Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2019.24458

164 (2019) 263–275
October

Design and evaluation of a novel ultrasonic desalination system by response surface methodology

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Received 1 January 2019; Accepted 23 May 2019

ABSTRACT

Due to the lack of drinking water people have been forced to obtain fresh and renewable water sources. For this reason, desalination systems are being developed around the world. Ultrasound technology is one of the most recent technologies in the desalination industry which improves the evaporation and distillation processes by increasing the mass and heat transfer that causes a reduction in energy consumption. This technology can help to maintain the health and safety of people because of avoiding the use of chemical material. In this study, an ultrasonic desalting system was evaluated in terms of salinity and the amount of produced water through response surface methodology (RSM). It was found that the salinity of incoming water had the highest impact on the produced water salinity level. By raising the temperature of incoming hot air the level of salinity decreased while by increasing the power of ultrasound the amount of produced water increased. The value of optimal experimental variables was obtained by RSM for the desalination system's operation for one hour, which yielded 200.737 ml water with a salinity level of 545 ppm. In addition to that, the economic analysis of this system was also investigated and it was proved that the operational and energy costs of this system were lower than those of the conventional methods such as RO and MSF. The salinity level in produced water by the desalination system was analyzed and the results matched with the WHO guidelines for drinking water quality. The results revealed that this system is practical and can be scaled up for testing industrial saline water desalination systems.

Keywords: Desalination systems; Ultrasound technique; RSM; Production cost; Energy efficiency

1. Introduction

Water is a necessity for life and an essential need for human beings. Therefore, the quality of consumed water has an immense influence on human beings. Life on earth, economics, security, politics, sustainable development and the health of societies can be affected by water crisis that has been rising rapidly around the world, which is considered to be a severe warning to various nations [1]. In addition to the growth of industrial activities and contamination by micro-fluids, agricultural consumption, and not observing the correct pattern of usage in most developing countries, alteration in people's lifestyle, the persistence or even reduction of available water resources on earth and the continuing rise in the world's population increase the necessity of safe water consumption [2,3]. On the basis of this evidence, human beings need to purify and desalinate salty water on earth as a new and renewable source of safe and drinking water.

In order to provide sustainable water supplies, desalination systems can be used in many areas due to the minimal distance of about three-quarters of the world's population from the sea [1]. Up to now, various methods have been developed for desalinating saline water, amongst which

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membrane and thermal methods have been further developed [4,5]. High energy consumption, which increases cost and pollution, is the most significant problem in desalination systems. In order to overcome this issue, renewable energy sources are being used to provide energy for these systems. However in most cases the efficiency and working capacity of desalination systems have barely been improved [6–8]. Application of ultrasound is one of the most recent technologies for improving water purification and desalination. This technology improves the evaporation and distillation processes by enhancing mass and heat transfer. Therefore, the application of ultrasound technology empowers desalination systems in order to use renewable energy sources which improves the economic and environmental conditions [7,8].

Ultrasound waves cause cavitation phenomena in liquids. Collapsing cavitation bubbles cause sono-chemical extinction of pollutants during the aqueous phase [9]. Symmetrically or asymmetrically implosion can occur when the solid particles are in the proximity of cavitation bubbles. Microscopic turbulence and/or thinning of the solid liquid film are the result of shock waves which are made by symmetric cavitation, in any case they pervade to the surrounding solids. Increasing the rate of mass transfer among the reactions and/or producing it through the film can be made by a phenomenon known as microstreaming. It cannot be a symmetrically collapse if solid particles are in close vicinity to the bubbles. Foundation of solvent micro jets which bombard the solid surface and cause pitting and erosion are made by asymmetric cavitation [10]. When the bubbles explode, a strong oxidation agent is produced. The use of this technology can break down many complex organic compounds into simpler compounds during cavitation [2,3,10].

The depth of liquid in droplet's production caused by ultrasound is important. For a long functional period, the depth of the liquid should be kept constant. In this case, there is no impediment to ultrasound operation over a long period of time [11].

According to previous studies, ultrasound is one of the most effective ecological methods to disinfect water from microbiological compounds, and by this method many organic compounds are decomposed into simple compounds so that the amount of chlorine will be reduced in order that disinfection can take place. [9,12]. Compared to many other processes which are negatively affected by increasing the effluent of suspended solids, the efficiency of ultrasonic may even improve [9,13]. Several studies have been carried out to investigate the effects of ultrasound on water purification namely reducing turbidity, water total suspended solid (TSS) [14], controlling growth and removal of algae from water [15], deactivation of microorganisms in water [16] removing hardness in water and also halothanes [17]. The positive and significant role of ultrasound in reducing and eliminating pollutants from water has been reported in all of these studies.

Ultrasonic technology also has been utilized in the field of desalination. Compared to other methods, especially the chemical membrane cleaning, ultrasound utilization has many advantages such as improving the performance of the desalination system, absence of secondary pollution, portability as well as the possibility of a system being cleaned during the membrane desalination process [18–20]. Research areas in this field which can be considered noteworthy are: potential of nanofiltration membrane cleaning (NF) by ultrasonic waves [21]; Study of ultrasound technology effects on the intensification of mass and heat transfer, control and removal of sediment in membrane systems [22]; Investigation on the process of filtration and membrane cleaning by ultrasound and ultrafiltration technology [23]. Based on the literature review, desirable results have been obtained from ultrasound implementation in association with membrane desalination. In the field of thermal desalination, Xiao [8] investigated the effects of 1.7 MHz ultrasound wave frequency on the evaporation rate of saline water, in combination with a solar desalination system. The results revealed that ultrasound technology increases the evaporation rate by eliminating the effects of seawater concentration growth on the desalination process. Thereafter, the effects of variable water temperatures on atomization rates with variable salinity levels by ultrasound frequency of 1.7 MHz have been considered, and it was proved that the optimum temperature for water atomization in the salinity range of 15000–35000 ppm was 50–65°C [7].

In all of the aforementioned studies, ultrasound technology has been used to overcome some problems in combination with other desalination systems except for Zhang's research [7], in which ultrasound effect was evaluated on the basis of the amount of saline water evaporation. However, the amount of produced water by the desalination system and its level of salinity have not been considered so far. Therefore, the purpose of this study is the process of atomizing saline water by ultrasound, and desalinating it with hot water exposal to determine the amount of produced water and its salinity content with the ultrasonic desalination system.

2. Material and methods

2.1. Materials

Distilled water and laboratory purified NaCl to a level of 99% and a molar mass of 58.44 g/mol were used to prepare saline water having different salinity levels (5000–15000). The ultrasonic desalination device and hot air channel was made of glass and galvanized sheet metal, respectively. This research was carried out in the Electronic Laboratory of the Agricultural Faculty, Tarbiat Modares University.

2.2. Experimental equipment

The ultrasonic desalination unit (Fig. 1) consists of an inlet saline water reservoir, an evaporation tank, a hot air channel for preheating and controlling the temperature system of the inlet saline water and a condenser. Piezoelectric crystals which create ultrasound waves (1.7 MHz) were placed at the bottom of the entrained saline water reservoir. The inlet saline water reservoir measuring 15 cm in length, 15 cm in width and 15 cm in height was fabricated in accordance with the dimensions given in [11]. The tank also has two vents to allow saline water to enter and remove the remaining water during each test. An evaporation tank had the size of $50 \times 15 \times 40$ cm^3 in length,

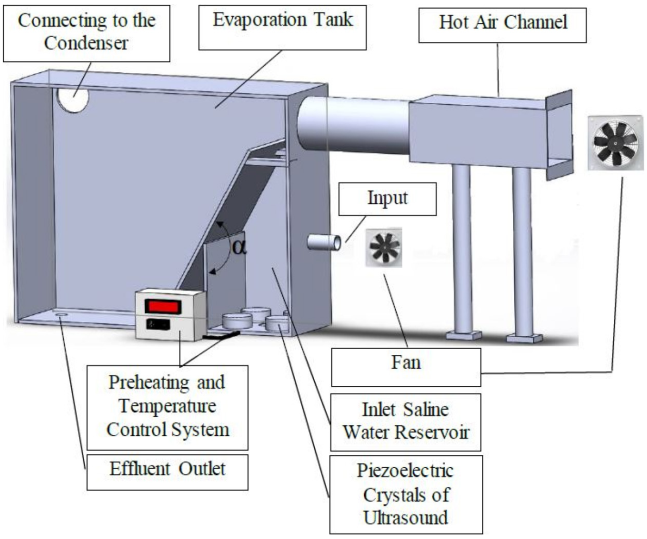

Fig. 1. Schematic view of ultrasonic desalination unit.

width and height, respectively. It also was equipped with one hot air entrance and two outputs to enable the exit of effluent and generated steam. Two thermal elements were embedded along the hot air channel and a fan was used to create a hot air stream. The preheating and temperature control system includes a thermostat, temperature sensors and thermal elements. In order to facilitate flow movement as a result of water atomization by ultrasonic waves, a diagonally shaped part was used inside the system. In this study, the flow has a Reynolds number of 0.87 < 1, which was the result of a creeping stream. Therefore, the corner angle of 150 degrees (α = 150°) was selected by following [24]. In order to increase the water atomization rate by ultrasound, a fan was used above the water level following [7,11] which was connected to the system through the entrance of the salt water reservoir during the test. A photograph of the fabricated ultrasonic desalination system can be seen in Fig. 2. In this research, the temperature sensors with ± 1°C precision and operating temperature range of –50 to + 80°C, as well as the ultrasonic piezoelectric crystals of +5 to 50°C.

2.3. Experimental procedure

During each experimental run, at the beginning, salty water within the salinity limits of 5000–15000 ppm was put into the tank via the salt water reservoir entrance and by means of the preheating and control system the desired temperature of saline water (15–45°C) was reached and noted at the end of the test. Heating elements in the hot air channel were activated and the hot air flow was guided into the evaporation reservoir by fans in order that the required temperature of each test (40–80°C) could be reached in the evaporation tank. The piezoelectric crystals of ultrasound were activated at this stage and atomized the saline water. The fan in the salty water tank was connected to the system through the entrance of the saltwater reservoir and due to its function channels lead the atomized particles of saline water into the evaporation reservoir. Particles of water collided with the hot air flow, evaporated, and moved towards the output, and when entered the condenser, the water construction changed and became liquid. Similarly, salt particles, which had a higher density than water particles, moved to the bottom of evaporation tank and repulsed from the system through wastewater discharge. When the test was complete, the remaining saline water was discharged from the system through the saline reservoir.

2.4. Product analysis

During each experimental run, an ultrasound desalination system worked for one hour, and the water extracted

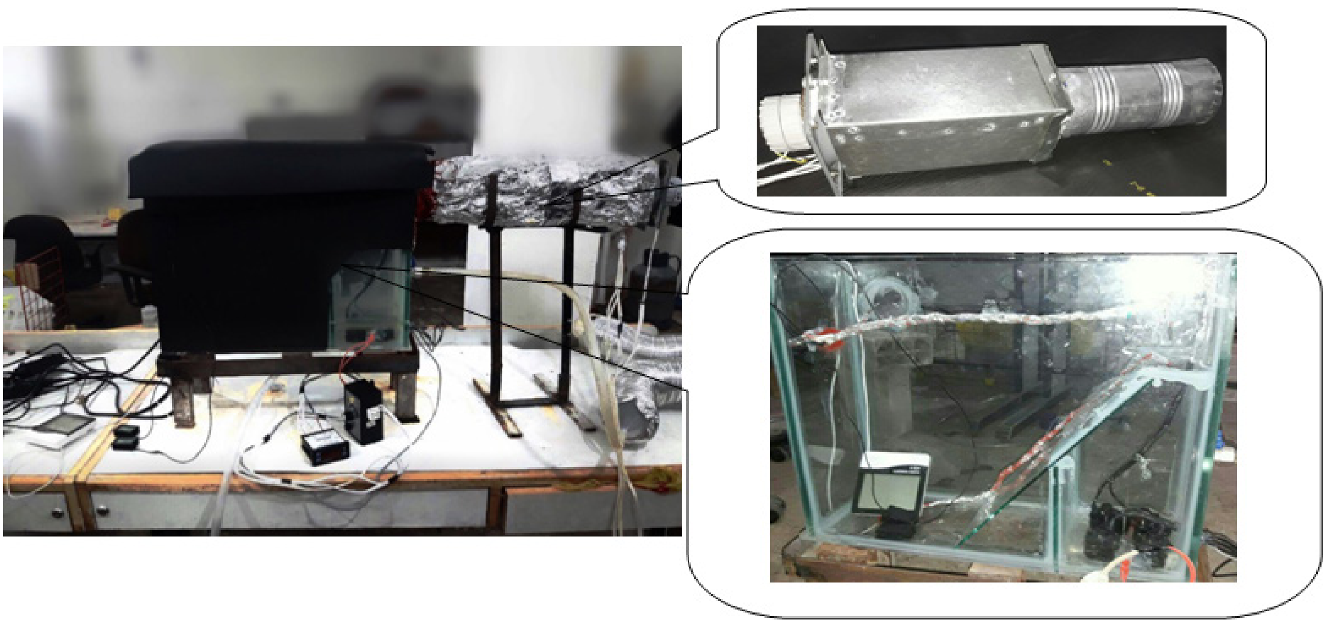

Fig. 2. Photograph of fabricated system.

from the condenser was collected in graded Burettes and evaluated quantitatively and qualitatively. The Lurton WA2017SD multifunctional quality gauge was used to measure the Total Dissolved Solids (TDS) of inlet water and produced water from ultrasound desalination process.

2.5. Experimental design

Response surface methodology (RSM) includes a group of mathematical and statistical technologies which investigate the relationships between several independent variables having one or more responses and then explains how these relationships can be used to predict the response of other operating parameter values. RSM also provides the ability to achieve optimum conditions in complex systems [25–27].

In this research, Design-Expert® Software (version 7) and a Box-Behnken design with three levels and four factors were used to evaluate the interaction between independent variables; the salinity of inlet water into the system, the salty water temperature which enters the system, the hot air temperature, the power of ultrasound piezoelectric crystals in the ultrasonic desalination system and their effects on responses, along with the amount and salinity in the produced water. The effects of supervening errors in the observed responses were minimized by randomizing the experimental runs. Moreover, uniform accuracy was created by setting five repeated center points. Table 1 indicates the actual and coded levels of the independent variables used in the Box-Behnken design, and Table 2 demonstrates the experiments conducted to reveal the amount and the salinity level of produced water in each run.

3. Results and discussion

In this section, the effects of operating parameters on the amount and salinity of produced water are reviewed as responses were being analyzed.

3.1. RSM model and statistical analysis

Design-Expert® Software suggested a polynomial quadratic model which is based on variance analysis (ANOVA). It is given in Eq. (1) for produced water salinity and in Eq. (2) for amount of produced water in terms of coded factors.

Table 1
The experimental matrix with encoded and actual levels of independent variables.

Independent variables	Symbols	Levels of each factor		
		Coded values		
		–1	0	+1
Salinity of inlet water, ppm	X_1	5000	10000	15000
Salty water temperature,°C	X_2	15	30	45
Hot air temperature,°C	X_3	40	60	80
Power of ultrasound piezoelectric crystals, W	X_4	48	72	96

$$\begin{aligned}Y_1 &= +955.40+226.3\times X_1+45.50\times X_2-60.25\times X_3\\&+22.25\times X_4-76.75\times X_1X_2-16.25\times X_1X_3-14.50\\&\times X_1X_4-25.75\times X_2X_3-8\times X_2X_4+63.75\times X_3X_4\\&-91.78\times X_1^2+32.22\times X_2^2+10.34\times X_3^2+23.09\times X_4^2\end{aligned} \tag{1}$$

$$\begin{aligned}Y_2 &= +220+5.50\times X_1+15\times X_2+15.33\times X_3+16.17\\&\times X_4+13.25\times X_1X_2-1.25\times X_1X_3-1\times X_1X_4-2.50\\&\times X_2X_3+8.25\times X_2X_4+5.75\times X_3X_4-20.50\times X_1^2\\&+0.75\times X_2^2-13\times X_3^2-21.75\times X_4^2\end{aligned} \tag{2}$$

where the salinity level of inlet water, saline water temperature, hot air temperature, power of ultrasound piezoelectric crystals, salinity level of produced water and the amount of produced water were defined as X_1, X_2, X_3, X_4, Y_1 and Y_2, respectively.

The probable value (p-value) of the model for produced water salinity level and its amount are 0.0001 and 0.0098, respectively which are considered to be statistically significant when 0.05 is the assumed level. In addition, the lack of this in the model relative to pure error in both cases was not significant.

In Table 3, RSM model statistic of the ANOVA reveals the analysis of the salinity level in produced water. In this case, X_1, X_2, X_3, X_1X_2 and X_1^2 are significant model terms. The model reveals that the effect of ultrasound piezoelectric crystal's power is insignificant. Fig. 3 reveals the surface plot which indicates the interaction between operational parameters on the level of salinity in produced water.

Similarly, in Table 4, RSM model statistics of the ANOVA analysis for the amount of produced water is visible. In this case X_2, X_3, X_4 and X_4^2 are significant in model terms. It can also be considered that the level of inlet water salinity is not significant. Fig. 4 depicts the interactive effects of operational parameters on the amount of produced water using a surface plot.

3.2.1. Effects of inlet water salinity levels (X_1) on responses

According to Fig. 3a, by enhancing the level of inlet water salinity, the salinity level in produced water increased up to 1150 ppm. Therefore, it can be concluded that by increasing the salinity level in the inlet water, the salinity level of atomized produced water particles which are created with ultrasound waves will also increase [7]. Enhancing the water salinity level will increase water viscosity, which causes produced water droplets to be smoother by means of ultrasonic waves [11], that ultimately causes a desalination process facing problems and, as a result, cannot be performed entirely. The statistical analysis of the model also confirms this result by providing a p-value of 0.0001 which is less than 0.05. This proves how effective this factor can be on the level of salinity in produced water. Also, according to the ANOVA analysis, it was determined that X_1^2 has a p-value less than 0.05. Fig. 3b indicates that by increasing the salinity level of inlet water higher than the levels considered in this study, its level in produced water by the ultrasonic desalination sys-

Table 2
The Box-Behnken experimental design proposed by RSM

Run	X_1 Salinity of inlet water (ppm)	X_2 Salty water temperature (°C)	X_3 Hot air temperature (°C)	X_4 Power of ultrasound (W)	Y_1 Salinity of produced water (ppm)	Y_2 Amount of produced water (ml/h)
1	5000	30	60	48	715	160
2	10000	30	60	72	990	220
3	10000	45	80	72	965	221
4	10000	30	60	72	994	220
5	5000	30	80	72	620	200
6	10000	15	80	72	950	210
7	5000	30	40	72	650	180
8	10000	30	60	72	900	220
9	5000	45	60	72	780	194
10	10000	45	40	72	1168	185
11	15000	30	60	96	1100	168
12	15000	30	80	72	1010	200
13	10000	30	40	96	1050	195
14	10000	30	60	72	998	220
15	5000	30	60	96	690	169
16	15000	30	40	72	1105	185
17	10000	30	80	96	1030	240
18	10000	15	40	72	1050	164
19	5000	15	60	72	500	193
20	15000	30	60	48	1183	163
21	10000	30	40	48	1060	158
22	10000	30	80	48	785	180
23	10000	15	60	48	900	168
24	15000	45	60	72	1123	250
25	10000	45	60	48	996	198
26	10000	45	60	96	1050	256
27	10000	15	60	96	986	193
28	15000	15	60	72	1150	196
29	10000	30	60	72	895	220

tem will decrease and the system's performance stability can be attained in most of the salinity ranges.

Fig. 4a indicates that X_1 has no significant effect on the second response which is the amount of produced water by the ultrasound desalination system. Providing a p-value of 0.2930 by statistical analysis which is more than 0.05 confirms the insignificant effects of this factor on the desired response. Increasing water salinity levels will raise the surface tension, viscosity and water density which causes water to restrain atomization and evaporation. However, by using ultrasonic waves there is no change in the amount of atomization and evaporation processes when the salinity level in water increases to the extent of seawater salinity levels and water concentration will also increase which will not influence these processes. Xiao [8] has also reported similar results. While in a microwave preheating desalination systems heating rate and therefor produced water decreased with increasing salinity [28].

3.2.2. Effect of inlet saline water temperature (X_2) on responses

Fig. 3e shows that by increasing the temperature of inlet saline water, the salinity level in produced water rises. Also the ANOVA analysis indicates that the p-value is 0.0232 < 0.05, which means it is significant. Raising the water temperature leads to a decrease in the density and surface water tension, which also produces very fine water droplets

Table 3
Quadratic model statistics and ANOVA of RSM model for produced water salinity

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	86.19	0.7944	0.7602	0.6846	273600	
2FI	86.18	0.8459	0.7603	0.5190	417200	
Quadratic	61.83	0.9383	0.8766	0.6989	261200	Suggested
Cubic	68.056	0.9680	0.8505	–1.7705	2403000	Aliased
Source	**Sum of squares**	**df**	**Mean-square**	**F-value**	**p-Value**	
Model	813800	14	58132.4	15.21	0.0001	Significant
X_1-salinity of inlet water	614700	1	614700	160.80	0.0001	
X_2-Salty water temperature	24843	1	24843	6.5	0.0232	
X_3-hot air temperature	43560.75	1	43560.75	11.39	0.0045	
X_4-power of ultrasound piezoelectric crystals	5940.75	1	5940.75	1.55	0.2330	
$X_1 X_2$	23562.25	1	23562.25	6.16	0.0263	
$X_1 X_3$	1056.25	1	1056.25	0.28	0.6074	
$X_1 X_4$	841	1	841	0.22	0.6463	
$X_2 X_3$	2652.25	1	2652.25	0.69	0.4189	
$X_2 X_4$	256	1	256	0.067	0.7996	
$X_3 X_4$	16256.25	1	16256.25	4.25	0.0583	
X_1^2	54643.33	1	54643.33	14.29	0.0020	
X_2^2	6732.41	1	6732.41	1.76	0.2057	
X_3^2	693.73	1	693.73	0.18	0.6766	
X_4^2	3458.76	1	3458.76	0.9	0.3576	
Residual	53520.45	14	3822.89			
Lack of fit	42301.25	10	4230.12	1.51	0.3683	Not significant
Pure error	11219.2	4	2804.80			
Std. Dev.	61.83					
C.V. %	6.55					

(about 15 μm) during the atomization process compared to water atomization at lower temperature levels using the ultrasound system [11], as if the process of separation in this case is more difficult and increases salinity levels in the produced water. In addition, according to the statistical analysis of the response to produced water salinity levels, the square sum of this factor is lower than other significant factors and therefore has less effect on increasing salinity levels in produced water.

It can be seen in Fig. 4d that an increase in temperature of inlet saline water also has a significant effect on the amount of the produced water by the ultrasonic desalination system. By increasing this variable, continuity and surface tension are being decreased and the velocity of the water surface molecules rises, which overcomes the force of the water surface tension and as a result, the amount of water atomization increases by ultrasound waves and also the evaporation rate and the amount of produced water increases [7]. However, the positive effect of this factor on increasing the amount of produced water will be useful as long as the excessive rise in water temperature does not damage the ultrasound piezoelectric crystals [11].

3.2.3. The effects of inlet hot air temperature (X_3) on responses

The effects of inlet hot air temperature on the salinity level in produced water are depicted in Fig. 3d. It can be seen that, by raising hot air temperature the salinity level in produced water was reduced which provides a p-value of 0.0045 in statistical analysis which is less than 0.05 which confirms a significant effect of this factor on the desired response. In Eq. (1) which demonstrates water salinity levels produced by a design expert, the coefficient of regression is negative. This suggests that there is an inverse relationship between inlet hot air temperature and salinity levels in produced water. Atomized saline water droplets which were created via ultrasound waves evaporated in a hot air mass and then directed as vapor into the condenser, a desalination phenomenon occurred and the main goal of this research was achieved. In this case, the salt existent in

Table 4
Quadratic model statistics and ANOVA of RSM model for produced water amount

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	21.44	0.4498	0.3581	0.2005	16034.12	
2FI	23.44	0.5067	0.2327	–0.3526	27125.86	
Quadratic	17.44	0.7877	0.5754	–0.2227	24522.24	Suggested
Cubic	18.23	0.9006	0.5362	–13.3101	287000	Aliased
Source	Sum of squares	df	Mean–square	F–value	p–Value	
Model	15797.84	14	1128.42	3.71	0.0098	Significant
X_1- salinity of inlet water	363	1	363	1.19	0.2930	
X_2-Salty water temperature	2700	1	2700	8.88	0.0099	
X_3- hot air temperature	2821.33	1	2821.33	9.28	0.0087	
X_4-power of ultrasound piezoelectric crystals	3136.33	1	3136.33	10.31	0.0063	
$X_1 X_2$	702.25	1	702.25	2.31	0.1509	
$X_1 X_3$	6.25	1	6.25	0.021	0.8880	
$X_1 X_4$	4	1	4	0.013	0.9103	
$X_2 X_3$	25	1	25	0.082	0.7785	
$X_2 X_4$	272.25	1	272.25	0.9	0.3601	
$X_3 X_4$	132.25	1	132.25	0.43	0.5203	
X_1^2	2725.95	1	2725.95	8.96	0.0097	
X_2^2	3.65	1	3.65	0.012	0.9143	
X_3^2	1096.22	1	1096.22	3.6	0.0784	
X_4^2	3068.51	1	3068.51	10.09	0.0067	
Residual	4257.33	14	304.10			
Lack of fit	4257.33	10	425.73			
Pure error	0	4	0			
Std. Dev.	17.44					
C.V. %	8.83					

water was not affected by heat intensity, and due to its high density compared with vapor, it remained in the system and was accumulated on the floor.

The effect of inlet hot air temperature on the second response, which is the amount of produced water by the ultrasound desalination system, can be clearly seen in Fig 4e. By increasing the amount of inlet hot air, the evaporation rate of atomized droplets also were increased. This eventually leads to much more water being produced by the desalination system. The p-value for this factor through the variance analysis is $0.0087 < 0.05$ which indicates that an increase in this factor has a significant effect on the amount of produced water by the ultrasonic desalination system.

3.2.4. The effects of ultrasound piezoelectric crystals (X_4) on responses

According to the variance analysis and the effects of operating parameters on the dependent variables of produced water salinity levels, the p-value for the X_4 factor was $0.2330 > 0.05$, indicating that it is not significant enough which is evident in Fig. 3c.

Fig. 4c depicts the effects of factor X_4 on the amount of produced water by the system. The amount of produced water had increased due to intensification of the ultrasonic power. Ultrasonic waves raised the velocity and acceleration of water surface molecules. The molecules overcame the tension force on the surface, thereby the amount of water atomization and evaporation were increased [7], which lead to an increase in the produced water by the ultrasonic desalination system. Variance analysis for the amount of produced water revealed that the p-value for X_4^2 factor was $0.0067 < 0.05$. This factor significantly demonstrates that intensified ultrasonic power increases the water atomization and evaporation rate to some extent. Even when ultrasonic power intensified even more, water droplets became much smaller, and as they did not have enough time to get to the water surface they remained in it, which reduced the atomized water amount [11], this can be seen in Fig. 4f.

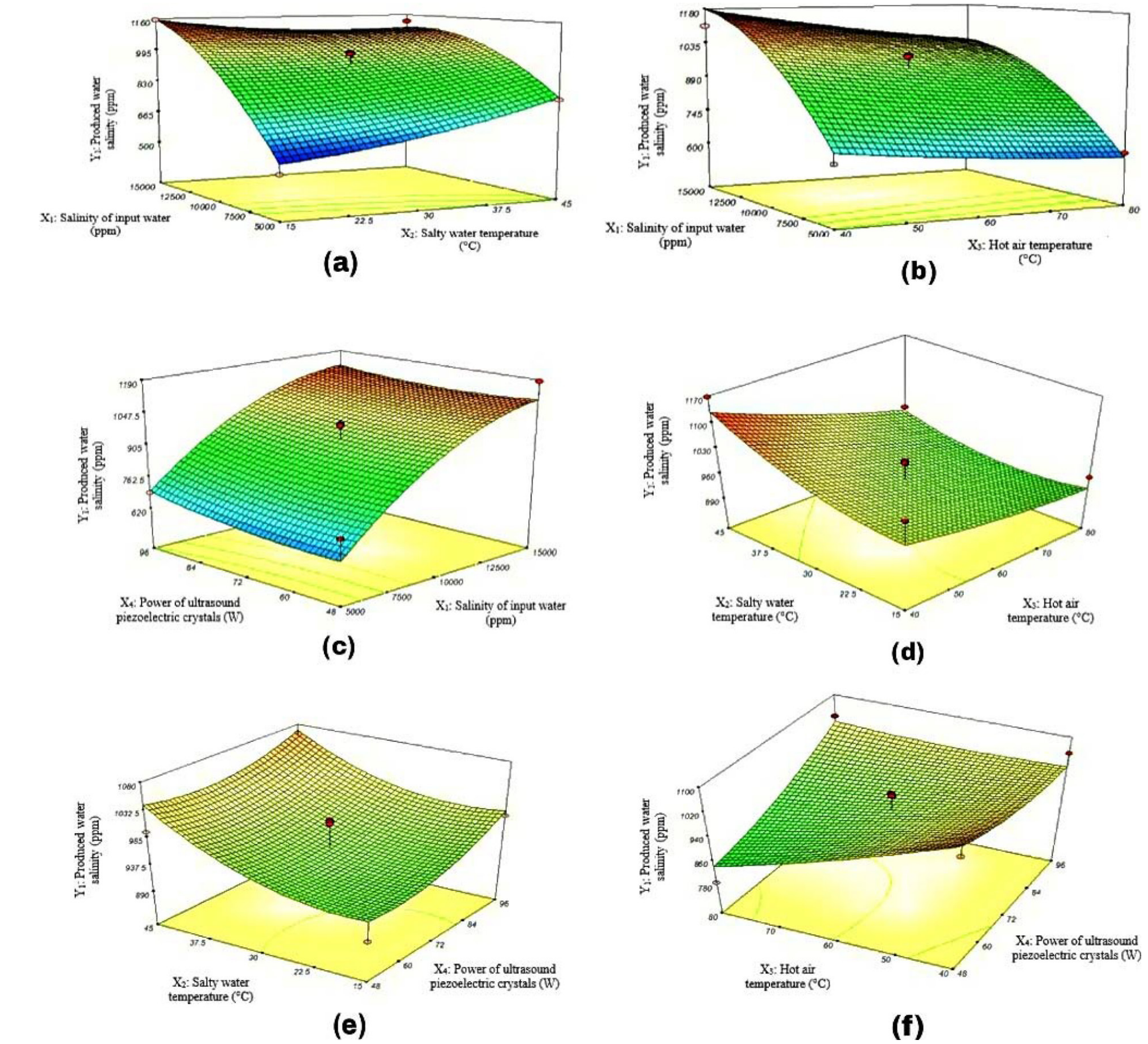

Fig. 3. Effect of interaction of operational parameters on produced water salinity.

3.3. Process optimization

The RSM model provided a regression polynomial equation which defined the values of an optimal level for operating parameters that would lead to a minimum amount of produced water salinity and a maximum amount of produced water. The optimal values of the operating parameters in the ultrasonic desalination system are indicated in Fig. 5. The optimum quantity for experimental variables were inlet water salinity of 5000 ppm, inlet saline water temperature of 15°C, inlet hot air temperature of 75°C and the ultrasound power of piezoelectric crystals of 73 W. By applying these optimal values, desirably at 0.702, the level of produced water salinity was 545 ppm and the rate of the water production was estimated by the ultrasonic desalination system at 200.737 ml/h.

In order to stabilize the predicted optimal values, they were applied in an experimental run, of which 550 ppm salinity for the produced water rate of 196 ml/h was achieved. This indicates that there is a reasonable relation between the RSM model and the experimental data.

In Table 5, the quality of produced water by the main desalination systems [29–33] as well as the Ultrasonic Desalination system were illustrated (the current study with optimal operating parameters).

It is observed that the salinity level of produced water is almost equal to that of membrane systems and more than in distillation systems. The evaporation reservoir and the condenser inlet in the system should be rinsed, but because the system was scaled in the laboratory glass stuff, it was difficult to rinse it. However, if it were built on a larger scale, an automatic mechanism for rinsing the interior parts could be an option, so that the quality of drinking water would improve. Water having TDS levels of less than 600 ppm is generally potable and non-potable when TDS levels are higher than 1000 ppm according to the WHO guidelines

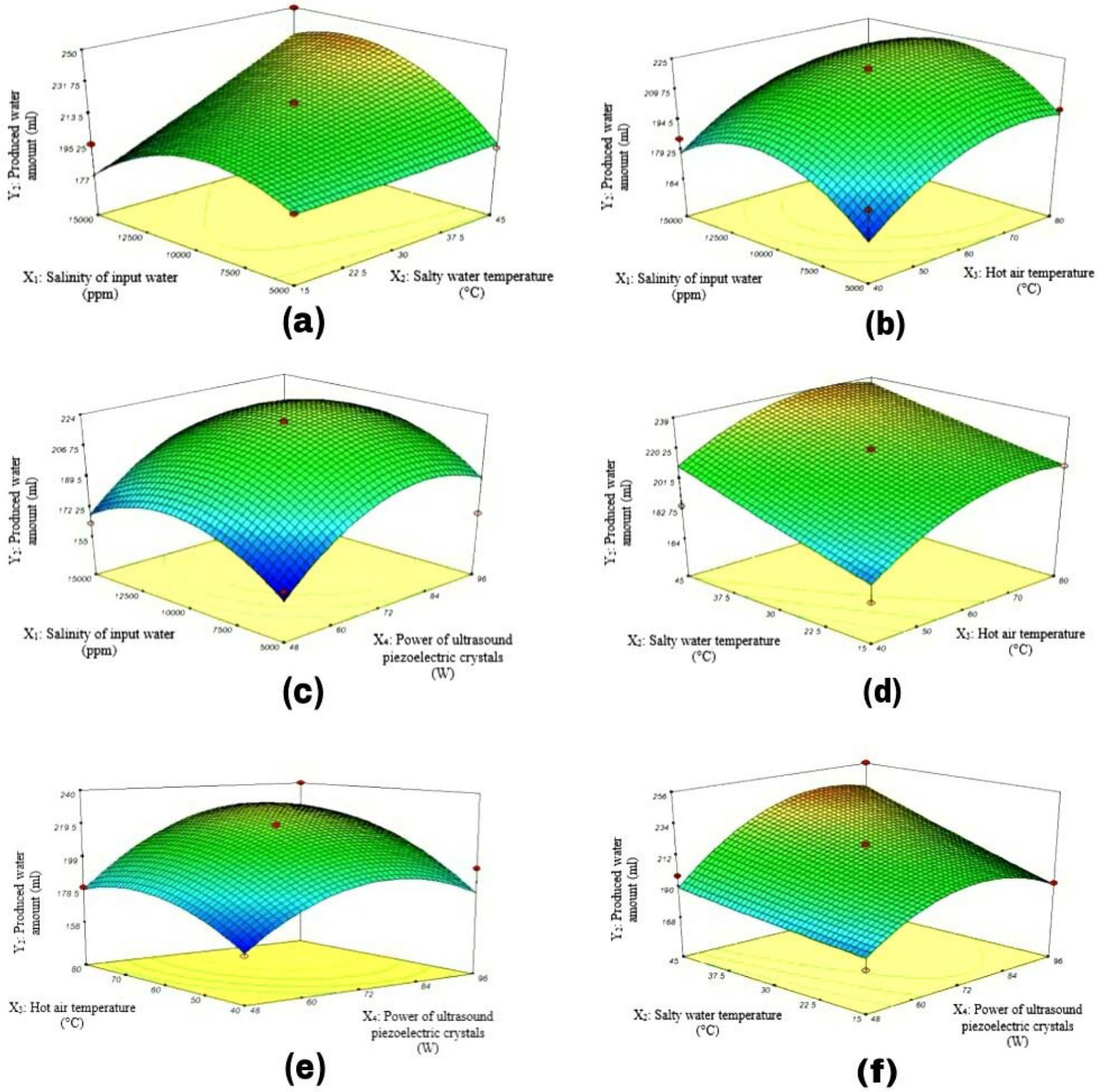

Fig. 4. Effect of the interaction of operational parameters on produced water amount.

for drinking water quality [33], as in this research, the rates of optimal variables comply completely with the set standards. The amount of soluble solids in produced water is also approximately the same level as it is in drinking water standards.

4. Electrical power consumption

The total energy consumption in the ultrasonic desalting system consists of heating elements in a hot air channel, a preheating and temperature controlling system of the inlet salty water, piezoelectric ultrasonic crystals and two air blowers. A list of the electrical components in a system by assuming one hour operating time can be seen in Table 6. All components in a system when continuously operating for an hour (3600 s) and the amount of consumed energy of each part was reached based on experimental measurements.

The electrical energy consumption of optimal functional parameters using the ultrasonic desalting system was calculated as following:

$$\begin{aligned} &E_{e,total} = P_{e,total} \cdot t = P_{e,\,ThE} \cdot t1 + P_{e,ps} \cdot t2 + P_{e,UP} \cdot t3 \\ &+ P_{e,Fan1} \cdot t4 + P_{e,Fan2} \cdot t5 = (330 + 13.5 + 75 + 16 + 16) \\ &W \times 3600 \quad s = 1621800 \quad W \cdot s = 0.45 \text{ kWh} \end{aligned} \tag{3}$$

Because all components work together, the system will function for 3600 s as a measure of time. According to the experimental measurements, it was determined that the maximum electrical energy consumption of the ultrasonic desalination system was related to the thermal elements. The process incorporating adiabatic conditions in the evap-

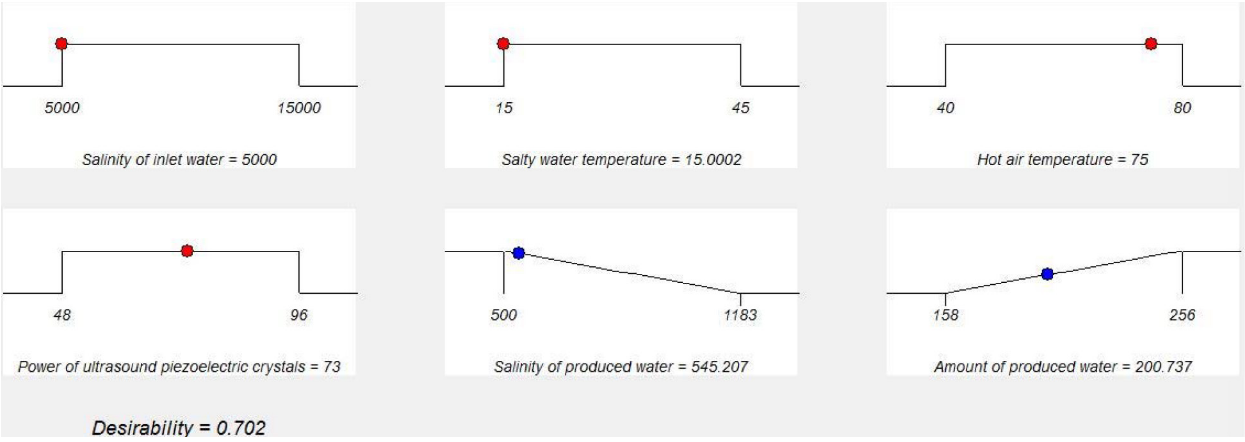

Fig. 5. The optimal levels of the operating parameters.

Table 5
Product water quality of main desalination systems [29–33]

Process	UDS (present work)	MSF	MED	MVC	TVC	SWRO	BWRO	ED
Classification	Ultrasonic	Distillation	Distillation	Distillation	Distillation	Membrane	Membrane	Membrane
Product water quality (ppm)	500–550	2–50	2–50	2–50	2–50	400–50	300–500	150–500

Table 6
Electrical power consuming components of the UDS (for 1 h in a day)

Component description	Operating period (s)
Thermal element (220 V, 1.5 A)	3600
Preheating and temperature control system (220 V, 0.06 A)	3600
Ultrasound piezoelectric crystals (24 V, 2 A)	3600
Fan (220 V, 0.073 A)	3600

oration reservoir which reduces energy consumption, can be a solution. Ultrasound piezoelectric crystals expended approximately 16% of the total energy consumption of the system, which was low. The amount of produced water by applying the optimum functional parameters was 200.723 ml/h. The amount of energy consumed by the entire ultrasonic desalination system for producing fresh water was 2.25 kWh/L. It should be noted that due to the ease of renewable energy sources for supplying energy to the ultrasound desalination systems, the total energy consumption will reduce.

5. Economic analysis

Economic analysis of a system in order to evaluate the cost effectiveness and also definition of the unit cost of the produced fresh water is required during any research. In recent years, desalination costs have reduced due to low equipment pricing, lower energy consumption and improved system designs. Costs for purchasing equipment, auxiliary equipment, land, construction, management and installation are capital costs which has been reduced in recent years. Annual costs include energy, labor, chemicals and spare parts [35]. Full details of the annual costs relating to each system are not yet available because they are difficult to calculate. The total cost of a system is assumed to include 40% of the capital costs and 60% of the annual costs [36].

The analysis presented in this study is based on the total cost of ownership (TCO), which includes fixed capital costs, production costs, and operating costs [35].

5.1. Annual freshwater production

It is assumed that the ultrasonic desalination unit works all day and night without being interrupted (ignoring possible damages to a system) throughout the whole year. Therefore, the average annual production cost for this system over 365 d was calculated by means of the following formula [34]:

$$Py = \frac{1}{365}\sum_{i=0}^{365}\left(P_{d\cdot i}\right) \tag{4}$$

Based on optimum operating parameters, 200.723 ml was produced per hour. According to this calculation, the system produced 4.81 L/d, and the annual performance of the system over 365 d, was 1758.34 L/y. According to the tests, a low amount of water was produced due to the use of non-standardized ultrasound piezoelectric crystals. According to catalogues, the atomization rate of this module was 550 ml/h but during experiments, its rate was 300 ml/h which caused a reduction in water atomization and consequently, lowered the amount of produced water by the system.

5.2. Capital costs (CC)

The total capital cost of an ultrasonic desalination system, including purchase, construction, installation and triggering costs, is presented in Table 7. All prices are based on the Iranian market in Rial and have been converted into US dollars. The total amount of capital costs in this research was equal to:

CC = 96.8 US$.

5.3. Operating costs

Amortization charges, operating and maintenance (O&M) and energy costs are a subset of the operating costs [37].

5.3.1. Amortization or fixed charges

There will be a gain charge for the funds required for the project which have been borrowed and that accounts for an annual interest rate for capital costs. This is obtained from amortization factor α shown in Eq. (5) [37].

Table 7
The total capital investment cost of the ultrasonic desalination system

Item description	Quantity	Unit cost (US$)	Total cost (US$)
Condenser	1	2	2
Evaporation tank (material + construction fee + insulation)	1	15	15
Fan	2	2.5	5
Faucet	3	0.83	2.5
Glass glue	3	1.5	4.5
Hot air channel (material + construction fee + insulation)	1	5	5
Power supply adapter	4	3.3	13.2
Temperature sensor	3	1.6	4.8
Thermal element	3	1.6	4.8
Thermal glue	2	1.5	3
Thermostat	1	16	16
Ultrasonic piezoelectric crystal	4	5.25	21
Total cost			96.8

$$\alpha = \frac{i\left(1+i\right)^N}{\left(1+i\right)^N - 1} \tag{5}$$

in which i is the annual interest rate (%) and N is the life time of the facility. In this research, i was 12% and N was assumed to be 10 years, and from this assumption, the value of α was calculated as 0.17. Now the annual fixed rate charges (A_{fixed}) was obtained from Eq. (6).

$$A_{fixed} = (a)(CC) \tag{6}$$

For the current ultrasonic desalination system A_{fixed} was 16.45 US$/year.

5.3.2. Operating and maintenance (O&M) costs

The O&M costs include not only the operation and maintenance costs, but also the spare parts, indirect material costs and others. For ultrasound desalination system this cost could be calculated for each item during the entire commercial operation in a year, of which 20% of the plant annual payment would be O&M costs that are calculated by Eq. (7) [1].

$$\text{O\&M} = (0.2)\,(A_{fixed}) = 0.2 \times 16.45 = 3.29\ \text{US\$/year} \tag{7}$$

5.3.3. Energy cost

The most important operating cost is energy consumption. The electrical energy consumption rate for the ultrasonic desalination system was calculated as 2.25 kWh/L by energy analysis considering Iran's electricity tariff of 0.01 US$/kWh. Therefore, the annual consumption rate over 365 working days was 39.42 US$/y.

5.4. Calculation method

At the end of the amortization course, according to TCO (total cost of ownership) the salvage cost of the units will be zero. The total cost of ownership is calculated according to the following logic [35]:

$$\text{TCO} = C_{OP} + C_{main} + C_{fix} \tag{8}$$

where C_{OP}, C_{main} and C_{fix} are cost of operation, cost of maintenance and cost for fixed charges, respectively. This factor was equal to 59.16 US$/y for the ultrasonic desalination system.

5.4.1. Product cost

By assuming 365 operational days, the produced water cost is estimated from Eq. (9) [35].

$$P_{prod} = \frac{TCO}{f \times P_{d \cdot i} \times 365} \tag{9}$$

where f is the plant availability of 90% [1]. The cost of the produced fresh water was calculated as 0.0374 US$/L = 37.4 US$/ m^3.

The total cost of the desalination system includes investment cost, operating cost (depreciation and repairs) and energy cost. It has been observed that the operating cost of an ultrasonic desalination system is lower than that of other conventional systems. Structural simplicity of the system, minimum costs for repair alongside fixed costs, where there is no need for any chemical additives in the ultrasonic desalination system thus as no payment for that is required, there are two reasons for this fact. In terms of energy consumption, the system uses lower energy than the conventional RO and MSF desalination systems, but systems based on renewable energy sources have a lower energy consumption than that of the current system. Not needing to raise the temperature of the water during the operating period of this system can be one of the reasons for a lower energy consumption in ultrasonic desalination. To increase the amount of evaporation and distillation of water (raising heat and increasing mass transfer) by ultrasound, it is easy to provide energy from the ultrasonic desalination system from renewable energy sources, which greatly reduces energy consumption [7–9]. The cost of capitalizing the ultrasonic system has been calculated more than other types (except for expensive solar systems). The reason for this is also very clear; since the other two parts are less costly, a large percentage of the total cost of the device is related to the cost of investment. However, PZT Ceramic types produce more powerful cavitation, but they are expensive, heavy and brittle. For low power ultrasounds, polymer-based transducers can be used to reduce energy consumption, but they have a low transmission efficiency. Although being flexible, they have low-cost and better acoustic impedance with water [2,38,39].

It should be noted that the reason for the high cost of water is that the daily production of the system is low. The main reason for this is the non-standardization of piezoelectric ultrasonic crystals used in this study, which did not manage to atomize the water based on their constant working conditions. If piezoelectric crystals are used with a high power of atomization, the amount of fresh water production by ultrasound systems will be increased and subsequently, the cost of produced water will reduce significantly. Therefore, the amount of energy consumption will reduce in proportion to the system's capacity.

Finally, if the current desalination system which is on a laboratory scale wants to be scaled up, some points should be considered; In a brief explanation, due to amount and speed increase of evaporation rate because of ultrasound activity in water, we can easily use solar energy for its energy consumption which results in a very low consumption of electricity. An automatic washing system is needed to clean the entire system, which improves the produced water quality.

6. Conclusion

In this study, the ultrasonic desalination system was developed and evaluated based on operating parameters. The system's operation was tested for one hour and two responses namely the salinity level and the amount of produced water were measured; and the following conclusions were reached:

- Using ultrasound waves in saline water desalination results in low operating and energy costs, no use of chemicals, positive effects on pollutants' removal, ease of providing the system's energy by renewable energy, uninterrupted working by adjusting the water depth in the inlet salty water reservoir and bringing the amount of soluble solids in produced water to the level of the drinking water standard.
- The results' analysis reveals that the quality of produced water complies with the WHO guidelines for the quality of drinking water.
- The RSM's proposed model for salinity and the amount of produced water was a quadratic polynomial model with P-value of 0.0001 and 0.0098, respectively.
- Inlet water salinity as an independent variable had the greatest impact on increasing the salinity level in produced water. According to data analysis of evaluated system, the ultrasonic desalination can certainly be used for salinity levels above the ones in the current study.
- Atomized droplets produced by ultrasound waves evaporated in the hot air stream. Therefore, as the temperature rises, the level of salinity in produced water decreases.
- The increase in power of ultrasonic crystals due to mass and heat transfer, leads to an increase in the atomization rate. However, due to an excessive increase, tiny water droplets would be generated and return to the surface again so that the atomization rate and produced water amount would be reduced.
- The amount of produced water has a relatively linear and direct relation to the inlet water temperature. The temperature should not exceed the range of ultrasonic piezoelectric crystals because the performance of crystals reduces.

Acknowledgement

The authors are grateful to the Tarbiat Modares University (http://www.modares.ac.ir) for financial supports given under IG/39705 grant for renewable Energies of Modares research group.

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