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Water distillation using an ohmic heating apparatus

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ABSTRACT

Many regions, including Basrah Governate in Iraq, suffer from undrinkable water due to high salt content and an economical means of desalinisation is needed. Ohmic heating was tested as a potentially more efficient method for water distillation compared to traditional resistance heating. An ohmic heating distillation apparatus was designed, manufactured, and tested to remove Ca and other metals from high salt content tap water. Ohmic heating was used as a lower operational cost alternative to a traditional distillation device. Three values of electric field strength (7, 9, and 11 V/cm) were used. The results showed that the highest water distillation productivity was 500 ml/hr using both electrode configurations at 11 V/cm, while the lowest yield of the device was at 7 V/cm with the vertical electrodes. The results showed a significant decrease ($p < 0.05$) in the electrical conductivity and TDS values for all electric field strengths compared to untreated tap water. The lowest values were 0.85 μS/cm and 0.45 ppm, respectively, with both horizontal and vertical electrodes, while the highest values were 1.65 μS/cm and 1.2 ppm, respectively, using the electric field strength of 7 V/cm with the horizontal electrodes.

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Water; distillation; ohmic heating; thermal heating; electric field

1. Introduction

Water is essential for life. Humans, fish, and plants contain 60, 80 and 80–90% of water, respectively. Water is also important for chemical reactions, which occur within microorganism cells. In addition, food production requires water (Chaouachi 2011).

Seawater represents about 97% of Earth's water, while fresh water is only about 0.5% of Earth's water (Saidur et al. 2011). The demand for potable water has increased as a result of population growth and poor sanitation processes that have resulted in natural potable water sources being polluted with viruses and bacteria (Jamil and Akhtar 2014). Like many other places in the world, the Basrah province of Iraq suffers from local water supplies that are unpotable due to high salt content (Al-Hilphy 2013). There are several methods used for desalination of water, such as multi-stage flash, multiple effect boiling, vapour compression, freezing (Gryta 2011), nano-filtration, ultrafiltration, microfiltration (Charcosset 2009), reverse osmosis (Robinson et al. 2019), water distillation using heat pump (Topper 1993), membrane distillation (Camacho et al. 2013), and solar distillation (Zuo et al. 2011; Al-Hilphy 2014; Kiwan and Salam 2018). Solar powered distillers include systems with a dish shaped solar collector and phase change material, such as paraffin wax, for storing solar energy and extending operation for hours after sunset (Chaichan and Kazem 2015; Chaichan, Abaas, and Kazem 2015). Nanoparticles added to phase change material in solar distillers have been shown to extend operation even longer after sunset (Chaichan and Kazem 2018). Multistage solar distillers have demonstrated capacity to recover latent heat of vapour, reduce heat losses, and improve water yields Huang et al. (2020). Solar distillers are a good solution for maximum energy efficiency and provide a solution when electrical power is unavailable. Traditional resistance type heating distillers are available to operate as convenient countertop kitchen appliances operating on electrical power. Alternative heating methods that could provide the convenience of a kitchen appliance while improving efficiency of resistance type heating are desirable.

Distillation is a conventional method used for water desalination and has disadvantages of relatively higher energy and longer time requirements. Conventional food heating methods also require heat energy to be generated externally and then transferred to the food material by conduction, convection, or radiation. Scientists have been researching alternative novel methods for desalination and more efficient heat transfer. Ohmic heating is a novel technology that has been used for food heating. The mechanism of ohmic heating consists of passing alternating electrical current through food, consequently raising food temperature due to conversion of electric energy to heat. In the case of ohmic heating, the electric energy is directly scattered into the food compared with other heating methods (Bozkurt and Icier 2010; Kaur, Gul, and Singh 2016).

Ohmic heating is an environmentally friendly method, which can generate internal and volumetric heat in treated materials leading to a relatively homogeneous temperature distribution in the material (Sakr and Liu 2014). Ohmic heating is more energy efficient than traditional resistance heating systems and has lower capital requirements and simpler maintenance (Gavahian et al. 2012). The range of the coefficient of performance values for liquids treated by Ohmic heating

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was from 0.47–0.92 using ohmic heating (Icier 2003). Ohmic heating has been studied to extract essential oils (Gavahiana et al. 2020), extract antioxidants (Jesus et al. 2020), pasteurise milk (Al-Hilphy, Ali, and Mohsin 2018) and thaw frozen meat (Duygu and Ümit 2015). Ohmic heating has also been studied as an alternative preservation technique (Muhammad, Shitu, and Tadda 2019). An advantage of ohmic heating is that it does not have the limited entrance profundity into solid materials of microwave heating. There have been reported disadvantages of ohmic heating. Allen, Eidman, and Kinsey (1996) illustrated that the installation cost of ohmic heating in food processing was higher than traditional methods. The second disadvantage was that ohmic heating was ineffective in heating food containing considerable amounts of fat or low salt content water due to low conductivity (Rahman 1999). Electric current does not pass through fat globules immersed in a solution of high electrical conductivity and the presence of pathogenic bacteria in globules slows heating due to the reduced electrical conductivity of these globules (Sastry and Palaniappan 1992). High salt content water would not be subject to this second disadvantage and ohmic heating is a novel technology that should be evaluated for desalination. One study investigated sea water evaporation by ohmic heating and measured electrical conductivity of the waste water after evaporation (Assiry et al. 2010). There is no published study on distillation of water with ohmic heating. Therefore, the aim of this study was to investigate the use of a novel ohmic heating technique for a water desalination distiller.

2. Materials and methods

2.1. Water source

Tap water used in this study was from Basrah province, Iraq. Tap water analysis indicated a Na level of about 602.2 ppm (Table 1), exceeding the recommended maximum of 200 ppm (WHO 1993), The high sodium content was due to the exposure of Basra Governorate to salt brine coming from the Persian Gulf in the summer, which was exacerbated by low levels of the Tigris and Euphrates Rivers. This high salt content tap water was used to perform ohmic and traditional distillation experiments in this study.

Figure 1. Ohmic distiller apparatus used for this study.

Table 1. Properties of water used with ohmic heating.

EC (μS/cm)	TDS (mg/L)	pH	K (ppm)	Na (ppm)	Ca (ppm)
1130 ± 0.70	1420 ± 0.70	6.76 ± 0.07	55 ± 0.56	602.2 ± 1.13	430.05 ± 2.47

2.2. Ohmic distiller apparatus

The ohmic distiller apparatus used in this study (see Figures 1 and 2) was designed and manufactured in the Food Engineering Laboratory, Department of Food Science, College of Agriculture, University of Basrah, Iraq. It consisted of half circle and straight electrodes in different distillation vessels, condenser, balance tank, voltage regulator, piping, and valves. Two stainless steel electrodes were mounted to each of two distillation vessels. The distance between electrodes was 10 cm. The shape of the electrodes in the first vessel was rectangular and oriented vertically, with dimensions of 3 × 10 cm and 2 mm thick. The electrodes in the second vessel were the same dimensions, but were oriented horizontally and formed in an arc, with a radius of 5 cm, along the inside curve of the vessel (Figure 3). Distillation vessels were made of polypropylene with a capacity of two litres each (diameter and height were 10.4 and 27 cm, respectively), which were connected to a 50 cm length of glass condenser. The plastic balance tank had a capacity of 5 litres (with the dimensions of 15 × 23 × 25 cm), which maintained a constant water level in the distillation vessels (500 ml). The delivery valve was connected to the distillation vessel to prevent backflow of the boiling water. The variac controlled the voltage to the electrodes. Water temperature was measured with a cooper-constantan thermocouple. Depending on the desired treatment, water could be treated in the first (vertically oriented electrode) or second (horizontally oriented electrode) vessel or both.

2.3. Chemical and physical properties

Chemical and physical properties either were measured directly or calculated using existing equations. The electric conductivity

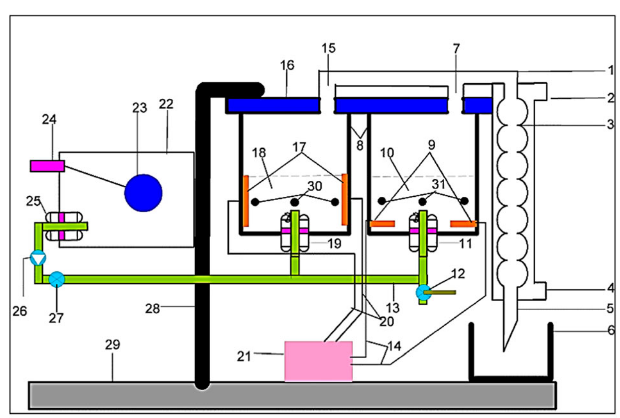

Figure 2. Labelled schematic of the ohmic distiller apparatus consisting of heat plastic pipe (1), output water (2), condenser (3), water input (4), distilled water output, distilled water container (6), steam output (7, 15), distillation vessels (8), horizontal stainless steel electrodes (9), salt water (10, 18), bolts (11, 19, 25), drain valve (12), pipes (13), wires (14, 20), cover (16), vertical stainless steel electrodes (17), variac voltage regulator (21), balance tank (22), float (23), salt water inlet (24), delivery valve (26), valve (27), support bar (28), device base (29), and thermocouples (30, 31).

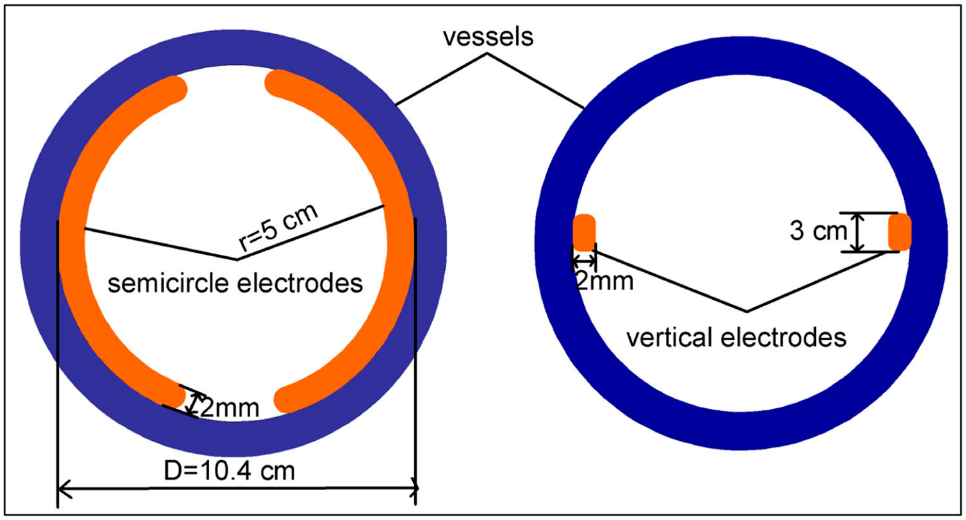

Figure 3. Top view of the two electrode designs in the vessels.

of tap water and distilled water was measured with a conductivity metre (Jenway 3510) at a water temperature of 25°C. Electric conductivity during the ohmic heating process was calculated according to the following equation (Wang and Sastry 1993; Içier, Yildiz, and Baysal 2008).

$$\sigma = \frac{I\,d}{V\,A} \tag{1}$$

where, 'σ' is the electric conductivity (S/m), 'I' is the electric current (A), 'd' is the distance between electrodes (0.1m), 'V' represents the voltage (V), and 'A' the section area (m^2).

Electric field (voltage gradient) was calculated using the following equation (Floury et al. 2006):

$$E = \frac{V}{d} \tag{2}$$

where, 'E' is the voltage gradient (V/cm).

A metre was used to measure water pH (Jenway 3505, England; ±0.02 pH accuracy). Total dissolved solids (TDS) was calculated as follows:

$$TDS = 640\sigma_d \tag{3}$$

where TDS is the total dissolved salts (ppm), σ_d is the electric conductivity measurement of distilled water (μ S/cm).

Calcium, sodium, and potassium were measured by using a flame atomic absorption spectrophotometer (Pye Unicam SP1900).

The heat transfer by natural convection was calculated from the following equation (Icier and Ilicali 2005),

$$E_{\text{loss}} = h\pi DL(T_w - \text{Tamb.})\,\Delta t \tag{4}$$

where, 'T_w' is the outer wall temperature (°C), 'Tamb' is the ambient temperature (°C), 'E_{loss}' is the heat loss by natural convection (J) and 'Δt' is the time.

The average of heat transfer coefficient was calculated from the following equation (Geankoplis 1993),

$$h = 1.32\left(\frac{\Delta T}{D}\right)^{(1/4)} \tag{5}$$

where, 'ΔT' is the average temperature driving force calculated from the initial and final outer wall temperatures and the ambient temperature. 'D' is the outer diameter of the cylinder (m).

The system performance coefficient (SPC) was calculated from the following equations (Icier and Ilicali 2005, 2004),

$$SPC = \frac{Q_t}{Eg} \tag{6}$$

$$Q_t = mCp(T_f - T_i) \tag{7}$$

$$E_g = Q_t + E_{\text{loss}} = \sum^{\Delta\, VIt} \tag{8}$$

where, 'm' represents mass (kg), 'C_p' represents specific heat (J/kg.K), 'T_f' is the final temperature of water (°C), 'T_i' represents primary temperature of water (°C), 'E' is the amount of given energy (J) and 'Q_t' is the amount of absorbed heat (J).

The specific heat was obtained as follows (Toledo, Singh, and Kong 2007).

$$C_p = 4176.2 - 9.0864 \times 10^{-3}T_f + 5473.1 \times 10^{-6}T_f \tag{9}$$

Energy efficiency ($\in$) was used to evaluate the performance of the ohmic heating system. It was calculated by the following equation (Nguyen et al. 2013).

$$\in = \frac{mCp(T_f - T_i)}{\Sigma VI\Delta t} \tag{10}$$

Power consumption (P) was calculated by the following equation.

$$\mathbf{P} = \mathrm{VI}t \tag{11}$$

Heating rate (°C/s) was calculated by the following equation:

$$\text{Heating rate} = \frac{\boldsymbol{T}}{\boldsymbol{t}} \tag{12}$$

where, 'T' represents the temperature elevation (°C), 't' is the heating time (min)

2.4. Statistical analysis

A fully randomised design was used for the experiments with three replications. Three different voltage levels were tested (7, 9, and 11 V/cm) with the ohmic distiller. The ohmic distiller was operated with three configurations of vertical electrode vessel, horizontal electrode vessel, and both vessels. Untreated (tap water) and traditional distillation (TD) samples were used for comparison. Traditional distillation used a 2.6 kW electrical powered distiller with a horizontal cylinder containing a heating element and glass heat exchanger for condensation of steam. Analysis of variance (ANOVA; $\alpha = 0.05$) and least significant difference (LSD) were calculated using the SPSS programme.

3. Results and discussion

Table 2 summarises the physical properties of distilled water samples after ohmic heating at electric field strengths of 7, 9, and 11 V/cm, in addition to the results of TD and untreated samples. The results showed that the pH values for all the ohmic distiller treated samples were 6.99–6.75 compared to 6.76 for the TD and untreated water samples. The highest pH value of 6.99 occurred at 9 V/cm for both the horizontal and combination of horizontal and vertical electrodes. The results were similar to Al-Hilphy (2013), who found that the pH values of distilled water using solar distillation were between 7.03 and 8.34. These results were within the recommended limits of AHS (2011), which stated that the pH range of drinking water was between 6.6 and 8.5. Values of pH less than 6.5 can cause corrosion and values above 8.5 can result in a bitter taste for water (AHS 2011).

The TDS values were significantly lower ($p < 0.05$) in all samples of distilled water, at 0.45–1.20 ppm, compared to the untreated water, at 1420 ppm. Among the distilled samples, only the ohmic distilled sample at 9 V/cm using both electrode configurations had a significantly lower TDS than the TD sample. The TDS values of all ohmic distiller samples and the TD sample were 0.45–1.2 ppm resulting in over a 10^3 reduction in TDS from untreated water. These values were about one-fifth of the maximum recommended level of 500 ppm for TDS (WHO 2004). These values were similar to levels of 39–44 ppm obtained with a solar water distiller (Al-Hilphy 2013).

The electrical conductivity values were significantly ($p < 0.05$) lower in all distilled samples compared to the untreated water sample. Among the distilled samples, only the electric field of 9 V/cm with the double dipole electrodes resulted in a significantly lower electrical conductivity than the TD method. The electrical conductivity of distilled water samples from the ohmic heating and the TD methods ranged from 0.85–1.65 μS/cm, while the electrical conductivity of the untreated water sample was 1130 μS/cm. This was due to the high TDS value of the untreated sample. The obtained result was not in agreement with (Al-Hilphy 2013) who mentioned that the electrical conductivity values of distilled water using solar distillation were 6.72–21.90 μS / cm. Walton (1989) reported that electric conductivity of distilled water ranged between 1 and 10 μS/cm, so results of the ohmic distiller were on the low side of this range..

Table 2. Physical properties of distilled water by ohmic heating at different electric field voltages at 25°C.

Electrical field (V/cm)	Electrode shape[a]	pH	TDS (mg/L)	EC (μS/cm)
7	H	6.85 ± 0.06	1.20 ± 0.14	1.65 ± 0.49
	V	6.75 ± 0.08	0.55 ± 0.07	1.00 ± 0.07
	H + V	6.92 ± 0.02	0.70 ± 0.14	1.55 ± 0.07
9	H	6.99 ± 0.01	1.10 ± 0.14	1.80 ± 0.14
	V	6.80 ± 0.04	0.60 ± 0.14	1.25 ± 0.07
	H + V	6.99 ± 0.02	0.45 ± 0.07	0.85 ± 0.07
11	H	6.96 ± 0.02	1.05 ± 0.07	1.45 ± 0.07
	V	6.95 ± 0.07	0.65 ± 0.07	1.15 ± 0.21
	H + V	6.87 ± 0.05	0.70 ± 0.14	1.35 ± 0.21
Traditional distillation (TD)		6.76 ± 0.07	1.10 ± 0.07	1.65 ± 0.07
Tap water (untreated)		6.76 ± 0.07	1420 ± 0.70	1130 ± 0.70
LSD		**0.120**	**0.556**	**0.622**

[a]H: horizontal, V: vertical, H + V: horizontal and vertical combination

Table 3. Metal elements of distilled water by ohmic heating at different values of electric field.

Electric field V/cm	Electrode Shape[a]	Ca (ppm)	Na (ppm)	K (ppm)
7	H	1.75 ± 0.21	1.60 ± 0.14	0.45 ± 0.07
	V	1.60 ± 0.56	1.30 ± 0.14	0.95 ± 0.07
	H + V	1.35 ± 0.21	1.50 ± 0.14	0.60 ± 0.14
9	H	2.20 ± 0.14	1.45 ± 0.21	0.85 ± 0.21
	V	2.30 ± 0.28	1.40 ± 0.28	1.00 ± 0.28
	H + V	1.15 ± 0.49	1.02 ± 0.35	0.32 ± 0.007
11	H	2.15 ± 0.35	1.95 ± 0.07	0.70 ± 0.28
	V	2.80 ± 0.14	2.25 ± 0.21	1.20 ± 0.28
	H + V	1.95 ± 0.56	2.50 ± 0.28	0.90 ± 0.28
Traditional distillation (TD)		3.25 ± 0.21	2.55 ± 0.21	0.80 ± 0.28
Tap water (untreaded)		430.05 ± 2.47	602.2 ± 1.13	55 ± 0.56
LSD		**1.804**	**0.880**	**0.864**

[a]H: horizontal, V: vertical, H + V: horizontal and vertical combination.

Table 3 shows the chemical composition of all ohmic distiller, traditional distillation, and untreated water samples. The results showed a significant ($p < 0.05$) decrease in Ca for ohmic and traditionally distilled water samples when compared to the untreated water sample. The Ca values of all ohmic and traditionally distilled water samples was 1.15–3.25 ppm. These values were within the maximum recommended level of 5 ppm (EAS 1999). These values were similar to Al-Hilphy (2013) who found that the Ca values of distilled water using solar distillation were 1.9–2.2 ppm.

These results showed a significant ($p < 0.05$) decrease in Na of all distilled water samples compared with untreated water sample. The Na values of the distilled water sample using ohmic and traditional distillation were 1.02–2.55 ppm, which was an order of magnitude lower than the maximum Na content recommendation of 200 ppm (WHO 1993). For ohmic heating, an electric field of 11 V/cm with both electrodes exhibited the highest Na of 2.5 ppm. This may be due to the increased electric field strength resulting in increased heating speed and generating more bubbles than lower electric fields. The bubbles move to the top and explode with steam, spreading salts back in the water. The Na value of traditionally distilled water was 2.55 ppm, which was not significantly different ($p > 0.05$) from any ohmic distillation samples using an electric field strength of 11 V/cm. The lowest Na value was 1.02 ppm when using an electric field of 9 V/cm with both electrode shapes. Ohmic electric field levels of 7 and 9 V/cm with any electrode configuration resulted in significantly lower Na levels than the TD sample. This finding was due to the use of lower electric field strengths that reduced the heating speed, thereby exploding bubbles when the steam was absent at the top.

The statistical analysis showed a significant decrease of K values ($p < 0.05$) in all distilled water samples using the ohmic heating and traditional method when compared to the untreated water sample. The K values of the distilled water samples using ohmic and traditional distillation were 0.32–1.2 ppm. The lowest K ppm occurred with ohmic distillation at 9 V/cm with the horizontal and vertical electrode combination. The resulting K values were well within the recommended maximum of 200 ppm (WHO 1993).

Figure 4 shows the productivity of distilled water using ohmic heating for both vertical and horizontal electrodes. The results showed that the productivity increased significantly ($p < 0.05$) with increased electric field strength for both vertical and horizontal electrodes. The productivity capacity was 240, 403, and 500 ml/hr at 7, 9, and 11 V/cm, respectively, when vertical and horizontal electrodes were used together. This may be due to the increased electric field strength, which increased the heating rate and increased the movement of ions within the water and resulted in an increased evaporation rate.

The results also revealed that the electrode design had a significant effect ($p < 0.05$) on production of distilled water. For example, the device productivity using the vertical electrodes was 133, 250, and 300 ml/hr at the electric field strength of 7, 9, and 11 V/cm, respectively. In contrast, the productivity of distilled water using the horizontal electrodes increased to 200, 316, and 429 ml/hr at the electric field strengths of 7, 9, and 11 V/cm, respectively. Furthermore, statistical analysis showed that the highest yield was achieved by using both vertical and horizontal electrodes together. This is due to the synergistic effect of electrode designs in both vessels heating at the same time, which contributed to increased steam productivity.

Figure 5. illustrates the relationship between temperature and heating time for vertical and horizontal electrodes at different electric field strengths. The results showed a significant decrease in time ($p < 0.05$) to boil the water with increased field strength using either electrode orientation. The electrode design had a significant effect ($p < 0.05$) on reducing the required time to achieve the boiling point. For instance, using the electric field at 7, 9, and 11 V/cm caused the achievement of the boiling point within 8, 12, and 20 min and 6, 7, and 14 min for horizontal and vertical electrodes, respectively. This result was consistent with Seidi Damyeh and Niakousari (2017). The speed of water distillation using the ohmic heating was higher than the speed of the traditional water distillation method. Al-Hilphy (2014) found that the required times to reach 80°C using ohmic heating were 6, 10, and 20 min in an electric field of 14, 20, 44 V/cm, respectively. Increasing the strength of the electric field enables an increase of temperature as well as increasing the electricity passing through the salt water, thus the heating rate will be raised, and the required time to reach the boiling point will decrease (Al-Hilphy 2014; Icier and Ilicali 2005; Kong et al. 2008).

Figure 6 shows the relationship between the electrical conductivity of salt water and the temperature using vertical and horizontal electrodes in different electric field strengths. The results showed a significant increase in electrical conductivity ($p < 0.05$) with increased temperature in all electric field strength values for both vertical and horizontal electrodes. This result agreed with Darvishi (2012) and Kong et al. (2008) who found that the electrical conductivity increased the ionic motion of water with high temperature. The results also showed a slight decrease in the value of electrical conductivity after the temperature reached 84°C, 88°C, and 87°C for the vertical electrodes and 81°C, 87°C, and 95°C for the horizontal electrodes at the electric field strength of 7, 9, and 11 V/cm, respectively. Beyond those temperatures, electrical conductivity plateaued or decreased. The observed decrease may be explained by the presence of bubbles caused at high temperatures. This result was consistent with Palaniappan and Sastry (1991), Icier and Ilicali (2005), and Darvishi (2012) who pointed out that the value of electrical conductivity decreased after the formation of bubbles and the formation of the electrolytic hydrogen bubbles in acidic fruit juices processed using ohmic heating. The results showed a significant decrease in the electrical conductivity ($p < 0.05$) with increased electric field strength for each of vertical and horizontal electrodes. Al-Hilphy and Majeed (2018) found that the electrical conductivity of a wheat bran water solution decreased significantly when the electric field was increased. For example,

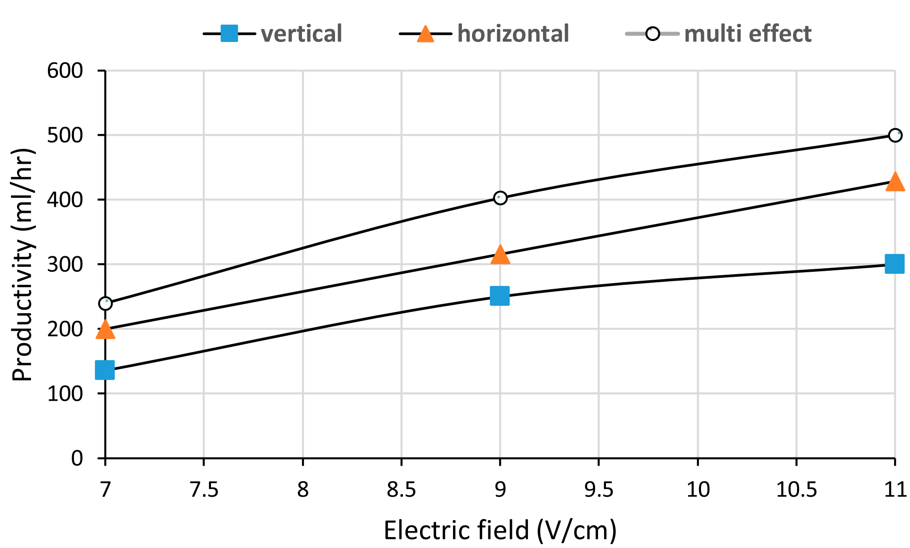

Figure 4. Distilled water productivity with ohmic distillation using vertical, horizontal and the multiple effect of both electrode shapes.

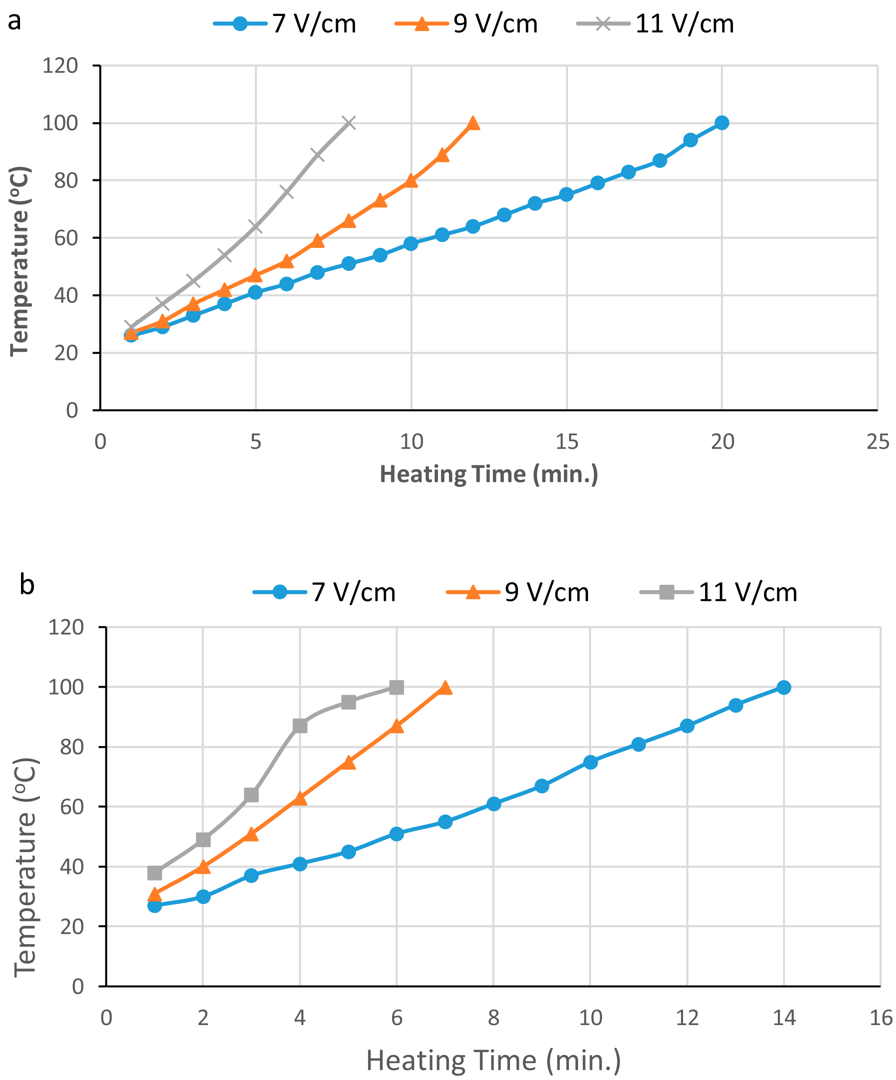

Figure 5. Heating curve of water treated using ohmic heating at different electric field values, (a) vertical electrodes and (b) horizontal electrodes.

when the electric field strength increased from 4.28–15.71 V/cm, the electrical conductivity decreased from 0.18–0.11 S/m. Their findings indicated that the intensity of the electric field was inversely proportional to the electrical conductivity according to the equation mentioned by Içier, Yildiz, and Baysal (2008),

$$\sigma = \frac{I}{EA} \tag{1}$$

In other studies of thermally pasteurised lemon juice (Altemimi et al. 2018), lemon juice (Darvishi et al. 2011), and strawberries (Castro et al. 2004) electrical conductivity increased with field strength, as electrical conductivity properties are dependent on the solution. As expected, the conductivity during ohmic heating for brackish water was less than the range of 5.5–40 (S/m) for seawater found by Assiry et al. (2010), as conductivity varies with TDS (Assiry et al. 2010).

Figure 7 shows the ohmic heating rate comparing horizontal and vertical electrodes at different values of electric field (7, 9, and 11 V/cm). The results showed that the heating rate increased significantly ($p < 0.50$) with the increase of electrical field strength (voltage gradient). The heating rate using horizontal electrodes was 7.14, 14.28, and 16.66°C/min at 7, 9, and 11 V/cm, respectively. The heating rate using vertical electrodes was 5.0, 7.14, and 12.5°C/min at 7, 9, and 11 V / cm, respectively. This increase in heating rate with voltage agreed with the Al-Hilphy (2014) result that heating rate increased significantly ($p < 0.05$) to achieve 1.15, 1.62, 2.93°C/min when the voltage was increased to 60, 70, and 80 V, respectively.

The heating rate using horizontal electrodes was faster than the vertical electrodes. This finding may be due to the volume of water exposure to the field of electricity, which was greater using the horizontal electrodes as compared to the vertical electrodes. In addition, the horizontal electrodes were in the form of two semicircles, which were on opposite walls of the vessel, causing a greater flow of water thereby increasing the heating speed. Al-Hilphy and Majeed (2018) reported that the heating speed increased significantly from 8 to 22°C/min with an increase in electric field strength from 4.28–15.71 V/cm. This increase was ascribed to the increase in electrical potential between the two electrodes, which increased the electrical current passing through the wheat bran water solution, thereby increasing the processing energy in the solution and reducing the required time to reach the desired temperature. In a study with seawater, the heating rate ranged from 41–373°C/min when the electric

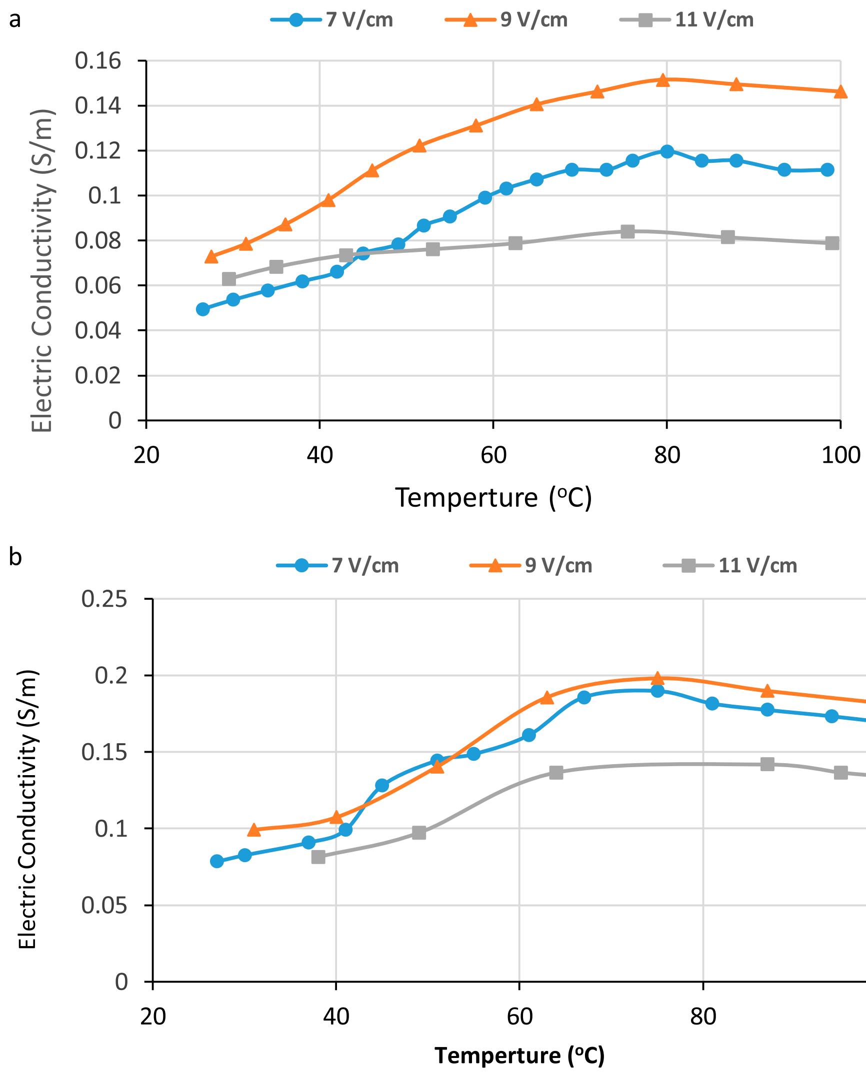

Figure 6. Electric conductivity of water treated by ohmic heating at different electric field values vs. temperature: (a) vertical electrodes; (b) horizontal electrodes.

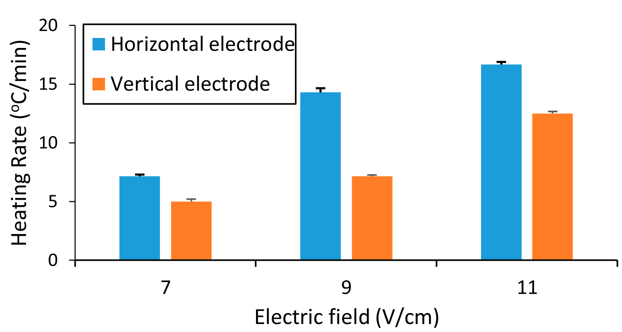

Figure 7. Heating rate of ohmic heating using horizontal and vertical electrodes at different values of electric field.

field was 6.35–11.04 V/cm depending on the concentration of the electrical field strength and TDS (Assiry et al. 2010).

3.1. Energy efficiency

Some studies confirmed that ohmic heating was more efficient than the traditional heating method because the ability of ohmic heating to distribute the heat homogeneously provided a greater heating rate and reduced the energy loss (Icier and Bozkurt 2011). Energy efficiency using the vertical and horizontal electrodes was calculated (Figure 8). The results showed that the energy efficiency at the electric field of 11 V/cm was significantly higher ($p < 0.05$) than the electric field of 7 and 9 V/cm for vertical electrodes. The energy efficiency at the electric field of 11 V/cm was significantly less ($p < 0.05$) than the electric field of 7 and 9 V/cm for horizontal electrodes because 11 V/cm used the highest current (5.39 A) which led an increase in the consumed power.

The energy efficiency using the horizontal electrodes was 32%, 51%, and 34% at the electric field of 7, 9, and 11 V/cm, respectively. In comparison, the energy efficiency using vertical electrodes was 77%, 80%, and 92% at electric fields of 7, 9, and 11 V/cm, respectively. This is due to the fact that when the voltage increased gradually, the rate of heat generation increased (Icier et al. 2017). Therefore, some studies reported that the reduction in electric field strength (voltage gradients) reduces the heat generation values in the treated food. Consequently, the required energy to evaporate the quantity of water required less time when the voltage increased. These results were in agreement with Cokgezme et al. (2017) who found that the energy efficiency using ohmic heating to treat

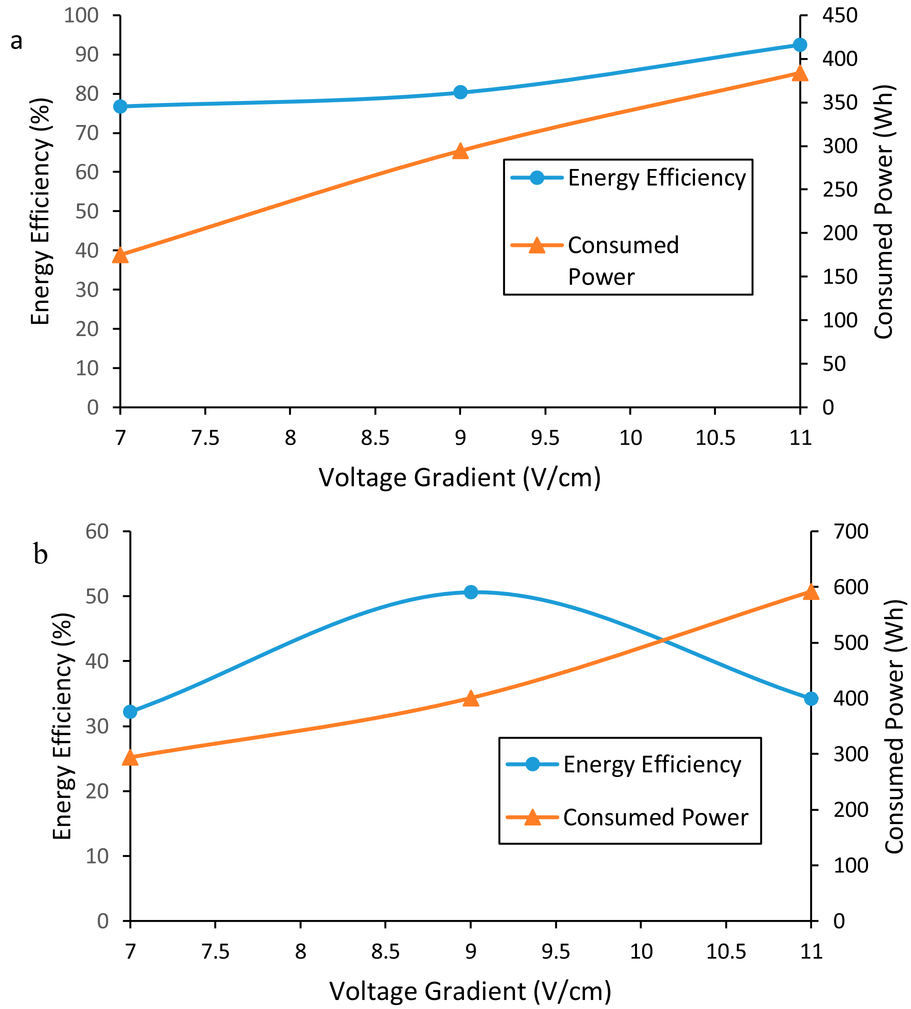

Figure 8. Energy efficiency and consumed power of ohmic heating with different electric field strengths: (a) vertical electrodes and (b) horizontal electrodes.

pomegranate juice increased when voltages were raised gradually, with energy efficiency of 5.5%, 11.3%, and 14.3% at electric fields of 7.5, 10 and 12.5 V/cm, respectively.

Figure 8 shows the consumed power using vertical and horizontal electrodes. The results showed that the highest power consumption was 384 and 592 Wh at 11 V/cm for the vertical and horizontal electrodes, respectively. The consumed power increased when the electric field increased, for example: when electric field.inc reased from 7 to 11 V/cm, the consumed power was increased from 175 to 384 Wh, and 294–592 Wh for the vertical and horizontal electrodes, respectively. This result was in agreement with Cokgezme et al. (2017) who found that the power consumption in pomegranate juice significantly increased ($p < 0.05$) with increasing electric field strength resulting in 230, 281, and 424 Wh at the electric fields of 7.5, 10, and 12.5 V/cm, respectively.

3.2. Performance coefficient of manufactured ohmic heater

Figure 9 illustrated the performance coefficient of the manufactured ohmic heating device at different values of electric field strength and different temperatures. The results showed that the performance coefficient decreased significantly ($p < 0.05$) when the temperature increased using both horizontal and vertical electrodes. The coefficient of performance decreased from 0.99–0.74 at the electric field of 7 V/cm using the horizontal electrodes and increasing the temperature from 30°C to 100°C. This may be due to increased heat loss when increasing the temperature. As the electrical energy was converted to heat, part of it was lost through the heating cylinder. This finding was in agreement with Al-Hilphy (2014) who found that the coefficient of performance increased significantly ($p < 0.05$) with increasing temperature when heating eucalyptus plant samples.

The results showed that there are differences in the coefficient of performance using different values of the electric field at the temperature range from 30–40°C. These differences were reduced as temperature increased above 45°C for both electrodes. In fact, the differences in horizontal electrodes at 30–40°C were larger than at the vertical electrodes. Al-Hilphy (2014) found that increasing the voltage gradually from 7.5–11 V/cm led to a decrease in the coefficient of performance from 0.99–0.98.

3.3. Future perspectives of ohmic heating for distillation

Ohmic heating has good potential for water desalinisation applications. Based on results of this study, water quality was as good as or better than traditional distillers. While ohmic heating

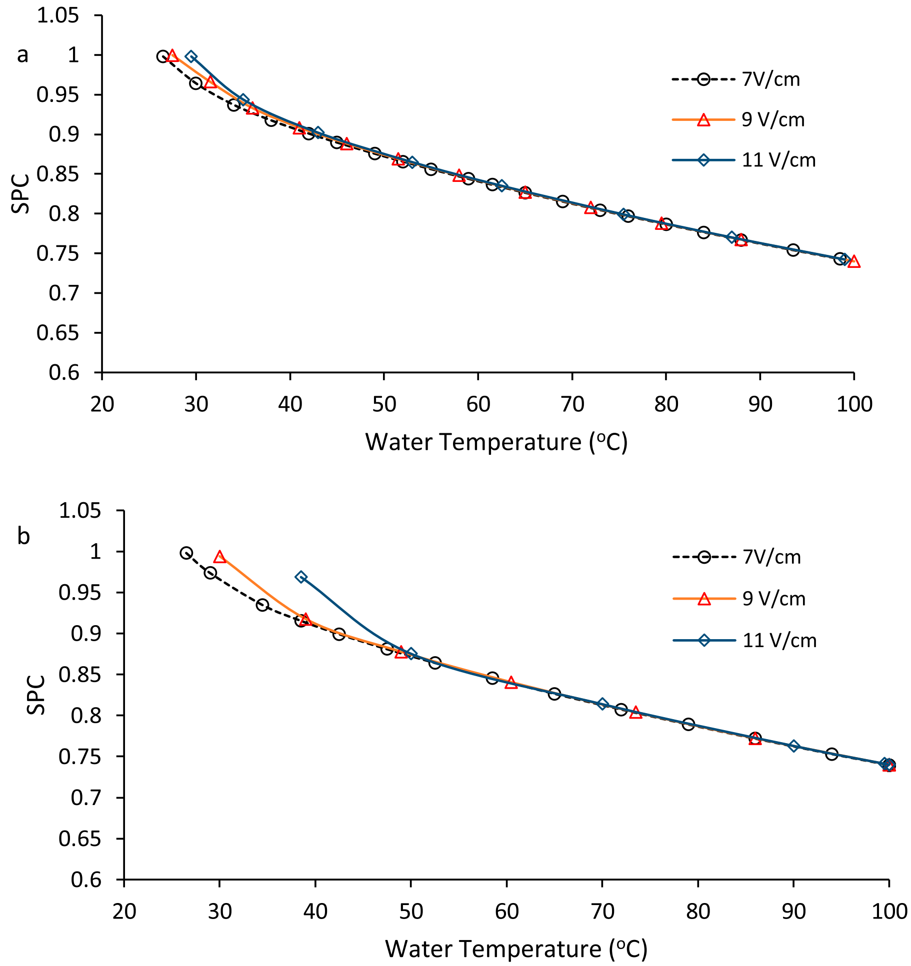

Figure 9. Performance coefficient of ohmic heating vs water temperature at different values of electric field using (a) vertical electrodes and (b) horizontal electrodes.

distillers would not reach the energy efficiency level of solar distillers, ohmic heating demonstrated improvements over traditional resistance type heating, while providing the same on-demand, 24-h operation capabilities.

Additional ohmic distiller development could include fine-tuning of power input parameters and electrode shape and configuration. Additional technologies such as flash or multistage distilling could be added. Pre-distillation filters could be added to remove certain impurities, such as clays.

Ohmic heating could potentially be used to replace any traditional resistance heating distiller. On a small scale, a countertop kitchen appliance (similar in size to a coffeemaker) would provide potable water on-demand in a relatively short time, while operating on less electricity than a traditional distiller. Unlike resistance heating electrodes, ohmic heating electrodes are not damaged by a lack of water, which is important for consumer operated devices. Large scale industrial ohmic distillers could also replace resistance heating distillers.

4. Conclusion

The physical properties of distilled water were clearly improved by using manufactured ohmic heating for a distiller. In addition, mineral components were reduced significantly in distilled water samples when compared to the traditional method of distillation and untreated tap water. Moreover, the productivity increased significantly with the increase of electric field strength and especially when using the horizontal and vertical electrodes together. In addition, the results indicated that the productivity of distilled water using the horizontal electrodes was higher than with the vertical electrodes. The required time to reach water evaporation was reduced by using a higher rate of the electric field. The results also confirmed that the electrical conductivity increased with increased temperature, while it decreased with the increased electric field. The energy efficiency increased proportionally with electric field strength. In contrast, the consumed power was reduced considerably when the electric field increased. Taken together, this study reveals that the system performance coefficient reduced significantly ($p < 0.05$) when the temperature was increased using both horizontal and vertical electrodes. Higher power inputs can cause salt water bubbles to rise, explode and pollute steam, thereby reducing distilled water quality.

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