Performance of finned and corrugated absorbers solar stills under Egyptian conditions

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ABSTRACT

An experimental study was conducted to improve the productivity of basin solar stills by increasing the surface area of absorber (base of still) and rate of heat transfer between saline water and absorber. In view of this, three solar stills are designed and fabricated in order to study the performance of each still. The first one is a conventional type and the second is a finned still while the third one is corrugated still. The performance of the finned and corrugated solar stills is tested and compared with conventional still under the same climate conditions. The performance of different solar stills were tested under two cases; stills at the same water depth (50 mm) and stills at the same quantity of saline water (30 and 50 l). The results indicate that the productivity of finned and corrugated solar stills is higher than that for conventional still. Also it is found that at quantity of saline water 30 l the productivity increased, when finned solar still and corrugated solar still are used approximately by 40% and 21% respectively. In this case the daily efficiency and estimated cost of 1 l of distillate for finned, corrugated and conventional solar stills are approximately 47.5%–0.041 $, 41%–0.047 $ and 35%–0.049 $ respectively.

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1. Introduction

The supply of drinking water is one of the major problems in developing countries. Clean water is a basic human necessity, and without water the life will be impossible. Nowadays the pollution in rivers and lakes by industrial effluents and sewage disposal resulted in scarcity of fresh water in many big cities around the world. In addition, with an ever increasing population and rapid growth of industrialization, there is a great demand for fresh water, especially for drinking.

A single basin solar still is a very simple solar device used for converting available brackish or waste water into potable water. This device can be fabricated easily with locally available materials. The maintenance is also cheap and no skilled labor is required. Moreover, it can be a suitable solution to solve drinking water problem. Productivity of such solar stills is very low. To enhance the productivity of the solar still, various research works are being carried out. The basin area of the still, free surface area of the water, depth of the water in the still and inlet water temperature are considered as the main factors affecting the productivity of the solar still.

Increase in basin area of the solar still is the main objective under study. To increase the basin area, fins [1–3] were used. Velimurugan et al. [1] investigated the integration of fins at the basin of the still and showed the increase of daily productivity from 1.88 to 2.8 kg/m² day as compared to other types. The fin type solar still is modified with black rubber, sand, pebble and sponge for enhancing its productivity by Velimurugan et al. [2]. They also concluded that the maximum increase in productivity of 75% occurs, when the fin type solar still was integrated with sand and sponge. Also, Velimurugan et al. [3] studied the augmentation of saline streams in solar stills integrated with a mini solar pond. Industrial effluent was used as feed for fin type single basin solar still and stepped solar still. The results showed that, maximum productivity of 100% was obtained when the fin type solar still was integrated with pebble and sponge.

Also, many researchers used fins for increasing the heat transfer rate. Experimental study of thermal performance of offset rectangular plate fin absorber-plates was studied by Hachemi [4]. For solar air heating collectors, optimized finned absorber geometries were studied by Pottler et al. [5]. To save material content in the fin material, Hollands et al. [6] introduced a ‘step-change’ in fin thickness. Heat removal from a triangular finned flat-plate solar-energy collector was analyzed by Norton et al. [7]. A finned double-pass photovoltaic-thermal solar collector was studied by Othman et al. [8]. Energy analysis of a solar air collector with rows of fins was studied by Moumni et al. [9]. Hellstrom [10] derived efficiency factors for uneven irradiation on a fin absorber. Harmim et al. [11] investigated a finned cooking vessel in order to increase the efficiency of solar cookers and to reduce cooking time.

Several investigations have been carried out on natural convection heat transfer and fluid flow with corrugated surfaces. Ali and Husain [12] investigated the effect of corrugation frequencies on natural convection heat transfer and flow characteristics in a square enclosure.
of vee corrugated vertical walls. This investigation showed that the overall heat transfer through the enclosure increased with the increase of corrugation in the case of low Grashof number, and a reverse trend was shown for high Grashof number. Later Ali and Ali [13] carried out a finite element analysis of laminar convection heat transfer and flow of the fluid bounded by vee corrugated vertical plate of different corrugation frequencies. Rakesh and Marc [14] investigated the thermal performance of integrated collector storage solar water heater with a corrugated absorber surface. The results indicated that, the introduction of a corrugated absorber surface over plane surface in collector/storage type solar water heater is an option to get more useful heat at higher temperature. The double-flow solar air heater having different obstacles on absorber plates were tested by Esen et al. [15–18]. The results demonstrate that increasing the absorber plate shape area will increase the heat-transfer to the flowing air.

When the exposed area of basin water is high, then the air mass subjected to natural convection inside the still will take more amounts of water particles. The water wets the surface of the materials available in the basin and exposed to a larger area and ready for diffusion. Nafey et al. [19,20] used black rubber and gravel for augmenting the productivity of the solar still. They showed that black rubber, black gravel and floating perforated black aluminum plate in the solar still increase the solar still productivity by 20%, 19% and 15% each, respectively. The performance of a solar still with different size sponge cubes placed in the basin was studied experimentally by Abu-Hijleh and Rababa’h [21]. The results indicated that the increase in distillate production of the still ranged from 18% to 27% compared to an identical still without sponge cubes under the same conditions.

From the previous work, it is seen that, increasing the basin area leads to an increase in the overall productivity of the solar still. Therefore, the goal of this study is to compare the performance of conventional single basin solar still with finned and corrugated solar stills under Egyptian climate.

2. Experimental setup

In this work, three solar stills were designed and fabricated to study and compare the performance of the solar desalination systems, as shown in Fig. 1. The first one is a conventional still and the second is a finned still while the third is a corrugated still. The conventional still (a single basin) has a basin area of 1 m² (50 cm × 200 cm). High-side wall depth is 49 cm and the low-side wall height is 20 cm, as shown in Fig. 2a. The still is made of iron sheets (1.5 mm thick). The whole basin surfaces are coated with black paint from inside to increase the absorptivity. Also, the still is insulated from the bottom to the side walls with sawdust 4 cm thick to reduce the heat loss from the still to ambient. The insulation layer is supported by a wooden frame. The basin is covered with a glass sheet 3 mm thick inclined at nearly 30° horizontally, which is the latitude of Kafrelsheikh city, Egypt, to maximize the amount of incident solar radiation. The whole experimental setup is kept in the south direction to receive maximum solar radiation throughout the year.

The finned still shown in Fig. 2b has the same construction and dimensions of the conventional one in addition to the nineteen fins which are welded to the still base to increase the heat transfer surface area. The fins are made of iron sheet with a height, length and breadth of 50, 490 and 1 mm, respectively. The pitch between two successive fins is taken as 100 mm and kept constant.

Also, the corrugated still shown in Fig. 2c has the same construction and dimensions of the conventional one except that the still base is not flat but has a corrugated form with a height of 50 mm. The angle of bending between any two successive tops or any two bottoms is 80°, and the space between any two tops is also taken as 100 mm, so the corrugated still base has nineteen tops and nineteen bottoms of corrugated form.

Feed water tank of 60 × 60 × 80 cm³ is used to feed water to every conventional, finned and corrugated still. The feed water tank is connected to the main line which is divided into three feed water lines. A flow control valve is integrated at each line inlet in order to regulate the flow rate of water as shown in Fig. 1. The experimental setup is suitably instrumented to measure the temperatures at different points of the still (brine, absorber and glass cover temperatures), total solar radiation and the amount of distillate water. The temperatures have been measured using calibrated copper constantan type thermocouples which were integrated with a modeler programmable logic control (MPLC) to measure all temperatures of the solar stills at the same time. The solar radiation intensity is measured instantaneously by a solarimeter. The digital air flow/volume meter is used to measure the wind velocity.

3. Experimental procedure

Experiments were conducted at the Faculty of Engineering, Kafrelsheikh University, Egypt and carried out from 9 a.m. to 8 p.m. during July 2010. The solar radiation, atmospheric temperature, basin temperature, glass temperature and distilled water productivity were measured every 1 h. However, the accumulated productivity during the 24 h is also measured in each experimental. All measurements were performed to evaluate the performance of the stills under the outdoors of Kafrelsheikh City conditions. During the experiments, the ambient climatic conditions (solar radiation, ambient temperature and wind velocity) were also measured.

Saline water in still is heated by solar radiation. The water vapor formed is condensed at the inner glass surface and the water droplets
are glided along the glass. The condensed water is collected in a calibrated flask, as shown in Fig. 1. The depth of the saline water in the solar stills is maintained constant manually using the feed water tank and control valves.

The present experimental study aims to study the effect of still surface area variation on fresh water productivity and the efficiency of basin still at two different cases. The first one is at equalizing the saline water depths inside the three tested stills, while the second case is conducted at equalizing the saline water volume (quantity) in the three tested stills.

4. Experimental uncertainty analysis

In this section, the method by [22] for estimating the uncertainty in the experimental results is presented. Suppose a set of measurement is made in order to measure "n" number of experimental variables. These measurements are then used to calculate some desired result of the experiment (R). Thus

$$R = R(X_1, X_2, X_3, \ldots, X_n).$$

Let $W_R$ be the uncertainty in the result and $W_1, W_2, W_3, \ldots, W_n$ be the uncertainties in the independent variables. The uncertainty in result is calculated according to the equation proposed by [22] as follows:

$$W_R = \left[ \left( \frac{\partial R}{\partial X_1} \right)^2 W_1 + \left( \frac{\partial R}{\partial X_2} \right)^2 W_2 + \ldots + \left( \frac{\partial R}{\partial X_n} \right)^2 W_n \right]^{\frac{1}{2}}. \quad (1)$$

If the relation between the measured parameters and the result is known and the uncertainties of the measurement of each quantity is further known, then the error or uncertainty in the result $W_R$ is calculated according to Eq. (1).

Uncertainty associated with the experimental measurements apparatus is given in Table 1 for thermocouples, solarimeter, anemometer and calibrated flask. The minimum error is equal to the ratio between its least count and minimum value of the output measured [23].

The hourly productivity $m=f(h)$ where $h$ is depth of water in the calibrated flask. Following Eq. (1), total uncertainty for the hourly condensate production can be written as:

$$W_m = \left[ \left( \frac{\partial m}{\partial h} W_h \right)^2 \right]^{\frac{1}{2}}. \quad (2)$$

From the measured data the daily efficiency, $\eta_d$, was calculated by summing up the hourly condensate production $m$, multiplied by the

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Accuracy</th>
<th>Range</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solarimeter</td>
<td>±1 W/m²</td>
<td>0–5000 W/m²</td>
<td>1.5</td>
</tr>
<tr>
<td>Temperature indicator</td>
<td>±0.1 °C</td>
<td>0–100 °C</td>
<td>0.75</td>
</tr>
<tr>
<td>Calibrated flask</td>
<td>±1 ml</td>
<td>0–2000 ml</td>
<td>1</td>
</tr>
<tr>
<td>Anemometer</td>
<td>±0.1 m/s</td>
<td>0.4–30 m/s</td>
<td>1</td>
</tr>
</tbody>
</table>
latent heat of vaporization $h_{fg}$ and divided by the daily average solar radiation $I(t)$ over the whole area $A$ of the device [2]:

$$
\eta_d = \sum m \times h_{fg} / \sum A \times I(t).
$$

If $A$ and $h_{fg}$ are considered constants, it can be written as:

$$
\eta_d = f(m, I(t)).
$$

Following Eq. (1), total uncertainty for the daily efficiency can be written as:

$$
W_{fi} = \left[ \left( \frac{\partial \eta_d}{\partial m} W_m \right)^2 + \left( \frac{\partial \eta_d}{\partial I(t)} W_{bi} \right)^2 \right]^{1/2}.
$$

The total uncertainty in determining the hourly productivity and daily efficiency were estimated by Eqs. (2) and (3), respectively. Calculations show that the total uncertainty in calculating productivity and daily efficiency approximated ±1% and ±2%, respectively.

5. Results and discussion

Depending upon the weather conditions the wind speed is varied from 0.4 to 4.3 m/s at different days and solar intensity is varied from 20 to 1100 W/m². The performance of different solar sills are tested from 0.4 to 4.3 m/s at different days and solar intensity is varied from 5.

Results and discussion

The variation of solar radiation, atmospheric temperature and basin water temperature of stills at the same water depth (50 mm) is shown in Fig. 3. It is observed that the temperatures at all points increase as the time increases till a maximum value in afternoon and start to decrease after that. This is due to the increase of solar radiation intensity in the morning and its decrease in the afternoon. Also, it can be observed from Fig. 3 that, the maximum temperature is obtained during the period from 3 p.m. to 4 p.m. depending upon the quantity of saline water in the still. In the case of corrugated solar still (35 l) the maximum temperature is observed at 3 p.m., while for finned (49 l) and conventional (50 l) stills is observed approximately at 4 p.m. This is because, the largest quantity of saline water needs a larger amount of energy to raise the water temperature and consequently take a longer time.

From Fig. 3 it can be noticed also that before 4 p.m. the basin water temperature of the corrugated solar still is higher than that of the finned and conventional stills by about 0–4 °C and 0–7 °C respectively. After 4 p.m. the basin water temperature of the finned solar still is higher than that of the corrugated and conventional stills by about 0–4 °C and 0–3 °C respectively.

5.2. Results of stills at the same water depth (50 mm)

Comparisons between the hourly variation of fresh water productivity for 1 m²/h of projected area on the horizontal surface in case of modified solar stills and conventional type at constant depth of saline water of 50 mm are illustrated in Fig. 4. From the figure it is found that the maximum fresh water productivity in the afternoon has the highest values for the present solar desalination systems. Also from the figure, it can be observed that, the water productions are increased from zero value in the morning and reached the maximum values in the afternoon. Also, the higher water production is observed in afternoon compared with that before. This is due to low temperature of water in the still in the early morning which needs more time to warm up.

Also, it can be observed from the figure that, the productivity of corrugated still increases as the time increase till a maximum value approximately at 3 p.m. and starts to decrease after that, while the maximum value of productivity for finned and conventional stills nearly at 4 p.m. In addition, it can be seen that, the maximum productivity occurs at maximum temperature of saline water as depicted in Fig. 3.

In addition, Fig. 3 indicates that, the corrugated still has higher productivity from 9 a.m. to 3 p.m. since it has the smallest quantity of saline water (23.75 l) so that it takes a short time for heating and evaporation. The corrugated surface based solar still shows a higher operating temperature for longer time than the plane surface (conventional still), as shown in Fig. 3. While, the finned (48.85 l) and conventional stills (50 l) have the largest quantity of water, therefore need a larger amount of energy to rise the water temperature and consequently take a longer time. Approximately after 3 p.m. The productivity of finned still has a highest value while the productivity of conventional still has a minimum value at all times.

![Fig. 3](image1.png) Hourly temperature variations of basin water and solar radiation for the tested stills at constant depth of saline water 50 mm.

![Fig. 4](image2.png) Comparison between the variations of fresh water productivity for the tested stills at constant depth of saline water 50 mm.
The finned and corrugated surfaces have a higher area exposed to saline water as compared to the conventional still, 1.55 m², 1.34 m² and 1 m² respectively, so that the heat transfer rate between the absorber surface and the water improved, as mentioned in [15]. The measured data indicate that, as a result of area increase the absorber plate temperature and saline water temperature increased, and as the temperature difference between water and glass increases, productivity increased.

Comparisons between the accumulative variations of fresh water productivity from sunrise to sunset (from 9 a.m. to 8 p.m.) for the three tested stills are shown in Fig. 5. It is found that the amount of accumulated distillate water for the corrugated solar still is higher than that of finned and conventional stills.

Measurements of accumulated distillate water during the day for different days of testing are tabulated in Table 2. It can be observed from this table that, at constant depth (50 mm) in all stills it was found that the productivity is increased when the finned solar still and corrugated solar still are used approximately by 20% and 30% respectively as compared to the conventional still. In this case the daily efficiency for finned, corrugated and conventional solar stills are approximately 41%, 45% and 34% respectively.

5.3. Results of stills at the same quantity of saline water (30 and 50 l)

Comparisons between the hourly variation of fresh water productivity for 1 m²/h of projected area on the horizontal surface in case of modified solar stills and conventional still at constant quantity of saline water (50 l) are illustrated in Fig. 6. From the figure it can be observed that, the finned still has a higher productivity, while the productivity of conventional still has a lower value at all times. This is because adding fins in the basin of a conventional single basin still decreases the preheating time required for evaporating of the still basin water, Ref. [2]. Also, using fins in the solar still leads to an increase in the area of the absorber plate. Hence, absorber plate temperature, saline water temperature and productivity increased.

Comparisons between the accumulative variations of fresh water productivity from sunrise to sunset (from 9 a.m. to 8 p.m.) for the three tested stills are shown in Fig. 7. It is found that the amount of accumulated distillate water for finned solar still is higher than that of corrugated and conventional stills. Also measurements of accumulated distillate water during the day for different days of testing at constant quantity of saline water (50 l) tabulated in Table 2. It can be indicate from this table that, the daily productivity increased approximately by 20%, when fins are used and by about 17% with corrugated still. In this case the daily efficiency for finned, corrugated and conventional solar stills is approximately 41%, 40% and 34% respectively.

From Figs. 8 and 9, it is also noticed that at constant quantity of saline water of (30 l) the absorber plate of finned still can absorb more solar radiation due to an increase in exposure area of the base and preheating time for the saline water decreased, thus productivity increased. From Table 2, it is also found that the daily productivity is increased approximately by 40%, when fins are used and by about 21% with corrugated still. In this case the daily efficiency for finned, corrugated and conventional solar stills is approximately 47.5%, 41% and 35% respectively.

6. Cost evaluation

The total cost of conventional still is about 412 $ where the minimum average daily productivity can be estimated from the analysis of different experimental data. Daily productivity is assumed at 2.5 l/m² day, and that the still operates 340 days in a year, where the sun rises along the year in Egypt with the still life at 10 years. The total productivity during the still life is 8500 l. The cost of 1 l from a conventional still = 412/8500 = 0.049 $.

The total cost of finned still is about 490 $ where the minimum average daily productivity can be estimated at 3.5 l/day, assuming that the still operates 340 days in a year with the still life at 10 years.

<table>
<thead>
<tr>
<th>Date</th>
<th>Conventional</th>
<th>Finned</th>
<th>Corrugated</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/7/2010</td>
<td>2650</td>
<td>3200</td>
<td>3400</td>
</tr>
<tr>
<td>10/7/2010</td>
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<tr>
<td>11/7/2010</td>
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<td>4400</td>
</tr>
<tr>
<td>13/7/2010</td>
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<td>3450</td>
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<td>14/7/2010</td>
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<tr>
<td>15/7/2010</td>
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<tr>
<td>20/7/2010</td>
<td>3250</td>
<td>4550</td>
<td>3950</td>
</tr>
</tbody>
</table>
The total productivity during the still life is 11,900 l. The cost of 1 l from a finned still = 490/13,600 = 0.041 $. Also, the total cost of a corrugated still is about 480 $ where the minimum average daily productivity can be estimated at 3 l/day. The cost of 1 l from corrugated still = 480/10,200 = 0.047 $. All estimated costs for different stills are based on 30 l of saline water.

7. Conclusion

The performance of a basin solar still system (conventional still) in addition to two different design modifications is investigated. The experimental results show that the thermal performance of a conventional still can be improved through the design modifications. The integrated fins at the base of the solar still gives an average of 40% increase in the amount of distilled water produced compared with a conventional still, while using the corrugated plate as the base increases the amount of distilled water produced by about 21% compared with a conventional still, at a saline water quantity of 30 l. In this case the daily efficiency and estimated cost of 1 l of distillate for finned, corrugated and conventional solar stills is approximately 47.5%–0.041 $, 41%–0.047 $ and 35%–0.049 $, respectively.

References


