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Studying different design parameters of a microwave preheating system in solar desalination

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ABSTRACT

An increasing number of microwave radiation applications have led to a large body of research on the effects of microwave radiation on heating. The effect of different design parameters was analyzed on the microwave-induced heating of saline water. In a completely randomized factorial experiment with three replications, effects of four salinity levels (0, 1,000, 10,000, and 30,000 ppm), three volume levels (100, 300, and 500 ml), and three power levels (200, 600, and 1,000 W) on heating time were studied. ANOVA results showed that the effects of power, volume, and salinity as well as all interactions were significant at the 1% level. The heating rate was calculated for heating water from 20 to 90°C. Heating rate varied from 0.0183 to 1.531°C/s, depending on the microwave power, volume and salinity. Results demonstrated that heating rate decreased with increasing salinity and increased with increasing microwave power and volume.

Keywords: Microwave; Salinity; Efficiency; Pre-heating; Heating rate

1. Introduction

Water scarcity due to erratic climatic conditions, increasing population growth, and improved living standards has turned into a great concern for researchers and governmental agencies around the world. According to the US Geological Survey, 96.5% of Earth's water is located in seas and oceans, and groundwater accounts for only 1.7%, out of which only 0.8% is considered to be fresh water [1].

Conventional methods of water desalination mostly used for high-capacity cases include multi-stage flash distillation, multi-stage distillation, vapor compression, and reverse osmosis [2]. However, among these methods, solar distillation systems can be a suitable solution for sparsely populated areas with high intensity of solar radiation. Its major problem is low system efficiency. To address this shortcoming, active solar distillation devices have been developed, in which efficiency is increased with increasing evaporation rate [3,4].

Experimental and theoretical studies of a solar desalination system connected to a parabolic collector with heat exchanger were investigated in [5]. Seawater electrical conductivity (EC) data were analyzed during ohmic heating. Based on EC data, design and modeling of a potential use for ohmic heating were also performed for generate heat within seawater during desalination

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process [6]. Another study on microwave-assisted membrane distillation showed that, between ionic conduction and dipole rotation, the former contributed more to microwave absorption [7].

Since microwave drying has been reported in many studies for heating food and developing dryers due to the polarization of water and ionic salt solution, microwaves were used for pre-heating a solar desalination system in this research.

Microwaves are electromagnetic waves, and their bandwidths and wavelengths range are between 300 MHz and 300 GHz, and 12 and 34 cm, respectively [8]. Microwaves belong to non-ionizing radiations and are completely separate from such ionizing radiations as X-ray and gamma. Specific frequencies are dedicated for industrial, scientific and medical (ISM) purposes to eliminate the chance of interference. Moreover, there are certain ranges for other purposes such as radio frequencies (13.6, 27.12, and 37.56 MHz). The microwave frequencies used for ISM purposes in different countries are fairly close to each other within the electromagnetic spectrum. The ISM band microwave ranges are 433, 915, and 2,450 MHz. The frequency of 915 MHz is widely used for industrial purposes, while 2,450 MHz is set aside for home microwave ovens. Each microwave device consists of three components, namely a magnetron (microwave source), waveguides, and a real actuator [9].

Microwave heating has several advantages including fast heating, simply controlled heating rate, and more efficient energy conversion. Due to the ever-increasing applications of electromagnetic waves and specially microwaves in different industries, it is necessary to study their behaviors. Microwave heating can be distinguished from other heat transferring methods including convection, conduction and radiation, due to its specific heat generation and transfer mechanisms. It has unique properties and capabilities, which make it suitable for processes such as heating, drying, polymerizing, and food industry in general [8]. At present, microwave vacuum dryers are used for producing fruit juice concentrates, powders and tea on a commercial scale. Effective factors in microwave heating are frequency, intensity and dielectric properties of the subject material. The material temperature changes depending on its density, specific heat, thermal conductivity, latent heat of melting, and evaporation [10]. Microwave heating can be also used in water desalination. This system is used not only for desalinating water, but also for purifying and removing pollutions from industrial wastes and effluents. Reusing the generated heat increases thermal efficiency. In this system, water is heated in a way that it can be desalinated in a single phase [11]. An advantage of microwave energy can be its higher efficiency (30–40%) than that of conventional heating (7–14%). Microwave systems can be also used simultaneously with other heating systems such as water vapor, hot air and infrared [12,13].

Microwave heating is because of waves as well as heat convection in samples [14]. Heat transfer in microwave systems is predicted by Lambert law which is valid for low diffusion depths. If sample depth is lower than the diffusion depth, heat diffusion will be high [15].

According to the research background on using microwave preheating and/or heating of water, this study investigated different effects of salinity, power, and inflow rate on the microwave heating of saline water.

2. Materials and methods

In order to study and determine effects of salinity, power, and flow rate of inlet water for microwave preheating, different laboratory devices and instruments were used. A microwave oven (Samsung, model ME3410W) was used for preheating. Its output microwave power was adjustable at 100 W intervals. A 600 ml Pyrex Borosilicate glass was used for holding water inside the microwave chamber. To produce water samples with different salinities, sea salts from Urmia lake (containing all the compounds available in lake water) were dissolved in distilled water. Urmia lake is located at 37.5°–38.15° North and 45°–46° East. A digital balance (A&D, GF-600, Japan) with 0.001 g readability was employed for weighing the salt samples. A LutronTM-925 (Taiwan) thermometer measured the water temperature inside the microwave chamber with 0.1℃ readability. The temperature sensor was connected to a PC and the temperature was recorded on a per-second basis. A power analyzer (Lutron, DW-6090-925, Taiwan) was used for measuring power consumption and the device's voltage and current. Its output was also connected to a PC using a RS-232 cable to record power consumption data every second.

2.1. Experimental design

In this research, an automatic desalinate with microwave preheating (Figs. 1 and 2) was designed and developed.

The experiments were performed at four levels of salinity (0, 1,000, 10,000, and 30,000 ppm), three levels of power (200, 600, and 1,000 W), and three levels of water volumes (100, 300, and 500 cc) in order to measure preheating efficiency and the required heating

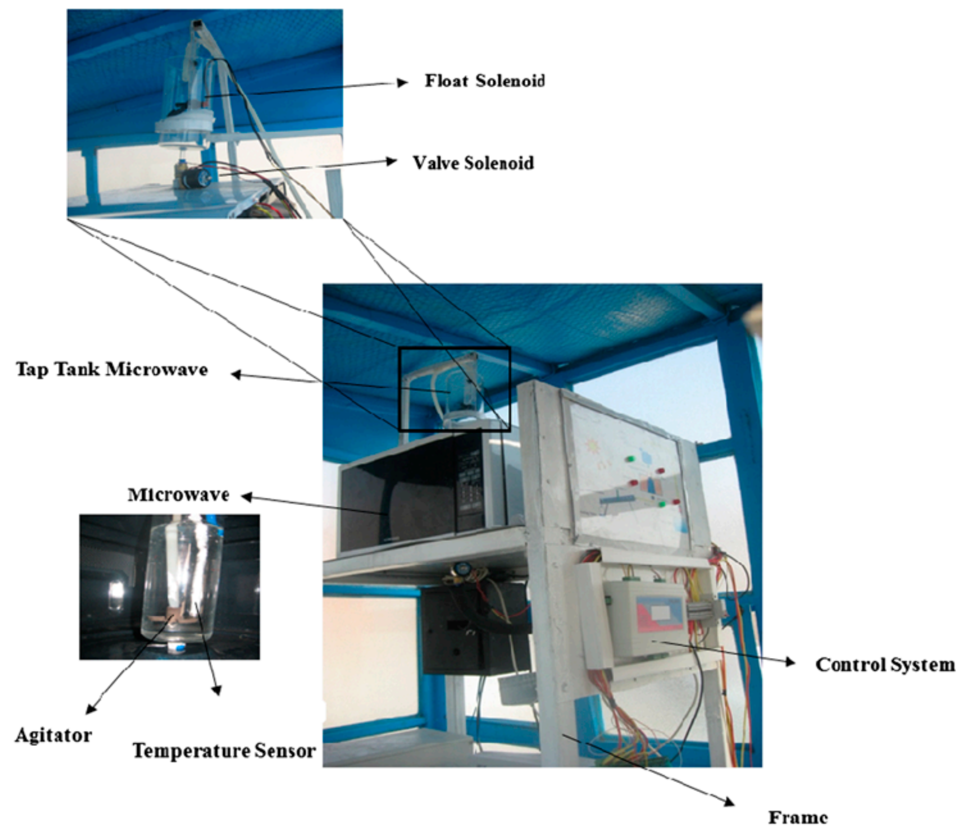

Fig. 1. Microwave pre-heating system.

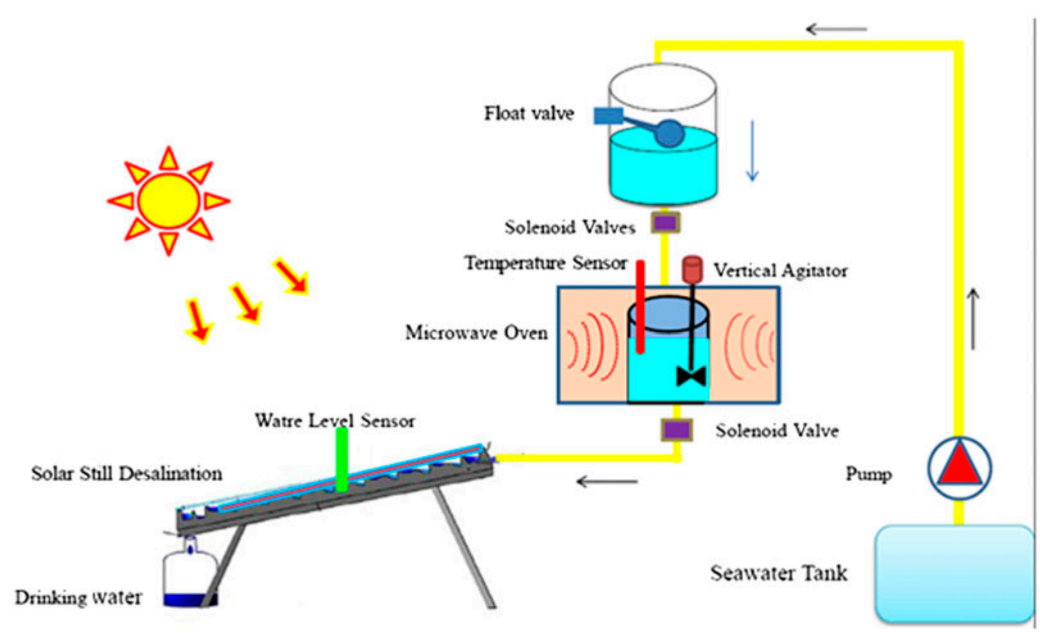

Fig. 2. Schematic of solar desalination with microwave pre-heating.

time for water to reach 50, 70, and 90℃. All the experiments were carried out in three replications and in the form of a factorial completely randomized design. SPSS 16 and Minitab 14 were used for analysis of variance and all mean values were compared by multi-range Duncan test at the 5% level of probability. First, all water samples with different salinity levels were prepared by adding sea salt to distilled water. These samples were then kept at 20℃ before treatment. Then, a 600-ml borosilicate glass jar was used for holding water inside the microwave chamber and a thermocouple was placed at the center of the reactor for the purpose of measuring temperatures. Once the microwave oven was turned on, the temperature and power consumption were recorded in the computer until reaching 50, 70, and 90℃. Next, heating time and thermal efficiency were determined for each treatment. Thermal efficiency was equal to the absorbed energy by water to raise temperature by ΔT (℃) divided by the total energy consumed by the microwave oven as follows:

$$\text{Efficeincy} = \frac{m \times c_{\rm p} \times \Delta T}{p \times t} \tag{1}$$

where, m (kg) is mass and c_p (J/kg ℃) is specific heat capacity. P (W) and t (s) stand for power and heating time, respectively.

3. Results and discussion

In order to study the effects of four levels of salinity, three levels of water volume, and three levels of power, a factorial completely randomized design was used. Table 1 presents the ANOVA results for time and efficiency. According to this table, the effects of power, volume, and salinity and all interactions were significant at the level of 1%.

3.1. Comparing effects of volume, power and salinity on heating time

Fig. 3 shows the interactions of salinity and power on heating time in a time interval. As shown in Fig. 3, the highlighted area belonging to powers higher than 600 W and salinity levels lower than 10,000 ppm and also the area related to the 1,000 W power and 30,000 ppm salinity had the lowest heating time. As the heating power increased at a constant salinity level, the heating time decreased. Salinity had more visible effects on heating time at higher powers.

As shown in Fig. 3, the lowest heating time occurred at higher power levels with distilled water (0.76 min), while its maximum value belonged to low powers with high salinity (63.87 min) for reaching 90℃. Additionally, as the heating power increased from 0 to 700 W, heating time decreased at all salinity levels. However, it took another increasing trend within the 700–1,000 W interval. Furthermore, concerning the curve's slopes at high and low salinities and their comparison, it can be found that heating time variations at low salinities were smaller than those at high salinities, indicating that salinity had larger effects on heating time with larger amounts. In other words, higher salinity levels had more effects on heating time.

Fig. 4 present the interactions of volume and power on heating time in a time interval. As shown in the figures, maximum heating time occurred at higher volumes and lower powers, while its minimum was at lower volumes and higher powers; a result which was predictable. For larger volumes, more energy was needed to heat water up to an intended temperature,

Table 1
ANOVA results of water heating time and its efficiency

Source	Degree of freedom	MS	
		Heating time	Efficiency
Power	2	11,757.015*	1,492.893*
Volume	3	3,402.715*	130.862*
Salinity	3	300.204*	781.563*
Power × volume	4	2,636.111*	47.959*
Power × salinity	6	1,374.312*	183.256*
Volume × salinity	6	444.67*	121.196*
Error	72	95.327	2.786
Total	96		

*Significant at 1%.

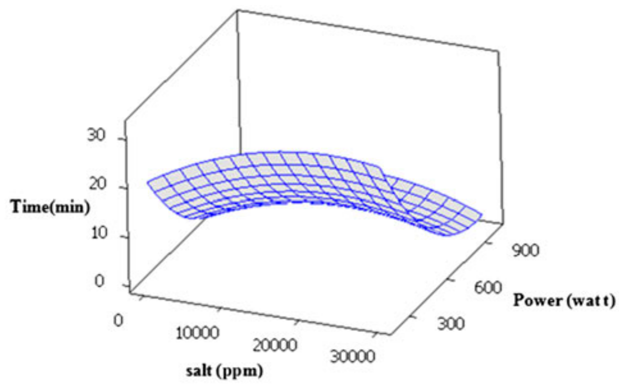

Fig. 3. Effects of salinity and power on heating time.

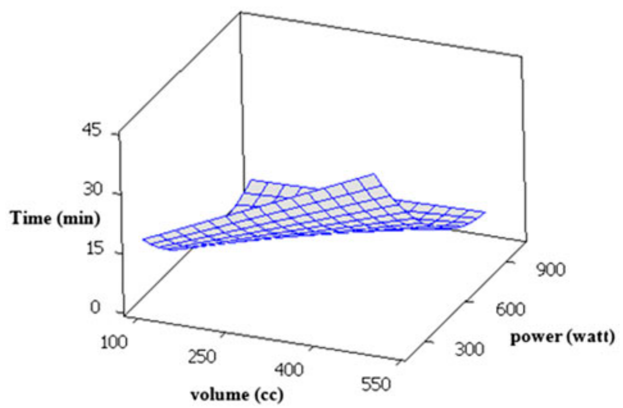

Fig. 4. Effects of volume and power on heating time.

which increased the heating time at a constant power. Cherbański and Rudniak [15] reported that wave absorption increases by as the height increases. Lower power levels caused less energy transfer to water per unit time, which also increased heating time for reaching a given temperature.

The effects of volume and salinity on water heating time are presented in Fig. 5. As shown in the figures, heating time increased with an increase in volume at different salinity levels. Moreover, it can be observed that increasing salinity level first increased and then heating time remained motionless.

In fact, the effect of salinity on heating time was more noticeable at higher volumes, because the slope of variations for heating time became more intense. Therefore, it can be found that higher salinity levels had a larger effect on heating time, and lower salinity levels had smaller effects on heating time till reached to assured salinity. From that point on, increased salinity levels had no effect on heating time. The maximum heating time (63.87 min) belonged to the 500 ml

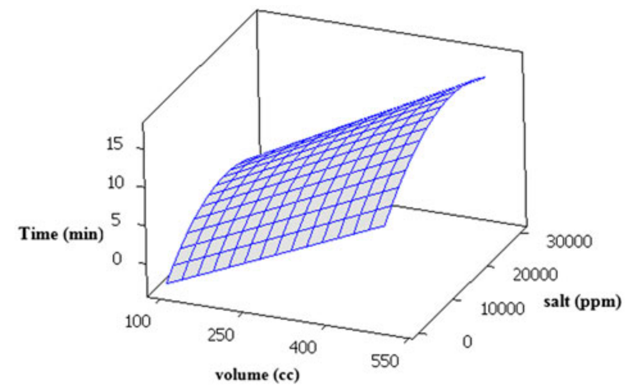

Fig. 5. Effects of volume and salinity on heating time.

volume and 10,000 ppm salinity, while its minimum (0.76 min) occurred at 200 ml and zero salinity. Ratanadecho and Aoki [16] showed that a 20% increase in salinity decreased microwaves absorption.

Fig. 6 shows the relationship between salinity and heating time. Increasing the salinity from 0 to 1,000 ppm can lead to longer heating times (i.e. an incremental trend). However, once passing the 1,000 ppm mark, salinity would have no influence on heating time with a constant value.

Fig. 7 presents the effect of power on heating time. As shown in this figure, the energy transferred to water increased with increasing power, which increased time required for reaching the target temperature. In other words, there was an inverse relationship between power and heating time.

The relationship between volume and heating time is demonstrated in Fig. 8; the larger the volume, the more the energy needed for raising the initial temperature to the target temperature; consequently, at a constant power, the required heating time would be higher than its initial value. Accordingly, there was a direct relationship between volume and heating time.

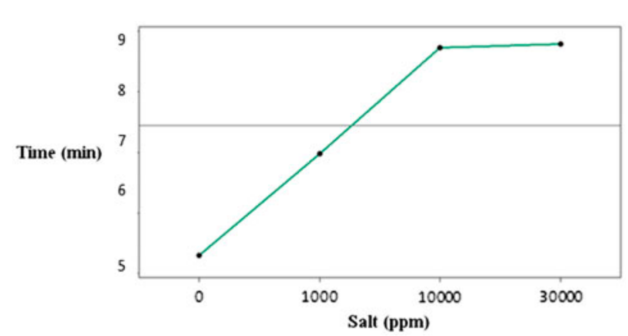

Fig. 6. Relationship between salinity and heating time.

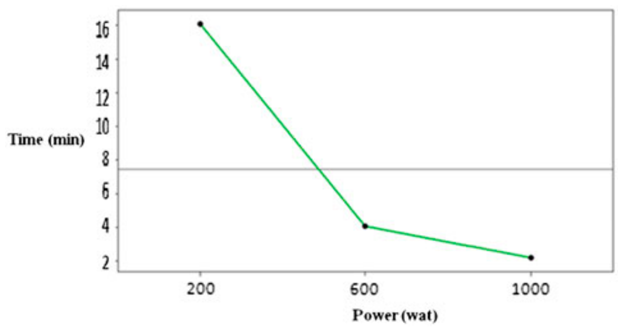

Fig. 7. Relationship between power and heating time.

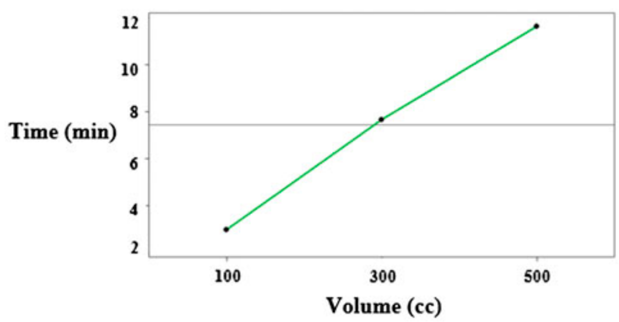

Fig. 8. Relationship between volume and heating time.

3.2. *Comparing effects of salinity, power and volume on heating efficiency*

Fig. 9 shows the interaction of salinity and power on efficiency. Accordingly, maximum efficiency belonged to the lowest salinity and highest power, and its minimum occurred at the highest salinity and lowest power. Based on Fig. 9, increasing power and decreasing salinity significantly increased efficiency. As mentioned earlier, increased salinity caused an increase in heating time, which, in turn, increased input energy (i.e. decreased efficiency). However, increasing power had an inverse relationship with heating time. Although the input energy increased for higher power levels, which can decrease the input energy due to its time-decreasing effect and ultimately increases efficiency.

The interaction between salinity and volume on efficiency is shown in Fig. 10. According to Fig. 10, maximum efficiency occurred at the lowest salinity and the maximum volume, and its minimum belonged to the highest salinity and the lowest volume. Moreover, as shown in Fig. 10, decreasing salinity and increasing volume can together increase efficiency; however, the effect of salinity on efficiency variations was more significant. Increasing salinity resulted in increased heating time and increased absorbed energy by water, which decreased efficiency. The effect of volume on efficiency was similar to that of power. In other words, increasing volume can increase heating time and input energy. However, on the other hand, larger volumes can increase energy output. The increase in output energy was larger than that in input energy, which finally increased efficiency.

The effects of volume and power on efficiency are presented in Fig. 11. According to this figure, maximum efficiency belonged to the highest power and volume values, while the combined values of the lowest power and volume resulted in the minimum efficiency. As represented in Fig. 11, efficiency took an incremental trend with increasing volume and power, the reason of which was explained earlier in the section.

The same results have been reported by Cherbański and Rudniak [15] and Ratanadecho and Aoki [16] for increasing efficiency by increasing absorption and therefore volume, and decreasing microwaves absorption with increasing salinity, respectively.

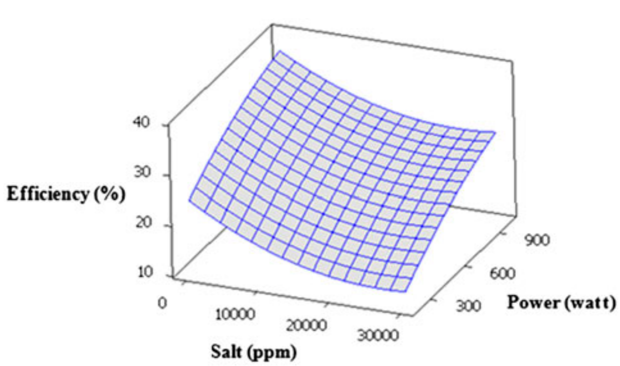

Fig. 9. Effects of salinity and power on efficiency.

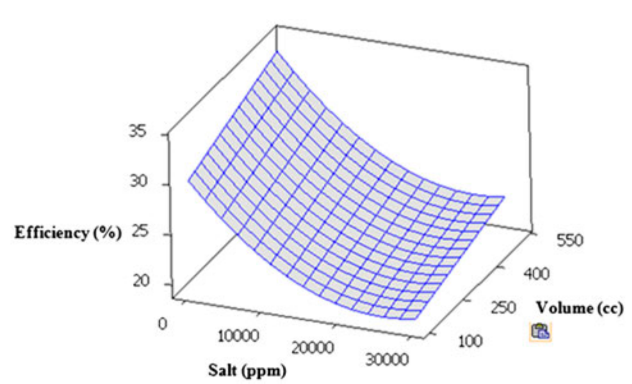

Fig. 10. Effects of salinity and volume on efficiency.

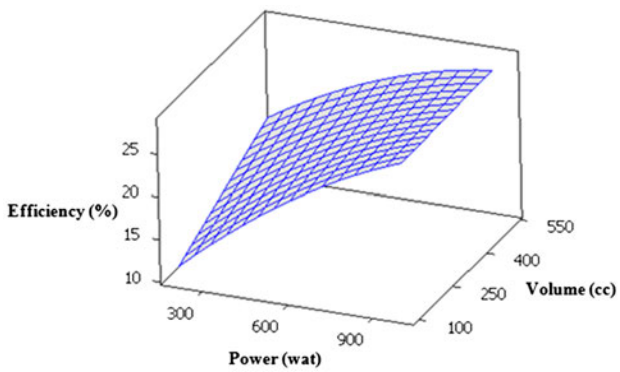

Fig. 11. Effects of volume and power on efficiency.

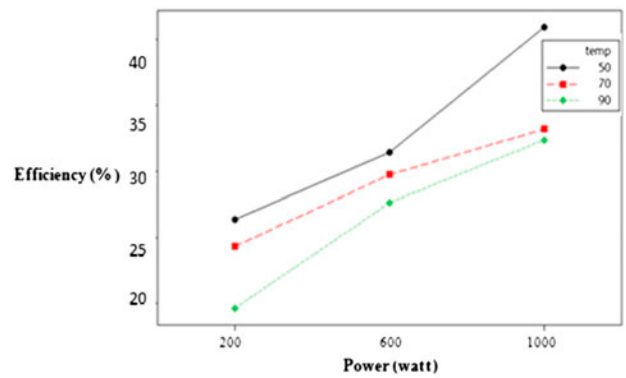

Fig. 13. Efficiency with power at different temperatures.

Fig. 12 shows efficiency values at different temperatures and salinities; as salinity and target temperature increased, efficiency decreased in general. The minimum efficiency belonged to 90℃ and the 30,000 ppm salinity with 21%, whereas its maximum amount was recorded at 50℃ and 1,000 ppm salinity with 46.8%. The decrease in efficiency by increasing salinity can be due to the decrease in absorption as mentioned earlier [16]. According to Eq. (1), at a constant temperature, efficiency decreased with increasing heating time. As shown in Fig. 15, the time required for reaching 50℃ is around 3 min, and this is 4 and 5 min for reaching 70 and 90℃ from 50 and 70℃, respectively. Therefore, the efficiency decreased for larger temperature variations. Microwave heating happens not only because of waves, but also it depends on heat convection in samples [14]. Moreover, the largest decreasing trend of efficiency occurred at 50℃, with increasing salinity from 0 to 1,000 ppm because heat convection is maximized at lower temperatures.

Efficiency variations with power at different temperatures are shown in Fig. 13. Accordingly, increasing power can bring about increased efficiency. The minimum efficiency (17.1%) occurred at 90℃ and 200 W, and its maximum amount (42.1%) was recorded at 50℃ and 1,000 W.

Efficiency variations with volume at different temperatures are shown in Fig. 14. Based on this figure, efficiency is improved by increasing the volume due to more absorption [15]. Accordingly, at the constant temperature of 50℃, increasing volume can first reduce and then increase efficiency. At 70℃, efficiency first followed an almost constant trend, but then increased. Moreover, at 90℃, efficiency increased with increased volume. This is because of the large difference of heating time for heating samples between 100 and 300 cc in comparison to 300–700 cc. The highest efficiency was recorded at 50℃ and 500 cc as 36%, whereas it's minimum was at 90℃ and 100 ml as 24%. This figure also shows that efficiency was higher at lower temperatures for a constant volume due to the maximum heat convection at lower temperatures which causes higher efficiency [14].

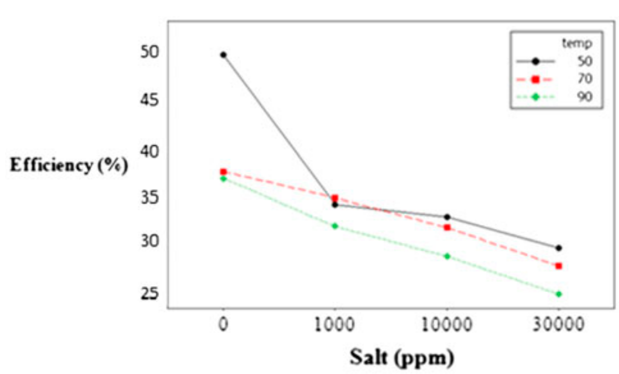

Fig. 12. Efficiency values at different temperatures and salinities.

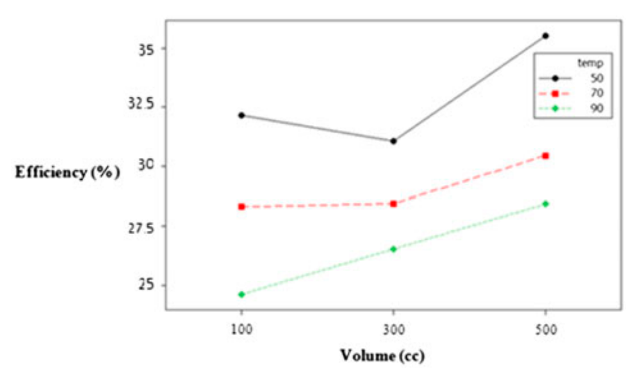

Fig. 14. Efficiency with volume at different temperatures.

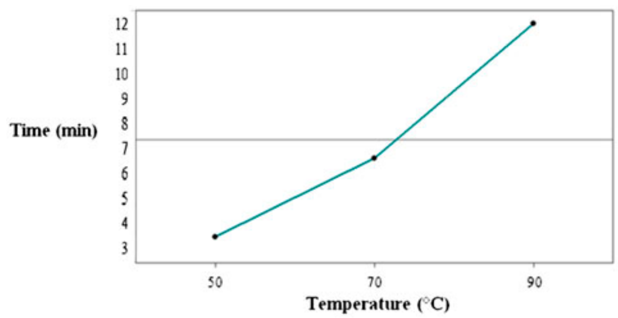

Fig. 15. Relationship between water temperature and the heating time.

3.3. Heating rate

Fig. 15 shows the relationship between water temperature and heating time. It is needless to say that increasing the target temperature increased the amount of energy needed for raising the temperature from an initial to a target value. Therefore, at a constant power, heating time was increased. In this study, heating rate was calculated from the time required to heat water from 20 to 90˚C. From Fig. 15, the heating rate ranged between 0.0183˚C/s for the microwave power of 200 W, volume of 500 cc, and salinity of 3,000 ppm and 1.531˚C/s for the microwave power of 1,000 W, volume of 100 cc, and salinity of 0 ppm. Heating rate depends on the microwave power, volume, and salinity. Results indicated that heating rate decreased with increasing salinity. Heating rate was 0.69–6.22˚C/s for saltwater in the ohmic method. Higher concentration and stronger electric field led to higher heat rate [6].

4. Conclusions

Analyzing the effects of salinity, volume, and power on preheating by microwaves resulted in the following conclusions:

(1) Increasing power can accelerate the heating process and increase the microwave efficiency. Therefore, for the final development stage, it is suggested to employ maximal microwave powers.
(2) The maximum heating time was for 500 cc volume and 10,000 ppm salinity (63.87 min) with its minimum time occurring for 200 cc volume and zero salinity (0.76 min).
(3) Efficiency and heating rate decreased as salinity increased; i.e. this system worked best with brackish water.
(4) Increasing the water volume inside the microwave chamber had negligible effects on efficiency.
(5) Maximum efficiency occurred at the highest power and volume, whereas its minimum amount belonged to the lowest power and volume.
(6) Efficiency took an incremental trend when volume and power were increased.
(7) The minimum efficiency was recorded at 90˚C and 30,000 ppm salinity as 21%, and its maximum amount was at 50˚C and 1,000 ppm salinity as 46.8%. Moreover, the largest decreasing trend of efficiency was observed at 50˚C, with increasing salinity from 0 to 1,000 ppm.

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