PERFORMANCE OF A PYRAMID SOLAR STILL WITH V-CORRUGATED ABSORBERS PLATE: EXPERIMENTAL STUDY

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ABSTRACT

An experimental work was designed and fabricated to improve the distillate water productivity of the pyramid solar still. A pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still was designed and fabricated at the same ambient conditions of Tanta city, Egypt. The performance of pyramid solar still with v-corrugated absorber plate are compared to conventional pyramid solar still, to describe the enhancement in distillate water productivity of the pyramid solar still with v-corrugated absorber plate. The experimental results showed that the distillate water productivity for pyramid solar still with v-corrugated absorbers plate is higher than that of conventional pyramid solar still. The distillate water productivity reached approximately 6.5 l/m^2 day for pyramid solar still with v-corrugated absorber plate while its value was 4.4 l/m^2 day for conventional pyramid solar still. The percentage improvement in the distillate water productivity for pyramid solar still with v-corrugated absorber plate was about 47.7 % compared to the conventional pyramid solar still in average. Moreover, the average daily efficiency for the pyramid solar still with v-corrugated absorbers plate and the conventional pyramid solar still are 48.4% and 32.76%, respectively. The estimated cost of one liter of distillate water productivity reaches approximately 0.2105 LE and 0.227 LE for pyramid solar still with v-corrugated absorbers plate and conventional pyramid solar still, respectively. This result is obtained during the period from June to August 2016 under the Egyptian conditions.

Keywords: Pyramid solar still, V-corrugated absorbers plate, Productivity improvement, Cost analysis
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1 INTRODUCTION

The increasing demand for freshwater in industry and agriculture and the daily life of human beings is of the utmost importance and especially that the demand is increasing day after day. It is expected that about 70% of the inhabitants of the world would suffer from a shortage of fresh water in 2025 (Hoffman (2008), Bajpayee et al. (2011) and Li CN et al. (2013)). Provision of freshwater is still being the most serious problem in many regions (Tian & Zhao (2013), and Shukla et al. (2013)).

The solar energy for the desalination of water is the most prominent roads, especially when used in areas where the rays of the sun, where fresh water is scarce (Ayoub & Malaeb (2012) and Omara et al. (2014)). A solar still is a very simple solar device used for converting available seawater, brackish and waste water into distillate water. This device can be fabricated easily with locally available materials. The maintenance is also cheap and no skilled labor is required.

Increases in absorber area of the solar still represent the main objective of this study. To increase the absorber area, fins and corrugated absorbers (Velmurugan et al. (2008), Velmurugan et al. (2008), Velmurugan et al. (2009) and Omara et al. (2011)) were used. Velmurugan et al. (2008) conducted the effect of fins at the basin still on the productivity of solar still. The results show that the daily productivity increase from 1.88 to 2.8 kg/m^2 day as compared to conventional still. The fin type solar still is modified with black rubber, pebble, sand and sponge for improving its daily productivity by Velmurugan et al. (2008). They also found that the improvement in the daily productivity reached to 75% for using the fin solar still integrated with sand and sponge. Also, Velmurugan et al. (2009) conducted the effect of pebble and sponge on the productivity of fin type solar still. The results showed that, the daily productivity increase by 100% for using the fin type solar still integrated with pebble and sponge as compared to conventional still. Omara et al. (2011) experimentally studied the performance of finned and corrugated absorbers solar stills and compared it to the conventional still to evaluate the improvement in the still productivity. They found that the productivity increased, when finned solar still and corrugated solar still are used approximately by 40% and 21% respectively compared to conventional still.

Many modifications have been done to increase the productivity of distillate of a basin type solar still, for example: solar collector integrated with basin still (Bacha, 2007), fan integrated with solar still (Ali, 1991), sun trucking system coupled with solar still (Abdallah & Badran, 2008), phase change material under basin solar still (Kabeel & Mohamed Abdelgaied, 2016), phase change material under basin and hot air injection (Kabeel et al., 2016) and cylindrical parabolic concentrator with oil serpentine loop integrated with modified solar still contains phase change material under basin (Kabeel & Mohamed Abdelgaied, 2017). Hiroshi (2009) studied the effect of reflectors on the behavior of a solar still. Omera et al. (2014) investigated the impacts of reflectors on the daily productivity of the modified stepped still. They found that, use the reflectors enhance the daily productivity by 125% as compared to conventional solar still.

Yazan Taamneh & Madhar Taamneh (2012) experimentally investigated the performance of the pyramid solar still. They found that, use the pyramids solar still improve the daily productivity by 25 % as compared to the conventional solar still. Ali Kianifar et al. (2012) investigated the behavior of a pyramid solar still. They found that the exergy efficiency of pyramid solar still is higher than that of conventional solar still, while the cost reduced by 8-9 % compared to conventional solar still. Ravishankar Sathyamurthy et al. (2014) studied the factors effects on the accumulated distillate yield of pyramid solar still. The resulted show that the accumulated distillate yield increased by 15.5 % for increase the wind speed from 1.5 to 4.5 m/s. Kabeel et al. (2016) experimentally studied the impacts of cover angles on the daily productivity of pyramid solar still. The resulted show that, the optimal angles equal to the latitude angle.

Review of previous studies, it is clear that a very large number of research on how to improve the productivity of conventional solar stills, but there are a limited number of research on how to improve the productivity of the pyramid solar stills. Despite that the freshwater productivity of the pyramid solar still is higher than that of conventional solar stills. The aims of the present experimental work improve the daily distillate water productivity of the pyramid solar still by using v-corrugated absorbers plate to increase the rate of the heat absorbed by the absorber plate as well as increase the rate of heat transfer from the absorber plate to the basin water. The performance of the pyramid solar still with v-corrugated absorbers plate are compared to conventional pyramid solar still, to show the enhancement in the daily distillate water productivity of the pyramid solar still with v-corrugated absorbers plate. The pyramid solar still with v-corrugated absorbers plate and the conventional pyramid solar still are designed, constructed and tested at the same ambient conditions.

2 EXPERIMENTAL WORK

In this study, the experimental work have been investigated to show the effect of v-corrugated absorber plate on the performance of pyramid solar still under Egyptian conditions. The performance of the pyramid solar still with v-corrugated absorber plate are compared with conventional pyramid solar still at the same ambient conditions of Faculty of Engineering, Tanta city, Egypt. Fig. 1 shows the schematic diagrams of the pyramid solar still with v- corrugated absorber plate and conventional pyramid solar still. Also, Fig. 2 shows the photo of the present experimental work.

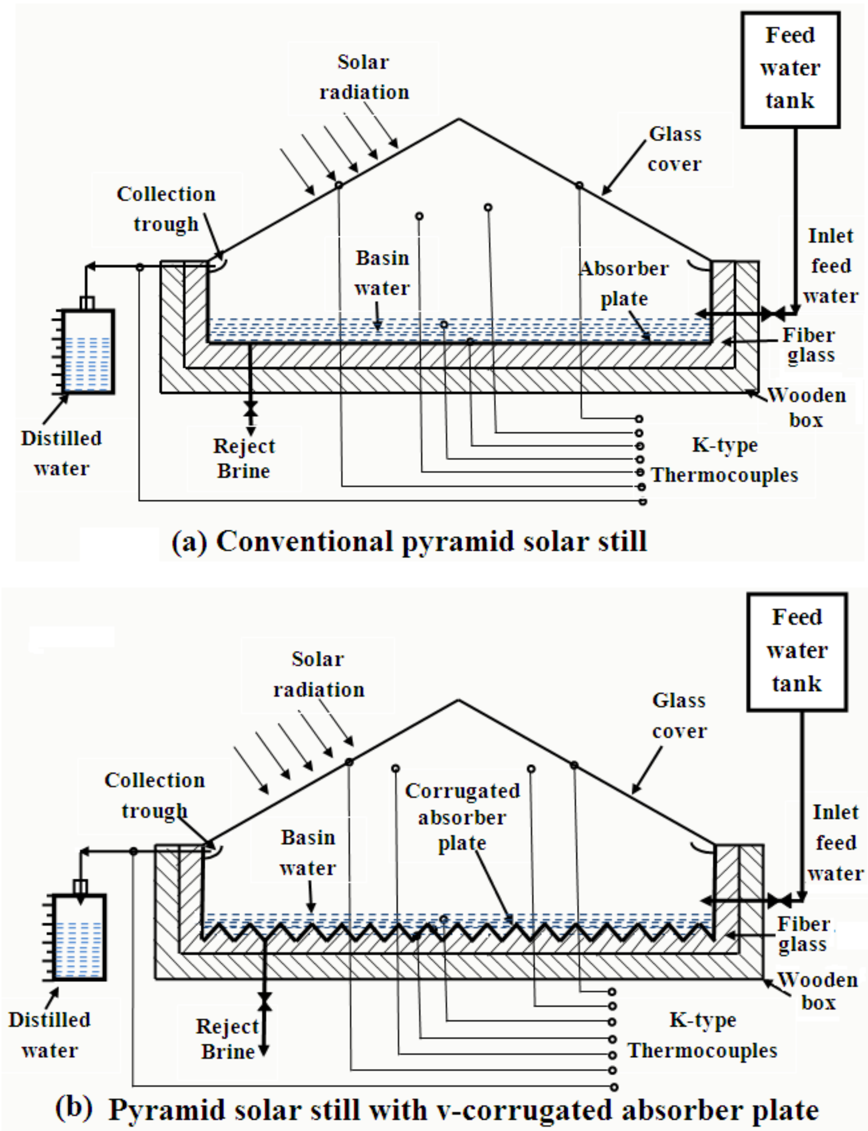

Figure 1. Schematic diagram of experimental work (a) conventional pyramid solar still and (b) pyramid solar still with v-corrugated absorber plate

Pyramid solar still with v-corrugated absorber plate has a square basin made from the copper material 1.5 mm thick with a v-corrugated absorber plate 80 cm × 80 cm. A v-corrugated absorber plate with a height of 3.5 cm, the angle of bending between each successive bend is 60^o. The absorber plate are coated with black paint to increase the absorption of solar radiation. The side walls height 15 cm. The average depth of the basin water are 2 cm, the depth of basin water above top bend 0.25 cm and above the bottom bend 3.75 cm. The whole basins are insulated from the side walls and the bottom with fiber glass of 5 cm thick to reduce the thermal energy loss from the basin to ambient. The insulation layer is supported by a wooden box. The four side of the glass cover made from commercial glass, with a 3 mm thick and it is inclined to the horizontal by 30.47° which is the latitude of Tanta city. The feed brackish water inlet to the basin through the flexible pipe integrated with the flow control valve to keep the depth of basin water constant. The condensate channel fixed at the end of the four side glass covers to collect the condensates water.

Conventional pyramid solar still has a square basin area made from a galvanized sheet of 80 cm × 80 cm × 1.5 mm thick. The height of side walls is 15 cm. The bottom and side walls of the basin of the pyramid solar still are coated with black paint to increases the absorption of solar radiation. The whole basins are insulated from the side walls and the bottom with fiber glass of 5 cm thick to reduce the thermal energy loss from the basin to ambient. The insulation layer is supported by a wooden box. The four side of the glass cover made from the commercial glass cover with 3 mm thick and was inclined 30.47^o on horizontal (Latitude angle of Tanta city – Egypt). The depths of basin water remain constant at 2 cm depth. The condensate channel fixed at the end of the four side glass covers to collect the condensates water. The feed brackish water inlet to the basin through the flexible pipe integrated with the flow control valve to keep the depth of basin water constant.

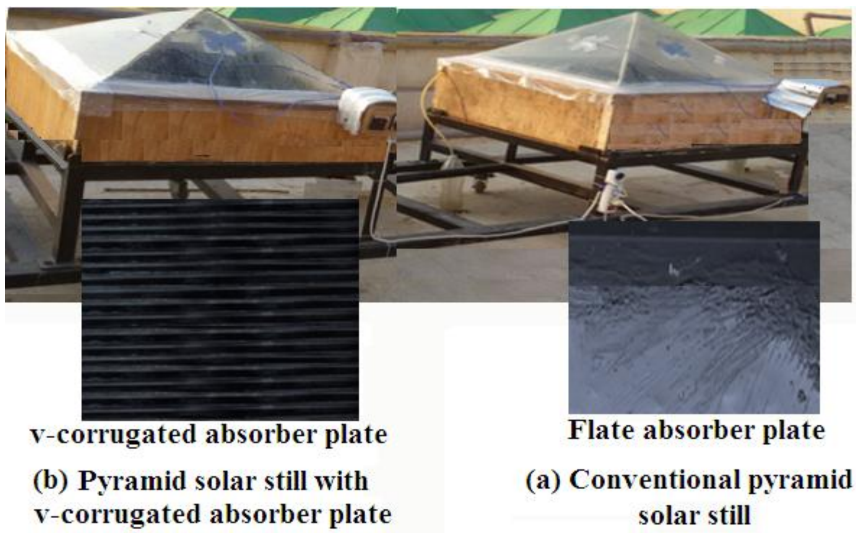

Figure 2. Photo of present experiment work: (a) conventional pyramid solar still and (b) pyramid solar still with v-corrugated absorber plate

3 EXPERIMENTAL PROCEDURE AND MEASUREMENTS

In the present experimental work the pyramid solar still with v-corrugated absorber plate and the conventional pyramid solar still has been designed, constructed and tested in the Faculty of Engineering - Tanta University- Tanta - Egypt (Latitude 30.47^{o}N and longitude 31^{o}E) to studied the effects of a v-corrugated absorber plate on the performance of the pyramid solar still with v-corrugated absorber plate. In the present experimental work the device of measurements used to measure the wind speed, solar intensity, temperature and the distillated water productivity. A vane type anemometer used to measure the wind speed. Solar radiation were measured by a pyranometer and supported at the same direction of glass cover. The temperatures at the different locations (absorber surface, basin water, glass cover, distillate water and ambient) were measured by calibrated K-type thermocouples. The distillated water productivity was measured by a calibrated flask. The depth of the basin water in the both conventional pyramid solar still and pyramid solar still with v-corrugated absorber plate remain constant at average value 2 cm along the working days. The starting time work at 8:00 am and contained to 7:00 pm, during the period from June to August 2016. During the experimental work the following parameters (wind speed, solar radiation, and temperatures) were measured hourly. Through the test days the speed of the wind changes from 0.4 to 6.2 m/s.

The uncertainty analysis for all the experimental data was performed. The sources of errors are vane type anemometer, pyranometer, thermocouples and calibrated flask. The accuracies of various measuring devices are shown in "Table 1". Based on the accuracy of measuring devices, the uncertainty of experimental results calculated using the procedure described by Barford (1990). Accordingly, the errors in the daily productivity and daily efficiency are ±0.55% and ±0.64%, respectively.

Table 1. Accuracies of all measuring devices

Device	Accuracy	Range	Error
Vane type anemometer	± 0.1 m/s	0.4 – 30 m/s	2.92 %
Pyranometer	± 1 W/m^2	0 – 4000 W/m^2	0.15 %
Thermocouples	± 1 ^oC	- 200 : 1250 ^oC	1.77 %
Calibrated flask	± 5 ml	0 – 2000 ml	0.88 %

4 DAILY EFFICIENCY

The daily efficiency, η_d, is defined as the ratio between the summation of the hourly distillate productivity m multiplied by the latent heat h_{fg} at average basin water temperature T_w, and average solar radiation I(t) over the absorber area A.

$$\eta_d = \frac{\sum m \times L_{fg}}{\sum I(t) \times A} \quad (1)$$

Where, the latent heat h_{fg} was calculated from "eq. 2" (Dashtban & Tabrizi, 2011):

$$h_{fg} = \left[2501.9 - 2.40706\, T_w + 1.192217 \times 10^{-3} {T_w}^2 - 1.5863 \times 10^{-5} {T_w}^3\right] \times 10^3 \quad (2)$$

5 EXPERIMENTAL RESULTS

The ambient and the basin water temperatures for the pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still and solar radiation are shown in "Fig. 3". This figure shows that, the solar radiation and an ambient temperature increases to their greatest value at midday and slowly diminishes after that. The maximum value of the basin water temperature for pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still are 79 ^oC and 72 ^oC respectively in 1:00 pm. This result shows that the basin water temperature for pyramid solar still with v-corrugated absorber plate is higher than that of conventional pyramid solar still due to the higher solar radiation intensity absorbed in the v-corrugated absorber plate, as well as, the high rate of heat transfer from v-corrugated absorber plate to basin water for the pyramid solar still with v-corrugated absorber plate.

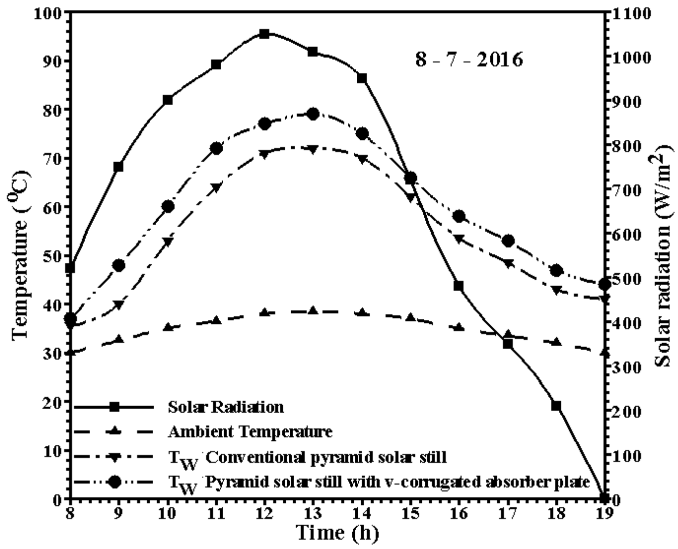

Figure 3. Hourly variations the solar radiation, ambient and basin water temperatures

The hourly variations of the glass cover temperature and basin water temperature for the pyramid solar still v-corrugated absorber plate and conventional pyramid solar still are shown in "Figs. 4 and 5". As shown in "Fig. 4" the maximum temperatures of glass cover reached to 45 °C, 49 °C, 47.5 °C, and 48.5 °C for north cover, south cover, east cover and west cover for the pyramid solar still v-corrugated absorber plate, respectively. The temperature difference between the basin water and glass cover change between 4.5-34 °C, 3.5-30 °C, 4-31.5 °C and 3 -30.5 °C, for north, south, east, and west directions respectively. As shown in "Fig. 5" the maximum glass cover temperatures reached to 44 °C, 48 °C, 46.5 °C, and 47 °C for north cover, south cover, east cover, and west cover for the conventional pyramid solar still, respectively. The temperature difference between the glass cover and basin water change between 2-28.5 °C, 1-24 °C, 2-27°C, and 1-26 °C for north, south, east, and west directions, respectively. The results from Figs. 4 and 5 show that the temperature difference between the basin water and the glasses covers for the pyramid solar still v-corrugated absorber plate is higher than that of conventional pyramid solar still. This mainly because the temperature of basin water for pyramid solar still v-corrugated absorber plate is higher than that of conventional pyramid solar still.

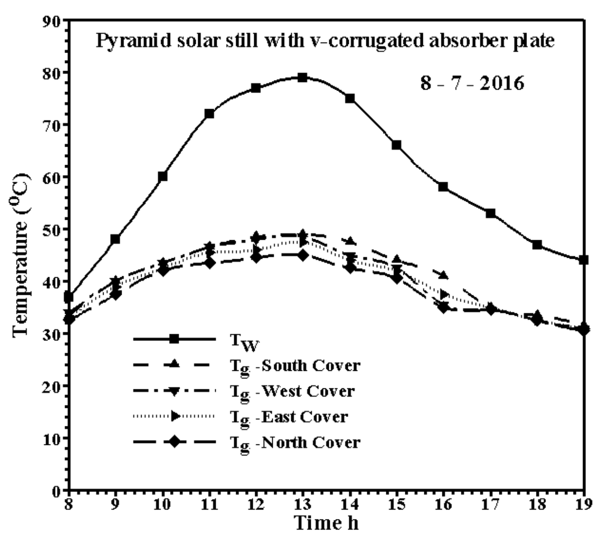

Figure 4. Hourly variations of basin water and glass cover temperatures for pyramid solar still v-corrugated absorber plate

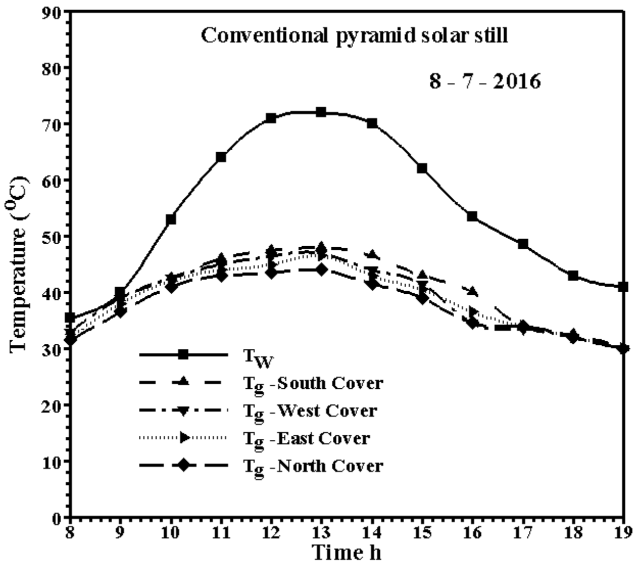

Figure 5. Hourly variations of basin water and glass cover temperatures for conventional pyramid solar still

Fig. 6 shows the hourly variation of distillate water productivity for the pyramid solar still v-corrugated absorber plate and conventional pyramid solar still. As shown in "Fig. 6" the maximum hourly distillate water productivity reached to 1.05 l/m^2 h and 0.82 l/m^2 h for pyramid solar still v-corrugated absorber plate and conventional pyramid solar still, respectively. The experimental results show that hourly distillate water productivity for pyramid solar still v-corrugated absorber plate is higher than that of the conventional pyramid solar still. This mainly because, the basin water temperature for the pyramid solar still v-corrugated absorber plate is higher than that of the conventional pyramid still, due to the high solar radiation intensity absorbed by the v-corrugated absorbed plate, as well as, the high rate of heat transfer from the absorber plate to basin water for pyramid solar still v-corrugated absorber plate. Furthermore, the absorber plate made from copper material for the pyramid solar still v-corrugated absorber plate and galvanized sheet for the conventional pyramid solar still.

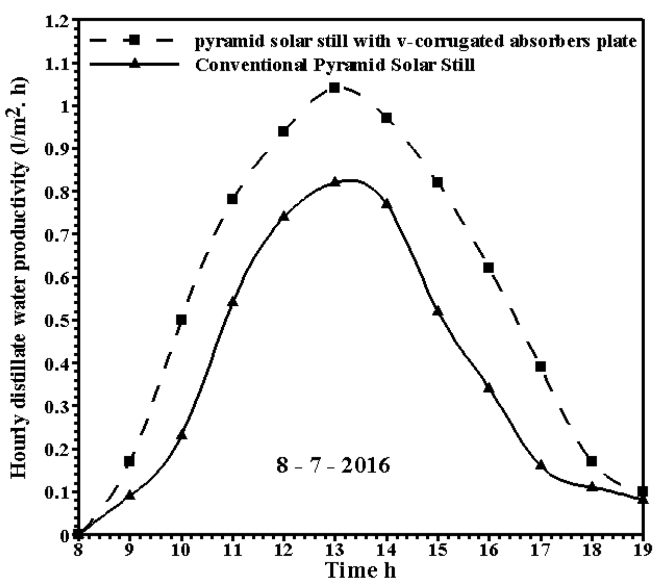

Figure 6. Hourly variations of distillate water productivity for pyramid solar still v-corrugated absorber plate and conventional pyramid solar still

Fig. 7 shows the accumulated distillate water productivity for the pyramid solar still v-corrugated absorber plate and conventional pyramid solar still. "Fig. 7" shown that the accumulated distillate water productivity reached to 6.5 l/m^2 and 4.4 l/m^2 for pyramid solar still v-corrugated absorber plate and conventional pyramid solar still, respectively. The results show that accumulated distillate water productivity for pyramid solar still v-corrugated absorber plate is higher than that of the conventional pyramid solar still. The percentage increases in the accumulated distillate water productivity for pyramid solar still v-corrugated absorber plate about 47.7 % as compared to the conventional pyramid solar still. This mainly because, the hourly distillate water productivity for pyramid solar still v-corrugated absorber plate is higher than that of the conventional pyramid solar still, due to the basin water temperature for the pyramid solar still v-corrugated absorber plate is higher than that of the conventional pyramid solar still.

Table 2 shows the daily distillate water productivity, percentage rise in daily distillate water productivity, daily efficiency for both pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still. As shown in "Table 2" the daily distillate water productivity for pyramid solar still with v-corrugated absorber plate is greater than that of the conventional pyramid solar still. The percentage enhancement in daily distillate water productivity for the pyramid solar still with v-corrugated absorber plate than the conventional pyramid solar still was in the range 46.9% – 48.9%. Also, as shown in Table 2 the daily efficiency for the conventional pyramid solar still various in the range between 32.39–32.76%, but for the pyramid solar still with v-corrugated absorber plate the daily efficiency various between 47.65-48.4%.

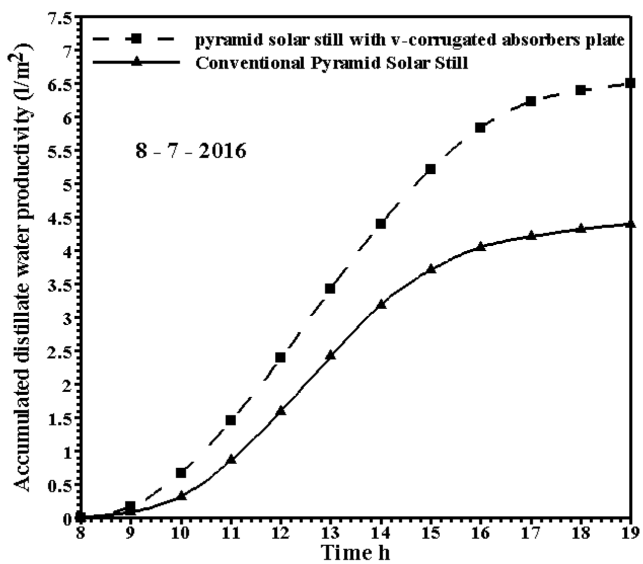

Figure 7. Accumulated distillate water productivity for pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still

Table 2. Daily distillate water productivity and daily efficiency

Date	Daily distillate water productivity (l/m^2)		Productivity rise (%)	Daily efficiency (%)	
	Conventional pyramid still	Pyramid still with v-corrugated absorber plate		Conventional pyramid still	Pyramid still with v-corrugated absorber plate
10-6-2016	4.38	6.45	47.3	32.6	48
25-6-2016	4.4	6.5	47.7	32.76	48.4
8-7-2016	4.4	6.5	47.7	32.76	48.4
18-7-2016	4.38	6.47	47.7	32.61	48.18
26-7-2016	4.35	6.4	47.1	32.39	47.65
3-8-2016	4.37	6.42	46.9	32.54	47.80
18-8-2016	4.38	6.5	48.4	32.61	48.40
22-8-2016	4.33	6.45	48.9	32.61	48.03

6 COST ANALYSIS

Economic analysis for both pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still is presented in this section. The average daily productivity along the year can be estimated 5.5 l/m^2day and 3.4 l/m^2 day for the pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still, respectively. Assume the working days per year are 340 days/year, where in Egypt the sun ascends along the year. The total cost of distilled water productivity per liter (TC/L) is estimate by using "eq. (3)".

$$TC/L = \frac{\text{Annual total cost}}{\text{Annual water productivity}} \qquad (3)$$

Annual total cost (ATC) is deduced from "eq. 4" (Fath et al. 2003)

$$ATC = AFC + ARMC - ASV \qquad (4)$$

Where; (ARMC) is the annual running and maintenance cost, (ASV) is the annual salvage value and (AFC) is the annual fixed cost is calculated by using (FC) fixed cost as deduced from "eq. 5" (Fath et al. 2003)

$$AFC = FC \times (RF) \qquad (5)$$

The recovery factor (RF) is deduced from "eq. 6" (Fath et al. 2003)

$$RF = \frac{i \times (1+i)^n}{(1+i)^n - 1} \qquad (6)$$

Take the life year (n) 10 years and the interest per year (i) 12%.

$$ARMC = 30\ \%\ AFC \qquad (7)$$

$$ASV = S \times SFF \qquad (8)$$

The salvage value (S) which represent about 20 % of the fixed cost (FC).

The sinking fund factor (SFF) is deduced from "eq. 9" (Fath et al. 2003)

$$SFF = \frac{i}{(i+1)^n - 1} \qquad (9)$$

Tables 3 shows the cost analysis for the two present systems, which shows that the total cost of one liter of distilled water productivity for pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still are 0.2105 LE/l and 0.227 LE/l, respectively.

Tables 3. Cost analysis

	Conventional pyramid solar still	Pyramid solar still with v-corrugated absorber plate
Fixed cost, LE	1200	1800
Annual fixed cost, LE	212.4	318.6
Annual running and maintenance cost, LE	63.72	95.58
Annual salvage value, LE	13.68	20.52
Annual total cost, LE	262.44	393.66
Annual productivity, l/year	1156	1870
Total cost per one liter distillate water, LE /l	0.227	0.2105

7 CONCLUSIONS

The present experimental work aims to enhance the daily productivity of the pyramid solar still. Two pyramid solar still in the present work (pyramid solar still with v-corrugated absorber plate and conventional pyramid solar still) are constructed and tested at the same ambient conditions of Tanta University, Egypt. The performance of pyramid solar still with v-corrugated absorbers plate are compared to conventional pyramid solar still, to describe the improvement in the performance of the pyramid solar still with v-corrugated absorbers plate. The experimental results showed that the daily distillate water productivity for pyramid solar still with v-corrugated absorbers plate is higher than that of conventional pyramid solar still. The daily distillate water productivity reached approximately 6.5 l/m^2 day for pyramid solar still with v-corrugated absorbers plate while its value was 4.4 l/m^2 day for conventional pyramid solar still. The percentage increases in the daily distillate water productivity for the pyramid solar still with v-corrugated absorbers plate about 47.7 % compared to the conventional pyramid solar still. Moreover, the average daily efficiency for the pyramid solar still with v-corrugated absorbers plate and the conventional pyramid solar still are 48.4% and 32.76%, respectively. The estimated cost of one liter of distillate water productivity reaches approximately 0.2105 LE and 0.227 LE for pyramid solar still with v-corrugated absorbers plate and conventional pyramid solar still, respectively.

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