Desalination 260 (2010) 9–17

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Electrical conductivity of seawater during ohmic heating

A.M. Assiry [a,*], M.H. Gaily [b], M. Alsamee [a], A. Sarifudin [a]

[a] Agricultural Engineering Department, Shaikh Mohammad Alamoudi Chair for Water Researches, College of Food and Agricultural Sciences, King Saud University, PO Box, 2460, Riyadh 11451, Saudi Arabia
[b] Chemical Engineering Department, Engineering College, King Saud University, PO Box 800, Riyadh, 11421, Saudi Arabia

ARTICLE INFO

Article history:
Received 6 July 2009
Received in revised form 26 April 2010
Accepted 10 May 2010
Available online 3 June 2010

Keywords:
Ohmic heating
Desalination
Seawater electrical conductivity
Heat generation
Heating rate
Electro-conductive heating

ABSTRACT

The aim of this study was to apply ohmic heating method to generate heat in seawater as an attempt to be utilized in desalination process as an alternative heating method rather than using steam boilers. The effects of temperature, electrical field strength and the concentrations of total dissolved solids (TDS) on electrical conductivity during ohmic heating of seawater were investigated. Heat was generated within the seawater using alternating electric current at frequency of 60 Hz, the range of electrical field strength was 6.35–11.04 (V/cm). Different concentrations of the seawater were prepared (range 38.9–106.1 PPT). Quality parameters include electrical conductivity, colour, pH, apparent specific heat and density of the seawater were measured at room temperature before and after the ohmic heating. The range of conductivity during ohmic heating was 55–399.6 (mS/cm) and strongly dependent on TDS and temperature. Ohmic heating can be applied for heating process of seawater with some limitations regarding the colour change. One major output of this research is the assessment of seawater electrical conductivity data during ohmic heating which adds a new perspective to system analysis, design and modeling of the potential use of ohmic heating to generate heat within the seawater during desalination process.

1. Introduction

Shortening in drinking water due to erratic climatic conditions, increasing population growth and improved living standards is a big concern of researchers and governmental agencies around the world. According to the U. S Geological Survey, 96.5% of Earth's water is located in seas and oceans and only 1.7% groundwater off which only 0.8% is considered to be fresh water [1].

Desalination technology has reached great importance as a solution for potable and fresh water generation. It is a process of removing salt from water to produce fresh water, which containing less than 1000 mg/L of salts or total dissolved solids (TDS), where above this value, properties such as taste, colour, corrosion propensity, and odour can be adversely affected [2]. The WHO and the Gulf Drinking Water Standards recommend a drinking water standard of 1000 mg/L TDS for drinking water [3].

A number of seawater desalination technologies have been developed during the last decades to guarantee the supply of water in arid and semi arid regions of the world. Technologies used in the industry are described by Khawaji et al. [4], these include: Multi-Stage Flash distillation (MSF), Multiple-Effect Distillation (MED), vapor compression distillation and reverse osmosis (RO). Other processes have been developed to desalinate seawater such as freezing, [5,6] and solar evaporation [7–13]. These processes have not achieved the level of commercial success that MSF, MED, and RO have, but they may become valuable under special circumstances or with further development.

Since seawater desalination needs some form of energy, a cogeneration scheme is essential in conjunction with the power generation from an economic point of view. Dual-purpose plants for the simultaneous production of water and electricity are extensively used [14]. In many cases of the thermal desalination systems either multi-stage desalination or flashing multi-effect systems, the major occurring problems in these systems are corrosion and scaling of carbonated steel used in different units especially in the boiler [15]. Those two factors limit the heat transfer and add extra operational and maintenance cost. Therefore, it is desirable to investigate other means to generate heat within the brine solution during the heating process rather than transferring heat. In this context, it is proposed to study the potential application of ohmic heating method in desalination of seawater.

Ohmic heating, direct resistance heating or the electro-pure process was used in the early 20th century where electric pasteurization of milk and other food materials was achieved by pumping the fluid between parallel plates with a voltage difference between them [16,17]. Ohmic heating occurs when alternating electrical current (I) is passed through a conductive material of resistance (R), with the

---

* Corresponding author. Fax: +966 1 4678502.
E-mail address: assiry@ksu.edu.sa (A.M. Assiry).

0011-9164/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.desal.2010.05.015

resultant energy generation causing temperature rise. The amount of heat generated is directly related to the current induced by the electrical field strength, and the electrical conductivity. The rate of ohmic heating is directly proportional to the square of the electrical field strength and the electrical conductivity [18]. Palaniappan and Sastry [17] reported that the electrical conductivity is a linear function of temperature.

Electrical conductivity is the measure of how well a substance transmits electric charge, expressed in Siemens per centimeter (S/cm). Electrical conductivity (σ) is the ratio between the current density and electrical field intensity— or, simply the opposite of resistivity. It is the most important parameter associated with ohmic heating, where the efficiency of ohmic heating is dependent on the conductive nature of the material to be processed and hence knowledge of the conductivity of the materials as a whole and its components is essential in designing a successful heating process. Therefore, it is very essential to determine and predict the electrical conductivity during ohmic heating process. Different designs and setups of electrical conductivity measurements of materials under ohmic heating process were studied by different researchers. This include a design of a batch isothermal ohmic heater with stainless steel electrodes [19–21] and a conductivity cell of a polyvinyl chloride (PVC) pipe, with high grade 316-stainless steel electrodes [22] and other different designs by different researchers [23–26].

Selection of suitable electrode to be used in an ohmic heater is an important parameter that has to be considered. Undesirable electrochemical reactions at the interface between the electrode and the solution and corrosion may affect the efficiency of the ohmic heater and this can be avoided by selecting a suitable electrode material. Different electrode materials have been investigated such as the use of titanium, stainless steel, platinized-titanium and graphite electrodes [27]. It was also noticed that a relatively inert electrochemical behavior of platinized-titanium electrodes at different pH values using a 60 Hz sinusoidal alternating current. The migration of the major key metal ions such as Fe, Cr, Ni, Mn and Mo from stainless steel electrode was studied during ohmic heating and it was reported that, applying high frequency (10 kHz) pulsed waveform for ohmic heating produced lower migration of most targeted metal ions [28].

Electrical conductivities of different materials during ohmic heating were reported by different researchers. This includes fresh fruits under ohmic heating such as apple, peach, pear, pineapple and strawberry (electrical conductivity in the range 0.05–1.2 S/m), and different types of meats such as chicken, pork and beef [23,25], and red bean *Phaseolus vulgaris* L. [29]. The electrical field strength that have been used in these studies range from 19 to 25 V/cm when samples were heated up to 140 °C using alternating current of 60 Hz and voltage between 15 and 20 V [23].

Pure water is not a good conductor of electricity and it has a conductivity of 0.055 μS/cm. Because the electrical current is transported by the ions in solution, the conductivity increases as water dissolved ionic species increase [30]. Electrical conductivity of oceans and seawater was reported to be 53 (mS/cm) [31]. The electrical conductivities of seawater were reported to be 58, 67.8, 67.5 and 72 (mS/cm) corresponding to TDS of 44, 58.26, 57.78 and 62.82 (mg/L) respectively [32]. In another RO experimental study, the conversion from bulk concentrate conductivity to TDS for seawater was given by ($C_b = 732.56\ \sigma_b - 3831.6$) where C_b is the bulk feed concentration in parts per million and σ_b is the electrical conductivity in milli Siemens per centimeter (mS/cm) [33]. No data has been found regarding the electrical conductivity of seawater during ohmic heating when alternating electric current is used to generate heat.

The properties of the ohmic heating process –which include the rapid and uniform heating, high energy efficiency, technical simplicity and low capital and maintenance cost– suggest that it could be a highly competitive heating method for thermal desalination processes. To design a successful ohmic process for desalination system, it is important to know the electrical conductivity as influenced by temperature, total soluble solids and electrical field strength. Within this part of the study, the changes of seawater electrical conductivity during ohmic heating before boiling temperature will be considered, however the performance of ohmic heater during the boiling process will be investigated in another study to follow. Thus, the specific aim of this study was to obtain electrical conductivity data for seawater at different concentrations of total dissolved solids during ohmic heating. Effects of temperature, electrical field strength and the concentration of TDS on ohmic heating rates of seawater were studied. Electrical conductivity of seawater was also mathematically modeled and some physical–chemical properties were measured before and after the ohmic heating treatments as quality parameters. It must be emphasized that we have not attempted a complete chemical and electrochemical or energy efficiency explanation and emphasis; we seek ways in which a practical ohmic heating method can be applied as a heating mechanism that can be utilized in seawater desalination process.

2. Materials and method

Seawater was obtained from the Gulf, East of Saudi Arabia, north of the desalination station in Jubail, (26° 54′ 50.78″ N, 49° 45′ 42.83″ E). Saline Water Conversion Corporation (SWCC) in Saudi Arabia reported that there is a feed variation in TDS from 39,000 ppm at Al-Birk plant to 41,492 ppm at Jeddah plant with an intermediate TDS = 41,157 ppm at Umm Lujj. By comparison the TDS content of the Gulf seawater at Jubail is about 43,500 ppm [34]. The main waste stream resulting from the desalination process is the concentrated effluent that is referred to as brine, blow down or reject. According to SWCC, the TDS upper limit for the reject was set at 67,000 ppm for the reject from the SWRO plants and at a maximum of 80,000 ppm for the final blow down from the MSF unit [35]. Thus, it is important to examine the application of ohmic heating in a wide range of TDS. Therefore, different concentrations of the seawater were prepared by evaporation process of the fresh seawater by boiling in a glass container using electrical hot plate till the predetermined TDS were reached. Then the TDS was checked using calibrated TDS meter (Cole-Parmer Instrument, Vernon Hills, USA). Five concentrations of seawater at 38.9 ± 0.12, 55.4 ± 0.001, 67.5 ± 0.10, 80.6 ± 0.10 and 106.1 ± 0.12 (PPT) were obtained.

Experiments were performed in a batch T-tube ohmic heater, shown in Fig. 1, which was made from T-inert glass tube covered with insulation hose to prevent heat losses. Two cylindrical platinized-titanium electrodes were used. The electrodes were purchased from Ti-anode Fabricators PVT.LTD, Chennai-India, coated with 10 μm platinum plating. Electrodes were inserted from the two openings of the T-tube, parallel to each others, the electrode gap was 5.8 cm, and the cross section area of the sample chamber was 4.3 cm^2. The volume of the T-tube was 30 ml, where seawater samples were poured into the ohmic heater through the thermocouple port. The electrodes of the ohmic chamber were connected to a relay switch which was protected by a 10 A fuse. The complete setup schematic diagram of the experiment is shown in Fig. 2. The sample was heated to 95 °C using alternating current of 60 Hz at applied voltages of 37, 47, 55 and 64 V, corresponding to electrical field strengths of 6.35, 8.04, 9.55 and 11.04 (V/cm), respectively. Temperature at the geometric center of the sample was continuously measured with a T-Type copper constant, Teflon coated thermocouple (Omega Instrument) to prevent interference from the electrical field. Voltage and current were measured using voltage and current transducers, respectively. The voltage and current transducers (model VTR-004X5 and CTRS-050x5, respectively, Ohio Semtronics, Inc.) were calibrated using portable multimeter (Digital Multimeter — DT9205, Manufacture by Mejdaf-Group Inc., KSA). Temperature, voltage and current data were recorded on a data logger (Model: OM-3000, Omega Engineering, Inc., New Zealand) at 0.5 second intervals.

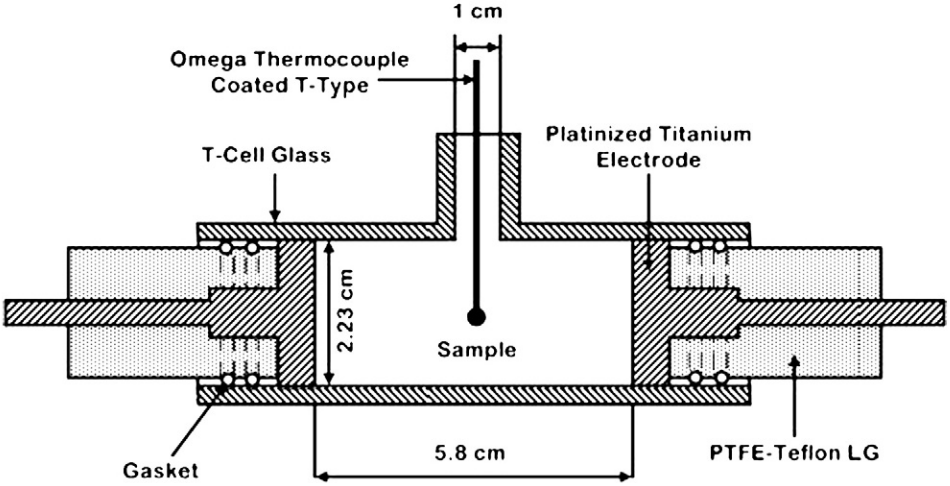

Fig. 1. Cross section drawing of T-tube ohmic heater.

The electrical conductivities of samples were calculated from the voltage and current data using the following equation [17,19,21]:

$$\sigma = \frac{L}{A} \times \frac{I}{V} \tag{1}$$

where;

σ	electrical conductivity, [S/cm].
L	distance between electrodes, [cm].
A	area, [cm^2].
I	alternating current passing through the sample, [Amp].
V	voltage across the sample, [V].

Conductivity measurements were performed on three replicates of seawater at each set of experimental conditions. The electrical field strengths which were recorded for the different experimental runs were 6.35 ± 0.37, 8.04 ± 0.20, 9.55 ± 0.25 and 11.04 ± 0.73 (V/cm). It should be noticed that at high electrical field strength (11.04 V/cm) and high TDS (106.1 PPT) the heating rate was very fast in which the current–temperature data was obtained for a few seconds. Applying more voltage would not allow the system to collect data in a reasonable time.

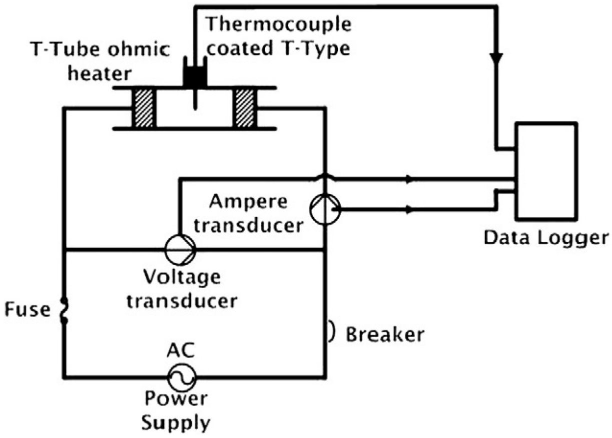

Fig. 2. The complete experimental setup of batch ohmic heater.

The constants of the temperature dependent electrical conductivity relations for different electrical field strengths and concentrations were obtained using linear regression analysis for Eq. (2) [17,26,31]:

$$\sigma_T = \sigma_0 + m \cdot T \tag{2}$$

σ_T	electrical conductivity at any temperature from 25 to 95 °C, [S cm^{-1}].
σ_o	initial electrical conductivity, [S cm^{-1}].
m	temperature factor [S cm^{-1} °C^{-1}].

The temperature, electrical field strength and TDS concentrations dependent electrical conductivity relation was obtained by using non-linear regression analysis (stepwise method) (SPSS. 2001. SPSS Statistical Package for windows. Ver.11.0. Chicago: SPSS, Inc.)

For the purpose of checking the effect of ohmic heating on some quality parameters, other properties of the seawater were recorded at room temperature before and after ohmic heating, including electrical conductivity, colour, pH, total dissolved solids (TDS), apparent specific heat and density. Electrical conductivity measurement (in the absence of alternating current) and TDS were checked using calibrated EC meter (Cole-Parmer Instrument, Vernon Hills, USA). Colour components were determined using Colorflex (HunterLab-ColorFlex, Hunter Associates Laboratory, Inc.-Reston, US). Sample of 27 ml was poured into the sample cup and then the cup was covered and inserted into the measuring chamber. Colour components were measured where L^* is the lightness or darkness, (black, $L^* = 0$; white, $L^* = 100$), $+ a^*$ is redness, $- a^*$ is greenness, $+ b^*$ is yellowness, and $- b^*$ is blueness. This instrument was calibrated with standard calibration plates provided by the manufacturer. A pH meter, (WTW, Weilheim, Germany) was used to determine the pH of the samples. The apparent specific heat was measured by differential scanning calorimeter (DSC-60, Shimadzu Cor. Japan). Densities (ρ) of samples were measured by Mettler Toledo Type PG203-Sq. The properties of the seawater at room temperature before the ohmic heating at different concentrations are listed in Table 1.

3. Results and discussion

3.1. Heating rate

Due to the passing electrical current through the seawater, a sensible heat was generated causing the temperature of the seawater

Table 1
Some properties of the seawater concentrates used for ohmic heating.

Property	TDS concentration [PPT]				
	38.9 ± 0.115[a]	55.4 ± 0.0005	67.5 ± 0.10	80.6 ± 0.10	106.1 ± 0.115
L^*	70.47 ± 0.03	70.20 ± 0.18	68.78 ± 0.03	68.21 ± 0.01	66.57 ± 0.41
a^*	− 0.79 ± 0.02	− 0.73 ± 0.02	− 0.81 ± 0.02	− 0.75 ± 0.04	− 0.74 ± 0.05
b^*	1.25 ± 0.02	1.20 ± 0.02	1.48 ± 0.03	1.57 ± 0.04	1.81 ± 0.10
pH	8.01 ± 0.02	8.32 ± 0.02	8.22 ± 0.02	8.10 ± 0.01	8.14 ± 0.02
ρ [g cm^{-3}]	1.042 ± 0.0003	1.048 ± 0.002	1.069 ± 0.0001	1.084 ± 0.0002	1.142 ± 0.0193
σ [mS cm^{-1}]	51.73 ± 0.25	72.07 ± 0.11	87.20 ± 0.10	103.30 ± 0.10	135.27 ± 0.06
Cp [KJ/kg °C]	3.98 ± 0.001	3.90 ± 0.00004	3.84 ± 0.001	3.79 ± 0.001	3.68 ± 0.001

[a] The 38.9 TDS refers to raw seawater.

to rise. The range of the heating rate was 0.69–6.22 (°C/s) depending on the concentration of the TDS and the electrical field strength as shown in Table 2. Fig. 3 indicates typical heating rate curves at some selected concentrations and electrical field strength. Higher TDS concentration and electrical field strength conditions resulted in higher heating rate. Thus, applying ohmic heating method in desalination process should consider the advantage of this high heating rate. Traditional heating of seawater in the MSF or MED process generally involves the use of steam in the boiler section. Due to increase thickness of the scaling material outside the boiler tubes, the overall heat transfer coefficient decreases. Thus cleaning of the tubes and in some cases the replacement of the tubes is necessary. In addition, some tubes suffered considerable corrosion and erosion–corrosion in service resulting in substantial reduction in wall thickness [36]. Heat is transferred across the boiler tubes due to the temperature difference between the steam and the seawater whereas ohmic heating uses electricity to generate heat within the seawater in which there is no heat transfer limitations. The advantages of this method are more rapid, uniform and immediate seawater heating. Effectiveness of ohmic heating against using steam boiler in terms of cost analysis was not attempted to be investigated in this study, however the data provided here will be essential for modeling methods to make fair and comprehensive comparison.

3.2. Electrical conductivity during ohmic heating

Electrical conductivity of the seawater during ohmic heating was plotted against the corresponding temperature to obtain electrical conductivity curves. During ohmic heating, a steady raise in the electrical conductivity was observed as the temperature was increased in all samples. The conductivity rise was greater for the more concentrated samples, and was linear. Similar relative increase in the electrical conductivity with temperature was observed on foodstuffs [17,30]. Fig. 4 indicates the relationship between the electrical conductivity and the temperature of the seawater at the high electrical field strengths (11.04 V/cm) and three concentrations (38.9, 67.5 and 106.1 PPT). It can be noticed that as the temperature approached 95 °C, there was a slight drop in the electrical conductivity especially at high concentration and high electrical field strength. This drop could be the result of localized boiling and generation of vapor bubbles that reduced the electrical conductivity of the solution [37]. The specific electrical conductivity range was 55–399.6 (mS/cm).

Table 2
The average heating rate and standard deviation at different electrical field strengths and concentrations of TDS.

∇V [V/cm]	TDS [PPT]	dT/dt [°C/S]	R^2 [%]
6.35 ± 0.37	38.9 ± 0.115	0.69 ± 0.01	0.997
	55.4 ± 0.0005	0.99 ± 0.03	0.997
	67.5 ± 0.10	1.27 ± 0.02	0.995
	80.6 ± 0.10	1.47 ± 0.02	0.996
	106.1 ± 0.115	1.91 ± 0.05	0.996
8.04 ± 0.20	38.9 ± 0.115	1.12 ± 0.06	0.995
	55.4 ± 0.0005	1.64 ± 0.06	0.995
	67.5 ± 0.10	1.99 ± 0.04	0.994
	80.6 ± 0.10	2.36 ± 0.08	0.995
	106.1 ± 0.115	3.09 ± 0.06	0.994
9.55 ± 0.25	38.9 ± 0.115	1.77 ± 0.04	0.994
	55.4 ± 0.0005	2.44 ± 0.11	0.992
	67.5 ± 0.10	2.88 ± 0.10	0.991
	80.6 ± 0.10	3.42 ± 0.02	0.991
	106.1 ± 0.115	4.48 ± 0.18	0.992
11.04 ± 0.73	38.9 ± 0.115	2.44 ± 0.04	0.992
	55.4 ± 0.0005	3.45 ± 0.11	0.989
	67.5 ± 0.10	3.91 ± 0.08	0.990
	80.6 ± 0.10	4.62 ± 0.05	0.990
	106.1 ± 0.115	6.22 ± 0.10	0.989

The temperature dependent electrical conductivity relations for different electrical field strengths and concentrations were obtained using Eq. (2). For all samples, electrical conductivity increased linearly with temperature, as expected and it is consistent with literature data [17,26,31]. The empirical relation constants (σ_o and m), and regression coefficients (R^2) are given in Table 3. The temperature factor range was 0.001227 to 0.003111 [S cm^{-1}°C^{-1}] with maximum standard deviation less than 0.00016. The temperature factor (m) increased linearly with TDS concentration as shown in Fig. 5. There was insignificant effect of the electrical field strength on the temperature factor.

The temperature, electrical field strength and TDS concentrations dependent electrical conductivity relation was obtained (Eq. (3)) using non-linear regression analysis. All the constants of the empirical relation are significant and the units of σ, T and C are (S/cm), (°C) and (PPT) respectively.

$$\sigma = 0.032 + 2.95 \times 10^{-5} T \cdot C + 8.58 \times 10^{-6} C^2 \tag{3}$$

Fig. 6 indicates the real data of the electrical conductivity vs. the empirical model, where the regression coefficient was 0.994. Both

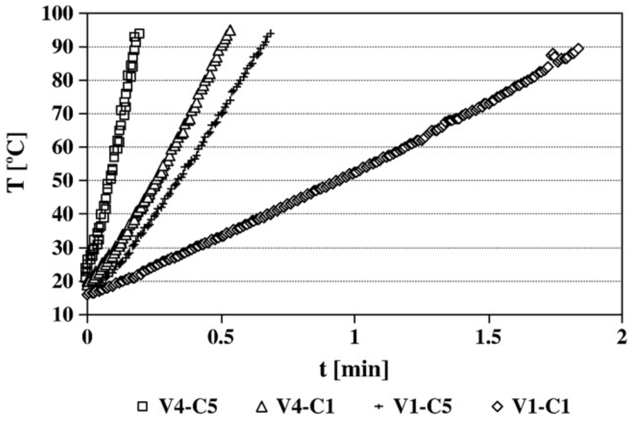

Fig. 3. Heating rate curves of seawater during ohmic heating. V1 and V4 indicate electrical field strengths at 6.35 and 11.04 (V/cm) respectively; C1 and C5 indicate TDS at 38.9 and 106.1 (PPT) respectively.

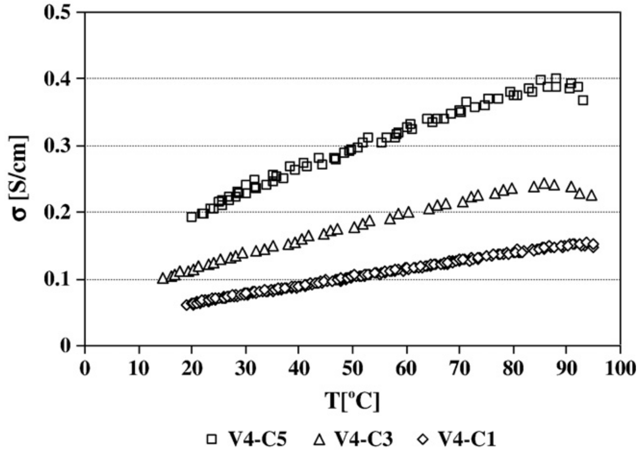

Fig. 4. The electrical conductivity profile of the seawater during ohmic heating at the electrical field strength V4 = 11.04 (V/cm). C1, C3 and C5 are the TDS at 38.9, 67.5 and 106.1 (PPT) respectively.

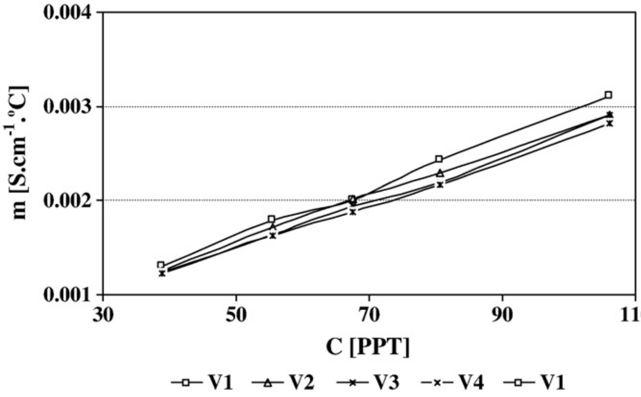

Fig. 5. The relationship between the temperature factor and the TDS concentration at different electrical field strengths.

temperature and concentration have a positive relation with the electrical conductivity. The concentration has more effect on the electrical conductivity than the temperature especially at high concentrations. It should be noticed that there was insignificant effect of the electrical field strength on the electrical conductivity. It was reported [37] that the low electrical field strength in the range of 3.3 to 13.3 (V/cm) in food material (surimi paste) containing 3–4% NaCl salts did not affect conductivity. It was also expected since the range of the electrical field strength allowed by the experimental setup was small (6.35 ± 0.37, 11.04 ± 0.73 (V/cm)). With regard to the ohmic heater used in this study, increasing the electrical field strength beyond 11 (V/cm) especially at high concentration of the TDS will heat the seawater very rapidly and instantaneous flashing of the seawater occurs. In a continuous process of seawater heating, this problem can be solved by optimizing the configuration of the ohmic heater utilizing Eq. (1), and the flow rate of the seawater. The implication of Eq. (3) is to determine the power generation rate within the system causing the seawater temperature to rise under ohmic heating. In a system with negligible heat loss, the rate of ohmic heating is directly proportional to the square of the electrical field strength and the electrical conductivity [18] as indicated by Eq. (4).

Table 3
The average and standard deviation of temperature factor (*m*), initial electrical conductivity (σ_o) and the regression coefficient of electrical conductivity–temperature relationship (Eq. (2)) of seawater ohmically heated at different electrical field strengths and TDS concentrations.

∇V [V/cm]	TDS [PPT]	m [S· cm^{-1}· °C^{-1}]	σ_o [S/cm]	R^2 [%]
6.35 ± 0.37	38.9 ± 0.115	0.001298 ± 0.00001	0.0348 ± 0.0005	1
	55.4 ± 0.0005	0.001791 ± 0.00003	0.0539 ± 0.0005	1
	67.5 ± 0.10	0.002008 ± 0.00004	0.0696 ± 0.0016	1
	80.6 ± 0.10	0.002427 ± 0.00008	0.0867 ± 0.0048	1
	106.1 ± 0.115	0.003111 ± 0.00004	0.1340 ± 0.0081	1
8.04 ± 0.20	38.9 ± 0.115	0.001256 ± 0.00001	0.0372 ± 0.0011	1
	55.4 ± 0.0005	0.001711 ± 0.00005	0.0564 ± 0.0013	1
	67.5 ± 0.10	0.002018 ± 0.00007	0.0729 ± 0.0018	1
	80.6 ± 0.10	0.002289 ± 0.00003	0.0918 ± 0.0023	1
	106.1 ± 0.115	0.002912 ± 0.00004	0.1312 ± 0.0037	1
9.55 ± 0.25	38.9 ± 0.115	0.001238 ± 0.00001	0.0388 ± 0.0007	1
	55.4 ± 0.0005	0.001642 ± 0.00001	0.0600 ± 0.0022	0.99
	67.5 ± 0.10	0.001945 ± 0.00005	0.0769 ± 0.0020	0.99
	80.6 ± 0.10	0.002189 ± 0.00003	0.0950 ± 0.0013	1
	106.1 ± 0.115	0.002903 ± 0.00002	0.1359 ± 0.0040	0.99
11.04 ± 0.73	38.9 ± 0.115	0.001227 ± 0.00001	0.0405 ± 0.0014	1
	55.4 ± 0.0005	0.001631 ± 0.00004	0.0632 ± 0.0021	0.99
	67.5 ± 0.10	0.001881 ± 0.00005	0.0810 ± 0.0017	0.98
	80.6 ± 0.10	0.002172 ± 0.00004	0.0982 ± 0.0019	0.99
	106.1 ± 0.115	0.002821 ± 0.00016	0.1459 ± 0.0093	0.98

$$\overset{\circ}{u} = \sigma|\nabla V|^2 \tag{4}$$

Where $\overset{\circ}{u}$ is the energy-generation rate per unit volume, ∇V is the electrical field strength and σ is the electrical conductivity (Eq. (3)). It should be noticed that the critical property affecting energy generation is σ. Heating rate (dT/dt) can be calculated by the following equation [30]:

$$\frac{dT}{dt} = |\nabla V|^2 \left[\frac{\sigma}{\rho Cp}\right]. \tag{5}$$

Where ρ and Cp are the density and specific heat capacity of the seawater.

3.3. Physical–chemical properties

During thermal desalination process, it is very important to make sure that the downstream quality would not affect the marine environment, thus checking some quality parameters would reflect any physical or chemical changes in the reject to the seawater. During ohmic heating, a number of reactions, including electrode reactions, electrolysis of the solution, as well as reactions between electrode materials and electrolysis products may influence the quality of the electrolyte during ohmic heating [19]. The extent of electrode corrosion can be studied by the use of colorimetry [38]. In this study, the electrical conductivity (measured by EC meter at room temperature in the absence of the electric field strength), colour, pH and apparent specific

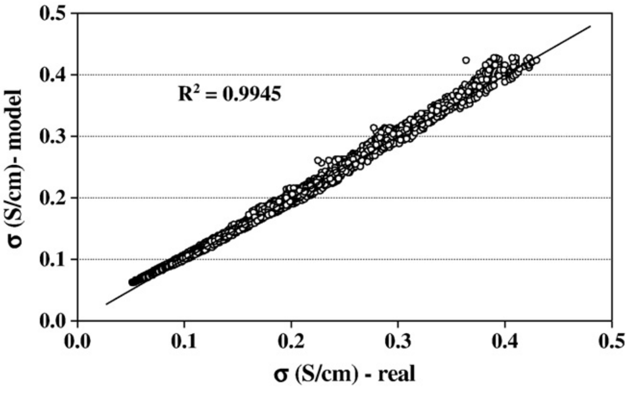

Fig. 6. The real data (circle markers) of electrical conductivity vs. the empirical model (line) generated by Eq. (3).

Table 4
The average electrical conductivity at room temperature ($\sigma_{25\,^\circ\mathrm{C}}$ mS/cm) and standard deviations as affected by the concentration of TDS and electrical field strength.

V [V/cm]	TDS concentration [PPT]				
	38.9 ± 0.115	55.4 ± 0.0005	67.5 ± 0.10	80.6 ± 0.10	106.1 ± 0.115
0	51.73 ± 0.25	72.07 ± 0.11	87.20 ± 0.10	103.30 ± 0.10	135.27 ± 0.06
6.35 ± 0.37	50.23 ± 0.15	73.73 ± 0.06	93.80 ± 0.10	107.77 ± 0.12	136.47 ± 0.06
8.04 ± 0.20	50.23 ± 0.15	73.60 ± 0.10	92.57 ± 0.25	107.10 ± 0.10	138.23 ± 0.15
9.55 ± 0.25	49.50 ± 0.17	72.53 ± 0.12	91.93 ± 0.06	105.60 ± 0.10	139.00 ± 0.10
11.04 ± 0.73	49.53 ± 0.21	71.80 ± 0.10	90.47 ± 0.21	103.90 ± 0.10	140.27 ± 0.25

($V = 0$) refers to the control samples where no ohmic heating was applied.

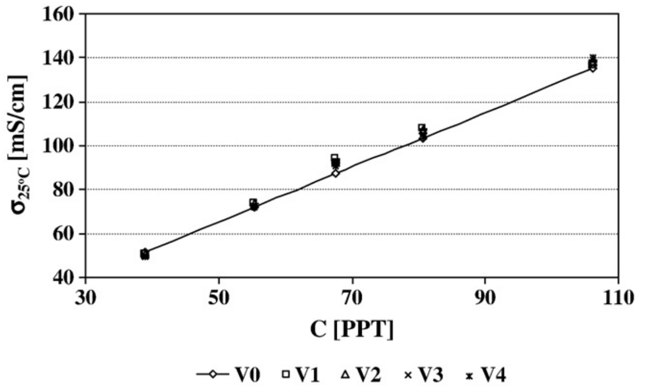

Fig. 7. The electrical conductivity of the seawater at room temperature before (V0 = 0) and after ohmic heating treatment. V1, V2, V3 and V4 indicate the electrical field strengths at 6.35, 8.04, 9.55 and 11.04 (V/cm) respectively.

heat changes before and after the ohmic heating of seawater in a batch closed system will be discussed as well as the density measurement.

Table 4 indicates the electrical conductivity of the seawater at room temperature before and after the ohmic heating treatment. It should be noticed that zero electrical field strength refers to the row seawater i.e. before applying ohmic heating. The electrical conductivity was not greatly affected by the electrical field strength as much as the TDS as shown in Fig. 7. It can be recognized that most of the electrical conductivity values overlapped at each concentration and increased linearly as the concentration increased. The range of the electrical conductivity at room temperature ($\sigma_{25\,^\circ\mathrm{C}}$) was 49.50–140.27 (mS/cm), which depends greatly on the concentration of total soluble solids. It is comparable to certain extent with the data obtained for seawater samples where the electrical conductivity reported to be 58, 67.8, 67.5 and 72 (mS/cm) corresponding to TDS of 44, 58.26, 57.78 and 62.82 (mg/L) respectively [32].

Table 5 indicates the average and standard deviations of the basic colour components of the seawater before and after ohmic heating treatment at different electrical field strengths. In general, both the colour components L^* (lightness) and a^* (red-green) slightly decreased by increasing the electrical field strength. On the other hand, there was a noticeable increase in the values of the colour component b^* towards yellowish, which could be attributed to the electrochemical reactions where it has been reported that titanium during ohmic heating forms various oxides having different colours such as TiO_2 (yellowish) [27]. The colour difference (ΔE) of the seawater was determined by Eq. (6) [39]:

$$\Delta E = \sqrt{(L^*-L_o^*)^2 + (b^*-b_o^*)^2 + (a^*-a_o^*)^2}. \tag{6}$$

Where L_o^*, a_o^*, b_o^* are the colour components of the raw seawater samples. The range of the colour difference was 0.599–6.39. Fig. 8 represents the colour difference as affected by the concentration at different electrical field strengths. It can be seen that increasing the concentration resulted in higher colour change at all different electrical field strengths; the highest colour changes occurred at high concentration (106.1 PPT) and high electrical field strength (9.55 and 11.04 V/cm) conditions. Dramatic colour changes occurred at concentration more than 80 (PPT), thus it is suggested to apply ohmic heating at concentrations less than 80 (PPT) to avoid severe reactions that might affect the quality of downstream seawater. According to individual ability of human eye to appreciate differences in colour [40], three different intervals were used to distinguish changes in colour values: $\Delta E<1$ — imperceptible by the human eye; $1.0<\Delta E<3.3$ — considerate appreciate only for skilled person, $\Delta E>3.3$ — easily observed. Accordingly, at high concentration more than 80 (PPT) and high electrical field

Table 5
The average values of the basic colour components and their standard deviations as affected by the concentration of TDS and electrical field strength. ($\nabla V = 0$) refers to the control samples where no ohmic heating was applied.

Colour comp.	∇V [V/cm]	TDS concentration [PPT]				
		38.9 ± 0.115	55.4 ± 0.0005	67.5 ± 0.10	80.6 ± 0.10	106.1 ± 0.115
L^*	0	70.47 ± 0.03	70.20 ± 0.18	68.78 ± 0.03	68.21 ± 0.01	66.57 ± 0.41
	6.35 ± 0.37	70.47 ± 0.001	70.03 ± 0.000	69.21 ± 0.000	68.46 ± 0.000	66.74 ± 0.000
	8.04 ± 0.20	70.46 ± 0.001	70.02 ± 0.000	69.23 ± 0.000	68.68 ± 0.001	67.03 ± 0.000
	9.55 ± 0.25	70.44 ± 0.001	70.03 ± 0.000	69.18 ± 0.001	68.66 ± 0.000	64.65 ± 0.001
	11.04 ± 0.73	70.51 ± 0.001	69.31 ± 0.000	68.78 ± 0.000	67.49 ± 0.000	65.15 ± 0.000
a^*	0	−0.79 ± 0.02	−0.73 ± 0.02	−0.81 ± 0.02	−0.75 ± 0.04	−0.74 ± 0.05
	6.35 ± 0.37	−0.98 ± 0.02	−0.86 ± 0.05	−1.00 ± 0.091	−1.17 ± 0.066	−1.19 ± 0.030
	8.04 ± 0.20	−1.02 ± 0.02	−0.90 ± 0.01	−1.05 ± 0.020	−1.25 ± 0.049	−1.28 ± 0.028
	9.55 ± 0.25	−1.00 ± 0.03	−0.98 ± 0.01	−1.18 ± 0.036	−1.29 ± 0.069	−1.12 ± 0.007
	11.04 ± 0.73	−0.95 ± 0.03	−1.06 ± 0.03	−1.18 ± 0.026	−1.28 ± 0.007	−1.06 ± 0.013
b^*	0	1.25 ± 0.02	1.20 ± 0.020	1.48 ± 0.030	1.57 ± 0.040	1.81 ± 0.100
	6.35 ± 0.37	1.81 ± 0.026	1.97 ± 0.036	2.22 ± 0.013	2.97 ± 0.024	3.42 ± 0.007
	8.04 ± 0.20	1.83 ± 0.034	1.99 ± 0.035	2.44 ± 0.024	3.22 ± 0.013	3.80 ± 0.024
	9.55 ± 0.25	1.83 ± 0.036	2.36 ± 0.028	2.88 ± 0.007	3.30 ± 0.007	4.27 ± 0.035
	11.04 ± 0.73	1.86 ± 0.030	2.43 ± 0.052	2.82 ± 0.052	3.54 ± 0.017	4.08 ± 0.007

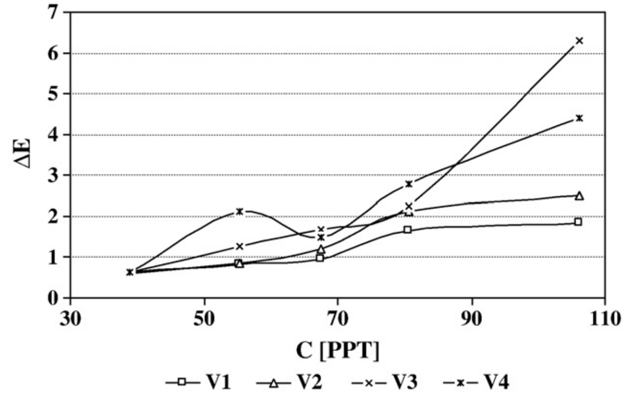

Fig. 8. The colour change of seawater as affected by the concentration of TDS at different electrical field strengths. V1, V2, V3 and V4 indicate the electrical field strengths at 6.35, 8.04, 9.55 and 11.04 (V/cm).

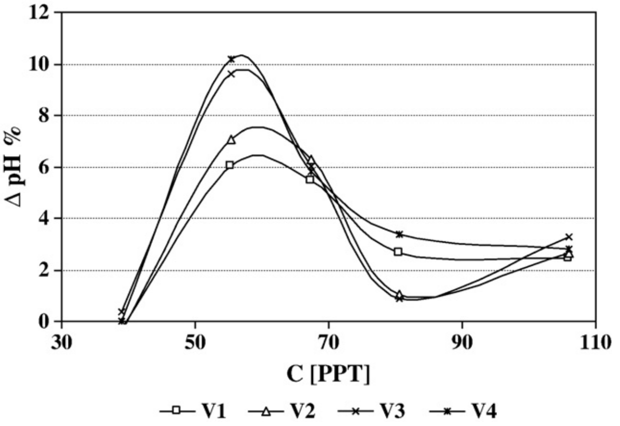

Fig. 9. The percentage of pH changes of seawater as affected by the concentration of TDS at different electrical field strengths. V1, V2, V3 and V4 indicate the electrical field strengths at 6.35, 8.04, 9.55 and 11.04 (V/cm) respectively.

strength above 9.55 (V/cm) the change in colour is significant ($\Delta E > 3.3$) which might be due to the electrochemical reactions during ohmic heating. In the thermal desalination process the seawater temperature is increased to the top brine temperature in the first effect where the TDS was very low (38.9 PPT). Thus at low concentration the electrochemical reactions might be limited and high electrical field strength (11.04 V/cm) can be used. In this regard, more studies are recommended to investigate the electrochemical reactions of different types of electrodes during the ohmic heating of seawater for the evaluation of the reject stream quality and the possible impact on the environment.

In the light of experimental results shown in Table 6, there was a slight change in the pH of the seawater based on the TDS and the applied electrical field strength. The range of the seawater pH after ohmic treatments was 7.48–8.25. The percentage of the pH change was calculated according to the following equation:

$$\Delta pH = \frac{pH_o - pH}{pH_o} \times 100. \tag{7}$$

The percentage of change of pH based on the (pH_o) of the raw seawater was plotted against the concentration at different electrical field strengths as shown in Fig. 9. It can be noticed that there was a decline in the pH values at concentrations above 38.9 (PPT) at all the electrical field strengths. The maximum decrease in the pH was 10% at 55.4 PPT and 11.04 V/cm. The change in the pH at low TDS (38.9 PPT) was negative (i.e. 1% increase in the pH), and then as the concentration increased, the change was positive. The same trend was observed at different electrical field strengths. This behavior was probably due to the residence time of different reactions such as hydrolysis of the seawater and corrosion of electrodes that might occur during the ohmic heating. For example, at high concentration (106.1 PPT) and high electrical field strength (11.04 V/cm) the heating rate was high (6.22 °C/s), therefore the residence time for the sample to heat up from 25 to 95 °C was short, thus the decline of the pH was limited (3%) because the reaction time was short. In comparison, at low concentration (55.4 PPT) and electrical field strength 11.04 (V/cm), the heating rate was 3.45 °C/s, which means high residence time at which the change in the pH was maximum (10%) because of the longer reaction time. It has been reported that during ohmic heating, hydrolysis and corrosion reactions between the electrodes and the electrolyte solution may occur, where at high electrical power and salt content, a significant loss of buffering capacity was noted [19]. Generally, the effect of ohmic heating on the pH was limited since the max percentage change was 10%.

Measurement of the apparent specific heat might give some estimate of the expected occurring reactions. The range of the apparent specific heat was found to be 3.664 to 3.981 (KJ/kg°C) at high and low concentrations respectively. Statistical analysis of the apparent specific heat of the seawater before and after the ohmic heating indicates that there were insignificant changes at different concentrations as shown in Table 7. Indeed the maximum changes in the apparent specific heat were less than 0.6%.

In the calculation of continuous ohmic heating system, the density of the seawater at different concentrations is important to be measured or modeled for the purpose of proper design of ohmic heater. The range of density was 1.03 to 1.14 (gm/cm^3) at TDS 38.9 and 106.1 (PPT) respectively. Fig. 10 represents the density change at different concentrations. The effect of the field strength on the density change was insignificant which can be an indication of that the residuals of the expected electrodes corrosion did not significantly affect the density.

In brief, ohmic method can be applied to heat seawater especially at low concentration of TDS, but more investigations regarding the energy efficiency and cost analysis are necessary. Also, the reactions that occur in the seawater due to ohmic heating causing colour and pH changes are worth to be deeply investigated at higher electrical field

Table 6
The average pH and the standard deviations of seawater at room temperature as affected by the concentration of TDS and electrical field strength. ($\nabla V = 0$) refers to the control samples where no ohmic heating was applied.

∇V [V/cm]	TDS concentration [PPT]				
	38.9 ± 0.115	55.4 ± 0.0005	67.5 ± 0.10	80.6 ± 0.10	106.1 ± 0.115
0	8.01 ± 0.02	8.32 ± 0.02	8.22 ± 0.02	8.10 ± 0.01	8.14 ± 0.02
6.35 ± 0.37	8.25 ± 0.01	7.82 ± 0.01	7.77 ± 0.01	7.89 ± 0.02	7.94 ± 0.00
8.04 ± 0.20	8.25 ± 0.01	7.74 ± 0.02	7.70 ± 0.01	8.02 ± 0.01	7.92 ± 0.01
9.55 ± 0.25	8.19 ± 0.02	7.52 ± 0.03	7.72 ± 0.01	8.03 ± 0.01	7.87 ± 0.03
11.04 ± 0.73	8.22 ± 0.01	7.48 ± 0.01	7.74 ± 0.03	7.83 ± 0.02	7.91 ± 0.00

Table 7
The average values of the apparent specific heat (Cp: KJ/kg°C) as affected by the electrical field strength at different concentrations of TDS. ($\nabla V = 0$) refers to the control samples where no ohmic heating was applied.

∇V [V/cm]	TDS concentration [PPT]				
	38.9 ± 0.115	55.4 ± 0.0005	67.5 ± 0.10	80.6 ± 0.10	106.1 ± 0.115
0	3.981^{a*}	3.900^{b}	3.844^{c}	3.786^{d}	3.681^{e}
6.35 ± 0.37	3.986^{a}	3.894^{b}	3.821^{c}	3.771^{d}	3.677^{e}
8.04 ± 0.20	3.986^{a}	3.894^{b}	3.824^{c}	3.774^{d}	3.672^{e}
9.55 ± 0.25	3.988^{a}	3.899^{b}	3.827^{c}	3.778^{d}	3.669^{e}
11.04 ± 0.73	3.988^{a}	3.902^{b}	3.832^{c}	3.784^{d}	3.664^{e}

*: For the same TDS, values followed by the same letter are not statistically different ($P \leq 0.05$).

strength and the potential impact of these changes on the marine environment. The empirical model for electrical conductivity provided in this study can be utilized in modeling process to design and evaluate the ohmic heating system against the conventional heating methds.

4. Conclusion

It can be concluded that the electrical conductivity of the seawater during ohmic heating is strongly dependent on TDS concentration and temperature. The effect of the electrical field strength was insignificant. The electrical conductivity of the seawater increased with temperature rise linearly; although expected bubbling occurred at temperatures approaching boiling point reduced the electrical conductivity in some cases. Therefore, it is expected that apparent electrical conductivity will drop during boiling process. The mathematical model of the electrical conductivity can be used to predict accurately the electrical conductivity as affected by temperature and concentration within the ranges specified in this study. The advantage of the ohmic heating in thermal desalination is its ability to generate heat. The rate of heat generation will increase as the electrical conductivity increases due to the increasing concentration as the seawater evaporate. The major output of this study is the assessment of electrical conductivity data which will add a new perspective to system analysis, design, modeling and evaluation of the potential application of ohmic heating method to generate heat in batch or continuous desalination process. In general, ohmic heating shows promise in seawater heating, but comprehensive understanding of the process as well as the energy efficiency are necessary to ensure the applicability of this method in the economical sense. Applying ohmic heating in desalination process can be an alternative method to the conventional heating i.e. using a boiler or any type of heat exchangers but the changes that occur in the seawater such as colour and pH change are worth to be investigated deeply at higher electrical field strength. Benefits expected from applying ohmic heating can be (a) no need for a boiler science heat can be generated volumetrically within the seawater. (b) Reduced need for chemicals and maintenance activities; and (c) improved plant reliability and duration. More research work and emphases are recommended to evaluate the application of ohmic heating during boiling and evaporation process of seawater as well as understanding the chemical and electrochemical reactions that may occur during this process.

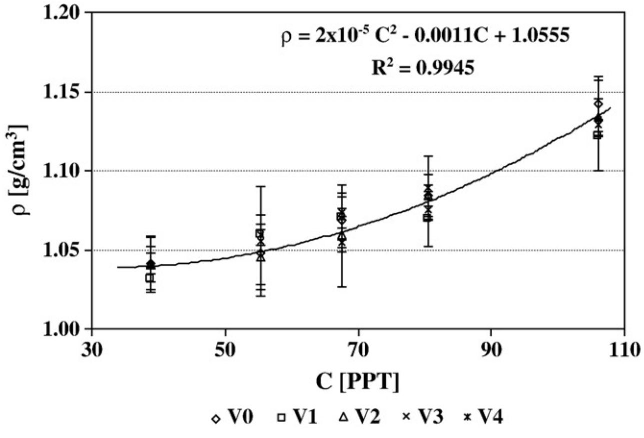

Fig. 10. The density of seawater as affected by the concentration of TDS. Y-error bars shown are the 95% confidence interval. V0, V1, V2, V3 and V4 indicate the electrical field strengths at 0, 6.35, 8.04, 9.55 and 11.04 (V/cm) respectively.

Acknowledgements

The authors wish to express their deep thanks and gratitude to “Shaikh Mohammad Alamoudi Chair for Water Researches” http://awc.ksu.edu.sa at King Saud University, http://www.ksu.edu.sa, who kindly sponsored this work.

References

[1] P.H. Gleick, S.H. Schneider (Eds.), Encyclopaedia of Climate and Weather, Water Resources, 2, Oxford University Press, New York, 1996, pp. 817–823.
[2] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: water resources, technology and today's challenges, Water Res. 43–9 (2009) 2317–2348.
[3] C. Fritzmann, J. Lowenberg, T. Wintgens, T. Melin, State-of-the-art of reverse osmosis desalination, J. Desalination 216 (2007) 1–76.
[4] A.D. Khawaji, I.K. Kutubkhanah, J. Wie, Advances in seawater desalination technologies, J. Desalination 221 (2008) 47–69.
[5] O.K. Buros, Desalination Manual, International Desalination and Environmental Association, the U.S.A.I.D, 1980.
[6] W.E. Johnson, The story of freeze desalting, desalination, Water Reuse 3 (4) (1993) 20–27.
[7] A.Y. Maalej, Solar still performance, Proceedings of the 12th International Symposium on Desalination and Water Re-Use, Malta, April 15–18, 1991.
[8] A. Hanafi, Design and performance of solar MSF desalination systems, Desalination 82 (1991) 165–174.
[9] E.E. Delyannis, V. Belessiotis, Solar application in desalination: the Greek Islands experiment, Desalination 100 (1995) 27–34.
[10] B. Milow, E. Zarza, Advanced MED solar desalination plants, configurations, cost, future-seven years of experience at the Plataforma Solar de Almeria (Spain), Desalination 108 (1997) 51–58.
[11] S. Toyama, K. Murase, Solar still made from waste materials, Desalination 169 (2004) 61–67.
[12] O.A. Hamed, E.I. Eisa, W.E. Abdalla, Overview of solar desalination, Desalination 93 (1993) 563–579.
[13] A.M. El-Nashar, An optimal design of a solar desalination plant, Desalination 93 (1993) 597–614.
[14] O.A. Hamed, M.A.K. Al-Sofi, M. Imam, G.M. Mustafa, K. Ba-Marouf, H. Al-Washmi, Technical Report No. TR 3808/APP 98002. SWCC, Al-Jubail Desalination and Power Plants, November, 2000.
[15] M.E. El-Dahshan, Corrosion and scaling problems present in some desalination plants in Abu Dhabi, Desalination 138 (2001) 371–377.
[16] A.A.P. de Alwis, P.J. Fryer, The use of direct resistance heating in the food industry, J. Food Eng. 11 (1) (1990) 3–27.
[17] S. Palaniappan, S.K. Sastry, Electrical conductivities of selected solid foods during ohmic heating, J. Food Process Eng. 14 (1991) 221–236.
[18] S.K. Sastry, S. Palaniappan, Ohmic heating of liquid-particle mixtures, Food Technol. (Dec 1992) 64–67.
[19] A. Assiry, S.K. Sastry, C.P. Samaranayake, Degradation kinetics of ascorbic acid during ohmic heating with stainless steel electrodes, J. Appl. Electrochem. 33 (2) (2003) 187–196.

[20] A.M. Assiry, S.K. Sastry, C.P. Samaranayake, Influence of temperature, electrical conductivity, power and pH on ascorbic acid degradation kinetics during ohmic heating using stainless steel electrodes, Bioelectrochemistry 68 (2006) 7–13.
[21] S. Salengke, S.K. Sastry, Experimental investigation of ohmic heating of solid–liquid mixtures under worst-case heating scenarios, J. Food Eng. 83 (2007) 324–336.
[22] B.M. McKenna, J. Lyng, N. Brunton, N. Shirsat, Advances in radio frequency and ohmic heating of meats, J. Food Eng. 77 (2006) 215–229.
[23] S. Sarang, S.K. Sastry, L. Knipe, Electrical conductivity of fruits and meats during ohmic heating, J. Food Eng. 87 (2008) 351–356.
[24] S.A. Kulshrestha, S.K. Sastry, Low-frequency dielectric changes in cellular food material from ohmic heating: effect of end point temperature, Innovative Food Sci. Emerg. Technol. 7 (2006) 257–262.
[25] M. Lima, S.K. Sastry, The effects of ohmic heating frequency on hot-air drying rate and juice yield, J. Food Eng. 41 (1999) 115–119.
[26] P. Tulsiyan, S. Sarang, S.K. Sastry, Measurement of residence time distribution of a multicomponent system inside an ohmic heater using radio frequency identification, J. Food Eng. 93-3 (2009) 313–317.
[27] P. Samaranayake, S.K. Sastry, Electrode and pH effects on electrochemical reactions during ohmic heating, J. Electroanal. Chem. 577 (2005) 125–135.
[28] S. Jun, S.K. Sastry, C. Samaranayake, Migration of electrode components during ohmic heating of foods in retort pouches, Innovative Food Sci. Emerg. Technol. 8 (2007) 237–243.
[29] A. Legrand, J.C. Leuliet, S. Duquesne, R. Kesteloot, P. Winterton, L. Fillaudeau, Physical, mechanical, thermal and electrical properties of cooked red bean (*Phaseolus vulgaris* L.) for continuous ohmic heating process, J. Food Eng. 81 (2007) 447–458.
[30] K. Halden, D.E. Alwis, A.A.P., P.J. Fryer, Changes in the electrical conductivity of food during ohmic heating, Int. J. Food Sci. Technol. 25 (1990) 9–25.
[31] A. Castro, J.A. Teixeira, S. Salengke, S.K. Sastry, A.A. Vicente, Ohmic heating of strawberry products: electrical conductivity measurements and ascorbic acid degradation kinetics, Innovative Food Sci. Emerg. Technol. 5 (2004) 27–36.
[32] M.A. Al-Sofi, Fouling phenomena in multi stage flash (MSF) distillers, Proc. Of Eur. Conf. Desalination Environ. 3 (1999) 61–76.
[33] David A. Ladner, Arun Subramani, Manish Kumar, Samer S. Adham, Mark M. Clark, Bench-scale evaluation of seawater desalination by reverse osmosis, Desalination 250 (2) (2010) 490–499.
[34] A. Hassan, S. Al-Jarrah, T. Al-Lohabi, A. Al-Hamdan, L. Bakheet, M. Al-Amri, Performance evaluation of SWCC SWRO plants, Desalination 74 (1989) 37–51.
[35] M. Al Sofi, A. Hassan, E. El-Sayed, Optimum integrated power/MSF/SWRO plants, International Desalination and Water Reuse Quarterly, Part-I, vol. 2/3, 1992, pp. 10–16.
[36] A.U. Malik, M.A. Al-Ghamdi, A.H. Hodhan, Investigation on the boiler tubes of Boiler #4, Jeddah-testing for microstructure and life prediction, 9th Middle East Corrosion Conference & Exhibition in Bahrain — Feb. 12–14, (2001), 2001.
[37] J. Yongsawatdigul, J.W. Park, E. Kolbe, Electrical conductivity of Pacific whiting surimi paste during ohmic heating, J. Food Sci. 60–5 (1995) 922–935.
[38] Y. Zhao, E.A. Kolbe, Method to characterize electrode corrosion during ohmic heating, J. Food Proc. Eng. 22 (1999) 81–89.
[39] G. Sharma, Digital Color Imaging Handbook, CRC Press, Boca Raton, 2003, pp. 30–31, FL CRC Press, ISBN 084930900X.
[40] S.T. Fontes, M.R. Fernandez, C.M. Moura, S.S. Meireles, Color stability of a nanofill composite: effect of different immersion media, J. Appl. Oral Sci. 17 (5) (2009) 388–391.