary of works by various authors for density calculation considering temperature, salinity, pressure variations and uncertainty are summarized in Table 1.

Millero and Huang [31] have determined the density of seawater in which temperature and salinity were varied. Their temperature range was 0–90 °C and the salinity was in the range of 5–70 g/kg. Their results concluded that for the given range the equation of state was valid for the samples made with known salinity with an uncertainty of 0.006 kg/m^3 and an error of 0.0063 kg/m^3.

Sadaroy et al. [32] have studied the density of seawater for temperature range 0 to 195 °C, pressure up to 140 MPa and salinity in the range of 3–29 g/kg and 32–56 g/kg [33] with reproducibility of 0.03 %. The density calculations were performed using Anton-Paar DMA 4500 vibrating tube densimeter with an uncertainty of 0.01 K. The resulting parameters were utilized for the formation of the seawater equation of state.

The measurement of the density of seawater calculated by Sadarov et al. [32]–[34] was restricted to temperature $0 \le t \le 195$ °C and pressure $0.1 \le p \le 140$ MPa, where these measurements are valid only for salinity of up to 56 g/kg. For salinity between 0 and 160 g/kg, temperature up to 0–180 °C and pressure 0–12 MPa the expression was given by Nayar et al. [35].

Sharqawy et al. [36] introduced a correlation based on the existing data, where Nayar et al. [35] used this correlation to measure the density of seawater. Variations in density along with temperature and salinity variation are shown in Fig. 2, which was presented by Sharqawy et al. [36].

Schmidt et al. [37] have used a vibrating tube densimeter to

Table 1
Density measurement experiments conducted by various authors.

Technique	Property	Temperature (°C)	Pressure (MPa)	Salinity (g/kg)	Error	References
OSP	ρ	−2–175	0.101	29.56–268.73	——	[30]
IM	ρ, T, S	22.5–88.3	0.101	32.11–139.98	$\pm 14 \times 10^{-4}$ gcm^{-3}	[25]
LP	ρ, T, S	25–150	0.101	35.17–175.88	±0.02%.	[26]
BGD	ρ, T, S	20–180	0.101	10–150	±0.05%.	[27]
——	ρ	−6–80	0.1–100	0–120	——	[29]

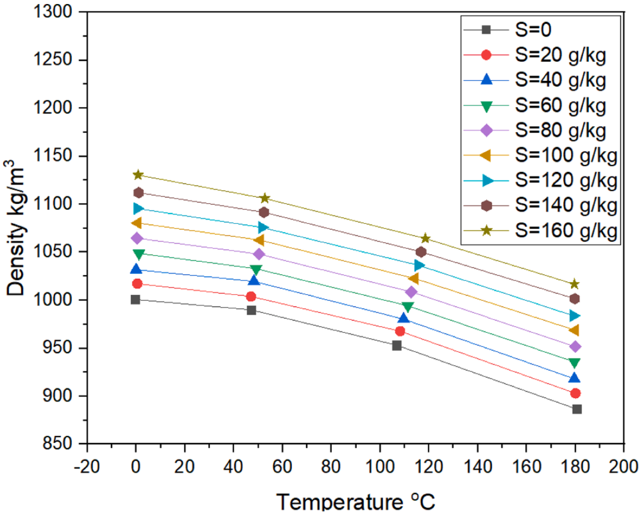

Fig. 2. Seawater density variations with temperature and salinity [36].

determine seawater density with an uncertainty of 10 g/m^3 and 20 g/m^3 respectively, for pressure upto 10 MPa and 65 Mpa for temperature range from 5 to 35 °C and salinity of 35 g/kg. They compared their results with a hydrostatic weight measuring apparatus.

Moreira et al. [38] have investigated the density of seawater by determining coefficients of lake water relating to electrical conductivity with density. These parameters were then used to calculate density by conversion of temperature and electrical conductivity into density based on CTD (Conductivity, Temperature and Density). The results indicated that the density calculated by this approach has an error of less than 10 %, which was more accurate than those calculated in the literature. An online calculator was developed for calculating this density.

Pawlowicz [39] has calculated the density of seawater from the correlation of electrical conductivity, where variation in properties due to the addition of salts with numerical models for conductivity, salinity and density were examined. The study's results indicated that densities were very low, at 0.02–0.3 kg/m^3, but with spatial variability.

Droghei et al. [40] have monitored sea surface density (SSD) using a multidimensional covariance model, where interpolation was carried out for density measurement. Their surface fields were developed in the optimum range and SSD maps were constructed. The root mean error was in the range of 0.09–0.32 kg/m^3 for an SSD level of 4.

Talley et al. [41] have determined the density of seawater and provided a relationship between density (ρ) and temperature (T), salinity (S) and pressure (p), which is given as:

$$\rho(S,T,p) = \frac{\rho(S,T,0)}{1-\frac{p}{K(S,T,p)}} \tag{1}$$

In accordance with the aforementioned studies, the density of water depends upon several factors that affect its properties. Some of the important parameters that affect the density of seawater are presented in Fig. 3.

The summary of different correlations developed by various researchers for density calculation along with the variation in temperature and, salinity is summarized in Table 2.

Variation of density with temperature is shown in Fig. 4, along with variation in salinity (60–150 g/kg) and pressure (2–12 MPa). Each point in the graph represents specific density against specific temperature, salinity and pressure from left to right. The comparison of density variation of Sharqawy et al. [36] and Nayar et al. [35] show no significant variation in data points. The effect of pressure also needs to be considered when dealing with pressure above atmospheric pressure. In this way, the trend is the same, where density decreases with an increase in temperature; where further to this, the limited variation between

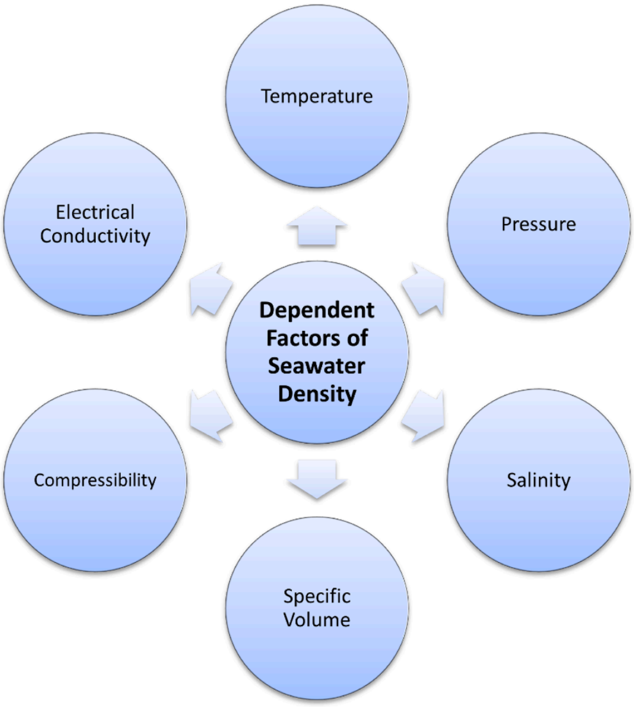

Fig. 3. Various factors that influence on density of seawater.

Table 2
Correlations of density used by various authors.

Correlation	Temperature range °C	Salinity g/kg	Year	References
$\rho = \rho_o + AS_A + BS_A^{1.5} + CS_A^2$(2) The constants A, B, C are function of temperature as given below $A = a_0 + a_1(T/K - 273.15) + a_2(T/K - 273.15)^2 + a_3(T/K - 273.15)^3 + a_4(T/K - 273.15)^4 + a_5(T/K - 273.15)^5 B = b_o + b_1(T/K - 273.15) + b_2(T/K - 273.15)^2 C = c_o S_A$ = Absolute Salinity	0–90	5–70	2009	[31]
$p/MPa = A(\rho/g\,cm^{-3}) + B(\rho/g\,cm^{-3})^8 + C(\rho/g\,cm^{-3})^{12}$(3) Where $A = \sum_{i=1}^{5} T^i \sum_{j=0}^{2} a_{ij} {S_A}^j B = \sum_{i=0}^{4} T^i \sum_{j=0}^{2} b_{ij} {S_A}^j C = \sum_{i=0}^{4} T^i \sum_{j=0}^{2} c_{ij} {S_A}^j$ where a_{ij}, b_{ij}, c_{ij} can be obtained from Ref. [32].	0–195	3–29	2013	[32]
$\rho_{sw}(t,S,P) = \rho_{sw}(t,S,P_o) \times F_p$(4) Where $\rho_{sw}(t,S,P_o)$ can calculated from Ref. [36] and F_p can be obtained from Ref. [35] Extrapolation: $0 \le P \le 12$ MPa U_{max}: 0.21 %	0–180	56–160	2016	[35]

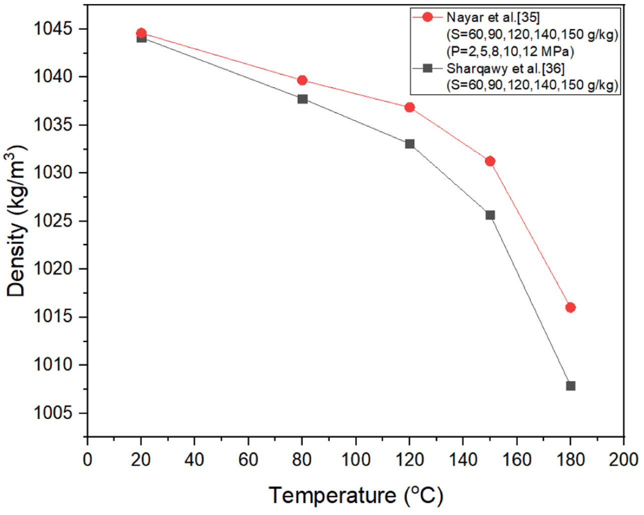

Fig. 4. Variation in density with temperature of various authors.

these two studies showed a good correlation for density.

2.2. Boiling point and vapor pressure

Number of salts affects the boiling point of seawater and vapor pressure. As the concentration of salts increases, vapor pressure decreases; thus, boiling point is enhanced. Accordingly, the boiling point of seawater is high compared to pure water, where this can be measured as boiling point elevation (BPE). The boiling point and pressure of vapors can thus be obtained by changing either of them. Raoult's law gives vapor pressure of vapors of seawater, considering perfect conditions, which are given by Eq. 5. This law refers to vapor pressure of seawater, and is obtained by multiplying mole fraction of water in seawater and vapor pressure of water in pure form. The mole fraction of seawater is salinity dependent factor [36].

The boiling point of water can be determined when the vapor pressure of the liquid becomes equal to atmospheric pressure (760 mmHg) [42]. Cottrell [43] has suggested an instrument that measures the boiling point of a solution, where the boiling point of a pure substance can be calculated by placing a thermometer above the liquid. However, in the case of a solution this is not possible. For pure substances, the thermometer can be placed above the boiling liquid, where recondensation to form in a thin coating of liquid with vapor, which gives equilibrium conditions. This cannot be done in the case of solution as seawater to produce these same mechanical conditions, but can be achieved via the Beckmann thermometer, which was invented by Ernst Otto Beckmann in 1887. Table 3 presents a summary of the work by various authors on boiling point elevation (BPE) and vapor pressure (VP) calculation along with temperature range, salinity range and uncertainty.

Emerson and Jamieson [46] have proposed Eq. 6, based on synthesized seawater for temperature in the range of $100 \leq T \leq 180$ °C and salinity $30 \leq S \leq 170\,\mathrm{g/kg}$. The pressure was determined using salinity in the given range of parameters. The BPE of seawater was deducted by Bromley et al. [47] as based on Eq. 7, which built up the calculations of natural seawater boiling point for the temperature range of $0 \leq T \leq 200$ °C and salinity of 120 g/kg with $\pm 2\,\%$ accuaracy. It was concluded that the correlation given by Emerson and Jamieson [46] in Eq. 6 and Bromley et al. [47] in Eq. 7 were the best correlation for explaining the boiling point and vapor pressure of seawater, as they were experimentally based and had less uncertainty.

El-Dessouky and Ettouney [50] have suggested a correlation, given in Eq. 8, showing boiling point elevation versus temperature and salinity. Their temperature and salinity range were $10 \leq T \leq 180$ °C and $1 \leq X \leq 16\,\%$, respectively. Their results showed this equation to be quite accurate for measuring BPE. Sharqawy et al. [36] have suggested a correlation, which is given by Eq. 9, whereby variation of boiling point elevation based on temperature and salinity was checked, concluding that BPE could be increased by increasing temperature and salinity, as shown in Fig. 5.

A summary of correlations developed by different researchers for BPE and VP calculation, along with temperature and salinity range, is summarized in Table 4.

2.3. Osmotic coefficient and pressure

Osmotic pressure is the minimum pressure applied to a solution to prevent pure solvent inward flow through a semipermeable membrane. The osmosis phenomenon occurs when different concentrations of two solvents are separated by a semipermeable membrane. Thus, the

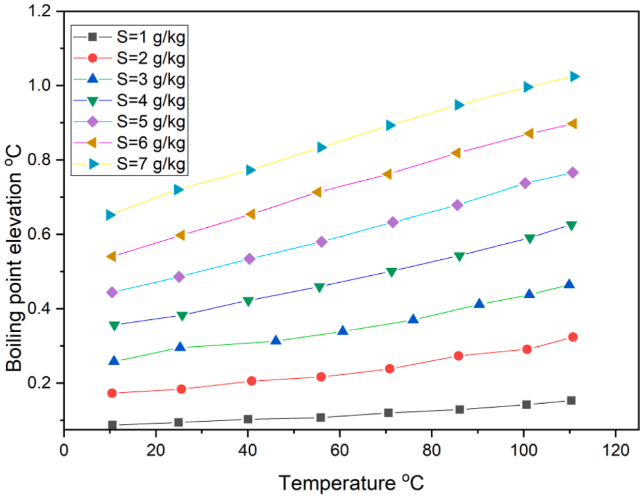

Fig. 5. Variation of boiling point elevation with temperature and salinity [36].

Table 3
Summarized work for BPE and VP calculation methods as applied by various authors.

Method	Property	Temperature (°C)	Salinity g/kg	%wtofsalt	Uncertainty (%)	Year	References
Beckmann's thermometer & certified stem thermometer	BPE	——	5–40	——	——	1939	[42]
IM	BPE	42–105	18–61	——	0.1	1950	[25]
Differential manometer	VP	0–175	10–160	——	0.2	1954	[43]
Isopiestic method	VP	25	18–40	17–20	0.2	1954	[44]
Additive rule for relative molal mass	BPE	20–180	35–100	2–10	0.02	1966	[45]
Isopiestic method	VP	100–180	30–170	——	0.069	1967	[46]
Lift and mechanical pumps	BPE	0–200	10–120	2–12	0.004	1974	[47]
Scholander micro gasometer	VP	0–40	0–40	——	0.01	1980	[48]
——	VP	0–40	0–40	——	0.02	1983	[49]

Table 4
BPE and VP correlations investigated by various authors.

Correlation	Year	Reference
$p_{v,w}/p_{v,sw} = 1 + 0.57357 \times \left(\frac{S}{1000 - S}\right)$ (5) Roult's law assumption where $p_{v,w}$ = vapor pressure of pure water $p_{v,sw}$ = vapor pressure of seawater S is salinity g/kg	2010	[36]
$\log_{10}(p_{v,w} - p_{v,sw})/p_{v,w} = 9.026 - 2.1609 \times 10^{-4} S_p - 3.5012 \times 10^{-7} S_p^2$ $p_{v,w}$ data from NEL steam tables, (6) Validity: $100 < t_{48} < 180\ ^\circ C$, $35 < S_p < 170$ g/kg	1967	[46]
$BPE = \frac{S_p T_{68}^2}{13832}\left[1 + 0.00137 T_{68} + 17.86 S_p - 0.00272 T_{68}\sqrt{S_p} - \frac{2.583S(1 - S_p)}{T_{68}} - 0.0152 S_p T_{68}\left(\frac{T_{68} - 225.9}{T_{68} - 236}\right)\right]$ (7) Validity: $0 \le T_{48} \le 200\ ^\circ C$, $0 < S_p < 0.12$ g/kg	1979	[47]
$TE = Ax + Bx^2 + Cx^3$ (8) And $A = 8.325 \times 10^{-2} + 1.882 \times 10^{-4} \times T + 4.02 \times 10^{-6} \times T^2$ $B = -7.625 \times 10^{-4} + 9.02 \times 10^{-5} \times T + 5.2 \times 10^{-7} \times T^2$ $C = 1.522 \times 10^{-4} - 3 \times 10^{-6} \times T - 3 \times 10^{-8} \times T^2$ T = BPT in °C, x = salinity in weight percentage Validity: $10 \le T \le 180\ ^\circ C$ and salinity was $1 \le X \le 16\,\%$.	2002	[50]
$BPE = AS^2 + BS$ (9) $A = -4.584 \times 10^{-4} t^2 + 2.823 \times 10^{-1} t + 17.95$ $B = 1.536 \times 10^{-4} t^2 + 5.263 \times 10^{-2} t + 6.56$ Validity: $0 \le t \le 200\ ^\circ C$ and salinity was $0 \le S \le 0.12$ kg/kg. Accuracy: ±0.018	2010	[36]

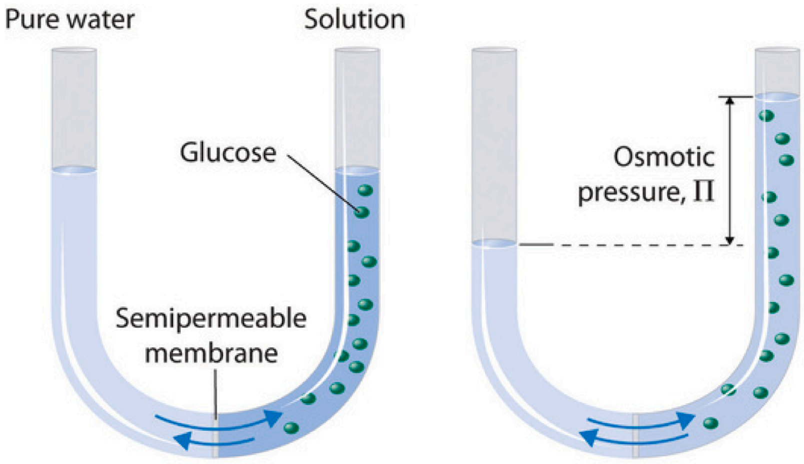

Fig. 6. Osmotic Pressure Phenomena [51].

membrane becomes the main source for determining osmotic pressure. The basic phenomena of osmotic pressure is illustrated in Fig. 6.

The basic equation for osmotic pressure suggests a relationship between osmotic pressure and solute concentration, which is given by [52]:

$$\text{Osmotic pressure} = iCRT \tag{10}$$

where "i" is the vent's Hoff index, "C" is the molar concentration of solute, "R" is the ideal gas constant and "T" is the temperature.

The osmotic coefficient refers to a quantity that gives the deviation of solvent from its ideal behavior, also called Routs law. The osmotic coefficient can be found from boiling point elevation, vapor pressure and freezing point measurement, all of which have been discussed by Sharqawy al. [36]. These authors reviewed the correlation used by Bromley et al. [47], in which they applied a temperature range of 0–200 °C and salinity range between 10 and 120 g/kg with a maximum ±1.4 % deviation. For salinity < 10 g/kg, Bromley et al.'s correlation was unable to interpret osmotic pressure due to complex expressions. Thus Bromsted's equation [53] can be applied for salinity of less than < 10 g/kg in ideal conditions, which is given by:

$$\varnothing = 1 - k\sqrt{m_s} + \lambda m_s \tag{11}$$

where m_s is the solution molality and k & λ are fitting parameters and m_s is based on IAPWS seawater composition given by [53]:

$$m_s = \frac{1000}{MW_s} \times \frac{S}{1000 - S} \tag{12}$$

where S is salinity and MW_s is the average molecular weight of every dissolved solute in seawater [11] which is 31.4038 g/mol. The deviation of seawater osmotic coefficient is based on correlation from values obtained from the IAPWS equation of state of seawater. Osmotic pressure can be calculated from Eq. (12), given by Robison and Stokes [55] as:

$$\pi(\mathrm{t,S}) = \frac{\varnothing_{\mathrm{sw}}\mathrm{RT} \times \rho_{\mathrm{sw}}(\mathrm{t,0g/kg,P_o})}{10^6} \times \frac{1000}{\mathrm{MW_s}} \times \frac{\mathrm{S}}{1000 - \mathrm{S}} \quad (13)$$

where $\pi(\mathrm{t,S})$ is the osmotic pressure of seawater in MPa, R is the ideal gas constant, T is the temperature in K, $\rho_{\mathrm{sw}}(\mathrm{t_o, g/kg, P_o})$ is the density of pure water and $\mathrm{MW_s}$ has a value of 31.4038. The summary of various authors' works on osmotic coefficient and pressure calculation methods, along with temperature and salinity range, is given in Table 5.

The osmotic coefficient given by Nayar et al. [35] consists of a piecewise correlation that consists of Bronsted equation for the salinity in the range of 0–10 g/kg, and Bromley correlation for a salinity range of 10–120 g/kg. The correlation is calculated by Eq. 14. The variation of the osmotic coefficient of seawater with salinity is shown in Fig. 7.

The one correlation developed by Nayar et al. [35] for calculating osmotic coefficient with variation in temperature and salinity is given in Table 6. This correlation considers a wide range of temperature and salinity range with more accurate results.

2.4. Surface tension

Surface tension is the property of a liquid that tends to attract the particles of the surface of the liquid by the bulk of the liquid. Fluid surface tension decreases with increasing temperature and becomes minimum when critical temperature is achieved. Salt type also affects surface tension of a liquid, especially in the case of organic contamination, such as surfactants.

Gittens [57] has measured the surface tension of pure water at small temperature intervals, where surface tension was determined by the two methods depicted in Fig. 8. Temperature was measured by a calibrated thermometer with an accuracy of ±0.05°. The results indicated that less variation in surface tension with temperature changing was observed when compared with data in the literature. The above methods were used within a very small temperature range, prompting lower accuracy for determining surface tension; hence, wider ranges of temperature should be explored in future research.

The surface tension of seawater depends upon the speed of flowing water rather than transparency, as suggested by Adam [58]. The author proposed that creeks, small harbours and confined areas of water may have surface tension lower than normal. According to the above mentioned study, very muddy looking streams have normal tension, while more sluggish but clear streams or lakes may exhibit less surface tension. The surface tension of seawater is higher than that of pure water owing to the presence of salts. Harkin and McLaughlin [59] have determined the surface tension of water with calcium chloride to be 25 °C, where they used the drop weight method in order to determine this surface tension. The results indicate the value of surface tension to be 72.03 dyne/cm, where the T.F Young equation gave an almost identical value of 72.02 dyne/cm.

The effect of salt concentration and temperature on interfacial surface tension has been investigated by Gaonkar [60], where the presence of salt led to a reduction in the surface tension of the liquid. The difference in interfacial tension increased in the presence of salts and with increasing temperature, where opposite trends were observed in case of temperature variations. Beattie et al. [61] have measured the effect of pH on the surface tension of water in the presence of salts, showing that he surface tension of water does not depend on pH when it is 1 and 13, but rather when pH is around 7 in NaOH or KCl solutions as sodium ions replace hydroxide ions. Various authors have studied and proposed different correlations on surface tension. A summary of previous works on the methods of calculating surface tension along with temperature range and salinity range is given in Table 7.

Table 5
Summary of methods for osmotic coefficient and pressure calculations by various authors.

Method	Temperature °C	Salinity g/kg	Year	References
Isopiestic method	25	16–40	1954	[15]
Single-electrolyte solution method	25–100	——	1973	[51]
Lift and mechanical pumps	0–200	10–120	1974	[18]
———	0–40	0–40	1976	[56]

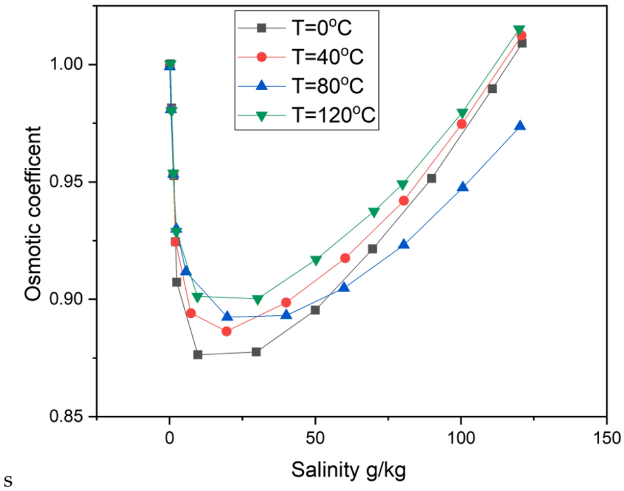

Fig. 7. Variation of osmotic coefficient based on temperature and salinity [35].

Table 6
Correlation of osmotic coefficient.

Correlation	Year	References
$\varnothing_{\mathrm{sw}} = \left\{\begin{matrix} \varnothing_{\mathrm{Bromey}}(\mathrm{t,S}) for S \geq 10\mathrm{g/kg} \\ \varnothing_{\mathrm{Brnsted}}(\mathrm{t,S}) for S < 10\mathrm{g/kg} \end{matrix}\right\}(14)$ Bromley correlation from Ref. [36] Bronsted model from Ref. [53] Validity: Bromley Correlation: $0 \leq \mathrm{t} \leq 120$ °C, $10 \leq \mathrm{S} \leq 10$ g/kg Bronsted model: $0 \leq \mathrm{t} \leq 120$ °C, $0 \leq \mathrm{S} \leq 10$ g/kg	2016	[35]

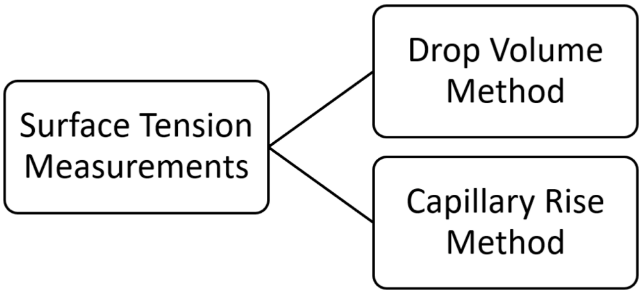

Fig. 8. Pure water surface tension measurement methods [57].

Table 7
Summary of data for surface tension calculation by various authors.

Temperature range (°C)	Salinity range (g/kg)	Year	References
0–40	10–35	1900	[62]
0–40	10–35	1939	[63]
15–35	5–35	1994	[64]

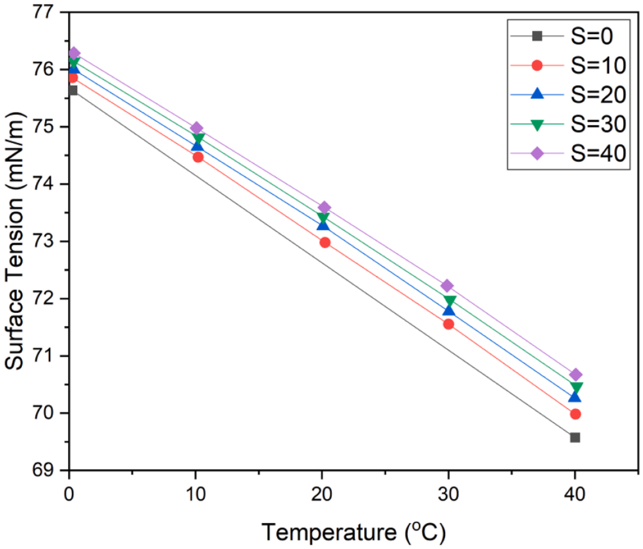

Fig. 9. Surface tension variation along temperature and salinity [36].

Studies conducted before 2010 measuring the surface tension of seawater included only a limited range of temperature and salinity ranges. The approximate maximum range of temperature and salinity range in these studies were 40 °C and 35 g/kg,respectively. This is not sufficient to cover a wide range in view of practical aspects. The accuracy of these results were not precise enough to give accurate results. Therefore, recent studies on surface tension correlation, including Shaqawy et al. [36] in 2010, Schmidt and Schneider [65] in 2011 and Nayar et al.[66] in 2014, later summarized by Nayar et al. [11] in 2016, have covered a wide range of temperatures and salinities. Pure water surface tension is mentioned in Eq. 15 which was obtained from IAPWS 2008 [67]. These corrections also have more accuracy in determining surface tension results.

The surface tension correlation was applied by Sharqawy et al. [36] as given in Eq. 16, valid for temperature in the range of 0–40 °C and salinity range of 0–40 g/kg. The change of surface tension with temperature and salinity is shown in Fig. 9.

Schmidt and Schneider [65] have measured surface tension for a temperature range of 0–40 °C and 0,11,34 g/kg salinity by considering the Wihlemy plate method. Their experiments were performed on organic free seawater and pure water surface tension measurements within arange of 0.01mN/m. A correlation for calculating the surface tension of seawater was proposed, given by Eq. 17. Nayar et al. [66] have measured the seawater surface tension for salinity above 35 g/kg and temperature of 35 °C, representing the first study of its kind in the literature. The temperature varied between 1 and 92 °C for the salinity range of 0–131 g/kg. Thus, this was extrapolateable in temperatures of 0–100 °C. The Wilhelmy plate method was used to measure surface tension, where seawater samples were taken from standard seawater. The average and mximum uncertainties were 0.22 and 0.37 mN/m respectively. The maximum uncertainty in these findimg were minor, where they showed very accurate results. A summary of various correlations developed by various researchers for surface tension calculation along with variations in temperature and salinity are summarized in Table 8. A comparison of different author correlations on surface tension is summarized in Section 3 and Fig. 23.

2.5. Thermal conductivity

Thermal conductivity is the ability of a material to be able to conduct heat. The thermal conductivity of pure water is not as good as ordinary water. The thermal conductivity of water has been determined by various authors [68–71]; however, the thermal conductivity of most fluids is difficult to determine, where limited data is available. Usually the thermal conductivity of liquid decreases with an increment in salt concentration [72], where in this regard, limited experimental data is available in comparison to pure water.

Yasufova et al.[73] have measured the thermal conductivity of sodium chloride at concentrations 5,10,15,20 and 25 wt % of sodium chloride for a temperature range of 20–330 °C. The relative flat layer method was used and a correlation was developed. The results indicated that the relative root means square error of thermal conductivity was less than 2 %.

Abdulagatov and Magomedov [74] have measured the thermal conductivity of NaCl and KCl at high pressure, applying the parallel plate method to measure thermal conductivity for the temperature range of 20–200 °C, pressure up to 100 MPa and concentration of 0.025 to 0.25 mass fraction of NaCl and KCl. The value of thermal conductivity of both solutions agreed with the data in the literature and the precision of the measurements was ±1.6 %.

Lewy [75] has studied the thermal conductivity of slush formed by NaCl, $CaCl_2$ and seawater between their freezing point and eutectic temperature. The conductivity of the slush was determined by introducing values of conductivity of brines at 0 °C and freezing point into Maxwell-Eucken equation and the higher conductivity of slush was obtained between −2 to 25 °C. A summary of previous works on the calculation of thermal conductivity along with temperature and salinity variation is given in Table 9.

The studies that were carried out in early years of the measurement of thermal conductivity have a high value of uncertainty associated with their results. Accordingly, Sharqawy [79] determined natural seawater thermal conductivity with accurate results at atmospheric pressure for the temperature range of 10–90 °C and salinity of 0–120 g/kg, applying a ratio of natural water to seawater ($\frac{k_w}{k_{sw}}$), as given by Eq. (19):

$$\frac{k_w}{k_{sw}} = 0.00022 \times S + 1 \tag{19}$$

In order to find seawater thermal conductivity as a function of temperature, pressure and salinity, a new correlation, given by Eq. 20, was proposed by Nayar et al. [35], which is pure water to seawater pressure dependent thermal conductivity. A summary of various correlations developed by previous researchers for thermal conductivity calculation in different temperature and salinity ranges is summarized in Table 10.

Rashid et al. [81] have investigated the thermal conductivity of seawater ice using the multiphysics analysis method, which included simulations as well as experimentation. The experimental setup was carried out by using an infrared camera (as shown in Fig. 10), which was placed in front of the surface. A power supply for data monitoring was attached to the camera. The finite difference method was applied to discretize the heat equation, and the results were determined in Matlab using the Forward-Time Central-Space method. The results indicated that the value of thermal conductivity was in agreement with the literature, in a range of 0.5–0.7 W/mK for a temperature range of −30 to 0 °C [82].

Melinder and Ignatowicz [83] have determined the thermal conductivity of seawater along ice slurry. The values of thermal conductivity were found to be higher than those measured in the literature, by $<$ 2%, which were adjusted for a better fit. The variation of seawater

Table 8
Correlations of surface tension investigated by various authors.

Correlation	Year	References
$\sigma_w = 0.2358\left(1 - \frac{t+273.15}{647.096}\right)^{1.256}\left[1 - 0.625\left(1 - \frac{t+273.15}{647.096}\right)\right]$(15) Validity $0.01 < t < 370\ ^\circ C$ Accuracy:$\pm 0.08\%$	2008	[67]
$\frac{\sigma_{sw}}{\sigma} = 1 + (0.000226 \times t + 0.00946)\ln(1 + 0.0331 \times S)$(16) Validity $0 < t < 40\ ^\circ C$, $0 < S < 40$ g/kg Accuracy:$\pm 0.18\%$	2010	[36]
$\sigma_w = 75.516 - 0.1285 \times T + 0.0353 \times S - 0.000429 \times T^2 - 0.000161 \times S^2$(17) T = Temperature in °C S = salinity in g/kg Validity temperaure 0–40 °C salinity (0,11,34) g/kg	2011	[65]
$\sigma_{sw} = \sigma_w\left[1 + 3.766 \times 10^{-4}.S + 2.347 \times 10^{-6}.S.T\right]$(18) S = salinity in g/kg T = Temperature in °C σ_w is given by Eq. (18) Validity; Ref: [66] $1 \le t \le 92\ ^\circ C$, $0 \le S \le 131$ g/kg,$0.1 \le P \le 1$ MPa $1 \le t \le 100\ ^\circ C$, $0 \le S \le 131$ g/kg,$0.1 \le P \le 1$ MPa	2014	[66]

Table 9
Summary of data for thermal conductivity calculation by various authors.

Method	Temperature (°C)	Salinity (g/kg)	Year	References
Hot Wire Principle	$0 < t < 180$	$0 < S < 160$	1970	[76]
Concentric cylinder apparatus	$0 < t < 60$	$0 < S < 60$	1974	[77]
Concentric cylinder apparatus	$0 < t < 30$	35	1974	[78]
Relative flat plate method	$20 \le t \le 330$	——	1975	[73]
Flat Plate Method	$20 \le t \le 200$	——	1994	[74]

Table 10
Correlation of thermal conductivity investigated by Nayar et al. [35].

Correlation	Year	References
$k_{sw}(t,S,P) = \frac{k_w(t,P)}{0.00022 \times S + 1}$(20) $k_w(t,P) = k_w(t,P_o) \times \left[1 + P' \times \left(a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4\right)\right]$$k_w(t,P_o) = b_1T^{-0.194} + b_2T^{-4.717} + b_3T^{-6.385} + b_4T^{-2.134}$where, $T = \frac{t+273.15}{300}$, $P' = \frac{P-0.1}{139.9}$, $a_1 = 21.942$, $a_2 = -77.387$, $a_3 = 102.81$, $a_4 = 60.727$ $a_5 = 13.464$, $b_1 = 0.797015$, $b_2 = -0.251242$, $b_3 = 0.096437$, $b_4 = -0.032696$, Validity: $10 \le t \le 90\ ^\circ C$, $0 \le S \le 120$ g/kg, $P = P_o$; $10 \le t \le 60\ ^\circ C$, $0 \le S \le 35$ g/kg, $0.1 \le P \le 12$ MPa; Ref: [79,80]	2016	[35]

thermal conductivity with respect to temperature is shown in Fig. 11.

2.6. Viscosity

The viscosity of any fluid is the internal resistance to flow, which is called dynamic viscosity. The viscosity of water is inversely proportional to temperature, and decreases with an increase in temperature. The effect of the addition of electrolytes in water has been investigated by Horne and Johnson [84], where their study concluded that the effect of electrolyte addition in water was less than on viscosity.

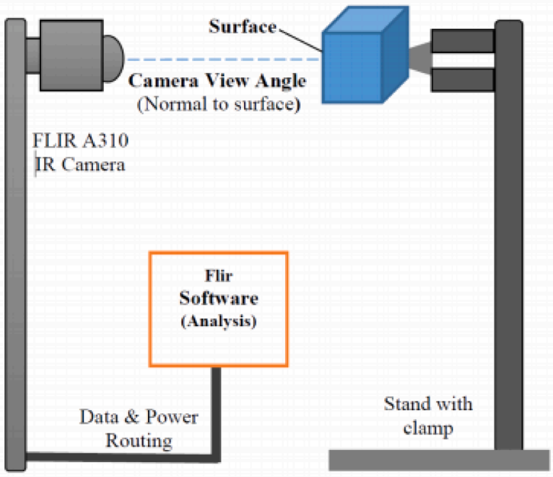

Fig. 10. Infrared Imaging Experimentation [81].

Seawater viscosity has a high value as compared to pure water due to the availability of various salts present in seawater and therefore, its very important to measure it. Horne and Johnson [85] measured the viscosity of compressed seawater using a rolling ball-type of high-pressure viscometer, applying a temperature range of −2 to 12 °C and hydrostatic pressure up to 1500 $\mathrm{kg/cm^2}$. Their results showed the viscosity of seawater to be different from pure water above 4 °C.

Sawamura et al. [86] have suggested a device to measure the viscosity of water. The high-pressure rolling-ball was designed using a glass cell consisting of a glass cylinder and its piston. The viscosity of water containing sodium chloride was measured at 25 °C and pressure upto 375 MPa. The viscometer was useful over a wide range of electrolyte solutions.

A summary of various works on viscosity calculation methods, considering the effects of temperature and salinity variations, is given in Table 11.

Pure water viscosity is given by Eq. 22, proposed by the International Association for the Properties of Water and Steam in 2008. The temperature was in the range of 0–180 °C and salinity varied between 0 and 0.15 g/kg with an accuracy of ±1.5 %. Islam and Carlson [95] have proposed Eq. 23 based on experimental data and viscosity values derived from the literature. This equation is the same as the one in the

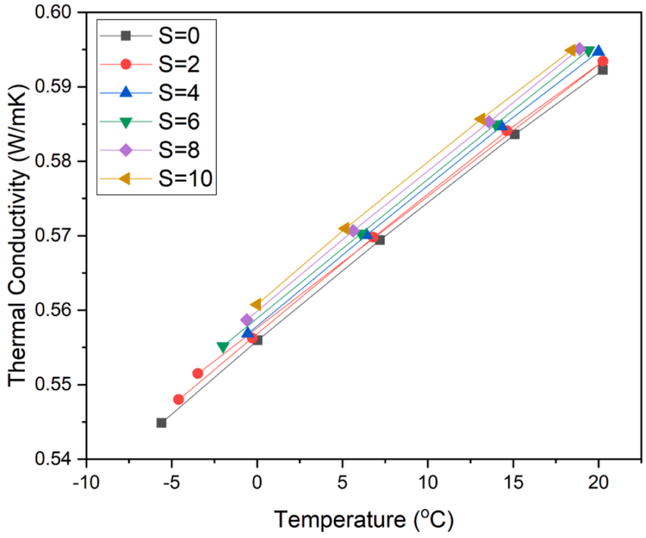

Fig. 11. Thermal conductivity of seawater [83].

Table 11
Summary of methods for viscosity calculation by various authors.

Method	Temperature (°C)	Salinity (g/kg)	Year	References
——	0–30	5–40	1907	[87]
——	0–30	5–40	1948	[88]
Rolling-ball type high pressure viscometer	−2 to 12	——	1966	[85]
Othmer rule method	25–150	≤ 110	1969	[89]
Rolling ball viscometer	0–30	35	1969	[90]
Pressurized glass capillary viscometer	10–180	0–150	1972	[91]
Pressurized glass capillary viscometer.	0–200	——	1973	[92]
——	5–25	0–40	1974	[93]
Tammann-Tait Gibson model	20	0–150	1979	[94]

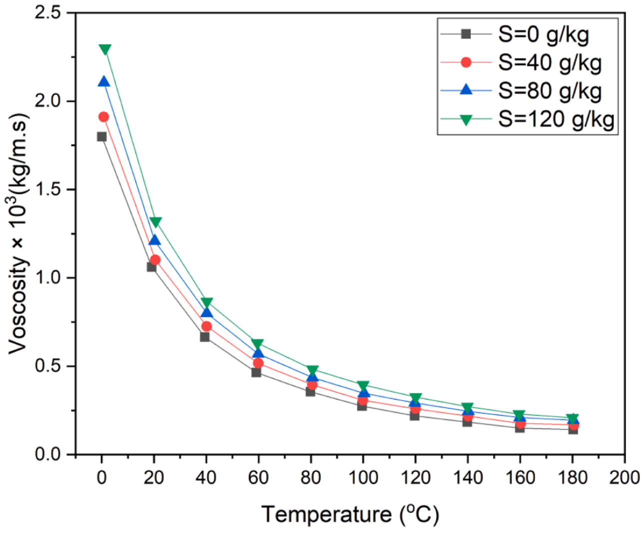

Fig. 12. Variation of viscosity with temperature and salinity [36].

Table 12
Correlations of viscosity investigated by various authors.

Correlation	Year	References
$\mu_{sw} = \mu_w(1 + AS + BS^2)$(21) $A = 1.541 + 1.998 \times 10^{-2}t - 9.52 \times 10^{-5}t^2$ $B = 9.745 - 7.561 \times 10^{-2}t + 4.724 \times 10^{-4}t^2$ And μ_w can be calculated from Eq. 23. T = temperature S = salinity Validity: $0 < t < 180\ ^\circ C$ $0 < S < 0.15$ g/kg	2010	[36]
$\mu_w = 4.2844 \times 10^{-5} + \left[0.157(t + 64.993)^2 - 91.296\right]^{-1}$(22) Validity: $0 < t < 180\ ^\circ C$ $0 < S < 0.15$ g/kg Accuracy:±1.5%	2008	[67]
$\mu_w = a_0 + \sum_{i=1}^{3} b_i \exp(-c_i T) + P\sum_{i=1}^{3} d_i (T - 293.5)^i$(23) iABCD 02.27 $\times 10^1$-2.08 $\times 10^{-1}$ 11.09 $\times 10^4$9.89 $\times 10^{-3}$2.02 $\times 10^{-2}$ 29.59 $\times 10^8$4.38 $\times 10^{-2}$-2.80 $\times 10^{-4}$ 3-8.60 $\times 10^8$4.41 $\times 10^{-2}$1.19 $\times 10^{-6}$ T = temperature in °C P = pressure in MPa $U_{max} = \pm 0.05\,\%$	2012	[95]

literature but with different coefficients. Earlier studies measuring viscosity had less temperature and salinity range in their correlations. Therefore, more recent researchers have explored new correlations with a large range of temperature and salinities. A more accurate correlation for the change of viscosity with the temperature and salinity can be calculated from Eq. 21, where variations are presented in Fig. 12.

The summary of various correlations developed by previous researchers for viscosity calculation for different temperatures and salinities are summarized in Table 12.

2.7. *Specific enthalpy*

The specific enthalpy is a thermodynamic property that is the sum of specific energy and the product of pressure and specific volume. The property of enthalpy is considered when adiabatic or isobaric mixing occurs. For adiabatic mixing of seawater, *T*-S diagram is considered but enthalpy-salinity diagram must be under consideration to avoid an error. Therefore, enthalpy must be derived as a function of temperature and salinity [96].

The enthalpy and temperature are directly related to each other due to many other thermodynamic properties related to it. The effect of temperature on enthalpy can be determined from heat capacity which has been studied by various authors [97]. The specific enthalpy of seawater is less than pure water due to the heat capacity of seawater being lower than pure water [98]. The enthalpy of seawater at constant temperature and pressure is given by [36]:

$$h_{sw=} w_s \overline{h}_s + (1 - w_s)\overline{h}_w \tag{25}$$

where $\overline{h}_s$ the partial enthalpy of sea salt, $\overline{h}_w$ is the partial water enthalpy, w_s is the salts mass fraction in the solution.

The calorimeter [99] is used to measure the change in the enthalpy of seawater. It consists of a simple thermometer attached to a metal container filled with water. The substance whose enthalpy per mole is to be measured is placed in the calorimeter and the initial and final temperatures are measured in which the temperature change with specific heat capacity gives the energy. The energy division with mole gives the change in enthalpy and the setup is shown in Fig. 13.

The summary of previous research on the enthalpy calculation

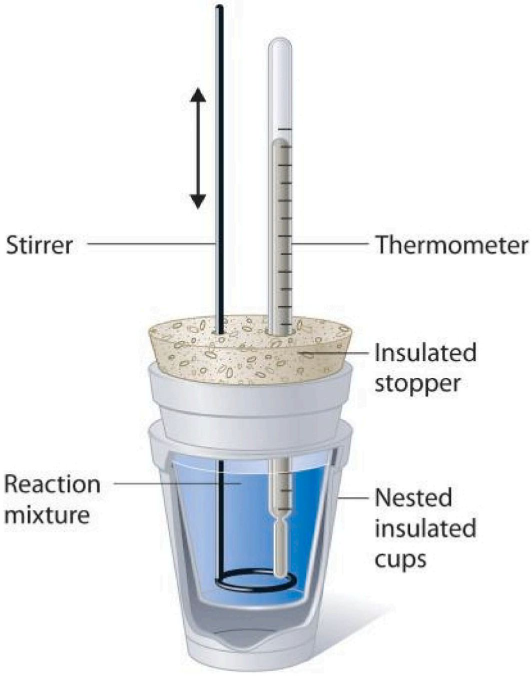

Fig. 13. Pressure Calorimeter for measuring change in enthalpy [100].

Table 13
Different methods for specific enthalpy calculation by various authors.

Method	Temperature (°C)	Salinity (g/kg)	Year	Reference
Debye-Huckel theory	25	≤ 108	1968	[101]
Calorimeter/Dewar Flask	2–25	≤ 61	1970	[96]
Pressure calorimeter	80–200	1–12 %	1970	[102]
Calorimeter	0–75	0–120	1973	[103]
Debye-Huckel theory	0–30	0–40 %	1973	[97]
——	0–30	0–42	1976	[56]

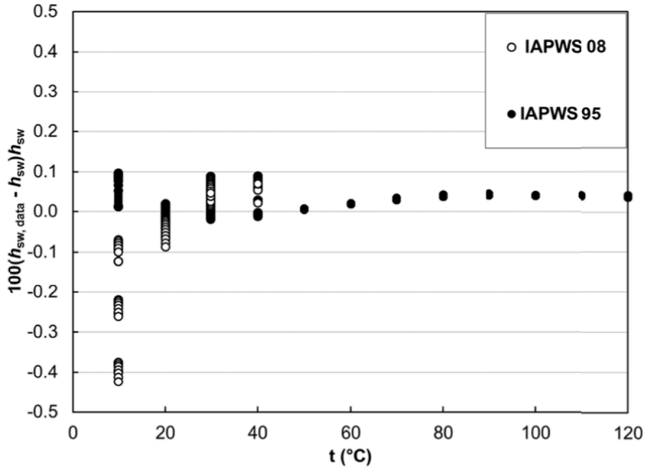

Fig. 14. Seawater enthalpy deviation calculated from IAPWS-08 [104] and IAPWS-95 [13] pure water formulation.

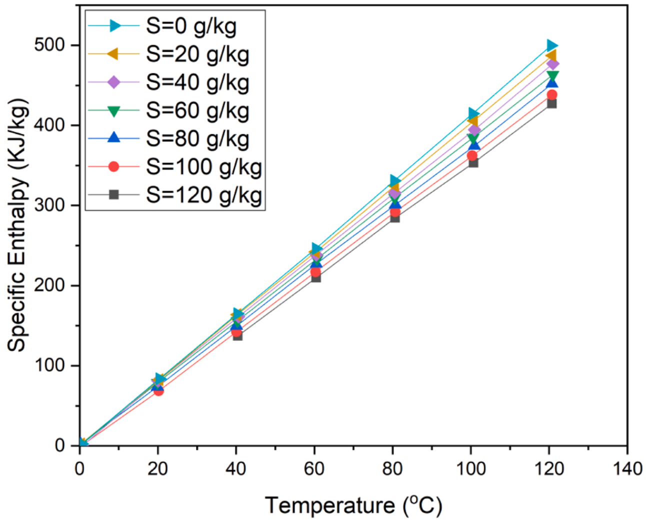

Fig. 15. Variation of enthalpy with temperature and salinity [36].

Table 14
Correlations of enthalpy investigated by various authors.

Correlation	Year	References
$h_{sw} = h_w - S(a_1 + a_2S + a_3S^2 + a_4S^3 + a_5t + a_6t^2 + a_7t^3 + a_8St + a_9S^2t + a_{10}St^2) a_1 = -2.348 \times 10^4, a_2 = 3.125 \times 10^5, a_3 = 2.803 \times 10^6, a_4 = -1.446 \times 10^7, a_5 = 7.826 \times 10^3, a_6 = -4.417 \times 10^1, a_7 = 2.139 \times 10^{-1}, a_8 = -1.991 \times 10^4, a_9 = 2.778 \times 10^4, a_{10} = 9.728 \times 10^1$ (25) Validity: $10 \leq t \leq 120$ °C, $0 \leq S \leq 0.12$ kg/kg Accuracy:±0.5% from IAPWS 2008 [59].	2010	[36]
$h_{sw}(t, S, P) = h_{sw}(t, S, P_o) + (P - P_o) \times (a_1 + a_2t + a_3t^2 + a_4t^3 + S \times (a_5 + a_6t + a_7t^2 + a_8t^3))$(26) where $h_{sw}(t, S, P_o)$ and constants can be determined from Ref. [35] Validity: $80 \leq t \leq 120$ °C, $0 \leq S \leq 120$ g/kg, $0.1 \leq P \leq 1.0$ MPa $40 \leq t \leq 120$ °C, $0 \leq S \leq 42$ g/kg, $0 \leq P \leq 12$ MPa $10 \leq t \leq 120$ °C, $42 \leq S \leq 120$ g/kg, $0 \leq P \leq 12$ MPa Accuracy:±1.47 %	2016	[35]

methods along with variation in temperature and salinity range is given in Table 13.

The studies that were carried out initially to calculate enthalpy have only temperature and salinity range, but later researchers also included pressure dependent factor. Sharqawy et al. [36] reviewed various studies on the enthalpy of seawater near atmospheric pressure. Nayar et al. [35] gave a new correlation at higher pressure ($0.2 \leq P \leq 12$ MPa) mentioned in Eq. 26 which is valid for the temperature range of 10–120 °C, salinity 0–120 g/kg and pressure 0–12 MPa. Nayar et al. [35] validated the expression in Eq. 27 and the maximum deviation was 0.47 % which was less than those in the literature by 1.2 % as shown in Fig. 14.

The variation of enthalpy along with temperature and salinity calculated from Eq. (25) is shown in Fig. 15. It can be seen that the specific enthalpy of seawater is less than pure water by 14 % at 12 g/kg salinity and 120 °C.

The summary of various correlations developed by previous researchers for calculation of enthalpy calculation considering the variation of temperature and salinity is summarized in Table 14.

2.8. Specific entropy

Entropy is a thermodynamic property that is the measure of the disorder of any system under consideration. The entropy of the system may not be a straight-forward calculation but can be determined if the state equation is the scope of knowledge. Thus, entropy is calculated by differentiating Gibbs energy function at constant pressure with respect to temperature. The specific entropy of seawater is less than pure water and the variation of pressure on specific entropy is small so it can be neglected in most cases [105].

Slesarenko and Shtim [106] determined the entropy of seawater by characteristics function which was based on thermodynamic Eqs. and the entropy was calculated by the sum of pure water entropy at a given temperature and solution entropy at a given temperature.

The summary of various authors works for the calculation of enthalpy considering temperature and salinity variations is given in Table 15.

As the deviation in correlation results was high, hence Sharqawy et al. [36] determined a new correlation due to a large deviation from the literaure data using IAPWS-2008 Gibbs energy function which was validated for temperature $10 \le t \le 120$ °C, salinity $0 \le t \le 0.12$ kg/kg. Nayar et al. [35] validated the entropy correlation in Eq. 28 by the addition of the saline part of IAPWS-08 equation of state for seawater and entropy determined by the state equation of pure water using IAPWS-95. The maximum deviation was 0.47 % which was less than the literature by 1.2 %. Therefore, more accurate correalation was obtained to meaure entropy of seawater including the pressure effect on seawater entropy. The deviation was calculated by taking the difference between Eq. 27 and 28. The variation of entropy along with temperature and salinity calculated from Eq. 27 is shown in Fig. 16. It can be seen that the specific entropy of seawater is 1.8 % less than pure water at 12 g/kg salinity and 120 °C.

The summary of various correlations developed by different researchers for entropy calculation along with temperature and salinity are summarized in Table 16.

Table 15
Summary of data for specific entropy calculation by various authors.

Property	Temperature (°C)	Salinity (g/kg)	Year	References
——	0–40	0–40	1983	[49]
Fitted polynomial equation	0–374	0–40	2002	[13]
——	0–40	0–40	2003	[28]
——	40–200	0–120	2008	[107]

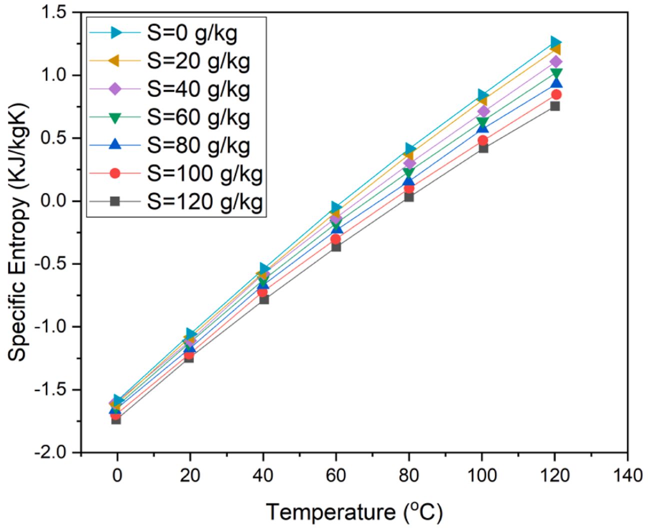

Fig. 16. Variation of entropy with temperature and salinity [36].

Table 16
Correlations of entropy investigated by various authors.

Correlation	Year	References
$s_{sw} = s_w - S(a_1 + a_2S + a_3S^2 + a_4S^3 + a_5t + a_6t^2 + a_7t^3 + a_8St + a_9S^2t + a_{10}St^2)$(27) $a_1 = -4.23 \times 10^2$, $a_2 = 1.463 \times 10^4$, $a_3 = -9.88 \times 10^4$, $a_4 = 3.095 \times 10^5$, $a_5 = 2.56 \times 10^1$, $a_6 = -1.443 \times 10^{-1}$, $a_7 = 5.879 \times 10^{-4}$, $a_8 = -6.111 \times 10^1$, $a_9 = 8.041 \times 10^1$, $a_{10} = -3.035 \times 10^{-1}$ $s_w = 0.153 + 15.383 \times T - 2.996 \times 10^{-2} \times T^2 + 8.193 \times 10^{-5} \times T^3 - 1.370 \times 10^{-7} \times T^4$ Accuracy: ±0.5 % from IAPWS 2008 [67].	2010	[36]
$s_{sw}(t,S,P) = s_{sw}(t,S,P_o) + (P - P_o) \times (b_1 + b_2t + b_3t^2 + b_4t^3 + S \times (b_5 + b_6t + b_7t^2 + b_8t^3))$(28) $b_1 = -4.47 \times 10^{-3}$, $b_2 = -1.165 \times 10^{-2}$, $b_3 = 6.115 \times 10^{-5}$, $b_4 = -2.069 \times 10^{-7}$, $b_5 = -1.553 \times 10^{-3}$, $b_6 = -4.005 \times 10^{-5}$, $b_7 = -1.419 \times 10^{-7}$, $b_8 = -3.312 \times 10^{-10}$, Where s_{sw} can be calculated by Eq. 27. And $s_w = 0.1543 + 15.383 \times t - 2.996 \times 10^{-2} \times t^2 + 8.193 \times 10^{-5} \times t^3 - 1.370 \times 10^{-7} \times t^4$Validity: $80 \le t \le 120$ °C, $0 \le S \le 120$ g/kg, $0.1 \le P \le 1.0$ MPa $40 \le t \le 120$ °C, $0 \le S \le 42$ g/kg, $0 \le P \le 12$ MPa $10 \le t \le 120$ °C, $42 \le S \le 120$ g/kg, $0 \le P \le 12$ MPa Accuracy:±1.47%	2016	[35]

2.9. Specific heat capacity

Heat capacity is the amount of heat required to raise the temperature of a substance by a certain degree means the amount of energy held by a unit mass. The specific heat capacity is the amount of heat required to raise the temperature of a substance per unit mass and it is an intensive property. The specific heat of almost all materials increases with temperature and the heat capacity of molten material is higher than solids.

The specific heat capacity of any substance can be measured by a differential scanning calorimeter. The apparatus works based on the temperature difference between the sample and the reference by heating the sample. The thermocouples are used to measure the temperature difference which gives specific heat to a given substance and at least three measurements are necessary. The specific heat capacity measured by many researchers and the summary of various authors' work on specific heat calculation along with different temperature and salinity ranges is given in Table 17.

The above discussed authors that proposed correlations also not included the pressure dependence effect. Sun et al. [107] used Gibbs function of IF-97 formulation for pure water which has 34 coefficients [114] to calculate the fresh water specific heat capacity. The results can then be used to calculate the specific heat capacity of saline water.

Table 17
Summary of methods for specific heat capacity calculation by various authors.

Method	Temperature (°C)	Salinity (g/kg)	Year	Reference
Electrically heated calorimeter	−2 to 30	0–40	1959	[108]
Classical calorimeter	2–80	1–12 %	1967	[109]
Debye-Huckel Theory	0–80	0–12 %	1968	[110]
Differential heating method	80–180		1969	[111]
Pressure calorimeter	80–200	1–12 %	1970	[102]
Heat capacity calorimeter	5–35	0.5–22 %	1973	[112]
——	0–200	0–120	2005	[113]
Fitted polynomial Eq.	0–374	0–40	2008	[107]

Table 18
Correlations of specific heat capacity investigated by Nayar et al. [35].

Correlation	Year	References
$c_{P,sw}(t,S,P) = c_{P,sw}(t,S,P_o) + (P-P_o) \times (b_1+b_2t+b_3t^2+b_4t^3+S\times(b_5+b_6t+b_7t^2+b_8t^3))$(29) $a_1 = -3.1118, a_2 = 0.0157, a_3 = 5.1014\times10^{-5}, a_4 = -1.032\times10^{-6}, a_5 = 0.0107, a_6 = -3.9716\times10^{-5}, a_7 = 3.2088\times10^{-8}, a_8 = 1.019\times10^{-9}$, Where $c_{p,sw}(t,S,P_o)$ is given by Ref. [36] $c_{p,sw}(t,S,P_o) = A + B(t+273.15) + C(t+273.15)^2 + D(t+273.15)^3$where $A = 5.328–9.76 \times 10^1 S + 4.04\times10^{-1}S^2$ $B= -6.913 + 7.351\times10^{-1}S + 3.15\times10^{-3}S^2$ $C=9.3\times10^{-3} -1.927\times10^{-3}S + 8.23\times10^{-6}S^2$ $D=2.5\times10^{-6} -1.666\times10^{-6}S + 7.125\times10^{-9}S^2$(30) Validity: $40 \le t \le 180$ °C, $0\le S \le 42$ g/kg,$0 \le P \le 1\ 2$ MPa $0 \le t \le 180$ °C, $42\le S \le 180$ g/kg,$0 \le P \le 1\ 2$ MPa Accuracy:±1%	2016	[35]

In order to check the pressure effect on the specific heat capacity of seawater, Nayar et al. [35] evaluated the percentage deviation calculated from the specific heat capacity for any pressure given by Eq. 29 and the specific heat capacity of seawater at pressure P_o is given by Eq. 30. The percnetage deviation showed the specific heat capacity reduced by 1.2 % for pure water at a pressure of 12 MPa.

The summary of correlations developed by Nayar et al. [35] for specific heat capacity calculation along with temperature and salinity variations along with pressure range is summarized in Table 18. This correlation also has more accuracy than correlations that previous authors presented.

2.10. Isothermal compressibility

The isothermal compressibility of any fluid is the volume change due to pressure applied and can be expressed by [115]:

$$\beta = -\frac{1}{V}\left(\frac{\delta V}{\delta P}\right)_T \tag{31}$$

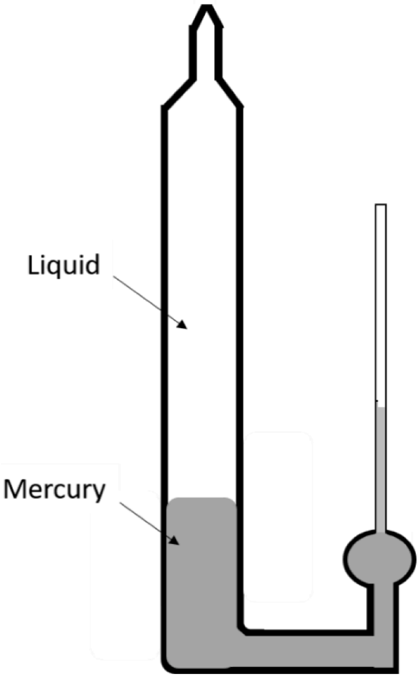

Fig. 17. Apparatus for measuring isothermal compressibility [116].

where V is the volume of fluid and P is the pressure applied and Eq. (31) is also known as bulk modulus of elasticity of fluid. The apparatus used for measuring the isothermal compressibility was suggested by Pena and McGlashan [116] as shown in Fig. 17. The piezometer apparatus was made of Pyrex glass that measured the compressibility at 30 atm and temperature of up-to 60 °C. The apparatus measured the isothermal compressibility of water from 5 to 60 °C.

According to Nayar et al. [35] isothermal compressibility is required for measuring pressure dependence of density or isothermal expansivity or related properties. Various authors [117]–[119] determined the speed of sound in seawater in order to measure isothermal compressibility. The velocity of sound is related to isothermal compressibility given by [120]:

$$\beta = \frac{1}{\rho U^2} + \frac{T\alpha^2}{\rho C_p} \tag{32}$$

whereρ = density, U = speed of sound, T = temperature, α= thermal expansivity, C_p=specific heat.

The summary of various authors' works on the isothermal compressibility calculation method along with variations in temperature and salinity is given in Table 19.

Millero and Huang [118] determined the compressibility of standard seawater for the temperature range of 0–95 °C as given by Eq. 33. The speed of sound was measured in order to determine compressibility from 25 to 95 °C and the salinity range of 0–50 g/kg at atmospheric pressure to a precision of 0.12 m/s. The thermal expansivity and heat capacity were measured from literature data. The variation of isothermal compressibility with salinity at constant temperature and pressure is shown in Fig. 18.

Nayar et al. [35] measured the isothermal compressibility of seawater by extrapolation for the salinity range of $56\le S \le 160$ g/kg. The isothermal compressibility of seawater was the sum of pure water compressibility and 4-terms saline part which was linear in salinity. The pure water isothermal compressibility was obtained from IAPWS-95 formulation for pure water [13] from 0 to 180 °C and 6×10^{-4} –12 MPa. The correlation is given by Eq. 36. The variation of isothermal compressibility with temperature and salinity at 6 MPa is shown in Fig. 19.

The summary of various correlations equations developed by various researchers for isothermal compressibility calculation for different temperatures and salinities along with pressure effect are summarized in Table 20.

2.11. Isobaric expansivity of seawater

The isothermal expansivity of any fluid is the volume change because of pressure applied and can be expressed by Eq. (37) [129].

$$\alpha = \frac{1}{V}\left(\frac{\delta V}{\delta P}\right)_P \tag{37}$$

The summary of various authors' work done on the isobaric expansivity calculation method along with variations in temperature and salinity is given in Table 21.

Nayar et al. [35] measured the isobaric expansivity of seawater by extrapolation for the salinity range of $56\le S \le 150$ g/kg. The isobaric expansivity of seawater for different salinity was formulated by the isobaric expansivity in the literature and density of seawater. For the verification, the final expression was compared with pure water isobaric expansivity obtained from IAPWS-95 formulation [13]. The correlation is given by Eq. (32) and the variation of isobaric expansivity with temperature and salinity at 6 MPa is shown in Fig. 20. Hence, an estimate of maximum deviation at high salinity was obtained by comparing correlation with aqueous sodium chloride expansivity data from previous author's work by extrapolation and therefore minimum isobaric expansivity was obtained at 60 °C.

Table 19
Summary of data for isothermal compressibility calculation by various authors.

Method/seawater type	Temperature (°C)	Salinity (g/kg)	Pressure (MPa)	Standard deviation/error	Year	References
Piezometer	2–15	——	50	——	1969	[121]
Piezo metric Technique	0–40	——	1.7–3.4	——	1971	[122]
Iterative Method	0–28	——	0.1–100	0.05 %	1973	[117]
Wilson;s Sound velocity measurements	0–100	——	0.1–100	± 0.016 × 10^{-6}/bar	1973	[115]
Piezometric Technique	0,15,30,45	——	0.87,1.68,2.57	——	1974	[123]
Least-square polynomial method	10	30–39 %	100	——	1975	[124]
High Pressure Magnetic Float Densimeter	0–40	5–40	0.1–100	0.05 %	1976	[125]
Pitzer Eq. technique	0–40	——	0–100	0.007 × 10^{-6}/bar	2000	[126]
Electrically heated calorimeter	0–180	0	6×10^{-4} –12	0.01	2002	[60]
Pitzer Eq. Technique	0–95	0–50	0.1	0.01	2012	[127]
Vibration tube Densimeter	0–195	32–56	0.5–21	0.03	2012	[33]
——	0–195	3–30	0.2–21	0.03	2013	[32]
——	5–90	40	——	——	2013	[128]

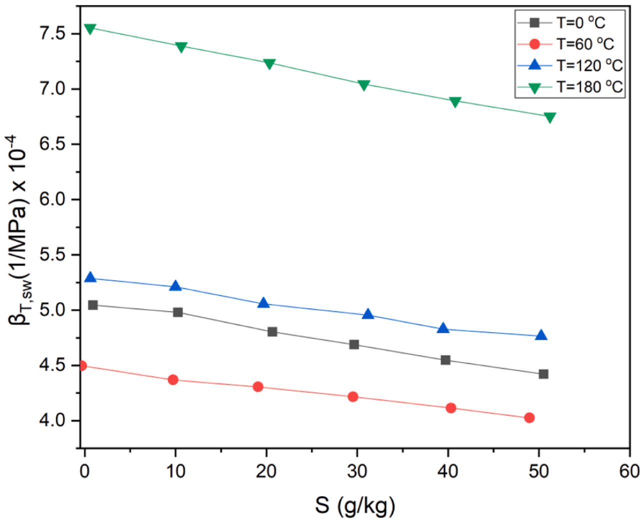

Fig. 18. Variation of isothermal compressibility with salinity [118].

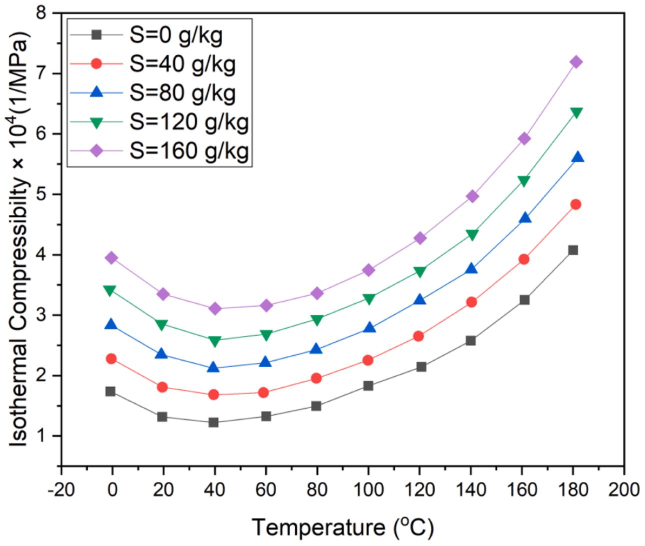

Fig. 19. Variation of isothermal compressibility of seawater calculated using Eq. 36 [35].

Table 20
Correlations of isothermal compressibility investigated by various authors.

Correlation	Year	References
$\beta_T = \beta_s \alpha^2 T / \rho C_p$(33) Where adiabatic compressibility β_s is given in Eq. 35 and s = entropy; ρ=density; C_p=heat capacity and $\beta_s = 1/\rho U^2$(34) U = speed of sound; α=thermal expansively Also, $\alpha = -(1/\rho)(\partial\rho/\partial T)_p$(35) Validity: $0 \le t \le 95$ °C, P = 1 atmospheric	2011	[118]
$\kappa_{T,sw} = \kappa_{T,w} + S \times \left(b_1 + b_2 t + b_3 t^2 + b_4 P\right)$(36) where $\kappa_{T,w} = a_1 + a_2 t + a_3 t^2 + a_3 t^2 + a_4 t^3 + a_5 t^4 + a_6 t^5 + P \times \left(a_7 + a_8 t + a_9 t^3\right)$And $a_1 = 5.097 \times 10^{-4}$, $a_2 = -3.416 \times 10^{-6}$, $a_3 = 5.693 \times 10^{-8}$, $a_4 = -3.726 \times 10^{-10}$, $a_5 = 1.446 \times 10^{-12}$, $a_6 = -1.70 \times 10^{-15}$, $a_7 = -1.33 \times 10^{-6}$, $a_8 = 4.86 \times 10^{-9}$, $b_1 = -1.107 \times 10^{-6}$, $b_2 = 5.558 \times 10^{-9}$, $b_3 = -4.25 \times 10^{-11}$, $b_4 = 8.37 \times 10^{-9}$ Validity: $0 \le t \le 180$ °C, $56 \le S \le 160$ g/kg,$0 \le P \le 1\ 2$ MPa $U_{max} = \pm 13.36\%$	2016	[35]

The summary of the correlation developed by Nayar et al. [35] for isobaric expansivity calculation for different temperatures and salinity along with pressure variation is summarized in Table 22. The drawback of this correlation was that uncertainty this correlation was very high around 13 % which means a more accurate correlation for the measurement of isobaric expansivity should be explored by future researchers.

2.12. Gibbs energy

Gibbs energy is a thermodynamic property that is minimized when any system reaches an equilibrium at constant temperature and pressure and is called available energy. Gibbs energy (g) of seawater can be expressed as [29]:

$$g_{sw} = h_{sw} - TS_{sw} \tag{39}$$

where h is the enthalpy of seawater which is the sum of internal energy and work done and S is the entropy of seawater.

The Gibbs energy calculated in the literature has a temperature range of 0–120 °C but there was a large error in the correlations resulting in a high deviation of data points. The large variation in Gibbs energy ap-

Table 21
Summary of data for isobaric expansivity investigated by various authors.

Method/seawater type	Temperature (°C)	Salinity (g/kg)	Pressure (MPa)	Standard deviation/error	Year	References
Direct technique Dilatometer	−2 to 30	30.6,35.2,39.7	0.8–100	9.3×10^{-6}	1970	[130]
Magnetic float densimeter	0–40	0–42	0–100	2×10^{-6}	1976	[125]
——	0–40	——	0–100	0.6	2003	[28]
Vibration tube Densimeter	0–195	0–56	0.1–140	16×10^{-6}	2012–13	[32,33]

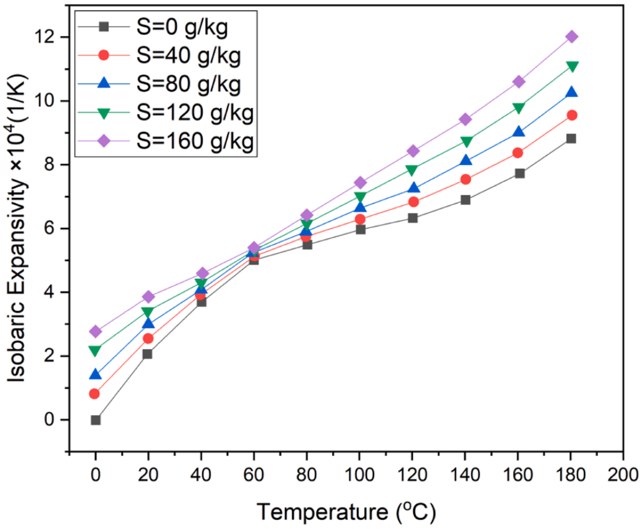

Fig. 20. Variation of isobaric expansivity of seawater calculated using Eq. 38 [35].

proaches zero at 40 °C and salinity of 110 g/kg and a correlation was obtained at a pressure P_o according to literature data.

The correlation of Gibbs energy mentioned in Eq. (39) at pressure P_o gives an error due to large values of the temperature difference. The Gibbs energy for pressure in the range of 0–12 MPa is given in Eq. 40 proposed by Nayar et al. [35] which is valid for the temperature between 10 and 120 °C and salinity of 0–120 g/kg. This expression was compared with IAPWS-08 Gibbs energy and IAPWS-95 for pure water Gibbs energy. The overall uncertainty of Gibbs energy was 0.07 KJ/kg. The summary of one correlation developed by Nayar et al. [35] for Gibbs Energy calculation along with the variation in temperature and salinity along with pressure variations is summarized in Table 23. The uncertainty in this correlation is also less which indicates more accurate results for Gibbs energy calculations.

Table 23
Gibbs Energy Correlation.

Correlation	Year	References
$g_{sw} = g_{sw}(t,S,P_o) + (P - P_o) \times (a_1 + a_2t + a_3t^2 + a_4t^3 + S \times (a_5 + a_6t + a_7t^2 + a_8t^3)$ (40) where $g_{sw}(t,SP_o)$ can be determined from [36] and F_p from [35] Validity: $40 \le t \le 120\ ^\circ C, 0 \le S \le 42$ g/kg,$0 \le P \le 12$ MPa $10 \le t \le 120^\circ C, 42 \le S \le 120$ g/kg,$0 \le P \le 12$ MPa Uncertainty: $U_{max} = \pm 0.11$ KJ/kg	2016	[35]

3. Comparison of correlations

The comparison of different correlations of seawater is summarized in this section. The boiling point of water enhances due to adding salts of various concentrations as presented in Fig. 21. From this figure, it is cleared that as the concentration of salinity increases in water then BPE also increases. Hence, the study of previous authors has revealed that

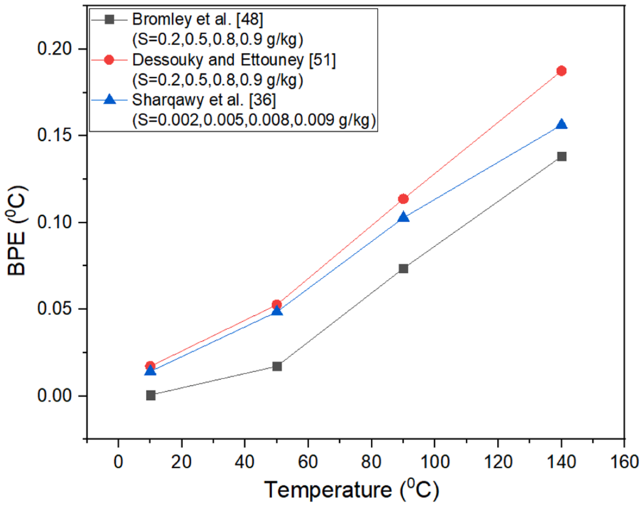

Fig. 21. Variation in boiling point elevation with temperature of various authors.

Table 22
Correlation of isobaric expansivity investigated by Nayar et al. [35].

Correlation	Year	References
$\alpha_{sw}(t,S,P) = -1/\rho_{sw(t,S,P)}\left(\rho_{sw}(t,SP_o)\left(\frac{\delta F_p}{\delta T}\right)_{S,P} + \left(\frac{\delta\rho_{sw}(t,S,P_o)}{\delta T}\right)_{S,P} F_p\right)$ (38) where $\rho_{sw}(t,SP_o)$ can be determined from [36] and F_p from [35] Validity: $10 \le t \le 180\ ^\circ C$ $56 \le S \le 150$ g/kg $0 \le P \le 12$ MPa Uncertainty: $U_{max} = \pm 13.36\%$	2016	[35]

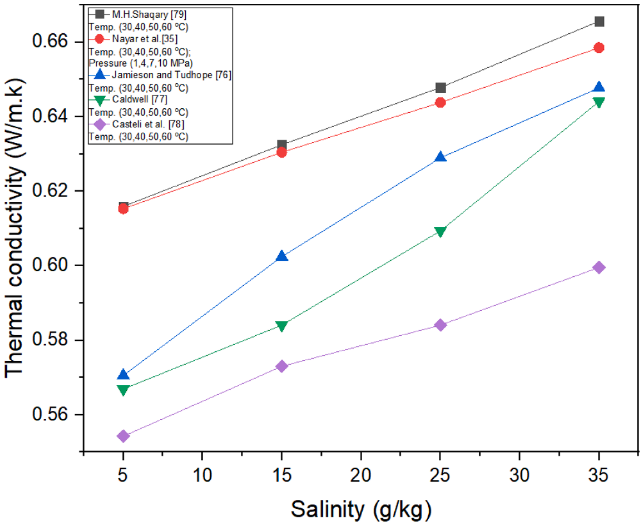

Fig. 22. Variation in thermal conductivity with salinity of various authors.

boiling point increases with increasing temperature. The comparison in Fig. 21 also shows that Dessouky and Ettouney [50] and Sharqawy et al. [36] experimental values are in close agreement for low temperatures but as the temperature increases, the data points deviate from each other. Each point in the graph represents specific BPE against specific temperature and pressure from left to right.

Moreover, the boiling point elevations for a given temperature are high in the case of Dessouky and Ettouney [50] which was close to 0.17 °C at 140 °C as compared to Bromley et al. [47] and Sharqawy et al [36] which were 0.14 °C and 0.12 °C respectively and Bromley et al. [47] was the case with lowest BPE at the same temperature.

The effect of salinity and temperature on thermal conductivity was also discussed by various authors. The correlations of previous authors on thermal conductivity were compared with IAPWS 2008 [104], Nayar et al.[35] and M.H Sharqawy [79] and presented in Fig. 22. It is cleared from this figure, that Nayar et al. [35] and M.H Sharqawy [79] have the best correlations when compared with other authors. It is also obvious that within the same range of temperature and salinity, the thermal conductivity increases with an increase in either of parameter. Each point in the graph represents thermal conductivity against specific salinity and temperature from left to right. It was observed that the thermal conductivity increment was maximum in the case of M.H Sharqawy [79] correlation as compared to other authors' correlations. The thermal conductivity increment was more rapid for IAPWS 2008 with increasing in temperature while the increment in thermal conductivity of Casteli at al. [78] was very low by enhancing the temperature. Although correlations proposed by Nayar et al. [35] and M.H Sharqawy [79] were the best correlations, they showed a large deviation from IAPWS 2008 in data. The correlations presented by authors [76–78] showed large deviations among their data points which indicates they are less efficient. Therefore, more correlations should be developed by future researchers with high accuracy and should be less deviations in their results.

The surface tension of water decreases with an increase in temperature as is the same for saline water as depicted in Fig. 23. It was due to the fact that the presence of salts in water decreases its surface tension as a result of decrement in intermolecular forces among them. Each point in the graph represents surface tension against specific salinity and temperature from left to right. From Fig., it is cleared that the surface tension of pure water decreases more rapidly with an increase in temperature as compared to Sharqawy et al.[36] and Nayar et al.[66]. The data values of both authors are close to each other and are better for defining the surface tension of seawater but deviate from IAPWS 2008 [67]. The decrease in IAPWS 2008 is large as compared to Sharqawy et al.[36] and Nayar et al.[66]. The minimum surface tension in the case of pure water while it was approx. 0.072 mN/m for Sharqawy et al.[36] and Nayar et al.[66] at the temperature of 35 °C.

The variation of enthalpy with the temperature of various authors is shown in Fig. 24. Each point in the graph represents enthalpy against specific salinity and temperature from left to right. It is cleared from this figure that the data points of Sharqawy et al. [36] and Nayar et al. [35] are very close which indicates that the correlations of both authors are similar except that the effect of pressure is added in Nayar et al. [35]. These two correlations are also compared with IAPWS 2008 pure water which reveals that an increment in temperature rapidly enhances the enthalpy of pure water as compared to seawater. It means that the internal energy of pure water increases more rapidly as compared to seawater as the presence of salts in seawater makes intermolecular forces and less increment in internal energy occurred in seawater with temperature increment.

The isothermal compressibility is compared by various authors and the comparison is presented in Fig. 25 which depicted that the variations in isothermal compressibility of Safarov et al. [33] and Nayar et al. [35] is almost the same. Each point in the graph represents isobaric expansivity against specific salinity, pressure, and temperature from left to right. The variation of isothermal compressibility with increment in temperature was checked and results indicated that the increment in

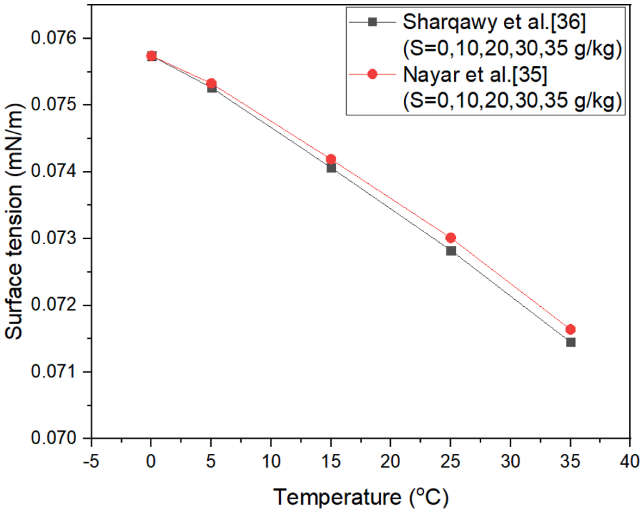

Fig. 23. Variation in surface tension with temperature of various authors.

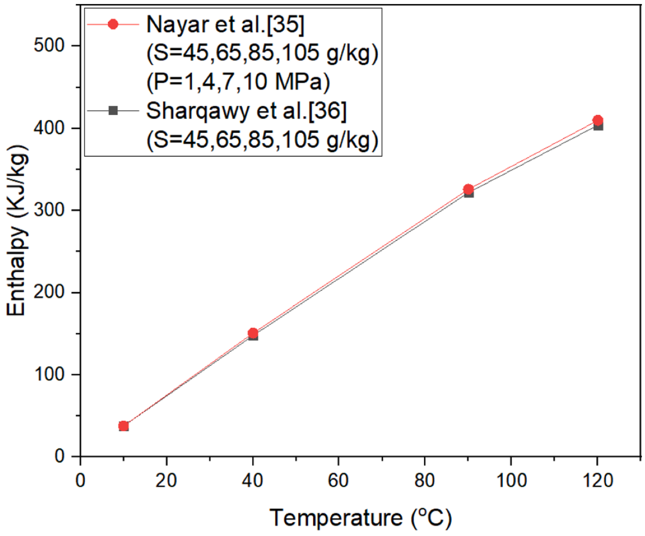

Fig. 24. Variation in enthalpy with temperature of various authors.

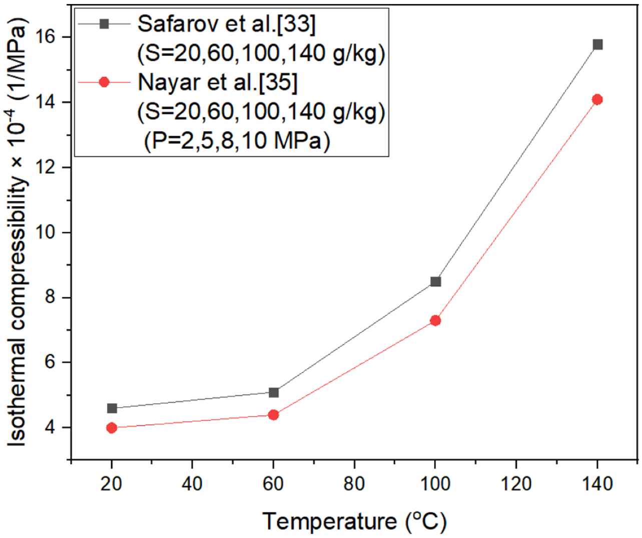

Fig. 25. Variation in isothermal compressibility with temperature of various authors.

isothermal compressibility is almost the same for both cases. However, more increase in isothermal compressibility can be seen in the case of Safarov et al. [33] in Fig. 26.

4. Thermal properties exhibited by seawater with organic materials

The thermal properties of seawater largely depend upon the organic matter present in it and dissolved organic carbon is the major source of organic matter in seawater [131]. Hernandez-Acosta et al. [132] measured the effect of photothermally-activated energy transfer using a vectorial two-wave mixing method. Thin film of single-wall carbon nanotubes was selected, and experiments were conducted. There was a great change in heat conduction and Fractional analysis was done to measure thermal behavior. The results concluded that this material could be beneficial in sensors design and nanodevices.

Sun et al. [133] determined that sunlight converted dissolved organic matter into carbon and nitrogen in seawater. They showed that sunlight-induced chemical aggregation and induce carbon material in relatively less than an hour. Guo et al. [134] determined the photochemistry of dissolved organic matter in seawater and concluded that it increased the photodegradation ten times greater than freshwater.

Chon et al. [135] investigated the fouling behaviour of dissolved organic matter in fresh water as well as seawater compartments of reverse electrodialysis system. The accumulation of organic matter in the membrane hindered the passage of water and resulting in the formation of fouling. This may result in pressure drop increment and hence overall performance of the system degraded. Yin et al. [136] investigated the fouling behavior of organic matter in seawater in the reverse osmosis desalination process. The experiments were carried out and the fouling mechanism was checked. The results concluded that divalent ions were formed which increased the fouling phenomena by enhancing adhesion and cohesion forces. As storage and degradation of groundwater dissolved organic matter are unclear so McDonough et al. [137] showed transformations of dissolved organic matter using ultra-high resolution mass spectrometry. The results concluded that groundwater extraction and subterranean groundwater discharge to oceans processes could make up to 13 Tg of dissolved organic carbon released to the environment in a year.

5. Application of seawater correlations in thermal processes

The seawater correlations are used in various types of thermal process or systems for a proper process analysis and simulations. The performance of systems using seawater as working fluid should consider these correlations for the smooth functioning of the process otherwise this may create problems for obtaining the unknowns. The various applications of seawater correlations are discussed below.

5.1. Seawater correlations in desalination process

The scarcity of water and energy resources has emerged in recent years as these are indispensable resources of life. Desalination is one of the solutions to meet the problem of scarcity of water as water plays a vital role for human economic as well as social development [138]. The purpose of producing fresh water at low cost and less energy consumption is a promising solution to optimize desalination plant performance as well as to increase the water production. In most of the desalination processes, seawater is utilized in the system to produce fresh water. Therefore, the temperature and salinity range along with the pressure of various properties of seawater must be known so that the system can be designed accordingly otherwise it may create a problem and severe harmful result for the running system. Ghenai et al.[139] proposed cost-effective technology for seawater desalination by using solar energy. The different types of seawater properties were optimized in multi-effect desalination process to increase the quantity as well as the quality of fresh water. The various factors including seawater temperature, total dissolved solids and HT fluid temperature were considered to maximize freshwater production. The results indicated that water productivity was increased by 2.68 times and 57.78 % lower energy consumption using this strategy.

Gao et al.[140] carried out simulations on flat sheet air gap membrane distillation integrated with evaporative crystallizer for zero liquid discharge desalination plant. The different factors were optimized along with seawater properties optimization to maximize the permeate flux, system components performance, and water production. The salt removal in the crystallizer was measured in terms of total dissolved solids in the base liquid. Moreover, the operating condition with minimum input energy was determined and it was 1651.5 KJ/kg-water. Farahbod et al. [141] conducted a study of a forced circulation evaporator in zero liquid discharge method to achieve distilled water. A solar pond was used after pre-treatment unit to obtain concentrated brine wastewater. The wastewater properties were measured to optimize the system performance. The results indicated that a suitable range of crystal growth was obtained having crystallizer capacity of 70 % and the residence time was 4 h. Dehghani et al.[142] investigated humidification dehumidification desalination system attached to a heat pump which was used for cooling as well as heating loads. The different factors like specific energy consumption, temperature, salinity and coefficient of performance were under consideration. It was concluded that a fully coupled humidification dehumidification system with a heat pump can be gained without adding more cooler at saline water temperature.

5.2. Seawater correlations in falling film evaporators

Falling film evaporators are broadly used in various applications due to high performance when mass flow, heat transfer area, and temperature difference are small. The different applications in various areas including low-temperature multi-effect desalination, air separation, and refrigeration [143144]. The horizontal falling film is quite complex due to film physical properties and tube shape which increases the manufacturing cost of the desalination process or any other under the considered system.

The various properties including surface tension and viscosity determined the film thickness [145]. Chen et al.[146] determined the film thickness for water and seawater with seawater salinity 26.6 g/kg and concluded that seawater has a thicker film than normal water. physical properties such as surface tension and viscosity affect the film thickness. Wang et al.[147] performed simulations of falling film for low flow regime and obtained the film thickness of seawater on crest region higher than simple water. The seawater having a salinity of 15, 30 and 45 g/kg was used along with an evaporation temperature 50–70 °C. A series of correlations were also proposed to predict the film thickness. Shen et al.[148] determined the heat transfer coefficient of the falling film evaporator outside the horizontal tube having parameters like spray density, evaporation temperature and salinity with seawater. The salinity of seawater was 1.5, 3.0 and 3.0 % while density was between 0.017 and 0.087 kg/m^3 and evaporation temperature was 50–70 °C. It was concluded that heat transfer coefficient was decreased with salinity for circular tube.

Chun hua et al.[21] compared falling film evaporation for elliptical and circular tubes to improve the seawater desalination system and comparisons between numerical, theoretical and experimental were made. The results showed that the heat transfer coefficient was increased by 20–22 % in the case of the elliptical tube in comparison to the circular tube. The overall heat transfer coefficient of seawater was determined by using two experimental devices to study falling film evaporation outside a horizontal tube by Mu et al. [149]. This was measured by changing saturation temperature, Reynold number and total temperature difference, and other factors. The results concluded that temperature and temperature difference increment lead to a decrease in the heat transfer coefficient. Wan et al. [150] studied two dimensional elliptical tube models based on the volume of fluid technique. The variation of tube perimeter, Reynolds number, inlet temperature, seawater salinity on falling film thickness, and heat transfer coefficients were under consideration. The tube perimeter range 31.4–94.2 mm, Reynolds number from 500 to 1500, the inlet temperature from 10 to 90 °C, and seawater salinity from 0 to 120 g/kg. Results showed that film thickness increased with increasing Reynold number and seawater salinity but decreased with tube inlet temperature.

5.3. Seawater correlations applications in mining sector

Seawater has been extensively used in the mining industry as it contains different kinds of minerals as a byproduct. During the extraction of seawater, many minerals are obtained as by-products and if these minerals are economically recovered then water production costs will be decreased, and pollution-related problems will also be reduced [151]. The economic gains obtained by extracting minerals depend on the concentration of minerals in seawater. This increased with an increment in concentration and sodium, calcium, magnesium, potassium, beryllium, and boron are potentially attractive elements for extraction [152]. The major usage of the mineral from seawater is illustrated in Table 24. From this table, it can be seen that mineral usage in various applications is very high, and hence seawater correlations helped a lot in extracting minerals from the mining sector result in expanding its applications in terms of usage.

The above table depicts that seawater minerals have been widely used in various areas of applications. So, determining seawater properties to extract mineral from seawater is necessity. If the seawater properties like temperature, salinity and pressure, are unknown extraction of minerals from seawater will be challenging and it may cause harmful effects during the operation.

Table 24
Seawater minerals with their usage [153 154].

Seawater minerals	Usage
Sodium	Food, glass, detergent, textiles, pulp and paper industries
Magnesium	Chemical and construction industries, fertilizer
Calcium	Soil amendment and construction industries, fertilizer
Potassium	Fertilizer
Beryllium	Fire retardant, agriculture, and petroleum additives
Boron	Glass products, soap and detergents, fertilizer

5.4. Seawater correlations in oceanography or biological applications

The symbiont-bearing calcifiers including planktic foraminifera, are very critical in the decrement of pH of seawater [155]. The decline in pH of seawater affects the living of biological species in the marine ecosystem and its impacts may become large over time. Dong et al. [156] carried out a series of experiments in western tropical on planktic foraminifer which has a great impact on decrement in pH of seawater. Some parameters were considered to determine the relationship between biological parameters and pH of seawater. The results concluded that decrement in pH may decrease the growth and calcification of planktic foraminifera due to the alteration of biological processes' energy. The proper utilization of seawater correlations can surely maintain the pH of seawater and may hinder the distortion in the ecosystem.

The sharp increment in anthropogenic atmospheric CO_2 has decreased the pH of seawater significantly. Kuroyanagi et al. [157] cultured Amphisorus Kzudakajimensis, a dinoflagellate endosymbiont-bearing large benthic foraminifera under various conditions of pH. The results concluded that as pH of seawater changed, it greatly affected the shell volume as well as the density of foraminiferal calcification. The pH of seawater can be controlled by using proper correlations proposed by various authors and may maintain pH of seawater. The concentrations of heavy metals in seawater may become harmful and can be threatening to ecospecies life. Although some heavy metals are necessary for plants as well as animals but increasing concentration beyond the limit has an adverse effect on the ecosystem. Sagar et al. [158] conducted experiments using juvenile specimens to quantify heavy metals. It was characterized using micro-analytical technique and found concentrations of heavy metals have a small effect on the life of ecospecies. Therefore, effective monitoring of seawater properties has a positive impact on ecospecies life.

6. Current status, challenges and the future direction

Seawater correlations have played a vital role to determine the smooth function of an operation in any system. Researchers around the globe are continuously working in this area to explore new correlations and have a great interest as some stats of the last ten years (2013–2023) is presented in Fig. 26 extracted from "Web of Science" having key words "seawater correlations" and "correlations". From this figure, it is clear that the number of publications is continuously increasing, and the topmost researcher is "Frank J. Millero" who studied the correlation of seawater properties. USA is full front of this research as is shown in Fig. 26.

Along that, there may be still many challenges and future opportunities which should be considered including:

- The current review covers a limited range of temperature and salinity of various correlations of seawater which depicts that there is not enough data available. Therefore, more focus on these aspects should be considered by future researchers.
- From the current manuscript review, the pressure dependent factor is considered only for a limited number of seawater correlations. This needs to be investigated for the other correlations by authors in their future work.
- More unique correlations of seawater that consider a wide range of temperature and salinity range need to be developed which are not presented by previous studies.
- For a library of determining seawater properties, there is still a limited number of correlations that have temperature, pressure, and salinity range in it while others have only temperature or salinity range. Therefore, more extension should be done in this library for determining seawater properties extensively in the future by relevant authors.
- The current review also summarized a few applications where seawater correlations have been used and thus, more areas of

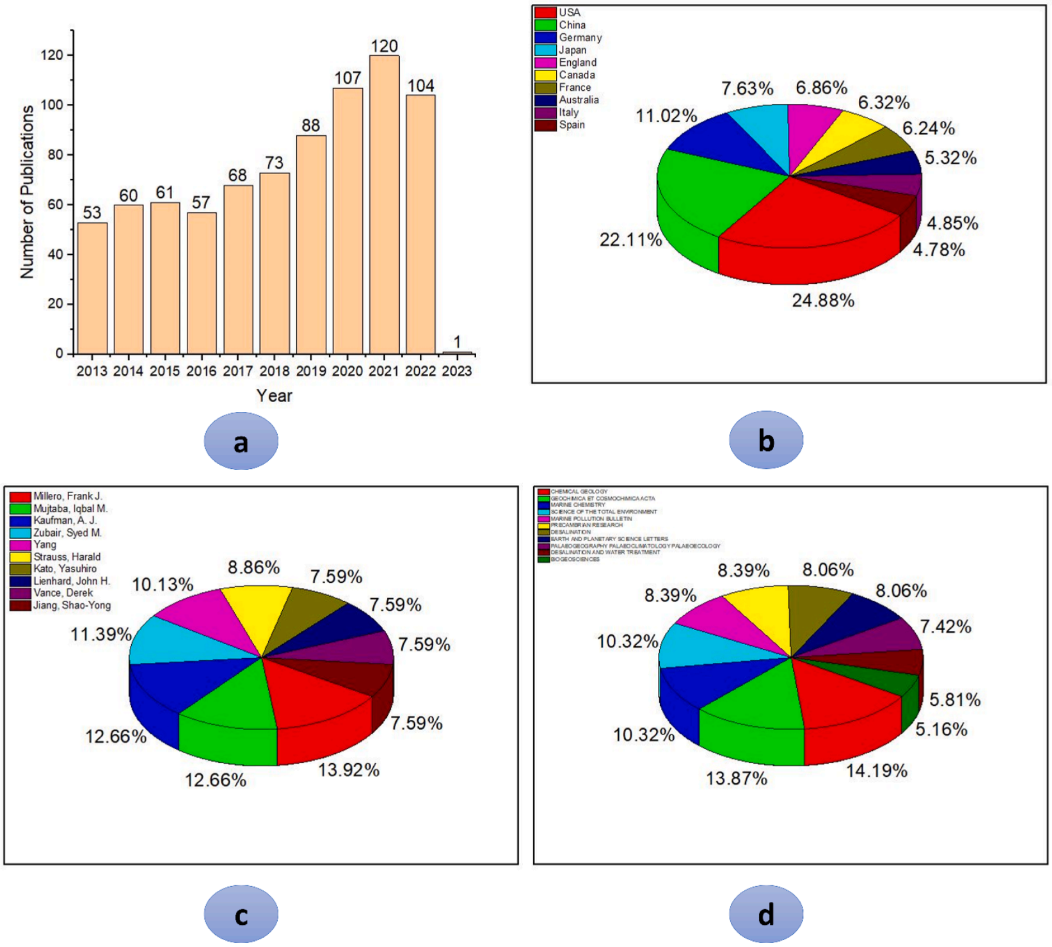

Fig. 26. Web of Science Stats having keywords “seawater properties” and “correlations” for 2013–2023 **(a)** publications **(b)** countries **(c)** authors **(d)** journals.

applications should be explored by future researchers in which seawater corrections can be used broadly.

7. Conclusions

The existing correlations of seawater properties are discussed in detail in the current review which also includes pressure dependent factors for a wide range of desalination processes. Some of the major concluded remarks are:

- The techniques for determining each property of seawater with temperature and salinity range published in the literature are summarized in a consistent way to attract readers in this review.
- The variation of temperature and salinity in each correlation of seawater is graphically summarized within their range which were around $10 \le t \le 120$ °C and $0 \le S \le 120\,\mathrm{g/kg}$ respectively.
- The current review also covered the pressure dependent factor for a few correlations that was considered by previous authors up to the range of 12 MPa. This review gives direction to researchers to explore more correlations having temperature, pressure as well as salinity ranges.
- The current review also highlighted accuracies for correlations of seawater. For most of the properties, the variations in the correlation were found to be around 1 % which depicts accuracy for the measurement of seawater properties. However, for enthalpy of seawater, the variation was 31 % which was very high. Therefore, authors should investigate an accurate correlation for this property of seawater.
- The current review also facilities the comparison of different correlations available in the literature along with maximum uncertainty which give some direction to researchers to explore new correlations of seawater.
- The thermal applications of seawater correlations are also summarized in this review, but more areas of applications should be explored by future researchers where seawater correlation can be broadly used.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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