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Solar water desalination using plate-like desalination unit enhanced by air flow

Hasan Mousa*,** and Farouq S. Mjalli*

** Sultan Qaboos University, Department of Petroleum and Chemical Engineering, Muscat 33, P.C. 123, Oman*

*** Jordan University of Science and Technology, Department of Chemical Engineering, Irbid 22110, P.C. 3030, Jordan*

ABSTRACT

A solar water desalination unit was built and tested. The unit mainly consists of an inclined black plate, glass cover, and condenser. On the black plate, metallic strips were attached, which act as heating fins in order to increase water residence time and increase evaporation area. The evaporation was enhanced by blowing air through the unit carrying the water vapor. The water vapor-air mixture was passed through a condenser, in which fresh water was obtained. The unit productivity, defined as the volume of fresh water obtained per unit area times unit time, was measured and presented. The results showed that the unit is capable of producing 0.2 l/m^2-hr with an average water electrical conductivity of 52 mS/cm and hot water of about 60oC. It was found that the productivity drops by 21% when the feed water salinity is increased to 20000 ppm. The experimental results showed that the countercurrent mode of operation enhances the unit productivity by 30%. Recycling the air out of the condenser to the unit improved its productivity by 3.6-fold (360%). Performing mass and energy balance around the condenser to predict the productivity of the unit showed an excellent agreement between the theoretical and the experimental results.

Keywords: solar desalination; solar units; humidity; productivity; water.

INTRODUCTION

One of the most challenging human kind survival issues is lack of potable water. This is more pronounced in areas such as the Middle East and North Africa (MENA) region. The ever-increasing population and the severe shortage of potable water resources in the MENA region countries put a great obstacle in the way of development and prosperity of these countries.

To address this issue, most countries in this area depend on seawater desalination and underground water to fulfill the ever-increasing water demand. The limited natural and underground water sources limit desalination technologies to those of high energy utilization such as membrane (RO) and thermal (MED, MVC, and MSF) desalination methods (Kalogirou, 2005).

To this end, this research focused on developing energy efficient and environmental friendly technologies that can assist or replace (if possible) conventional water production facilities (Pugsley et al., 2016).

The lack of energy resources for driving these desalination technologies dictates the search for renewable and sustainable alternatives. Solar heating energy is one of the best alternatives in this regard as it is boundless, clean, and readily available all over the globe. This abundant source of energy is inadequately utilized especially in areas of low population and wide open areas such as the MENA region (El-Sebai, 2015). For these countries, solar energy can be economically used to fulfill the daily requirements of small families. Solar stills have shown a great promise in this aspect due to their simple design, reasonable production rate, and economical practical implementation.

The idea of using solar stills for producing water dates back to the mid of the fifteenth century, and the first practical design was built by Charles Wilson in 1872 to supply fresh water to the mining industry (Frick et al., 1973). Since then, many improvements on the design and complication of the still were introduced and evaluated (Durkaieswaran, 2015).

In its simplest form, the solar still is composed of a single-basin, which has a very basic design and is easy to operate and maintain. However, this design attains very low yield that is mainly governed by the solar radiation intensity, which varies considerably by season and location.

The still operates by utilizing direct solar energy for heating water in a closed enclosure. The evaporated water accumulates and condenses on the glass collector on top of the still and is then collected. The collected water will be pure from any impurities, salts, or biological micro-species.

The thermal performance of the solar still was improved by introducing a diversity of enhancements and modifications basically to increase the surface contact area and minimize heat losses. These modifications involved the basic structural parts of the still as well as the use of finned, corrugated, stepped, tubular, or multi-effect designs (Sampathkumar et al., 2010; Salah et al., 2008; Velmurugan et al., 2008; Shanmugan et al., 2008; Tiwari et al., 1998). Considerable enhancement in the solar still economy and productivity was achieved by these new designs so far. However, a lot of further advances need to be achieved in order to have more practical and affordable still designs. Falling film desalination units improved the performance of solar stills (Kalidasa et al., 2011; Abu Arabi et al., 2009) due to the enhancement of the evaporation process as a result of the movement of water. The productivity can further be improved if the water is uniformly distributed on the surface of the collector (black surface) and the feed water flow rate is reduced (Abu Arabi et al., 2009; Aybar et al., 2005). Reducing the flow of the feed water makes it difficult to distribute the water uniformly as a film. To overcome this problem, Al-Otoom et al. (2015) designed and tested a unit in which a uniform film is achieved by introducing a continuously rotating belt that acts as a solar collector. The belt sinks through the basin carrying the water as a film, and then the film evaporates as the belt rotates. A productivity of 0.5 l/m2-hr in hot weather conditions was achieved. Another problem such units face is the condensation of the water vapor on the glass surface leading to the attenuation of the sun radiation, hence reducing productivity. Abu Arabi et al. (2017) utilized the same unit designed by Al-Otoom (2015) to desalinate water. They improved its performance by withdrawing the evaporated water and condensing it in an external condenser. The withdrawn air-water vapor mixture was discharged to the surrounding after being condensed in the condenser. A production of 9 l/day was achieved. On the other hand, Venkatasamy and coworkers (2017) enhanced the productivity of an inclined solar still using a baffled plate placed on the inclined surface. They stated that the unit was capable of producing 3.5 kg/m2-day. Mousa and coworkers (2016) performed a theoretical analysis to predict the productivity of solar stills involving a phase change material (PCM). Their theoretical analysis showed that the productivity is a function of the type and quantity of the PCM. In an attempt to improve the productivity of the conventional solar still, Ramanathan et al. (2017) embedded a flat mica plate just parallel to the glass cover of the solar still. This modification resulted in increasing the temperature inside the still from 67 °C to 95 °C and increasing the distillate output by 25%. However, the distribution of water in the bare absorber plate was not uniform, which limited the possible solar cell productivity improvement.

In this work, a plate-like desalination unit enhanced by air flow to produce fresh water and hot water is designed and tested under different operational conditions including feed water flow rate, solar intensity, and different ambient conditions. The evaporated water is carried out and condensed in an external condenser. The unit was tested for the case when the air is discharged to the surroundings after being cooled in the condenser (open circle) or recycled to the unit (closed circle). This work involved the novel addition of metallic strips on the black plate of the still. These strips served two important roles. Firstly, they contributed as heating fins, which resulted in maximizing the evaporation area available in the still, and secondly, the new water flow geometry attained by these fins increased water residence time. This still presents a preliminary fundamental design that can be improved further in future work.

Experimental Setup

The improved solar still is illustrated schematically in Fig.1. The feed water tank is filled with water supply with its level controlled by the included float. A relevant feed flow rate is adjusted through the feed valve to the inlet of the condenser. The water flows through the condenser, then exits as a feed to the solar absorber box, which is adjusted with an inclination angle of 23º. The absorber box has the dimensions of “0.6m´0.6m´0.15m” with its outside surface being made of glass that can be opened for regular maintenance. The absorber surface facing sun is equipped with (30) parallel fin perpendicular to the surface of the plate, each with the dimensions of “0.6m length and 0.02m height” and placed 0.02m apart. As water enters the box, it fills the parallel fin channels and goes to the fin beneath it through a hole (6 mm) and so on making a zigzag rout until it reaches the box exit and is collected at the hot water tank. In this zigzag motion, the water travels 18 m, and hence it flows longer in the unit giving it longer time to evaporate leading to higher productivity. The hot water leaving the unit can be recycled as a feed supply or used as a hot water for domestic use. With the aid of a vacuum pump (Edwards 2-stage type), the vapor collected in the box is pumped to the countercurrent stream of the condenser. Then it gets cooled down and converted to liquid that can be collected in the fresh water product tank. On the other hand, the uncondensed vapor from the condenser is returned back to the absorber box through the exit split assembly shown in the zoomed figure portion labeled 7 in Fig.1.

Experimental Runs

The experiments were run by allowing the feed water to enter the condenser to cool the air-water vapor withdrawn from the unit. It is then allowed to enter the top first lip of the unit at a specified flow rate. The water moves along each fin and transfers to the next. As it moves, its temperature increases and reaches its maximum at the exit of the unit where it is collected as hot water. The vapor accumulates in the space between the fins and the glass cover and is withdrawn by a vacuum pump where it is cooled in a glass condenser. The condensate is collected as fresh water. The experiments were carried out in two modes: in the first mode, the air is discharged to the surroundings, while in the second mode, it is recycled to the bottom end of the unit. The reason for this is to see the effect of air recycling to the unit. It should be added that the air and water are contacted in the condenser either in concurrent or countercurrent modes.

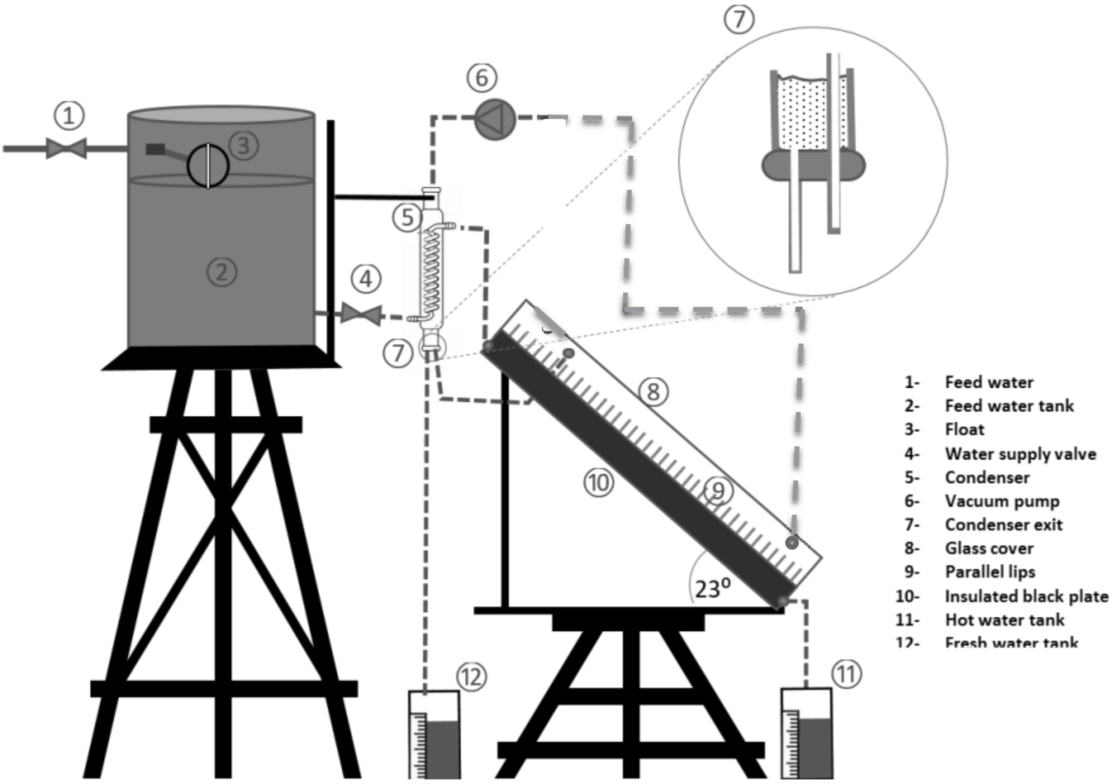

Figure 1. Schematic of the used solar still.

The effects of the following parameters on the unit productivity were investigated: air recycling, air-water contact in the condenser (concurrent or countercurrent modes), solar irradiation intensity, ambient weather conditions, and feed water salinity. In the following section, these effects are discussed.

Results and Discussion

Table 1 shows experimentally measured amount of fresh water presented as l/m2-hr at a water feed flow rate of 2.52 l/hr. The table also shows the average ambient temperature and the ambient air relative humidity. It can be seen that, on average, 0.2 l/h-m2 is produced by this unit. The table also shows that as the air relative humidity decreases, the production increases (see Fig. 2). The flux of water from the water-air interface to the bulk air is N=ky(yi-y), where yi and y are the mole fraction of water at the water-air interface and the bulk air. Therefore, as the relative humidity increases, hence y, the driving force for evaporation (yi-y) decreases resulting in a drop in the unit productivity. The electrical conductivity of the fresh water produced was measured to be 52 mS/cm. The average temperature of the hot water produced was 53.8oC.

Table 1: Amount of fresh water produced (l/m^2-hr), the average ambient temperature, and the % humidity in the month of May.

Date	Production (l/m^2-hr)	Average ambient temperature (°C)	Average % humidity
2-May	0.17	35.9	-
3-May	0.27	42.5	-
4-May	0.23	42.5	21.80%
8-May	0.18	43.2	26.00%
9-May	0.22	43.4	23.90%
10-May	0.22	42.7	25.70%
11-May	0.22	41.8	26.60%
12-May	0.18	39.3	33.00%
15-May	0.24	40.1	32.30%
16-May	0.22	42.5	23.00%
17-May	0.21	43.4	22.90%
18-May	0.17	43.8	24.90%
23-May	0.15	39.8	36.70%
24-May	0.17	39.1	35.00%
25-May	0.17	39.1	36.00%
	0.20	41.3	28.30%

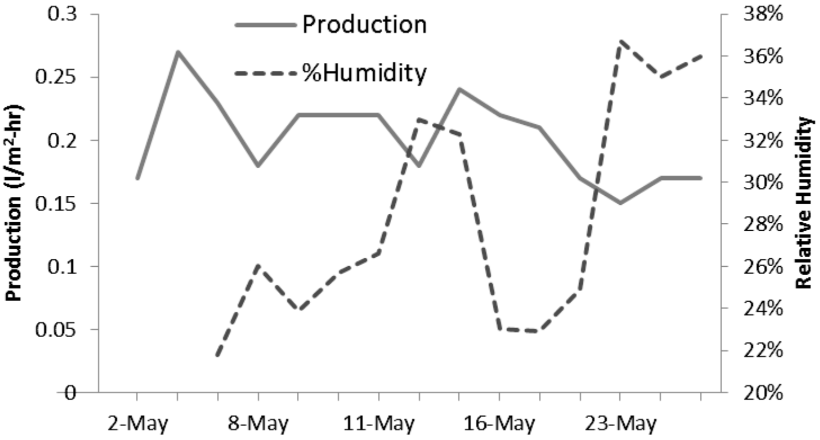

Figure 2. Fresh water production and air humidity.

Effect of Operation Mode

Air was admitted to the unit from the left side bottom of the unit. It carries the water vapor and then passes in the shell side of the condenser. In the condenser, the feed water is used to cool the air-water vapor mixture. The condensed water is withdrawn from the bottom side of the condenser as fresh water. The water and the air streams can be contacted either in a concurrent (co-current) or countercurrent mode. In the countercurrent flow mode, air enters from top in the shell side of the condenser, and feed water enters from the bottom in the tube side. In the concurrent mode of operation, air-water vapor mixtures and feed water enter in the same direction (both from the bottom).

The reason for testing the concurrent mode of operation is to see if sudden cooling has any effect on water productivity. The results are depicted in Fig. 3. It can be seen that, in the countercurrent method of cooling, the air-water vapor mixture gave larger productivity. In fact, an increase of about 30% in fresh water productivity is achieved using countercurrent mode of operation.

Effect of Air Circulation

Earlier experiments were performed by withdrawing the air-water vapor mixture from the unit, cooling it, and then discharging the cooled air to the surroundings (open circle). To test the effect of circulating the discharged air to the unit on its productivity, the discharged air was connected to the point at which the air is admitted to the unit (closed circle). The status of the air-water vapor mixture at the different points of the unit for the open circle and closed circle case is illustrated on the psychometric chart shown below (Fig. 4).

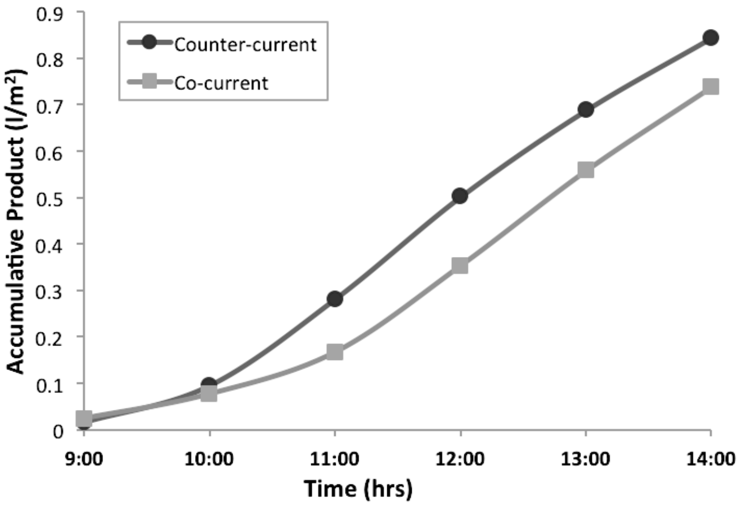

Figure 3. Effect of the mode of operation on the productivity of the unit.

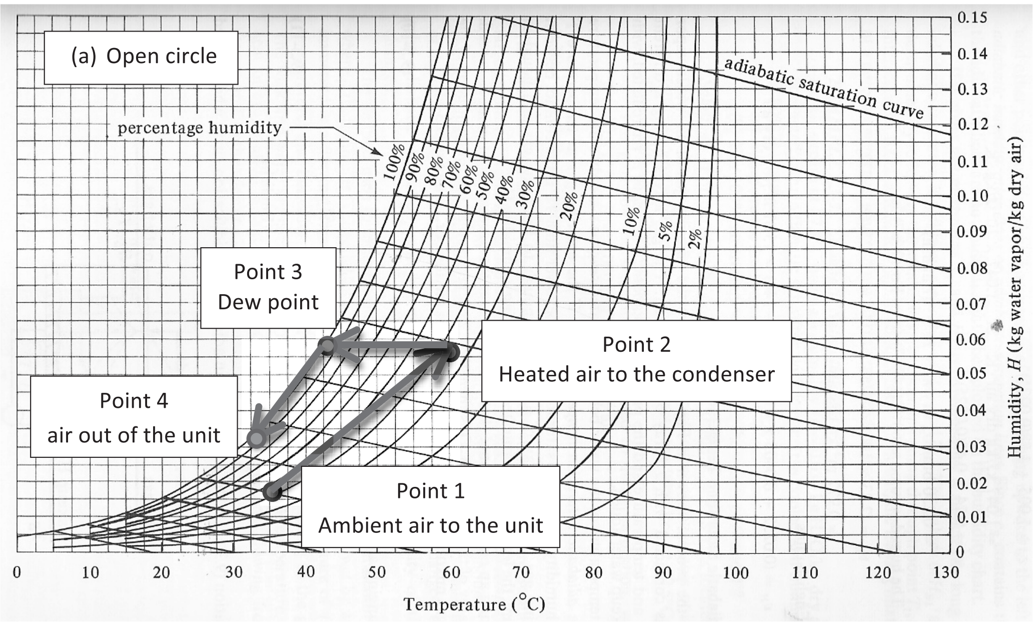

Figure 4. Air-water vapor mixture circle at different points of the unit: (a) open circle; (b) closed circle.

Circulating the discharged air to the unit had appreciable effect on the unit productivity as can be seen in Fig. 5, where it can be seen that the productivity increased by 3.4-fold (the productivity of the unit increased from 0.5 to 1.7 l/m2). The reason for this improvement may be attributed to the fact that cooling of the unit when ambient air is introduced is avoided by circulating the air. In addition, in the closed circle case, the returned air is usually saturated since excess water is condensed (point 1) on Fig. 4-b, and as it enters the unit it heats up, reducing its relative humidity (point 2), which enhances evaporation as the driving force for mass transfer represented by the difference between the humidity at the water air interface and the bulk air humidity increases. Therefore, cooling the air to a temperature below the dew point and recirculating it to the unit ensure that no water is lost to the surroundings. These points improved the unit's productivity.

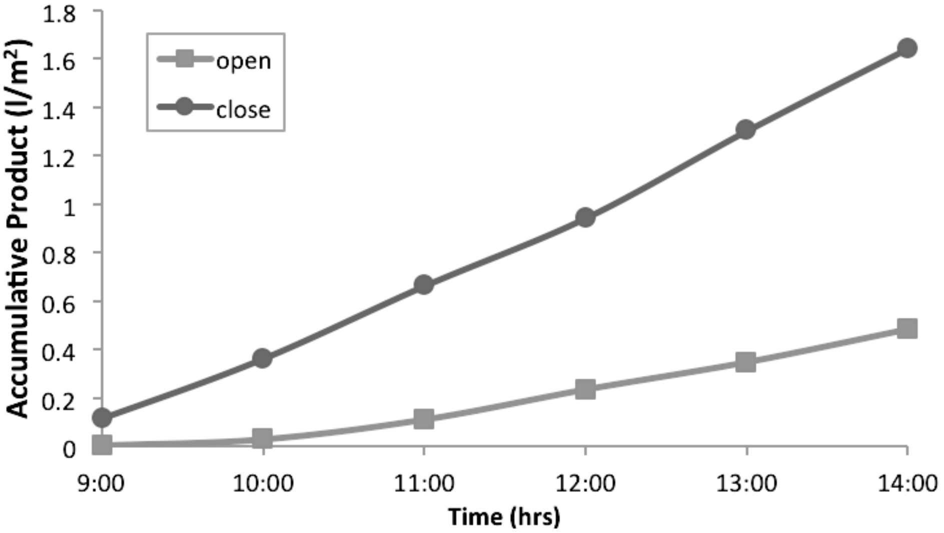

Figure 5. Effect of circulating air on the productivity of the unit.

Effect of Water Salinity

The experiment was performed with water salinity of 20000 ppm and was compared to those performed on tap water. The salinity was adjusted by adding NaCl salt to the water. The results showed that the production dropped from 0.28 l/m2-h to 0.16 l/m2-h. Note that the weather conditions for both experiments were similar (the average ambient temperature and % humidity for the tap water experiment and the saline water experiment were 42.5oC, %H=23% and 42.25oC and %26, resp.).

Theoretical Analysis

Energy and mass balances can be carried out either around the whole unit (solar collector and condenser), around the solar collector, or around the condenser to estimate the production rate of fresh water. In this work, mass and energy balance was performed around the condenser. Consider the condenser as shown in Fig. 6. An energy balance around the condenser gives

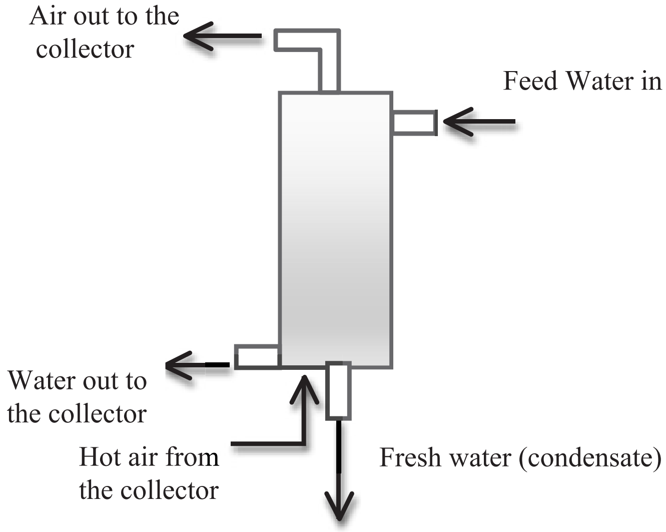

Fig 6. Schematic diagram of the condenser

$$WH_{w,in} + GH_{G,in} = WH_{W,out} + GH_{G,out} + D'H_D + Q_{loss} \tag{1}$$

where W is the water flow rate, $H_{W,in} = C_p(T_{w,in}-T_r)$ is the enthalpy of the water entering the condenser (*kJ/hr*), $H_{W,out} = C_p(T_{w,out}-T_r)$ is the enthalpy of the water leaving the condenser (*kJ/hr*), C_p is the heat capacity of water=4.2 kJ/kg.°C, Tr is the reference temperature, 25o*C*, *D* is the rate of fresh water produced (*kg/hr*), $HD=C_p(T_D-T_r)$ is the enthalpy of fresh water produced (*kJ/hr*), Q_{loss} is the heat loss (*kJ/hr*) from the condenser to the surroundings and assumed zero since the condenser is well insulated, *G* is the dry air flow rate (kg dry air/hr), and $H_{G,in}$ and HG,out are enthalpies of air entering and leaving the condenser kJ/kg dry air and given by Treybal (1981):

$$H_{\mathrm{G,in}} = (1.005 + 1.884\mathrm{Y}_{in})T_{G,in} + 2502.3\mathrm{Y}_{in} \tag{2}$$

$$H_{\mathrm{G,out}} = (1.005 + 1.884\mathrm{Y}_{out})T_{G,out} + 2502.3\mathrm{Y}_{out} \tag{3}$$

Y_{in} and Y_{out} are the absolute humidity of the air entering and leaving the condenser (kg water/kg dry air) and $T_{G,in}$ and $T_{G,out}$ are the dry bulb temperatures of air entering and leaving the condenser.

Substituting Eqns. (2) and (3) in Eqn. (1) gives

$$D' = \frac{WC_p(T_{w,in}-T_{w,out})+G[C_A(T_{G,in}-T_{G,out})+C_B(Y_{in}T_{G,in}-Y_{out}T_{G,out})+2502.3(Y_{in}-Y_{out})]}{C_p(T_D-T_r)} \tag{4}$$

The cumulative amount of fresh water collected, D=$\int D'dt$ or

$$D = \int \frac{WC_p(T_{w,in}-T_{w,out})+G[C_A(T_{G,in}-T_{G,out})+C_B(Y_{in}T_{G,in}-Y_{out}T_{G,out})+2502.3(Y_{in}-Y_{out})]}{C_p(T_D-T_r)}dt \tag{5}$$

To integrate the above equation it should be noted that the above parameters, namely, $T_{G,in,}$ $T_{G,out,}$ $Y_{in,}$ $Y_{out,}$ are all functions of time since the solar irradiation intensity increases during the day reaching maximum at noon time then drops. The variation of the above parameters with day time is shown in Fig. 7. The difference between the inlet and outlet water temperature was assumed constant such that ($T_{w,out}$ - $T_{w,in}$) = 5 °C. The fresh water temperature was also assumed constant and equal to 42°C.

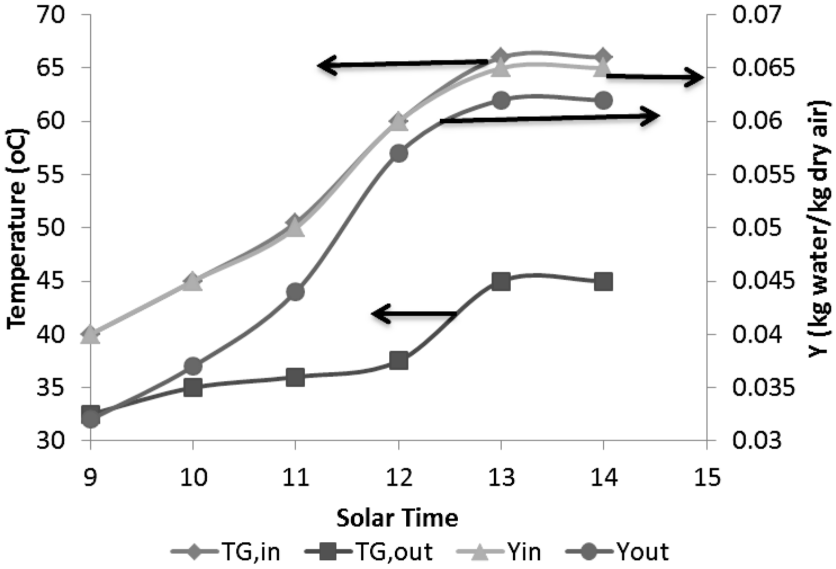

Figure 7. Measured gas temperature to and out of the condenser and its absolute humidity.

The above equation was integrated into MATLAB using Runga-Kutta 4th order ODE solver. The mass flow rate of water, W, and air, G, were 10.8 kg/hr and 8.03 kg/hr, respectively. A comparison between the experimentally measured fresh water produced by the unit to the theoretically calculated ones is shown in Fig. 8. A good agreement between the results was found. It should be mentioned that the small discrepancies between the theoretical and the experimental results are because of neglecting the heat loss from the system.

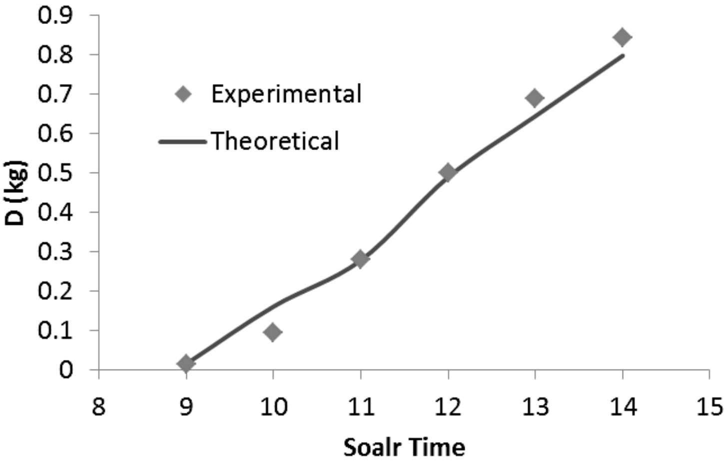

Figure 8. Experimentally measured fresh water produced by the unit with the model predictions.

Conclusion

Solar water desalination using a novel plate-like desalination unit enhanced by air flow was constructed and tested. The effect of various parameters such as solar irradiation, ambient weather conditions, air circulation, and contact mode in the condenser on the productivity of the unit expressed as the amount of fresh water produced per unit area per hour was investigated. The experimental results showed that the productivity of the unit increases when a closed air circuit and countercurrent air-water contact in the condenser are used and when the solar irradiation intensity is high. On the other hand, higher air humidity was noticed to reduce the unit productivity since the driving force for evaporation drops. An equation to predict the unit productivity was derived by performing energy balance around the condenser. An excellent agreement between the experimental and the theoretical results was obtained. It should be mentioned that the condenser design plays an important role in determining the unit productivity. The design should ensure enough surface area to increase water condensation and, hence, unit productivity.

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تحلية المياه بالطاقة الشمسية
باستخدام وحدة تحلية معززة بواسطة تدفق الهواء

حسن موسى*، ** ، فاروق مجلي ***

* جامعة السلطان قابوس، قسم الهندسة الكيميائية والبترول، مسقط 33، ص.ب . 123، عمان

** الجامعة الأردنية للعلوم والتكنولوجيا، قسم الهندسة الكيميائية، إربد، 22110، ص. ب . 3030، الأردن

الخلاصة

تم بناء واختبار وحدة تحلية للمياه باستخدام الطاقة الشمسية. تتكون الوحدة بشكل رئيسي من لوح أسود مائل وغطاء زجاجي ومكثف. تم تعليق أشرطة معدنية على اللوح الأسود لتعمل كزعانف تسخين لزيادة وقت استقرار المياه وتوسيع مساحة التبخير. وتم تعزيز التبخير عن طريق نفخ الهواء في الوحدة ليحمل بخار الماء. تم تمرير خليط بخار الماء والهواء عبر مكثف ليتم من خلاله الحصول على المياه العذبة. تم قياس إنتاجية الوحدة والتي هي عبارة عن حجم المياه العذبة الناتجة لكل وحدة زمنية. وأظهرت النتائج أن الوحدة قادرة على إنتاج 0.2 لتر / م2 – ساعة بمتوسط توصيلية كهربائية للماء تبلغ 52 mS / cm ومياه ساخنة بدرجة حرارة تبلغ 60 درجة مئوية. وقد وُجد أن الإنتاجية تنخفض بنسبة 21٪ عند زيادة ملوحة مياه التغذية إلى 20000 جزء في المليون. وأظهرت النتائج التجريبية أن طور التيار المعاكس للتشغيل يعزز إنتاجية الوحدة بنسبة 30٪. وقد أدى إعادة تدوير الهواء من المكثف إلى الوحدة إلى تحسين إنتاجيتها بمقدار 3.6 أضعاف (360%). أظهر تحقيق التوازن بين الكتلة والطاقة حول المكثف للتنبؤ بإنتاجية الوحدة توافق ممتاز بين النتائج النظرية والتجريبية.