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Some Parameters Affecting The Productivity of Single-Slope Solar Still

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Abstract: Consumption of fresh water is increasing all over the world mainly due to the population explosion and the rapid industrial growth. Solar distillation is one of the most important methods of utilizing solar energy for supplying potable water to small communities where the natural supply of fresh water is inadequate, and where sunshine is abundant. This investigation is an attempt to study the effect of brine volume on daily productivity of active single-slope distillation system under local climatic condition. Other different parameters (i.e. solar radiation, ambient temperature and heat transfer coefficients) to enhance the productivity were also studied. The system was tested using different brine volumes from 15 l to 75 l on a south facing, single slope, and solar still of 30° inclination of condensing cover coupled with a flat plate collector. The results indicated that the increase of brine volume decreased the productivity, while the still productivity is found to be proportional to the solar radiation intensity. The daily efficiency ranged from 32 to 45% and the solar still distillate output ranged from 3.33 to 4.74 $l/m^{-2}d^{-1}$. The maximum daily efficiency was obtained at the lowest brine volume (15 l), and the minimum daily efficiency was obtained at the highest brine volume (75 l). Also the heat transfer coefficients decreased with increasing brine volume due to decreases in water temperature.

***Keywords*:** Solar distillation; still productivity; still efficiency.

INTRODUCTION

Egypt is considered one of the richest countries of the world in solar energy potential. Mosalam (1998) reported that most of the Egyptian lands receive a considerable annual average of solar radiation, ranging between 5.6 $kWh/m^2/d$ at Marsa Matrouh in the north coast and 6.5 $kWh/m^2/d$ at Aswan in the south of Egypt. Also, it is found that the mean value of the energy density ranges from 500 to 1400 W/m^2. At the same time, some small communities living in remote areas are suffering from a scarcity of fresh water. These communities obtain their share of fresh water from other places by transportation. Thus, producing fresh water by a solar still would be suitable solution of the water shortage problem.

Other equally important functions of providing water in this manner are that it can be used for irrigating farm lands (Constantz, 1989; Krous *et al.,* 2009). Water produced in this way can be fed to plants using a drip irrigation method to maximize its value. Constantz (1989) had proposed a method for combining solar distillation and drip irrigation to simultaneously desalinize water and apply this water to row crops. His results indicated that distillation irrigation include the ability to convert impaired water resources to water containing no salts or sediments; and to efficiently and automatically irrigate crops at a rate that is controlled primarily by radiation intensities

The first "conventional" solar still plant was built in 1872 by a Swedish engineer Charles Wilson in the mining community Salinas in what is now northern Chile. This still of Las was a large basin-type still used for supplying fresh water with very high salinity. Thereafter many design variations exist with a wide variety of construction materials. The amount of produced distilled water varies dramatically with the geographical position, the sun's position, prevailing meteorological conditions, solar still design, and operational techniques (Malik *et al.,* 1982). Akash *et al.* (2000) found that other parameters such as water depth, salinity, black dye, wind speed and direction have an effect on the output of the solar stills.

The basic principles of solar water distillation are simple, yet effective, as distillation replicates the way by which nature purifies water. When the water evaporates water vapor rises and then condenses on the glass surface for collection. This process removes impurities such as salts and heavy metals, as well as destroys microorganisms (Al-Hayek and Badran, 2004). Solar energy is the best alternative heating energy source. It is inexhaustible, clean and available in almost all parts of the world. The use of solar energy is more economical than other energy sources such as fossil fuels especially in remote areas having low population densities, low rainfall and abundant solar energy. Solar stills can easily provide enough water for family drinking and cooking needs (Hamdan *et al.,* 1999).

The performance of solar stills can be improved by using non-conventional designs. Naim and Abd El Kawi (2002) constructed a solar still in which charcoal particles bed was used as an absorber medium and a wick. The productivity was improved by 15% over wick-type stills. Several theoretical and experimental studies were conducted on cooling the glass cover by following water film in the cover. Wibulswas and Tidtiam (1984) and Abu-Hijleh (1996) studied the regenerative effect on the vertical wall of a solar still, an arrangement of cold water to follow over the vertical glass cover. Their results indicated an increase in productivity. Nafey *et al.* (2001) studied the effect of different parameters such as rubber thickness and gravel size. They found that black rubber improves the productivity by 20% at the condition of 60 l/m^2 brine volume and 19% when black gravel of 20-30 mm size was used at the condition of 20 l/m^2 brine volume.

Many researches have been carried out to increase the productivity per unit area of the still by increasing the rate of condensation or the rate of evaporation

(Garg, 1987). Metias (1999) used an external reflector to increase the input energy to the still which results in an increase in water basin temperature. Although there were increases of glass cover outer surface temperature due to the reflector, the daily productivity was improved to some extent. Tanaka and Nakataka (2006) conducted a theoretical analysis of a basin type still with internal and external reflectors. They found that the internal and the external reflectors increased the distillate productivity throughout the year except for the summer season, this increase for the entire year would be averaged as 48%. Recently, Tiwari *et al.* (2003*a*) have studied the convective heat transfer coefficient for a passive/active solar still by using inner glass cover temperature for a limited period of operation, but they did not consider different water depths in the basin to calculate the convective heat transfer coefficient. Furthermore, Tiwari *et al.* (2003*b*) reviewed the present status of research work on both passive and active solar distillation systems. Tripathi and Tiwari (2005) studied the effect of different water depths in the basin on the heat and mass transfer coefficients. They concluded that the convective heat transfer coefficient between water and inner condensing cover depends significantly on the water depth in the basin, they also observed more yield during the off shine hours as compared to daytime for higher water depths in solar still (0.10 m and 0.15 m) due to storage effect.

The objective of this study was to determine the effect of brine volume on daily productivity of active single-slope distillation system under local climatic condition. Other different parameters (i.e. solar radiation, ambient temperature and heat transfer coefficients) to enhance the productivity were also studied.

THEORETICAL BACKGROUND

Heat and mass transfer processes in the solar still.

In the studies published about solar stills, it is assumed that heat and mass transfer processes take place in a few millimeters limit layer over the evaporation surface (water) and the condensation surface (glass), and the air in the solar still is considered in isothermal conditions (Kudish, 1991).

The heat transferred by free convection of humid air q_{cw} (W/m^2) between glass and water surfaces inside the still, is proportional to the difference of their temperatures (T_w and T_g, respectively)

$$q_{cw} = h_{cw}\left(T_w - T_g\right) \tag{1}$$

The coefficient of heat transfer by free convection h_{cw} (W/m^2 K) for horizontal surfaces can be expressed by the dimensional numbers of Nusselt (Nu), Grashoff (Gr) and Prandtl (Pr):

$$\mathrm{Nu} = \frac{h_{cw} l}{k_{as}} = \mathrm{C}\,(\mathrm{Gr}\,\mathrm{Pr})^{\mathrm{n}} \tag{2}$$

Where, k_{as} is the thermal conductivity of saturated air (W/m K), l is the distance between water and glass surfaces (m), C and n are parameters depend on Gr value for solar stills where a turbulent regime can be considered for air flow, Malik *et al.* (1982) proposed values of C = 0.075 and n = 1/3. These coefficients are valid for free convection from a horizontal surface without evaporation.

For solar stills where there is a simultaneous mass transfer, these authors proposed adjustment of the Gr number with an equivalent temperature increase calculated by:

$$\Delta T' = \frac{\left(P_w - P_g\right)\left(273 + T_w\right)}{268.9 \times 10^3 - P_w} + \left(T_w - T_g\right) \tag{3}$$

The constant in the previous expression is valid for systems with humid air at atmospheric pressure.

For the usual conditions of solar radiation and temperature in a solar still, Dunkle (1961) obtained h_{cw} coefficient using the following expression:

$$h_{cw} = 0.884\left[\frac{\left(P_w - P_g\right)\left(273 + T_w\right)}{268.3 \times 10^3 - P_w} + \left(T_w - T_g\right)\right]^{1/3} \tag{4}$$

Where, P_w is the saturated water vapor pressure at basin water temperature (Pa) and P_g is the saturated water vapor pressure at glass temperature (Pa).

So, the rate of the heat transfer by convection is:

$$h_{cw} = 0.884\left[\frac{\left(P_w - P_g\right)\left(273 + T_w\right)}{268.3 \times 10^3 - P_w} + \left(T_w - T_g\right)\right]^{1/3}\left(T_w - T_g\right) \tag{5}$$

Mass and heat transfer by evaporation between water and glass in the solar still.

The heat transfer rate from the water surface to the glass q_{ew} (W/m^2) due to evaporated mass transfer is the mass flow m_w (kg/m^2 s) multiplied by water vaporization latent heat λ (J/kg):

$$q_{ew} = m_w \cdot \lambda \tag{6}$$

The heat transfer can be calculated by multiplying an equivalent coefficient for transfer by evaporation h_{ew} (W/m^2 K) by the difference between the partial pressure of water vapor at water and glass temperatures $(P_w - P_g)$:

$$q_{ew} = h_{ew}\left(P_w - P_g\right) \tag{7}$$

Based on experimental data for solar stills, Malik *et al.* (1982) obtained the relationship between heat transfer coefficients by convection and by evaporation (h_{ew} / h_{cw}) :

$$h_{ew} / h_{cw} = 16.273 \times 10^{-3} \tag{8}$$

Introducing this relationship in equation (7) leads to:

$$q_{ew} = 16.273 \times 10^{-3} h_{cw}\left(P_w - P_g\right) \tag{9}$$

From equation (6), distilled water production per hour and m^2 of still basin can be expressed as:

$$m_w = \frac{q_{ew}}{\lambda} 3600 \tag{10}$$

EXPERIMENTAL PROCEDURE

A solar still system was designed, installed and tested at the Agricultural Engineering Department, Faculty of Agriculture, Suez Canal University. A single sloped solar still was coupled with a solar water collector. The still was made of a rectangular iron basin (1.3 m x 0.8 m) and 0.1 m depth. The bottom frame was constructed of black painted wood. It was insulated from below by a 0.02 m of rock wool (thermal conductivity = 0.0346 $Wm^{-1}k^{-1}$). The basin area of 1.04 m^2 was filled with brackish water with E.C. of 35000 ppm (obtained from Suez Canal) supplied to it from a collector which preheats the water to act as an enhancer to the solar still. The solar still was covered with glass sheet (4 mm thick) to transmit the maximum possible of solar radiation flux incident on it. It was orientated to face the south direction with an inclination angle of 31°. This inclination angle may be maximized the solar radiation flux incident. Moreover, with this inclined angle (31°) condensation will run down the underside into the trough rather than dropping from cover into the basin. A trough running along the bottom side of the glass cover ensures the collection of the distilled water and leads it to the distilled water-collecting vessel and then measured by a graduated cylinder. The system has the capability to collect distillates from three sides of the still (i.e. the north, south and east sides). Rubber is used to prevent leakage from any gab between the glass cover and the still box. An inlet pipe is also fixed at the rear wall of the still for feeding brackish water.

A photograph of the still-collector system is shown in Fig. (1). Schematic diagram of solar still coupled with a flat-plate collector is shown in Fig. (2a). Also, Fig. (2b) shows a cross section view of solar still. The hot water from the collector was pumped into the basin of the still to increase the temperature difference between the glass and water surface. The pump was operated only during the sunshine hours, i.e., from 8:00 am to 5:00 pm, and was kept off during off-sunshine hours to avoid heat losses caused by reverse flow. The brine volume effect was studied by filling the basin of the solar still with water at different brine volumes: 15, 30, 45, 60 and 75 l. Water temperature, inner glass temperature, outer glass temperature, vapor temperature and total radiation on the glass cover were measured every hour for a period of 10 hours for different brine volumes.

Temperature of water, glass and vapor as well as the ambient temperature were recorded with the help of calibrated copper constantan thermocouples and a digital temperature indicator having accuracy of 0.1 °C. The distillate output was recorded with the help of a measuring cylinder. The solar intensity was measured by using a calibrated solar-meter. The hourly variation of solar intensity, water, glass, ambient temperatures and hourly output for different depths of water in solar still were recorded.

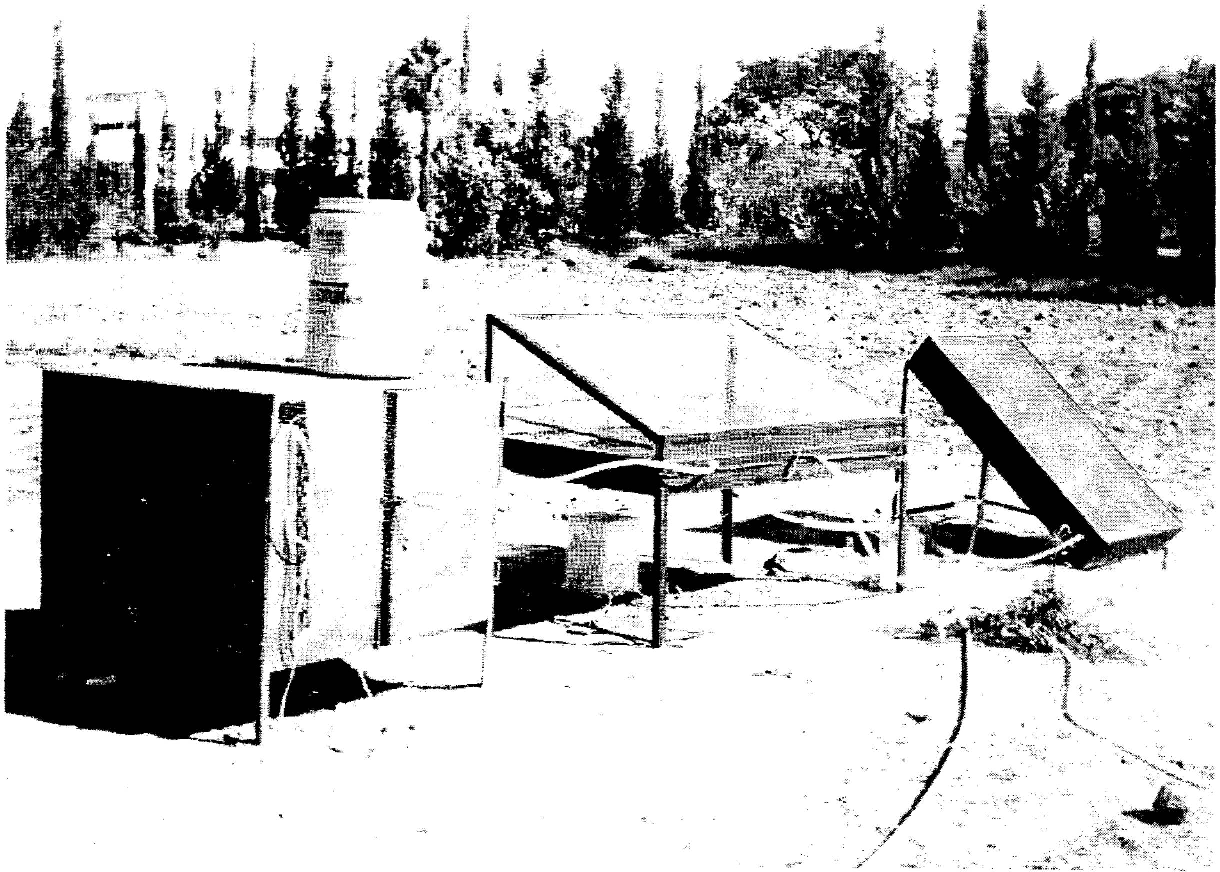

Fig. (1): Photograph of the solar still-collector system.

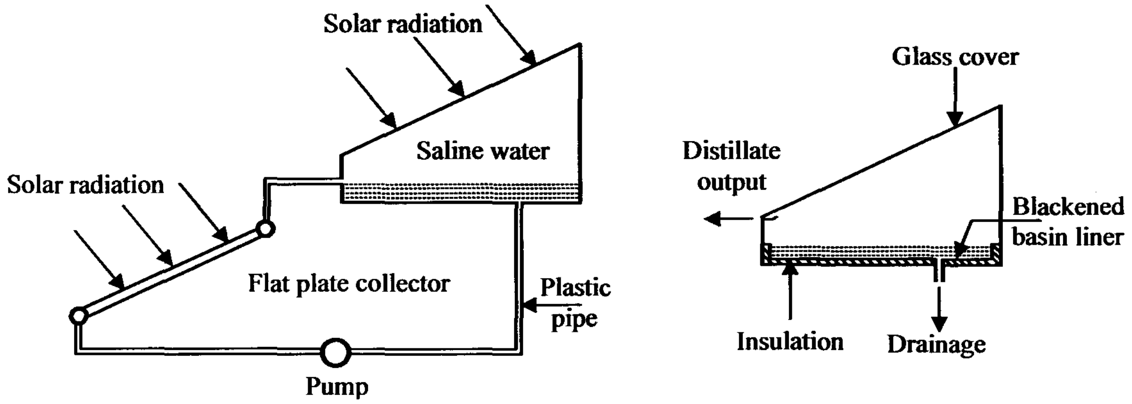

Fig. (2): Schematic diagram of solar still. (a) solar still coupled with a flat-plate collector (b) Cross sectional view of solar still.

RESULTS AND DISCUSSION

The hourly temperatures of basin water and inner glass for different brine volumes are shown in Figs. (3) and (4) respectively. As expected, it is explicit that the fluctuation in temperatures decreases with increase of brine volume due to storage effect. It is obvious that water temperature decreases as brine volume increases throughout the test. The same trend was also observed for inner glass temperature which decreased as brine volume increased. The maximum recorded temperature of basin water was 77.1, 73.1, 71.1, 68.0 and 56.3 °C for 15, 30, 45, 60 and 75 l brine volume, respectively, and the maximum recorded temperature of inner glass was 71.1, 67.7, 66.1, 64.2 and 53 °C for 15, 30, 45, 60 and 75 l brine volume, respectively. The maximum registered difference in temperature (Δt) between basin water and inner glass temperatures was 6.0, 5.4, 5.0, 3.8 and 3.3 °C for 15, 30, 45, 60 and 75 l brine volume, respectively. This difference occurred at 13 hour for all brine volumes.

It is a well-known that the amount of received distillate output will be higher when the temperature of evaporative surface is high and the temperature of condensing surface is low. In other words, the higher temperature of evaporative surface and lower temperature of condensing surface will lead to abundant distillate output. Fig. (5) shows the difference in temperature (Δt) between water and inner glass throughout the day for all brine volumes in still. It is clear that during morning hours glass encounters the radiation first and its temperature rises very fast compared to the rise in water temperature, and as a result the difference becomes negative. These differences remains negative till water temperature exceeds glass temperature. The higher the brine volume the higher the negative value of Δt. The lowest negative difference (Δt) was -8.2 °C attained by higher brine volume of 75 l and -4.3 °C for the lowest brine volume of 15 l. The more the brine volume is the more stored energy within the water in the form of sensible heat.

The volumetric rates of distilled water produced from different brine volumes are presented in Fig. (6). As shown in Fig. (6), the production rate increased very slowly at the beginning due to warming of the still and the somewhat low solar energy during the morning hours. The production rate reached its maximum value at about 13 hour for brine volumes 15 and 30 l, and about 14 hour for brine volumes 45, 60 and 75 l, after that it begins to decrease. This figure also indicated that as the brine volume increased from 15 to 75 l the output decreases by 29.8%. Also, it can be noted that the hourly yield of 75 l brine volume was the lowest compared to the other brine volumes. According to Tiwari and Tiwari (2006) this result could be due to the facts that the yield is the product of evaporative heat transfer coefficient and ΔT. When one of these two parameters is low the yield will subsequently be low. In case of higher brine volume the water and inner cover temperature both remain on the higher side and ultimately ΔT falls, which reduces the yield obtained.

Fig. (7) shows the productivity of the still as a function of brine volume. It is evident that the productivity decreased with the increase of brine volume. This increase in still productivity as the brine volume decreased could be attributed to the lower heat capacity of the water basin that resulted in a higher temperature in the basin and increased the evaporation rate. It can be concluded that the output of the still (with E. C. of 500 ppm in average) reached its maximum value at the lowest brine volume in the basin (15 l). Therefore the 15 l brine volume was used for all experiments in order to determine different effects on the still productivity.

The daily efficiency of solar still using the different brine volumes was determined and illustrated in Fig. (8). From this figure it can be concluded that, the maximum daily efficiency was obtained for the lowest brine volume (15 l). Moreover, the minimum daily efficiency was obtained at the highest brine volume (75 l). The daily efficiency ranged from 32 to 45% and the solar still distillate output ranged from 3.33 to 4.74 $\mathrm{l/m^{-2}\,d^{-1}}$.

The influence of climatic conditions and mainly solar radiation on the system production was also investigated without coupling the collector (still alone). The variation of the daily solar still output and the average solar radiation for different days in October are shown in Fig. (9). The figure shows that the still productivity is proportional to the solar radiation intensity, which depends on climatic condition of each day. The effect of the ambient temperature is shown in Fig. (10). It can be seen from this figure that gradual increase in the ambient temperature tends to increase the yield of the solar still.

The heat transfer from the water surface to the condensing cover inside the solar still occurs in three different modes convection, radiation, and evaporation. The variation of heat transfer coefficients of different brine volume is shown in Fig. (11). These coefficients were calculated as daily average of each brine volume. The evaporative heat transfer coefficient (h_{ew}) is the maximum and radiative heat transfer coefficient (h_{rw}) is the minimum where as the convective heat transfer coefficient (h_{cw}) is the lowest. This figure also indicated that the heat transfer coefficients decreases with increasing brine volume due to decreases in water temperature. More evaporative heat transfer coefficient is desirable for more output.

The heat transfer in solar distillation could be occurred by two modes i.e. external and internal heat transfer. The external heat transfer mode is governed by conduction, convection and radiation processes, which are independent of each other. These heat transfers occurred outside the solar distiller from the cover, bottom and side insulation. The heat transfer within the solar distiller is referred to be internal heat transfer mode, which consists of radiation, convection and evaporation. The convective heat transfer occurs simultaneously with evaporative heat transfer and these two heat transfer processes are independent of radiative heat transfer.

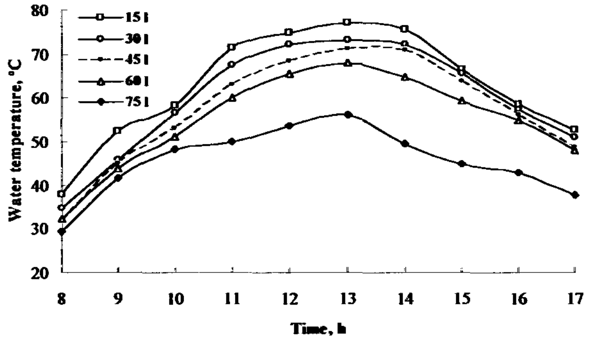

Fig. (3): Variation of water temperature for different brine volumes.

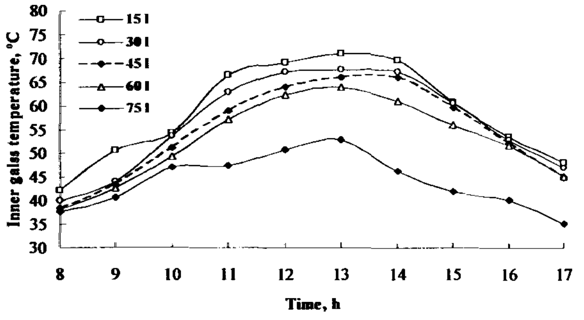

Fig. (4): Variation of inner glass temperature for different brine volumes.

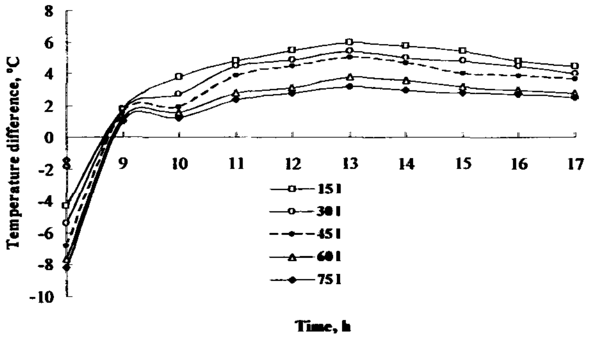

Fig. (5): Temperature difference (Δ*t*) of water and inner glass for different brine volumes.

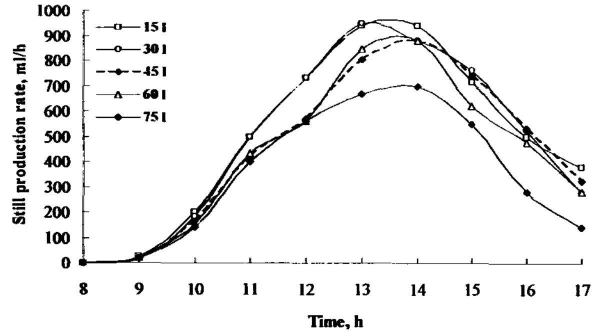

Fig. (6): Volumetric production rate for all brine volumes as a function of the hour of the day.

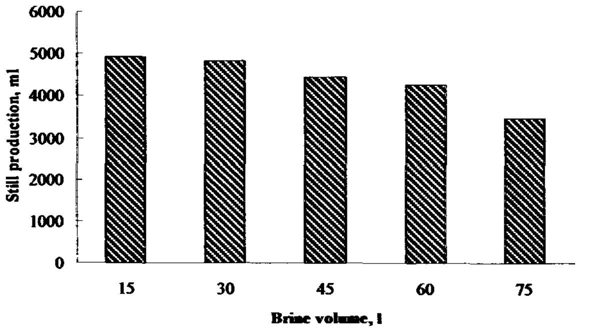

Fig. (7): Effect of brine volume on solar still productivity.

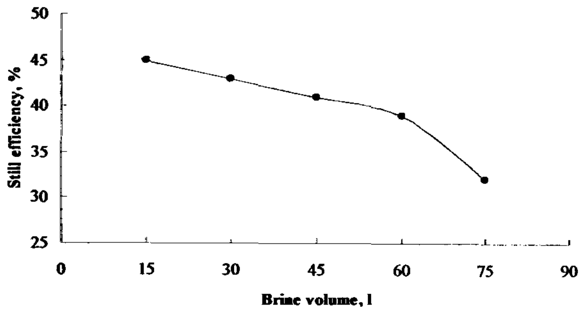

Fig. (8): Efficiency of solar still for different brine volumes.

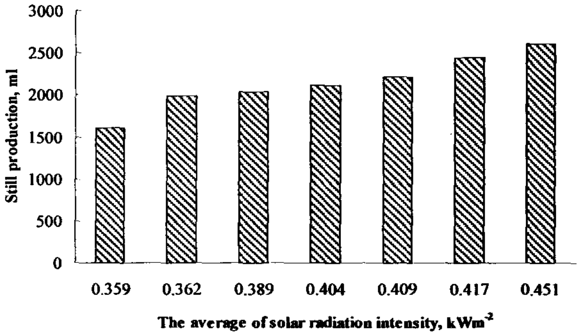

Fig. (9): The relation of solar intensity and still output during October.

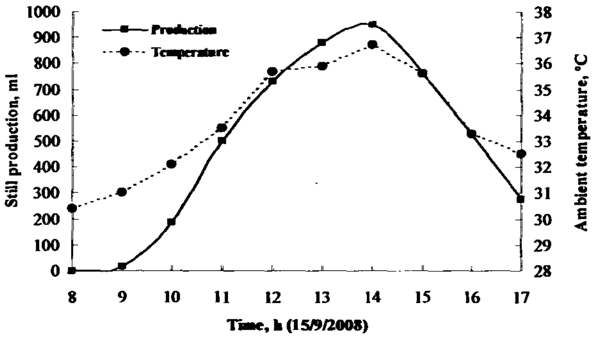

Fig. (10): Effect of ambient temperature on solar still productivity.

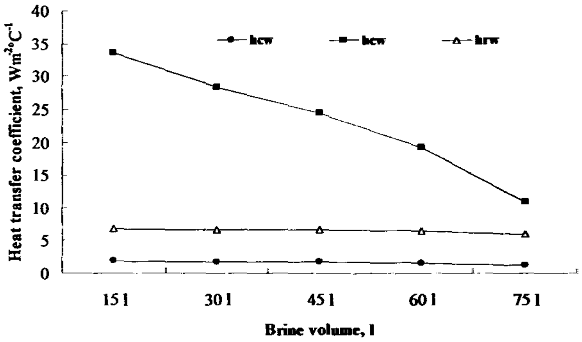

Fig. (11): Variation of heat transfer coefficient of different brine volumes.

CONCLUSION

The obtained results from this study have been led to the following concluded points:

1. As the brine volume increased from 15 to 75 l, the output decreases by 29.8%.
2. The maximum daily efficiency was obtained at the lowest brine volume (15 l), and the minimum daily efficiency was obtained at the highest brine volume (75 l). The daily efficiency ranged from 32 to 45% and the solar still distillate output ranged from 3.33 to 4.74 l/m^{-2} d^{-1}.
3. The still productivity is proportional to the solar radiation intensity, which depends on climatic condition of each day.
4. The gradual increase in the ambient temperature tends to increase the yield of the solar still.
5. The calculated evaporative heat transfer coefficient (h_{ew}) is maximum and radiative heat transfer coefficient (h_{rw}) is minimum where the convective heat transfer coefficient (h_{cw}) is the least, these coefficients decreased with increasing brine volume.

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دراسة بعض العوامل المؤثرة علي إنتاجية وكفاءة وحدة تقطير شمسي ذات الميل من جانب واحد

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أجري هذا البحث بقسم الهندسة الزراعية – كلية الزراعة - جامعة قناة السويس ويهدف إلي دراسة بعض العوامل التي تؤثر علي إنتاجية وكفاءة وحدة تقطير شمسي ذات الميل من جانب واحد تحت الظروف المحلية. وتتكون الوحدة من حوض معدني سمكه ١,٠ مم وأبعاده هي ١,٣ × ٠,٨ × ٠,١ م طول وعرض وارتفاع علي الترتيب ، موضوع داخل صندوق خشبي أبعاده ١,٤٤ × ٠,٩٤ × ٠,١٢ م طول وعرض وارتفاع علي الترتيب ، تم عزل الحوض المعدني من الجوانب بطبقة من الفوم سمكها ٠,٠٧ م ومن الأسفل بطبقة من الصوف الزجاجي سمكها ٠,٠٢ م. أما سطح التكثيف الرئيسي فهو عبارة عن غطاء من الزجاج الشفاف بسمك ٤ مم موجه ناحية الجنوب ويميل بزاوية مقدارها ٣١ درجة علي الأفقي للسماح للقطرات المتكاثفة بالسريان إلي قناة التجميع الموجودة أسفل الغطاء من الناحية الأمامية. والوحدة متصلة بخزان بلاستيك سعة ٥٠ لتر لإمداد الوحدة بمياه البحر. تم توصيل وحدة التقطير بسخان شمسي، والذي يتكون من سطح ماص مطلي باللون الأسود أبعاده ١,٢ × ٠,٦ م طول وعرض بالترتيب. ويحتوي السخان علي ٢٠ أنبوبة نحاسية بقطر داخلي ٦ مم والمسافات البينية ٠,٠٣ م. تم استخدام خمسة أحجام مختلفة من ماء البحر(١٥، ٣٠، ٤٥، ٦٠ و٧٥ لتر) لدراسة تأثير حجم الماء المستخدم علي كفاءة وإنتاجية الوحدة وكذلك حساب معامل انتقال الحرارة بالحمل والإشعاع والتبخير في كل حالة من الحالات السابقة. وتم تشغيل الوحدة بمفردها لدراسة تأثير كل من الإشعاع الشمسي ودرجة الحرارة المحيطة علي الإنتاجية.

وقد أوضحت النتائج ما يلي:

١. بزيادة حجم الماء من ١٥ إلي ٧٥ لتر تنخفض الإنتاجية بمقدار ٢٩,٨ %.
٢. تم الحصول علي أعلي كفاءة للوحدة عند استخدام الحجم ١٥ لتر وأقل كفاءة عند استخدام الحجم ٧٥ لتر وكانت قيم الكفاءة هي ٤٥، ٤٣، ٤١، ٣٩، ٣٢ % لكل من ١٥، ٣٠، ٤٥، ٦٠، ٧٥ لتر علي الترتيب.
٣. كان معدل إنتاج الوحدة ٤,٧٤، ٤,٦٣، ٤,٢٧، ٤,١، ٣,٣٣ لتر/م^{٢}/يوم لكل من ١٥، ٣٠، ٤٥، ٦٠، ٧٥ لتر علي الترتيب.
٤. تتناسب إنتاجية الوحدة طرديا مع درجة الحرارة المحيطة حيث تزداد الإنتاجية تدريجيا من بداية التشغيل صباحا حتي تصل إلي أعلي معدل عندما تصل درجة الحرارة المحيطة إلي أقصاها ثم تبدأ الإنتاجية بعد ذلك في الانخفاض التدريجي.
٥. أعلي قيمة لمعامل انتقال حرارة هي معامل انتقال الحرارة بالتبخير يليه معامل انتقال الحرارة بالإشعاع بينما كانت قيمة معامل انتقال الحرارة بالحمل هي الأقل، وقد وجد أيضاً أن قيمة هذه المعاملات تقل بزيادة حجم ماء البحر داخل الوحدة.