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Investigation of the factors influencing the efficiency of a solar still combined with a solar collector

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ABSTRACT

A solar still was designed for the evaporation of desalination brine. The influence of several factors, such as the basin heating, the material of the cover (glass or polycarbonate), the existence of a mirror, the activation of an air extractor, and the existence of a black painted floor in the solar still, was evaluated in terms of their contribution to brine evaporation. The experiments were conducted with a factorial design approach. The combination of the factors that produced the best results was used in a subsequent daily monitoring study for brine evaporation. The monitoring parameters were the hourly average incident radiation, the changes in the temperature, the brine mass, and the brine volume. The accumulated amounts of the solar energy were calculated, and the correlation relationship was assessed.

Keywords: Basin heating; Factorial design; Solar radiation; Air extractor; Mirror

1. Introduction

The shortage of freshwater resources and the need for additional water supplies are already critical in many arid regions of the world and will be increasingly important in the future. Seawater desalination is usually found as a reliable solution in arid regions to meet the continuously growing demands for water due to population growth and economic and social developments and to reduce the dependence on groundwater resources [1,2].

Desalination plants generate pure water and brine (also known as retentate, concentrate, or reject), which is reported to be approximately 55% of the collected seawater [3]. The unwanted by-product, brine, may have a concentrated salinity as high as two times the typical seawater salinity [4]. The salinity of brine produced by desalination plants is reported to be approximately 60 parts per thousand (ppt) [2]. The temperature of the brine depends on the desalination technology. For example, the temperature of brine produced by evaporation technologies such as multi-stage flash (MSF) and multi-effect distillation (MED) could be very high [2,5]. Al-Mutaz and Al-Namlah [5] reported that in Saudi Arabian desalination plants, operational temperature during MSF process ranges between 90 and 115˚C, although much lower temperatures were reported for reverse osmose brine [6]. One of the operational problems of the high-temperature desalination plants is the precipitation of carbonates. Glade et al. [7] reported that in multiple-effect distillers with horizontal tube falling film evaporators,

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scale is formed on the outside of the tubes subjected to artificial seawater at a temperature of 75˚C; tubes were covered mainly with $CaCO_3$ and $Mg(OH)_2$. The crystallization of salts is another operational problem encountered with the membrane distillation plants [8,9]. Therefore, chemical pretreatment and cleaning against scaling is a necessity in most of the desalination plants. The chemical residues and by-products are typically washed into the sea along with concentrate [10].

When a desalination plant is situated close to the sea, the brine generated is generally discharged into the sea [2]. Einav et al. [11] reported that an increase in the salinity may have negative effects on marine life by disturbing the osmotic balance of marine species and their environment, which may lead to the death of species. Species such as neptune grass (*Cymodocea nodosa*) and a green seaweed known as *Caulerpa prolifera* are reported to be sensitive to increased salinity [12], and embryos of giant Australian cuttlefish (*Sepia apama*) cannot survive increased levels of salinity [13].

Brine management strategies include seawater discharge, sewer discharge, deep well injection, evaporation ponds, land application, and thermal processes for zero liquid discharge [2,14]. Each management option has challenges in terms of being economically and ecologically feasible [14]. Therefore, research on the development of energy-efficient, cost-effective, and environmentally sound management options is necessary if desalination plants will be a solution to meet freshwater demands in several regions in the world.

Due to the environmental problems that brine disposal can cause as well as the high disposal cost, many technologies have been developed for recovery. Examples are the use of evaporation ponds to produce salt or chemicals for industry [15] or membrane distillation coupled with solar ponds or other residual heat sources [16,17]. Nevertheless, more investigation is needed to reduce the volume and quantity of the brine and to allow for recovery and reuse.

Solar energy is one of the most promising applications for seawater desalination [15]. Qiblawey and Banat [18] provided an overview of solar thermal desalination technologies and concluded that solar energy aided desalination offers a promising solution for covering the fundamental needs of power and water in remote regions. The use of solar energy for brine management has been primarily based on the use of evaporation ponds historically. Solar evaporation consists of leaving brine in shallow evaporation ponds and then taking the remaining salt for disposal [19]. Although evaporation ponds are relatively easy to construct and are frequently the least costly means of disposal, the need for large tracts of land and impervious liners causes them to have a limited use [15,20,21]. In addition to this extensive land use, evaporation ponds have been criticized because they do not recover the evaporated water [20], and the productivity of the process is reported to be quite low (approximately $4\ L/m^2\ d$) [22]. Wind-aided intensified evaporation technology (WAIV), which uses wind energy to evaporate wetted surfaces previously sprayed with brine, is estimated to increase the evaporation rate 10-fold over natural evaporation and enables the evaporation ponds to be 10 times smaller [19].

A limited number of studies report the different applications of solar energy for brine management, although a considerable number of investigations related to the use of solar energy in desalination can be found in the literature. Philip et al. [23] evaluated the performance of a solar- and wind-aided cross-flow evaporator prototype as an alternative to conventional evaporators for brine in a reverse osmosis system. They concluded that solar pre-heating significantly increased the evaporation rate and that the evaporation rate decreased as the salt concentration in the water increased. Refalo et al. [24] used a solar chimney to create a cross-convective flow that varies with solar irradiation to enhance the productivity of a solar distiller. Taghvaei et al. [25] studied the long-term simultaneous effects of collector area and brine depth on the performance of active solar stills. They concluded that for active solar stills with low brine depth and high solar collecting areas, brine may boil, and this boiling might lower the thermal efficiency of the system and cause damage due to high temperatures in the basin. Kabeel [26] investigated the performance of a solar still with a concave wick evaporation surface and reported an increase in the evaporation area for brine. More research is necessary to increase the productivity of solar stills and observe their efficiency to reduce the volume and quantity of the brine.

This study is aimed to investigate the factors that influence the performance of a solar still designed for evaporation of brine obtained from a seawater desalination plant. Influence of several factors such as using a mirror, heating the basin, black painted floor, steam extractor, and glass or polycarbonate cover material was investigated. Although the effects of most of these factors were individually well established in the previous literature, the joint effect of these factors is still missing. Therefore, this study aimed to investigate the relative and joint effects of these factors.

2. Materials and methods

A solar still was designed for the evaporation of desalination brine. A set of experiments were performed to determine the factors that influence the evaporation performance of the designed solar still. Factorial design (2^{k-1}), as used by Montgomery [27], was conducted to determine the importance of the factors.

2.1. Source of the brine studied

The brine used in the experiments was obtained from a solar thermal desalination plant and used after it cooled down to ambient temperature. The flowchart of the desalination plant is shown in Fig. 1. The plant consists of a horizontal steel tank of 300 L filled with seawater, which is heated using a heat pipe solar system. The conductivity of the seawater was 51 mS/cm. The seawater that reaches a temperature of 70˚C in the tank is pumped to a vertical PVC tank of 250 L, where the seawater falls as small rain droplets. In the upper zone of the PVC tank, there is an air extractor that takes the steam generated out to a condenser, where freshwater is produced. During this process, the seawater that remains in the system without evaporation forms the brine with increased salinity and conductivity compared to seawater. The brine used in this study had an average conductivity of 78.7 mS/cm (measured using a conductivity meter Hanna 8633). The conductivity of this thermal desalination plant is comparable with that of a reverse osmose brine which was reported by Ge et al. [28] to range from 85 to 95 mS/cm.

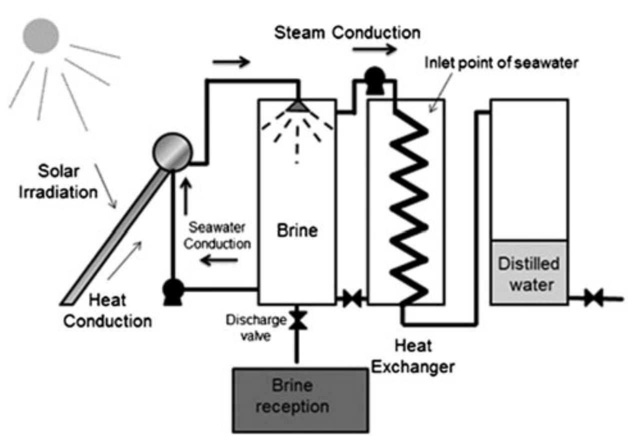

Fig. 1. The flowchart of the desalination plant.

2.2. Solar still system designed

The system consists of a solar still and a solar collector; a general view of the system can be seen in Fig. 2. The cross section of the solar still is shown in Fig. 3. It was constituted on a basin made of concrete of 10-cm thickness. The solar still has a cover that was made of glass or policarbonate, oriented to the north, and tilted 30˚ (the same latitude of Coquimbo, Chile, where the experiments were carried out). The glass had the following characteristics: 4 mm thickness, 85% optical transmittance, and 0.8 W/m˚C transmittance of thermal conductivity. The polycarbonate surface had the following characteristics: 4-mm thickness, 80% optical transmittance, and 0.2 W/m˚C transmittance thermal conductivity. The frontal and lateral walls of the solar still are made of polycarbonate. The back wall is made of wood equipped with a mirror that allows the redirection of the solar irradiation to improve the receipt of the solar irradiation by the brine. Al-Hayek and Badran [29] also used mirror walls to enhance the efficiency of the solar still for seawater distillation.

A hydronic underfloor heating system was applied to half of the concrete basin of the solar still (Fig. 3). A copper pipe of 8 m in length and 1.9 cm in diameter was installed; propylene glycol flowed through the copper pipe. The copper pipe was thermally isolated to avoid heat losses. The basin was heated externally by a solar collector (Fig. 2). The solar collector, a Cromagen cr 120, has a surface area of 2.5 m^2 and a performance of 73.3%. The incorporation of the solar collector and the heated basin was also used by Omara et al. [30] to enhance the productivity of the desalination system. A tray 7 cm in height, 50% filled with brine, was located above the heated concrete basin. The area of the tray was 1,000 cm^2.

The other half of the concrete floor, which was not heated, was painted with black paint to facilitate the preheating of the air entering the system, considering that black paint increases the absorptivity of the sunlight. Similarly, Omara et al. [30] coated the still basin surface with black paint.

The steam produced in the system was removed using an air extractor (20 W of power) located above the mirror on the back wall (Fig. 3). An air filter of 0.4 m in width and 0.1 m in height was installed on the frontal wall of the solar still, which was made of cellulose, to enable a forced input of external air into the system. Varun et al. [31] reported that forced convection can improve the performance of evaporation compared to natural convection, and Akpinar [32] indicated that the drying rate in the solar dryer operating under forced convection could be much higher

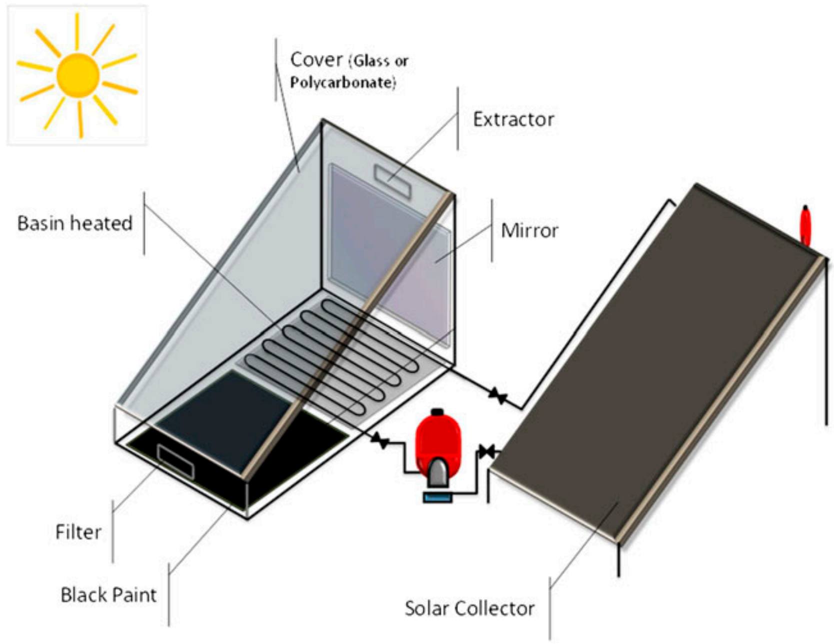

Fig. 2. General view of the solar evaporation system designed for brine.

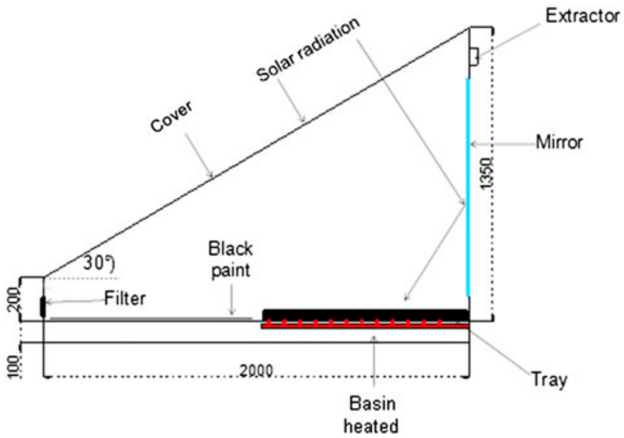

Fig. 3. Cross section of the solar still designed (units expressed in mm).

than the natural open-air sun drying. Additionally, according to Sharma et al. [33], systems using forced convection might be suitable for drying high amounts of moisture.

2.3. Calculation of the solar irradiation

To compare the effect of the factors studied in different solar irradiation conditions, an adaptation of the cumulative energy equation proposed by Malato et al. [34] was used. The equation allows for calculation of the accumulated amount of the global solar energy (Q_{rad}) that was received by the solar still (Eq. (1)):

$$Q_{\text{rad},n} = Q_{\text{rad},n-1} + \frac{\Delta t_n \times \text{rad}_{g,n} \times A_r}{V_t} \quad (1)$$

where $Q_{\text{rad},n}$ and $Q_{\text{rad},n-1}$ is the global solar energy accumulated per liter (kJ/L) at times n and $n-1$, respectively. The parameter $\text{rad}_{\text{g,n}}$ is the average incident radiation on the irradiated area (W/m^2), Δt_n is the experimental time of the sample (see Eq. (2)), A_r is the illuminated area of the collector (m^2), and V_t is the total volume of the brine on the tray (L).

$$\Delta t_n = t_n - t_{n-1} \quad (2)$$

The parameter $\text{rad}_{g,n}$ was measured using a global CPM 10 Kipp & Zonen pyranometer, the Netherlands (285–2,800 nm wavelength, 7 to 14 μV/W/m of sensibility), which was tilted 30˚, the same angle with the local latitude. The pyranometer provides data in terms of incident irradiance (W/m^2), which is the solar radiant energy rate incident on a surface per unit area.

Hourly data for each sample during the 6-h experimental period were used to calculate the accumulated amount of solar energy received by unit volume of brine ($Q_{\text{rad},n}$) by using Eqs. (1) and (2).

2.4. Factorial design

A fractional factorial design 2^{k-1} was applied, where k is the number of factors, to evaluate the influence of the factors over the performance of the solar still used for brine evaporation. In this case, five factors ($k = 5$) were analyzed. Fractional factorial design was used as a tool to facilitate the comparison of the effects by each factor with a reasonable number of experimental tests.

The factors evaluated were (a) basin heated, (b) cover, (c) mirror, (d) extractor, and (e) paint. For all the factors, two levels, high (+1) and low (−1), were tested, where +1 and −1 represented the existence and nonexistence of the factor, respectively. For cover, +1 and −1 represented the cases that the cover made of glass was used or the cover made of polycarbonate was used, respectively. The response of each experiment was the quotient between the evaporation obtained and the solar energy used (%/Wh). The factors were tested in series; experimental runs were conducted in different days, consequently with different weather conditions. Solar irradiation and air temperature were measured and stated when the results were compared. The experimental conditions tested are presented in Table 1. Data were analyzed by the software Minitab17.

As shown in Table 1, 16 experiments with different operational conditions were realized. The output of each test was the amount of the brine evaporated measured by weight. To realize each run, 3 trays, each carrying 500 g of brine, were placed over the heated basin of the solar still. The trays were removed after 6 h to determine the amount of brine evaporated. The difference between the initial and final weight of each tray was used as the evaporated mass of the brine.

The initial volume (V_t) of the brine in each tray for each test run was 0.5 L. The weight of the brine and its temperature was recorded every hour; a reduction in the mass (due to evaporation) and an increase in the temperature of the brine were expected. The temperature was measured with a thermometer Hanna model HI 98501-1, with a precision of 0.1℃.

Control trays with the same amount of brine were exposed to open solar irradiation (outside the solar still) during the experimental process. The temperature and mass of control trays were also measured and recorded every hour.

3. Results and discussion

3.1. The factors affecting brine evaporation

The significance of the factors that affect the performance of the solar still was evaluated. A Pareto chart to highlight the relative importance of the factors is given in Fig. 4. The absolute values for the effects of the main factors and the interaction of the factors are provided in the chart. The chart shows a reference line for the t-value of 1.421, which corresponded to a 95% confidence level. The chart showed that the factors C (Mirror) and A (Basin heated) are the most significant factors affecting the productivity.

The results agree with the findings of Omara et al. [30], who reported an increased productivity of a solar still equipped with mirror. The mirror works as a

Table 1
Factorial experimental design of the conditions tested

Run order	Basin heated	Cover	Mirror	Extractor	Paint
1	−1	−1	−1	1	−1
2	−1	1	−1	−1	−1
3	1	−1	−1	−1	−1
4	1	1	1	−1	1
5	1	1	1	1	1
6	1	−1	1	−1	1
7	1	1	−1	−1	1
8	−1	−1	1	−1	−1
9	−1	1	1	1	−1
10	−1	1	−1	1	1
11	1	−1	1	1	−1
12	−1	1	1	−1	1
13	−1	−1	1	1	1
14	1	−1	−1	1	1
15	1	1	−1	1	−1
16	−1	−1	−1	−1	−1

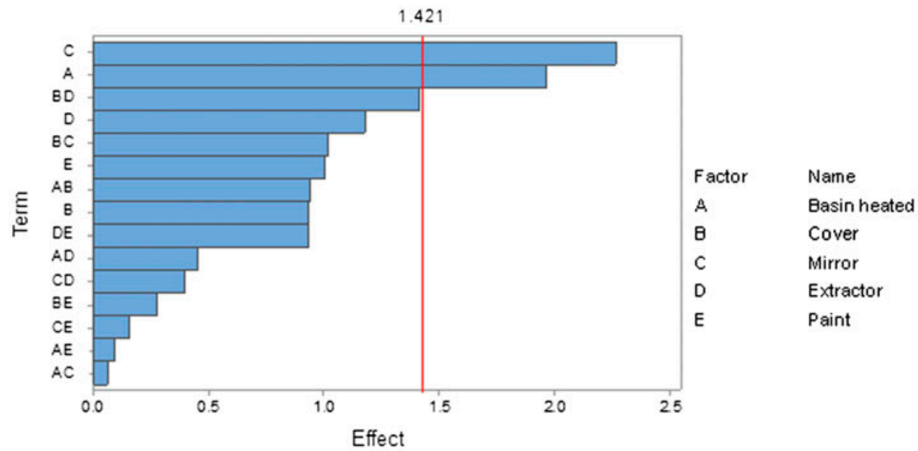

Fig. 4. Pareto chart of the effects (α = 0.05).

reflector, receiving solar radiation, and then redirecting it to the trays. The importance of the heated basin was underlined by Hamadou and Abdelatif [35], who reported that productivity can be increased by providing an extra supply of heat to the seawater through an exchange with a heat transfer fluid heated previously in a solar collector system.

The main effect plot on productivity is given in Fig. 5. The main effects plot displays the magnitude and direction of change in the output (productivity = %evaporation/k Wh) as the value of the input (such as high and low levels of each factor) changes. The figure helps to gain an understanding of the main effect of a change in each factor on the productivity of the solar still.

It is seen that the presence of all the factors (situation +1) increased the evaporation performance of the solar still, except for factor D (extractor). When the extractor was turned on (situation +1 for the extractor), the productivity of the solar still was lower compared to the condition when the extractor was turned off. This might be the result of the outside air, which had a lower temperature than the inside air, being sucked by the extractor when it is turned on. This air from outside might have had a cooling effect over the heated brine. Al-Hinai, Al-Nassri and Jubran [36] reported a direct relationship between the ambient temperature and the productivity of the solar still.

A scatter plot of the productivity of the solar still vs. the run order is given in Fig. 6. As seen, the run that produced the highest productivity was number 4, for which the heat basin and the mirror were activated (+1), the sun roof was glass (+1), and the extractor was turned off (−1).

The run order that obtained the lowest productivity was run 10. In this experiment, the heat basin, the mirror, and the black paint were deactivated; the cover was glass, and the extractor was turned on (Table 1).

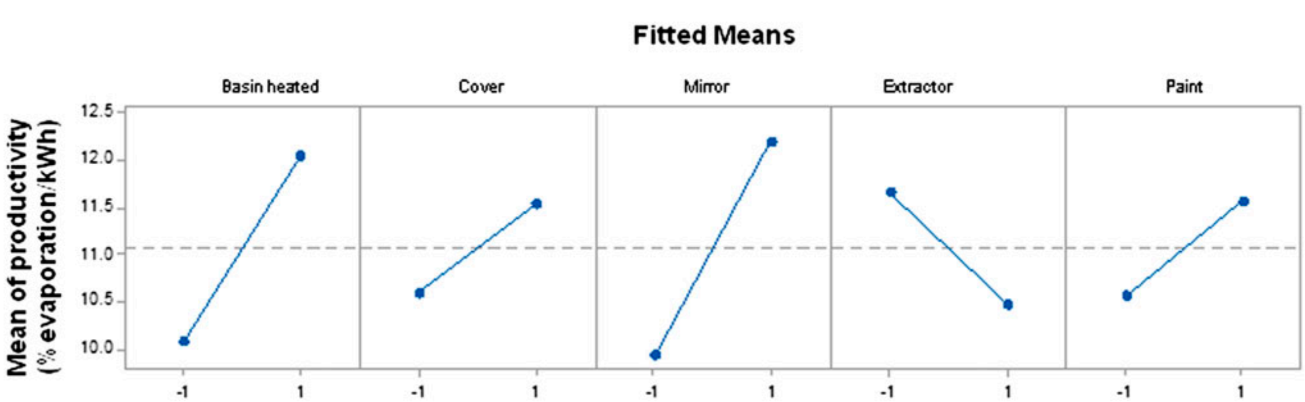

Fig. 5. Main effect plot for productivity.

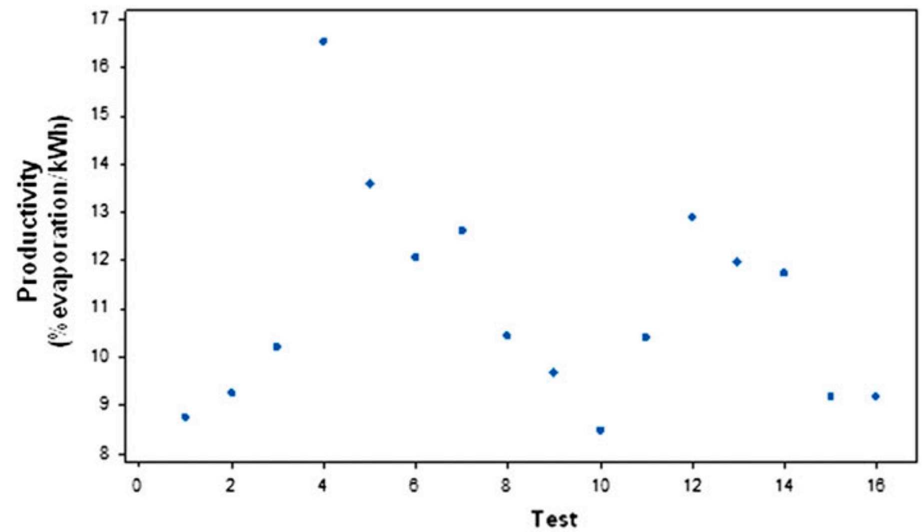

Fig. 6. Productivity and test.

3.2. Drying performance of the solar still

The conditions that yielded the best productivity in terms of drying, namely basin heated on, glass in the sun roof, with mirror, without extractor, and with black paint, were repeated in a 7-h monitoring experiment. The mass and temperature of the brine and the solar irradiation were measured every hour, and the corresponding accumulated solar energy levels (Q_{rad}) were calculated according to Eq. (1). A control sample with the same amount of brine outside the solar still was also monitored.

Fig. 7 shows the temperature and mass differences between the brine samples inside and outside the solar still. As shown in Fig. 7(a), the temperature of the brine sample inside the solar still was always higher than that of the sample outside. The temperature of the outside air ranged between 11.2 and 15.5℃ during the monitoring hours; the temperatures obtained with both of the brine samples were higher than the outside air temperature. The maximum temperatures were obtained between the hours of the day of 13.00–15.00. As shown in Fig. 7(b), the evaporation rate (36.7%) inside the solar still during the 7 h of the day was higher than the evaporation rate (13.3%) of the brine outside the solar still.

The incident radiation received by the solar still during the monitoring can be seen in Fig. 8. A significant correlation was found between the incident

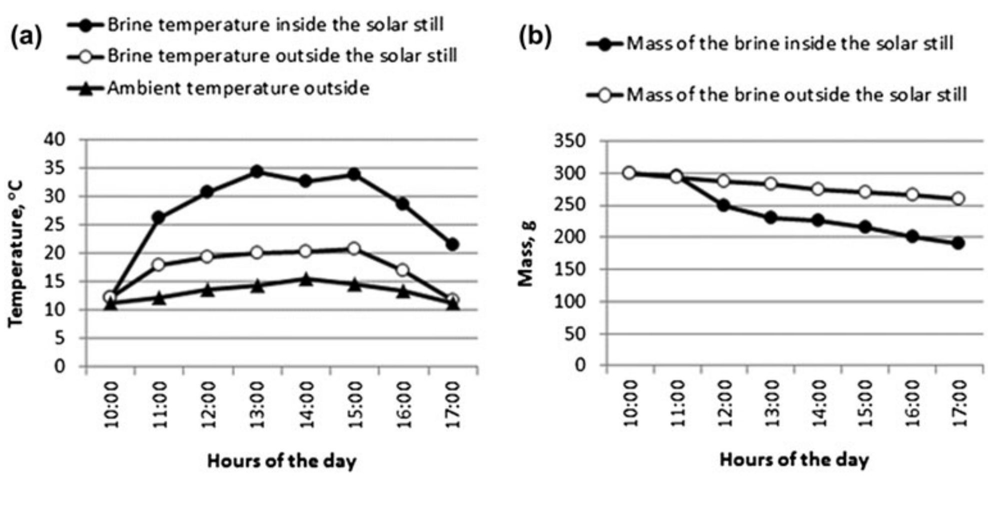

Fig. 7. Differences between the brine samples inside and outside the solar still: (a) Temperatures and (b) Masses.

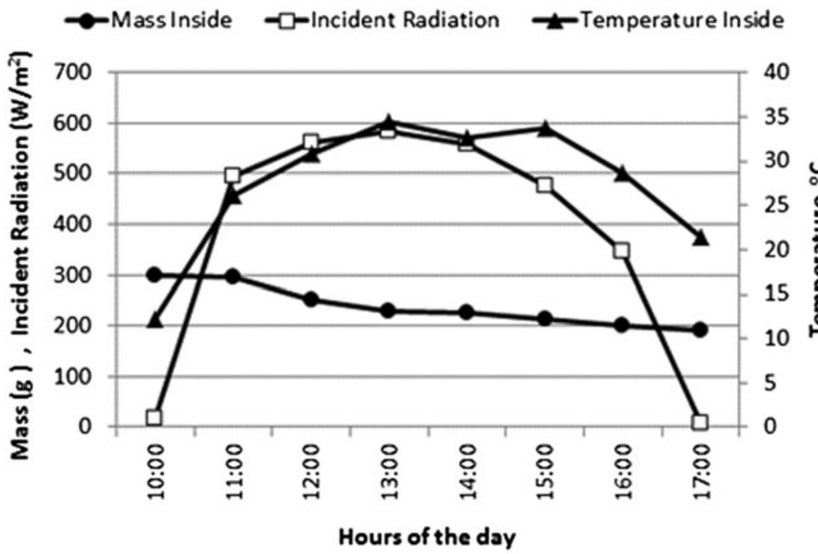

Fig. 8. Incident radiation received by the solar still during the mass reduction and temperature increase in the brine sample.

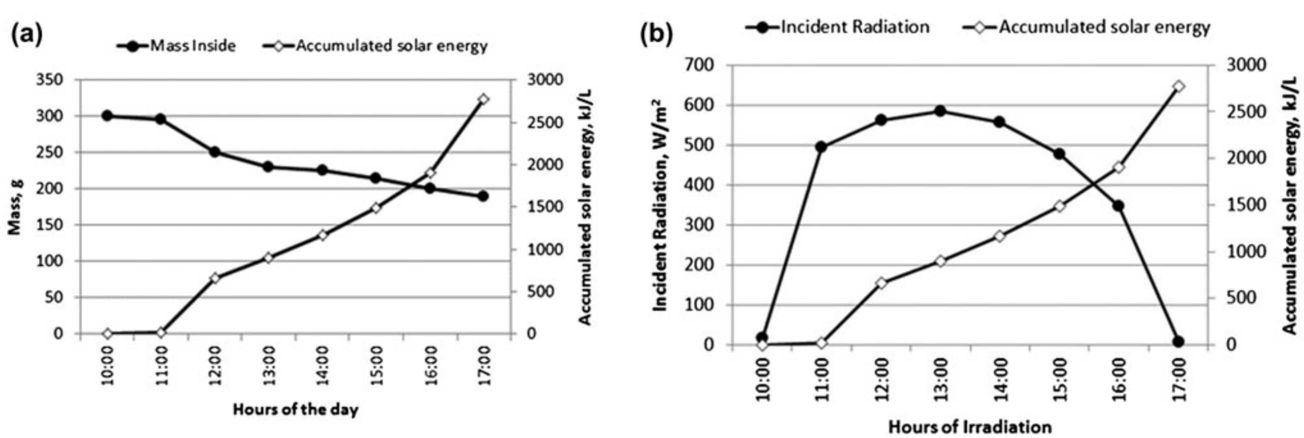

Fig. 9. Relationship between the solar energy accumulated and (a) the mass of the brine in the solar still and (b) incident radiation.

radiation and the temperature inside the solar still ($R = 0.880$, $p < 0.01$, two-tailed). The incident radiation, which was measured as 18 W/m^2 at the beginning of the process at 10:00, peaked at 585 W/m^2 at 13:00 and then decreased to 7 W/m^2 as the process completed at 17:00.

The solar energy accumulated in the brine sample inside the solar still increased from 0 to 2,770 kJ/L in 7 h, as shown in Fig. 9. The correlation between the brine mass and the accumulated solar energy was found to be highly significant ($R = -0.941$, $p < 0.01$, two-tailed), implying that the accumulated solar energy represents the most vital factor in still productivity. The results are in agreement with the results of Feilizadeh et al. [37] and Taghvaei et al. [25], who reported that the productivity of a solar still can significantly improve with increased input energy.

4. Conclusions

The factors influencing the performance of a solar still designed for the drying of brine obtained from a seawater desalination plant were investigated. The existence of a mirror and a heated basin of the solar still were found to be the most important factors (confidence level: 95%). The factor having the least effect was the material of the cover (glass or polycarbonate). The existence of the air extractor was found to adversely affect the evaporation performance of the solar still. This result might be the unintentional result of the cooling effect of the outside air that might have been sucked by the extractor when it is turned on. It was seen that the experimental conditions that produced the highest productivity were the existence of the heated basin and the mirror, the sun roof being glass, and the extractor being turned off.

A considerable difference was observed between the temperatures and the drying performances of the brine inside the solar still and the brine outside. The evaporation rate inside the solar still during the 7 h of the day was found to be 36.7%, whereas the evaporation rate of the brine outside the solar still was 13.3%. The correlation between the brine mass and accumulated solar energy was found to be highly significant ($R = -0.941$, $p < 0.01$, two-tailed), implying that the accumulated solar energy represents the vitality in the evaporation performance of the solar still.

It can be concluded that the drying performance of the solar still can be increased using adequate operational controls in the dewatering of brine.

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