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Solar desalination unit with falling film

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ABSTRACT

Desalination of water by a solar unit with falling film was investigated. Even distribution of the water film on the collector plays an important role on the amount of desalinated water that can be produced. Several distribution systems were designed and tested. A combination of water distributor and a wick on the plate surface were needed to achieve uniform film on the plate surface. The effect of various parameters such as feed water flow rate, ambient temperature, water salinity and cooling the outer glass surface on the unit productivity was investigated. A linear relationship between the amount of fresh water produced and time is exhibited. On average about 0.6 L/h.m^2 of water was produced by the unit during the hot months. Reducing the feed water flow rate and cooling the outer glass surface improved the unit productivity. Cooling the outer glass surface improved the unit productivity by 30%. On the other hand, water salinity adversely affected the unit productivity. The productivity is reduced by 40% upon increasing the salt concentration in feed water to 20,000 mg/L. The quality of the produced water was assessed by measuring its conductivity and it was found to be about 23 μS/cm. An equation to estimate the amount of desalinated water produced from the falling film was derived based on mass and energy balances. The agreement between the theoretical predictions and the experimental results is good.

Keywords: Desalination; Solar collector; Falling film; Inclined plate; Water

1. Introduction

In many regions worldwide, need for desalination of saline water is increasing due to an increase of population and limited supply of potable water. The conventional desalination methods are classified as membrane or thermal (distillation) processes. Utilization of solar energy for fresh water production from saline water by distillation has been practiced for several decades.

Documented use of solar stills began in the 16th century. Different designs of solar stills have emerged. The single-effect solar still (the conventional solar still) is a relatively simple device to construct and operate. However, the low productivity of the conventional solar still triggered initiatives to look for ways to improve its productivity and efficiency. Among these improvements; cooling the surface cover to increase the temperature difference between water in basin and glass cover [1–6], using internal condenser [7], double or triple effects to utilize the latent heat of the condensing vapor [2,3,8-11]. Recently, a falling film approach in solar distillation systems has been considered by several studies [12–16], which has been in practice for about 50 years in conventional distillation methods. The film is established on flat plate or on tubes. In the case of flat solar absorber plate, the feed water is spread as a film on the plate which has a glass cover. This way the amount of water to be heated is reduced. Evaporation takes place from the falling film as it absorbs solar irradiation and condensation occur on the glass cover. The heat and mass transfer

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coefficients of falling film evaporation and condensation are very high, which results in higher system productivity. Such systems can be used to produce fresh water and hot water for domestic use.

Aybar et al. [15] and Aybar [16] investigated experimentally and theoretically an inclined solar water distillation with falling film. Three different surfaces of the absorber plate were used; bare plate and plate covered with black-cloth wick or with black-fleece wick. Covering the plate increased the system productivity with the black-fleece giving more yield. The theoretical investigations [16] revealed that their unit is capable of producing 3.5–5.4 kg/d.m^2 in a typical summer day.

The falling film approach as indicated by the previously studied cases seems to be promising, resulting in more solar still productivity. In this work, a unit similar to that used by Aybar et al. [15] was designed and used to investigate its performance under the weather conditions of Jordan. Also the effects of water salinity and cooling the glass cover on the system productivity were investigated.

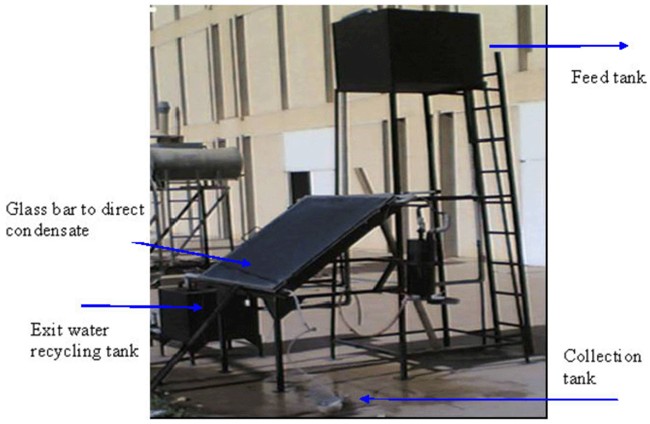

Fig. 1. Falling film solar desalination unit.

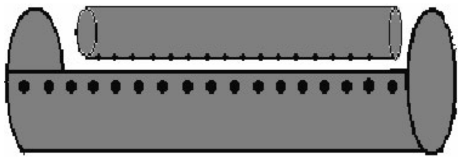

Fig. 2. Water distributor.

2. Experimental set-up

The experimental set-up consists of a solar collector (1 m ×1 m), a feed water distributor, a feed tank of 250 L capacity, a collecting tank of 150 L capacity and a pump to circulate water through the system. A photograph of the experimental set-up is shown in Fig. 1. The solar collector is a flat plate made of galvanized steel (1 mm thick) painted black. The plate was tilted from the horizon by 45° during testing the system at the Jordan University of Science and Technology in Irbid (northern Jordan). The flat plate is insulated from the bottom using rock wool (5 cm thickness) to minimize heat losses. A glass cover (4 mm thick) was placed parallel to the flat plate collector at a distance of 8 cm.

The glass cover was manufactured as a window so that it is easy to open and clean the system from the inside and make it possible for any modification on the system whenever necessary. Evaporation took place from the falling water flowing as a film on the hot surface. The condensate on the glass cover glides down to the lower part of the glass cover. To prevent product water from falling by gravity and mixing with the water leaving the system, a glass bar was glued to the bottom part of the glass cover few centimeters away from the exit water outlet. The bar makes an angle (20°) with the horizon so that produced water flows by gravity to the product water collection tank.

The feed, exit and produced water temperatures were continuously measured using Cu-Co thermocouples type K. The ambient and produced water temperatures were measured by using mercury thermometer (scale from 0–100°C). Global solar irradiation in W/m^2 and ambient temperature during the experiment were measured every 10 s using multiplexer and pyranometer (Kipp and Zonen, Germany). Conductivity of product water was measured by a conductivity meter (Cyber Scan 500).

The function of the distributor at the top of the black plate is to produce a water film evenly distributed over the entire surface. Several design trials of distributor were made in order to achieve a regular water film on the surface. The best distribution system based on experimental results is a tube 8 mm inside diameter, with 1.5 mm diameter holes pierced evenly along its length at a distance of 1 mm apart, impeded in a half cut tube containing holes of 3 mm diameter as shown in Fig. 2. The water that flows through the inside pipe flows into the half cylinder filling the space between the tube and the half cylinder. Once the level of water reaches the holes in the half-cylinder, it starts to flow out evenly to the flat plate.

To further improve water distribution over the flat plate, strips of rough cloth painted black were laid on the flat plate in a manner perpendicular to the water flow direction. The cloth strips were 1 cm in width each and distributed 3 cm apart. The space between the strips was filled with 3 cm width black mesh.

3. Theoretical estimation of the water produced

As shown in Fig. 3, the feed water enters as a film with mass flow rate at $\dot{m}_F$ temperature T_F and with enthalpy

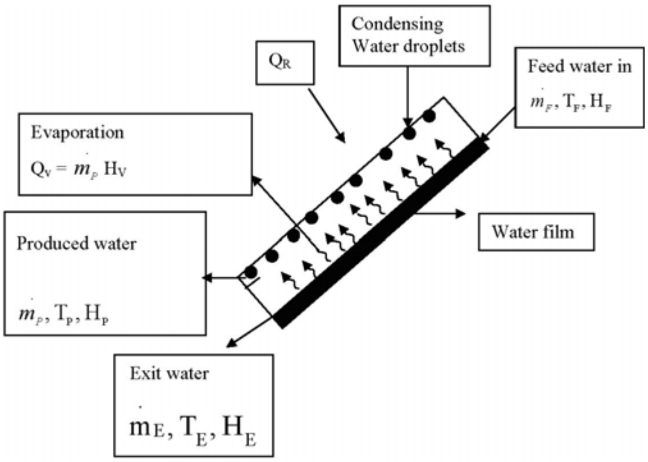

Fig. 3. Schematic diagram of the falling film for mass and energy balances.

H_F. The film receives solar energy at a rate of Q_R causing evaporation from the water film. The evaporated water condenses at the inner glass surface, glides down and then is collected at a rate $\dot{m}_P$. The remaining water exits the unit at a rate $\dot{m}_E$ at temperature T_E and with enthalpy H_E.

In order to derive an equation to estimate the amount of water produced, $\dot{m}_P$, the following assumptions are made:

1. The unit is well insulated from the bottom and edges so that there are no heat losses taking place.

2. Q_R is the average solar irradiation received in the time interval (t_1–t_2). In the calculations the arithmetic average of Q is used.

3. The heat capacity, C_p, within the range of temperatures involved in the experiments is constant and equals 4.2 kJ/kg-°C.

4. The vapor enthalpy, H_v, was obtained from the steam table at the average water film temperature, T_f, equals $(T_F + T_E)/2$.

Performing mass and energy balances on the film yields

$$\dot{m}_F = \dot{m}_P + \dot{m}_E \tag{1}$$

$$H_F \dot{m}_F + Q_R A = Q_v + H_E \dot{m}_E \tag{2}$$

where $H = C_P(T - T_R)$, A is the surface area of the film, T_R is the reference temperature and $Q_v = \dot{m}_P H_v$. Substituting Eq. (1) in Eq. (2) and rearranging gives

$$\dot{m}_P = \frac{\dot{m}_F C_P (T_F - T_E) + Q_R A}{H_v - C_P (T_E - T_R)} \tag{3}$$

The total amount of water produced, m_p, within the time interval $\Delta t = t_2 - t_1$ is

$$m_p = \dot{m}_P \Delta t \tag{4}$$

4. Results and discussion

4.1. Experimental part

In this section the effect of the various parameters: feed water flow rate, cooling glass cover, ambient temperature and water salinity are presented. Although it was possible to control the cooling of glass cover, feed water flow rate and salinity, unfortunately the ambient temperature was beyond control in an outdoor testing. The ambient temperature changes with solar irradiation (time of the day and time of the year) and the apparent weather conditions (wind speed and direction). In Jordan, the northwesterly wind is usually cool whereas the south-easterly wind is hot. Careful planning was made to minimize this effect by carrying experiments at times where the weather conditions are similar. The various weather conditions prevailed at the time of the experiments are indicated in the figure caption.

The amount of desalinated water is shown in Fig. 4. The accumulated amount varies linearly with time. Moreover, the rate of water production is affected by both the feed water flow rate and the ambient temperature. The effect of feed water flow rate on the amount of water produced is depicted in Fig. 5. As the feed water flow rate decreases the amount of water produced increases. The reason for this is that when the flow rate is low, most of the energy absorbed goes to evaporate the water instead of heating large amount of water. Accordingly the rate of evaporation increases leading to a higher rate of production. This is in accordance with the results of Aybar [16] that were obtained from theoretical simulation of a similar system.

The effect of the ambient temperature on the amount of produced water is portrayed in Fig. 6. When the ambient temperature is higher, more water production is obtained. The ambient temperature varies with solar irradiation depending on the day on which the experiment was performed. The experiments shown in Fig. 6 were performed between November 27th and May 28th, 2006, where the average irradiation energy was 689 W/m^2 and 766 W/m^2 respectively. Obviously on hot days more water production is achieved.

4.2. Effect of cooling the outer glass surface

To investigate the effect of cooling the outer glass surface on the productivity of the unit, experiments were performed where water was sprayed on the outer glass

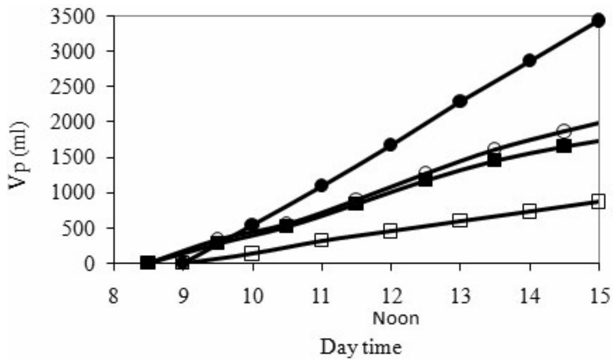

Fig. 4. Volume of produced water vs time. Feed water flow rate, ambient temperature and average irradiation are: ● 3 ml/s, 38°C, 822 W/m^2; ○ 5 ml/s, 31°C, 839 W/m^2; ■ 6 ml/s, 28°C, 790 W/m^2; □ 11 ml/s, 34°C, 838 W/m^2.

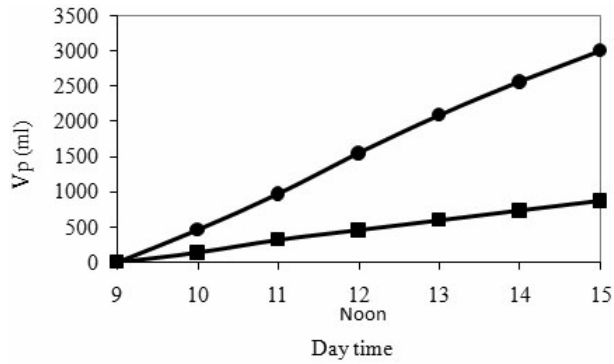

Fig. 5. Effect of feed water flow rate on amount of desalinated water vs. time. Feed water flow rate, ambient temperature and average irradiation were: ● 3 ml/s, 34°C, 883 W/m^2; ■ 11 ml/s, 34°C, 838 W/m^2.

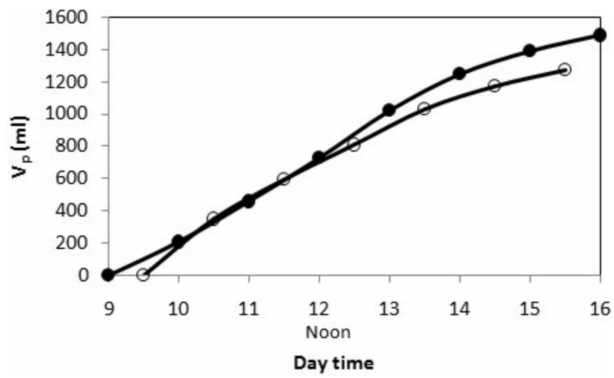

Fig. 6. Effect of the ambient temperature on the volume of produced water vs. time. Feed water flow rate, ambient temperature and average irradiation are: ● 9 ml/s, 28°C, 766 W/m^2; ○ 10 ml/s, 19°C, 689 W/m^2.

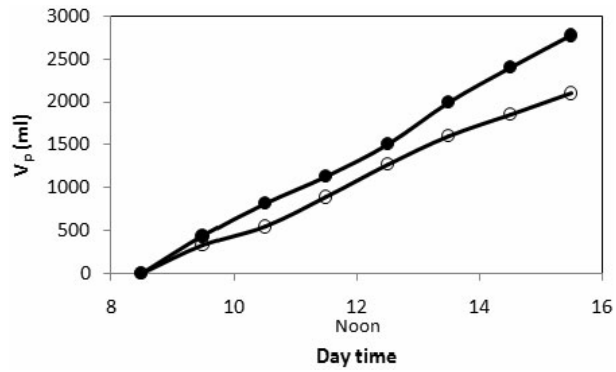

Fig. 7. Effect of cooling outer glass surface on volume of water produced vs. time. Feed water flow rate, ambient temperature and average irradiation are: ● 6 ml/s, 39°C, 767 W/m^2 (with cooling); ○ 7 ml/s, 39°C, 839 W/m^2 (without cooling).

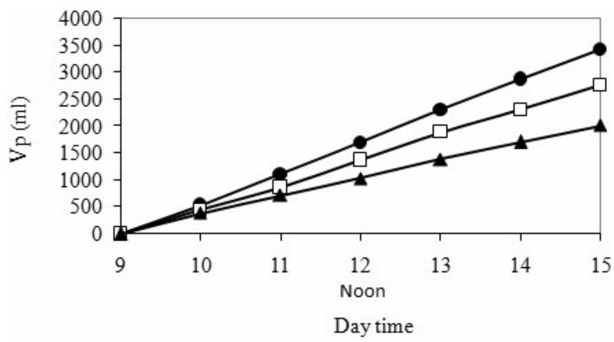

Fig. 8. Volume of water produced vs. time. Feed salinity, feed water flow rate, ambient temperature and average irradiation are: ● tap water, 3 ml/s, 38°C, 822 W/m^2; □ 10,000 mg/L 4 ml/s, 36°C, 849 W/m^2; ■ 20,000 mg/L, 2 ml/s, 41°C, 872 W/m^2.

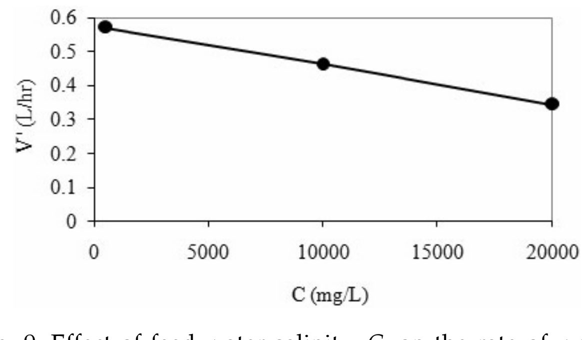

Fig. 9. Effect of feed water salinity, C, on the rate of water production, V'.

surface. The results are shown in Fig. 7. More water production is achieved when the outer glass surface is cooled. This is an expected result since water condensation is enhanced upon cooling the outer glass surface, increasing the temperature difference between the water film and the glass. Comparing the results showed that the productivity of the unit is improved by about 29% upon cooling the outer glass surface.

4.3. *Effect of water salinity*

To investigate the effect of water salinity on the productivity of the unit, NaCl was added to the feed water with concentrations of 10,000 and 20,000 mg/L. The results are presented in Fig. 8. As anticipated, the presence of salt in the feed water reduces the vapor pressure (p_v) of water. As a result of this, the rate of evaporation, which is proportional to (p_v–p_p), is reduced causing reduction in water production, where p_p is the partial pressure of water in the vapor phase above the water film. The water production is reduced from 0.57 L/h when tap water was used to 0.46 L/h (19% reduction) when salt concentration in the feed water became 10,000 mg/L and to 0.34 L/h (40% reduction) when the salt concentration was increased 20,000 mg/L. Plotting the rate of production versus the feed water concentration (see Fig. 9) shows that a linear relationship exists.

4.4. Theoretical part

In order to estimate the amount of water produced, Q_R should be first calculated. A typically measured Q as a function of day time is shown in Fig. 10. An arithmetic average of Q was used to represent Q_R, which is used to calculate m_p according to Eq. (4). On the other hand, the feed, T_F, and the exit water temperatures, T_E, were measured as presented in Fig. 11. The average water film

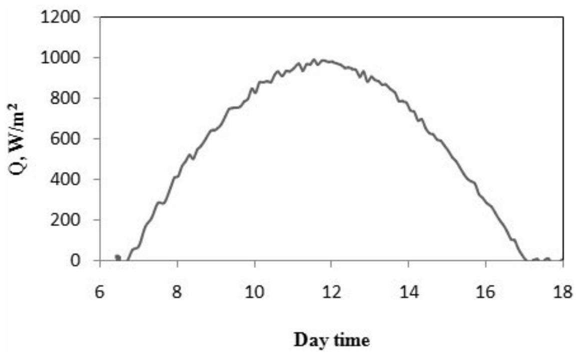

Fig. 10. Measured irradiation, Q, during day time of November 11, 2006.

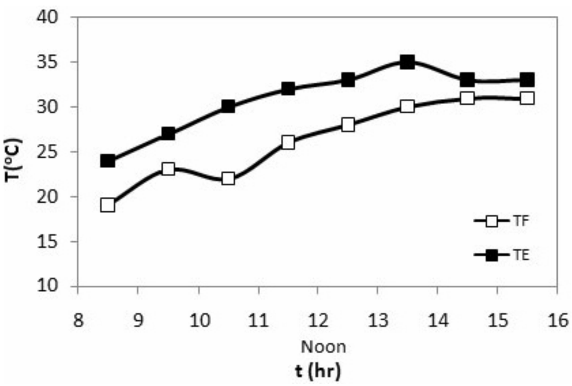

Fig. 11. Measured feed and exit water temperature during day time of November 11, 2006.

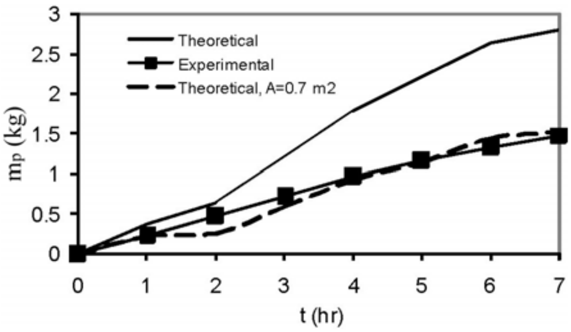

Fig. 12. Comparison of theoretically calculated and experimentally measured mass of water produced.

temperature, $T_f = (T_F + T_E)/2$, was used to estimate the vapor enthalpy from the steam tables. Fig. 12 shows the calculated and measured amounts of produced water versus time. The overall agreement between the predicted and the measured values of m_p is good. The deviation can be attributed to the water film coverage on the collector plate area. In fact 100% wetting of the collector surface for low flow rate is impossible. As shown on the figure, repeating the calculations but assuming 70% of the surface area is wetted by water gives an excellent agreement between the theoretical prediction and the experimental measurements.

5. Conclusions

Adopting the falling film approach in a thermal solar desalination system enhanced the system productivity, giving about 0.6 L/h.m^2. Uniformity of the water film over the black plate seriously affects the amount of water produced. The cumulative water produced varies linearly with time. Cooling the outer glass surface improved water production by 30%.

The amount of water produced was theoretically predicted. An excellent agreement between the theory and the experiments was achieved.

6. Symbols

A — Area, m^2
C — Salt concentration, mg/L
C_p — Heat capacity, kJ/kg-°C
H_v — Vapor enthalpy, kJ/kg
$\dot{m}_E$ — Exit water flow rate, kg/s
$\dot{m}_F$ — Feed water mass flow rate, kg/s
$\dot{m}_P$ — Produced water mass flow rate, kg/s
Q — Solar irradiation, W/m^2
Q_R — Average solar irradiation over a time interval (t_1–t_2)

t — Time, s
T_E — Exit water temperature, °C
T_f — Average film temperature = $(T_F+T_E)/2$
T_F — Feed water temperature, °C
T_p — Produced water temperature, °C
V_p _ Volume of the produced water, ml

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