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Augmentation of the basin type solar still using photovoltaic powered turbulence system

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ABSTRACT

The present paper concerns with enhancing productivity of basin type solar still through experimental investigation. Therefore, two solar stills are designed and constructed to study the performance of two suggested solar desalination systems. The first one is a conventional still and the second is a modified still uses a rotating fan with a vertical shaft. A DC-motor powered by a small photovoltaic (PV) system is used to rotate the fan. The influence of the rotational speed of the fan and the depth of saline water on the performance of the still is investigated experimentally. The experiments were conducted with fan rotational speeds of 30, 35, 40 and 45 rpm and saline water depths of 1, 3, 5 and 7 cm. The results indicate that the daily productivity of still increases with increasing rotational speed of the fan and the maximum difference of daily productivity between fan and conventional solar stills is achieved at depth of saline water of 3 cm (with rotation). Also it is found that using rotating fan in the solar still increases the productivity by 25% at 3 cm and 45 rpm. In this case the daily efficiency and estimated cost of 1 l of distillate for fan and conventional solar stills are approximately 38%–0.0447$ and 35.5%–0.049$, respectively.

Keywords: Basin solar still; Solar still efficiency; Solar desalination; Productivity enhancement; Fan

1. Introduction

Single basin solar still is a very simple solar device used for converting available brackish or wastewater 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. But it is not popularly used as a result of its low productivity. Therefore, a number of works is undertaken to improve the productivity of the still.

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The concentration of water vapor within the air is a function of air temperature and exposed still basin area. When the exposed area of basin water is large, 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 larger area and ready for diffusion. The rubber, gravel and charcoal are used in the basin [1–3] to improve the absorption; heat capacity and also the evaporation area enhance the production. Nafey et al. [4,5] 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 [6]. They had proved that the distillate productivity increased by 18–27% compared to an identical still without sponge cubes under the same conditions.

Two modifications for solar desalination systems were presented by Zeinab and Ashraf [7]. The first modification used a packed layer that installed in the bottom of the basin to increase efficiency of the still. The second modification used a horizontal rotating shaft installed close to the basin water surface. The results showed that the two modifications enhanced the performance of the solar desalination system. The efficiency of the modified solar desalination system using packed layer thermal energy storage was increased by 5% at May, 6% at June, and 7.5% at July, while it was increased by 2.5% at May, 5% at June, and 5.5% at July for the modified one using rotating shaft.

Several other designs have been developed to improve the performance of conventional solar stills, such as double-basin type [8], multi-basin [9,10], inverted trickle [11], multi-effect [12,13], regenerative [14], with reflectors [15–17], spherical [18], hemispherical [19], triangular [20], pyramid type solar still [21,22], stepped still [23,24] and a concave wick evaporation surface [25]. A review of various designs of solar stills was made by [26,27].

From the previous work, it is seen that, the daily yield per still area in the basin solar still mainly depends up on the evaporative area and condensing surfaces [19,21,28]. Also, the target of using the rotating horizontal shaft is to break the boundary layer of the basin water surface, which in turn increasing the water vaporization and condensation.

Therefore, the objective of the present experimental study is to improve the performance of a basin solar still using a rotating fan with a vertical shaft.

2. Experimental setup

Two solar stills were designed and fabricated to study and compare the performance of the solar desalination systems. The first one is a conventional still (a single basin) with a basin area of 1 m^2 (0.5 m × 2 m). High-side wall depth is 49 cm and the low-side wall height is 20 cm. 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 of 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 of 3 mm thick inclined at nearly 30^o horizontally, which is the latitude of Kafrelsheikh City, Egypt. Fig. 1 shows a photograph of tested solar desalination systems.

The second still (fan solar still) is a modified still which uses a rotating fan with vertical shaft. A schematic diagram of the new fan solar still is shown in Fig. 2. The fan solar still has the same construction of the conventional still, in addition to fan with a vertical shaft. This fan has four flat vanes which made of 0.5 mm sheet iron plate (20 cm × 10 cm) fitted and welded in the

Fig. 1. Photograph of experimental setup.

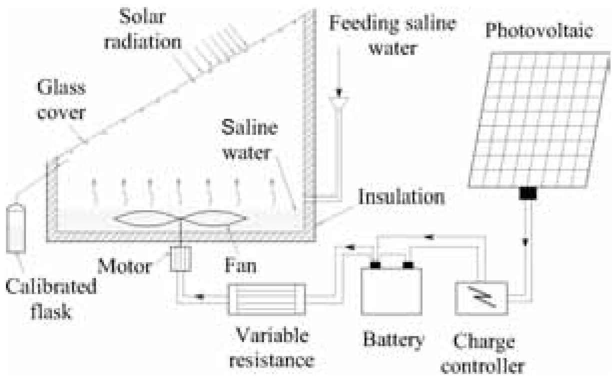


Fig. 2. Schematic diagram of fan solar still.

vertical shaft. The vanes contain some holes to increase the turbulence kinetic energy of saline water, as shown in Fig. 1. The vanes are located above the bottom of still basin by about 0.5 cm. A DC-motor is used to rotate the fan and powered by a photovoltaic (PV) system. The PV system consists of PV cell, battery and charge controller. The PV cell used in this work is four silicon panel 60 W, each panel 0.3 × 0.9 m^2, open circuit voltage 22 V, short-circuit current 3.4 A and working voltage 17.5 V. A variable resistance is used to achieve the required rotational speed of the motor.

The experimental setup is suitably instrumented to measure the temperatures at different points of the still (brine and glass cover temperatures), total solar radiation and the amount of distillate. The temperatures have been measured using calibrated copper constantan type thermocouples which were connected to a digital temperature indicator. The glass temperatures are measured at two specified locations for each still. Thermocouples are shaded from direct exposure to the sun and protected from water by using a suitable cover. While for brine water the temperatures are measured at 0.5 cm above the bottom surface at two different points. Also, a thermocouple is used to measure the ambient temperature. The solar radiation intensity is measured instantaneously by solarimeter.

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 2009. 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 experiment. The motor of the fan works from 11 a.m. to 8 p.m. 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 recorded.

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. 2.

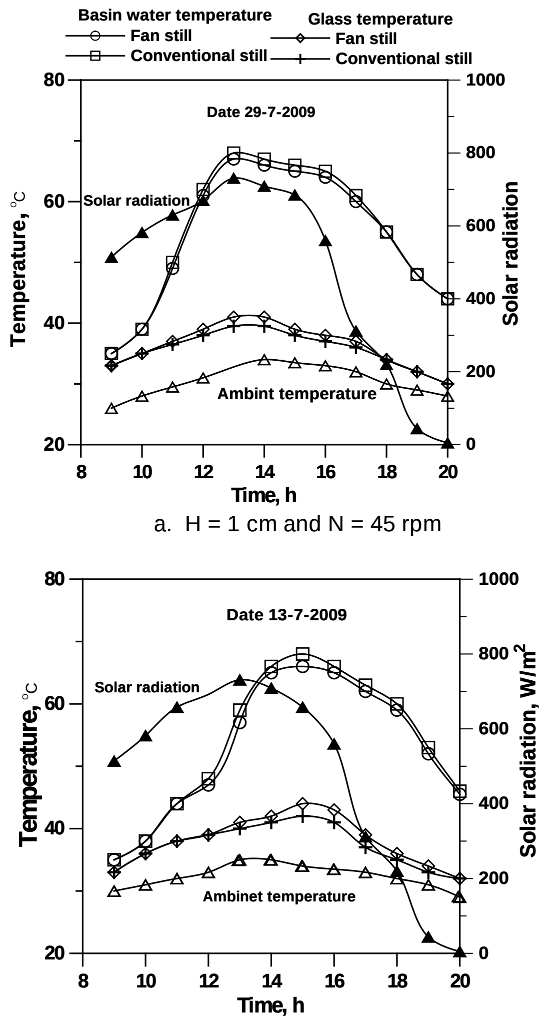
Effects of fan rotational speed (N) and depth of saline water (H) in the still on the performance of the still were studied. The experiments were conducted with fan rotational speeds of 30, 35, 40 and 45 rpm and saline water depths of 1, 3, 5 and 7 cm, respectively. It is important to mention that when the speed of the fan becomes higher than 45 rpm the fan pushes the saline water in different directions. Then the saline water reaches the glass cover and mixes with the fresh water. The depth of the saline water in the solar still is maintained constant manually using make up saline water tank and control valve.

4. Results and discussion

The experimental work was performed on the solar still during July 2009 since the sky is clear during this month. The saline water depth in the still and rotational speed of fan were varied during 16 days of testing in order to investigate the effect of water depth and fan rotational speed on the distillate productivity. The conventional still and fan solar still experiments are conducted at the same conditions.

4.1. Effect of solar radiation on the performance of the solar still

The variation of solar radiation, atmospheric temperature, basin water temperature, and glass temperature of stills at rotational speed of N = 45 rpm at different saline water depths 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 2 p.m. to 4 p.m. depending up on the depth of saline water. In the case of saline water depth 1 cm the maximum temperature is observed at 1 p.m. and 3 cm at 3 p.m., while at 5 cm and 7 cm is observed approximately at 4 p.m. This is because, the largest depth needs a larger amount of energy to rise the water temperature and consequently take a longer time. Depending upon the weather conditions the wind speed is varied from 0.4 to 4.3 m/s at different



a. H = 1 cm and N = 45 rpm

b. H = 3 cm and N = 45 rpm

Fig. 3. Hourly temperatures variations and solar radiation for conventional and fan solar stills at $N = 45$ rpm and different saline water depths.

days. Also, from Fig. 3 it can be noticed that the glass temperature of fan solar still is higher than that of conventional still by about 0–2 °C and basin water temperature of fan solar still is lower than that of conventional still by about 0–2 °C. This may be due to the effect of the rotating fan which converts the free evaporation to forced evaporation, thus consequently leads to increase the evaporation rate.

4.2. *Effect of fan speed on productivity*

Comparisons between the hourly variation of fresh water productivity per unit area for fan solar still and conventional type 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 this 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 and water needs more time to warm up. In addition, it can be seen that the maximum productivity occurs at maximum temperature of saline water.

Also, it can be observed from the figure that, the fresh water productivity for modified still is greater than that of conventional type for different depths of saline water. The fresh water productivity is increased due to the increase of water evaporation and condensation, since the rotating fan converts the free evaporation to forced evaporation, which consequently enhances the evaporation rate, and this is may be the dominant effect of rotating fan. In addition, the rotating fan breaks the boundary layer of the basin water surface, thus increasing the water evaporation. The waves generated as a result of fan rotation through saline water increases the solar radiation absorption area as well as the evaporation area. Also, the convection heat transfer between saline water and absorber (base of still) increases as the fan works. This is because the fan rotation increases the turbulence intensity of saline water molecules. Also, the fan during operation causes a little vibration of the system; hence the condensate water runs faster downward towards the outlet. In addition, the fan is producing heating to the saline water. Also, it can be noticed that the daily productivity highly depends up on rotational speed, where the daily productivity increases with increasing rotational speed.

It is important to conclude that, the difference in productivity between the fan solar still and the conventional still increases more from 1 p.m. to 7 p.m., as shown in Fig. 4. This is because the temperature of water is low at morning (before 1 p.m.) and amount of solar radiation is low after 6 p.m. Therefore, it is recommended to operate the fan from 1 p.m. to 7 p.m. to reduce the power consumed by the motor used in the second model.

4.3. *Effect of operation of fan on daily productivity*

Comparisons between the accumulative variations of fresh water productivity from sunrise to sunset for the two tested stills are shown in Fig. 5, at different water depths and fan rotational speeds. It is found that the amount of accumulated distillate for fan solar still is higher than that of conventional still at all depths and rotational speeds, where the hourly fresh water productivity is higher for fan solar still. Also, it can be noticed that at the end of the testing period (8 p.m.) of each day, the accumulated distillate increases with increasing rotational speed of the fan.

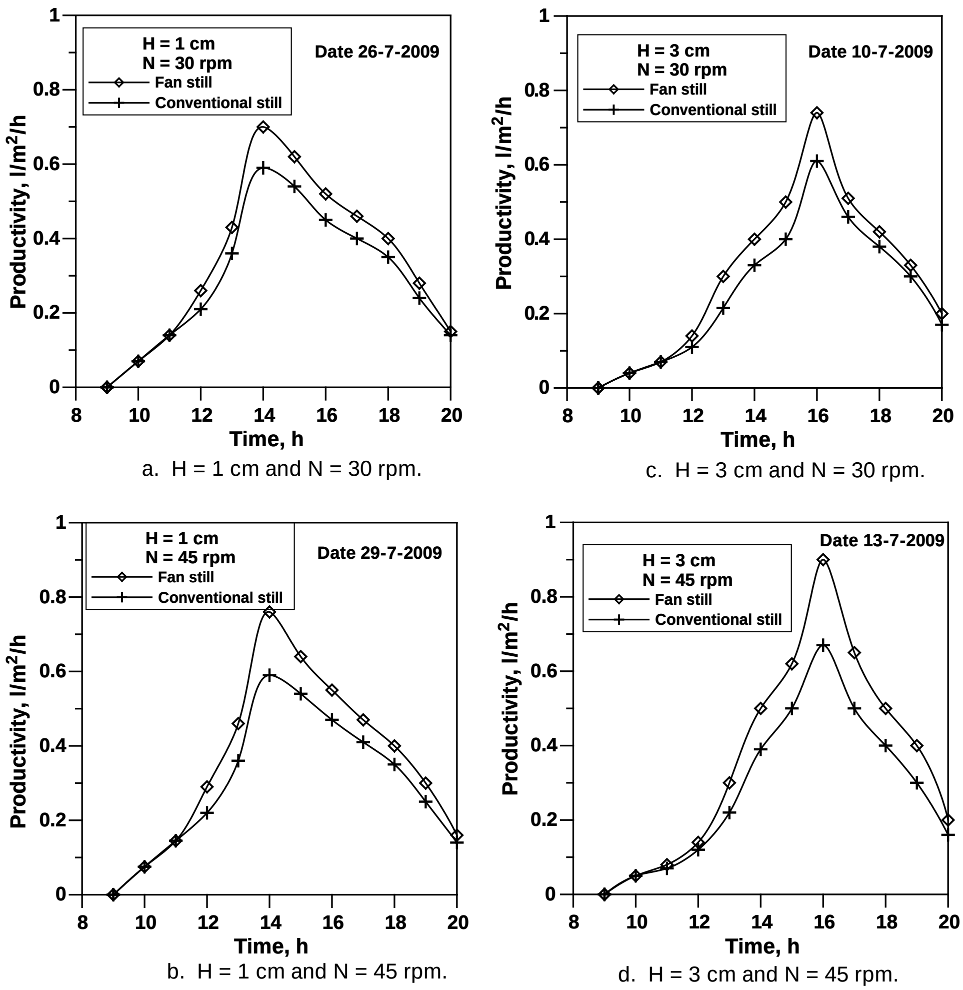


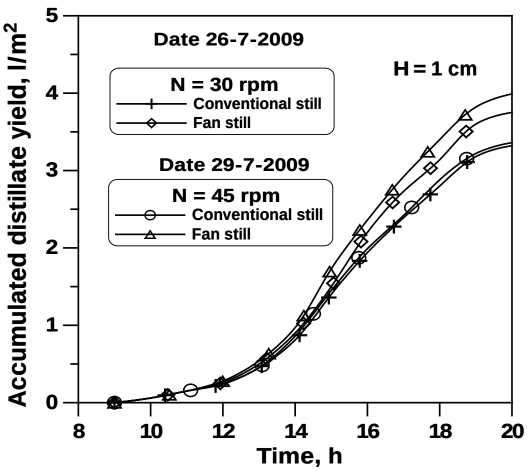
Fig. 4. Hourly variations of fresh water productivity for the fan and the conventional solar stills at different *H* and *N*.

Comparison of the daily productivity (24 h) and percentage of the daily productivity rise for both conventional still and fan solar still at different depths of saline water and N = 30, 45 rpm is tabulated in Table 1. It is found that the amount of daily accumulated distillate for fan solar still is higher than that of conventional still at all depths and rotational speeds, where the hourly fresh water productivity is higher for fan solar still. Also, it can be noticed that at the end of the testing period (24 h) of each day, the accumulated distillate increases with increasing rotational speed of the fan. It can be noticed from Table 1 that the daily productivity (24 h) reaches approximately 3.8 and 4.75 l/m^2/day for conventional still and fan solar still, respectively, at H = 3 cm and N = 45 rpm. In this case the increase in daily productivity for fan solar still is 25% higher than that for conventional still.

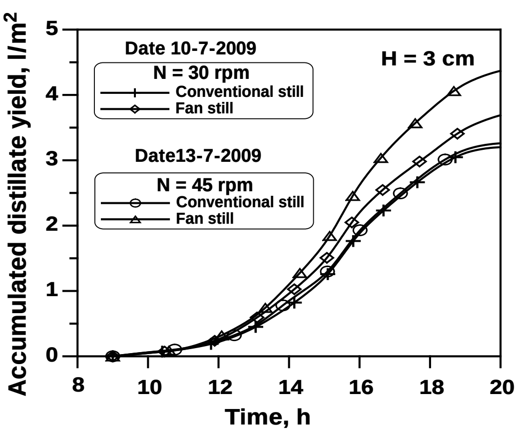
In the present study, it can be seen that in July the difference in accumulated distillate between the fan solar still (with a vertical rotating shaft) and the conventional still approximately 0.85 l from 9 a.m. to 5 p.m. at H = 3 cm and N = 45 rpm. While in Ref. [7] it was found that, in July the difference in accumulated distillate between the fan solar still (with a horizontal rotating shaft) and the conventional still approximately 0.55 l from 9 a.m. to 5 p.m. This is may be due to the presence of rotating fan with a vertical shaft. Since the fan with vertical shaft rotates all saline water in the basin and the generated waves become higher, so that the absorption area becomes larger. Also, the convection heat transfer between saline water and absorber increases in the case of fan with a vertical rotating shaft.

4.4. Effect of rotational speed on the difference of daily productivity

The basin water depth is having significant effect on productivity of the solar still. Investigations show that, the water depth is inversely proportional to the productivity of still [29–30]. Therefore, the effect of water depth



a. H = 1 cm



b. H = 3 cm

Fig. 5. Comparison between the accumulative variations of fresh water for the fan and the conventional stills at different *H* and *N*.

on the productivity is not included here. The present study is concerns with the effect of rotational speed of the fan on the difference of daily productivity between fan solar still and conventional still at different depths of saline water, as shown in Fig. 6.

It can be observed from this figure that increasing the rotational speed of the fan leads to improve the daily productivity. Where, the amount of heat transferred from basin (absorber) to saline water by convection and the evaporation area of water surface increase with increasing the rotational speed of the fan. The difference of daily productivity between the fan solar still and the conventional still showed an increase of 0.95 and 0.65 l/m^2/day at H = 3 cm for N = 45 and 30 rpm, respectively.

Fig. 6 shows also that the difference of daily productivity increases with increasing the depth of saline water to its maximum value around H = 3 cm (with rotation) and then decreases as the depth increase, since the effect of rotation is high at H = 3 cm, for basin area of 1 m^2. It can be observed that, for fan still, at water depth H = 3 cm the generated waves are higher than H = 1 cm, so that the solar radiation absorption area as well as the evaporation area becomes larger. In addition, the higher water waves obstruct with vertical walls of still and lead to increase water evaporation. Since there is a big part of solar energy receive by the vertical walls of still and works as absorber. Also, the surface tension is dependent on temperature. The general trend is that surface tension decreases with the increase of temperature. In case of conventional still decrease water depth leads to increase the water evaporation due to decrease water surface tension, since the water temperature goes high temperature at water depth 1 cm about 3 cm. In case of fan still the rotating fan breaks the boundary

Table 1
Comparison between daily productivity for conventional and fan solar stills

Date	Average daily solar radiation, W/m^2	Conditions		Daily productivity (24 h), l/m^2/day		Daily productivity rise, %
		H, cm	N, rpm	Conventional still	Fan solar still	
1-7-2009	500	7	30	3	3.45	15
4-7-2009	520	7	45	3.16	3.86	22.2
5-7-2009	535	5	30	3.6	4.2	16.7
9-7-2009	530	5	45	3.55	4.37	23.1
10-7-2009	520	3	30	3.82	4.47	17
13-7-2009	520	3	45	3.8	4.75	25
26-7-2009	490	1	30	3.1	3. 55	14.5
29-7-2009	500	1	45	3.14	3.82	21.6

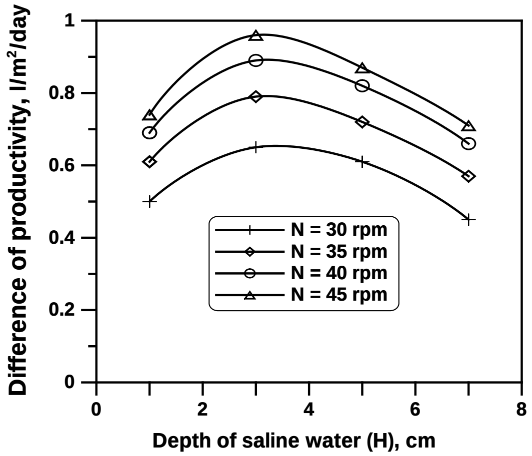


Fig. 6. Effect of saline water depth on the daily productivity (24 h) of still at different rotational speed during the 16 days.

layer of the basin water surface, thus may be increasing the water evaporation for water depth 3cm about 1cm. Also, the productivity at H = 3 cm is better than H = 5 cm and 7 cm due to the fact that increasing in the water depth reduces the evaporation yield where the bulck water heat capacity increases with the depth, hence increasing the required evaporation time. The difference of daily productivity between the fan solar still and the conventional still showed an increase of 0.95 and 0.7 l/m^2/day at N = 45 rpm for H = 3 and 7 cm, respectively.

4.5. Effect of rotational speed on daily efficiency

The daily efficiency, η_d, is obtained by summing up the hourly condensate production (m), multiplied by the latent heat of vaporization (h_{fg}), and divided by the daily average solar radiation (I(t)) over the whole area (A) of the device [31]:

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

The whole area of the conventional still is the absorber projected area (1 m^2), [32]. While the whole area of fan solar still is obtained by summing up the absorber projected area (1 m^2) and the projected area of PV cell (the projected area of one panel 0.3 × 0.9 × cos30 = 0.23 m^2).

The effect of rotational speed of the fan on the daily efficiency for the present desalination systems at different depths of saline water is shown in Fig. 7. It can be observed from this figure that the behavior of daily efficiency curves is similar to the difference of daily productivity curves (Fig. 6). Where, increasing the rotational speed of the fan leads to improve the daily efficiency. In addition, it is found that the calculated daily efficiency of fan solar still and conventional still is approximately equal 38% and 35.5%, respectively, at H = 3 cm and N = 45 rpm.

5. Cost evaluation

Cost analysis must be considered for practical units not experimental set up. The cost estimation for various components used in the present solar stills depends upon the type of solar still and its components, as given in Table 2.

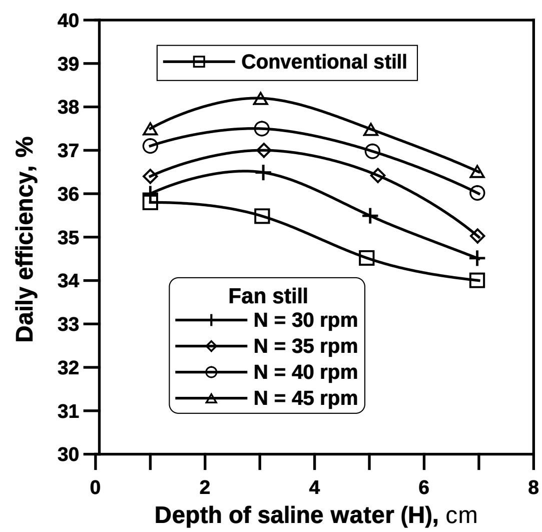


Fig. 7. Effect of rotational speed of fan on daily efficiency (24 h) of still at depth of saline water H = 3 cm.

Table 2
Cost of fabricated solar stills

Unit	Cost of fan still ($)	Cost of conventional still
Iron sheet (1.5 mm thick.)	12	12
Wooden box	25	25
Glass cover	11	11
Inlet and outlet ducts	9	9
Paint	9	9
Insulation	5	5
Production	25	20
Support legs	12	12
Photovoltaic system (18 W)	120	–
DC-Motor (12W)	10	–
Total fixed cost (F)	238	103

5.1. Cost estimation for conventional still

The total fixed cost of conventional still is about F = 103\$. To obtain the average value of the cost of distillate output, it is important to assume that n is the expected still life time, V is the variable cost, C is the total cost, where, $C = F + V$. Assume variable cost V equals 0.3F per year, as reported in Ref. [25], and the annual variable cost includes the maintenance cost, the expected still life time is 10 years, then $C = 103 + 0.3 \times 103 \times 10 = 412$\$ where the minimum average daily productivity can be estimated from the analysis of different experimental data, and it is taken as 2.5 l/day. To determine the annual cost for 1 l assuming that the still operates 340 days in the year, where the sun rise along the year in Egypt. The total productivity during the still life time $P_n = 2.5 \times 10 \times 340 = 8500$ l. Then the cost of one liter from conventional still = 412/8500 = 0.049\$.

5.2. Cost estimation for fan solar still

The total fixed cost of fan solar still is about F =238\$. Assume the expected still life 10 years but the expected life of PV system 20 years, so that it is possible to take half price only (120/2 = 60\$), so that the total fixed cost of fan still is about $F = 238 - 60 = 178$\$. The variable cost of fan stall approximately the same for conventional still except the maintenance of motor. Assume the variable cost V equals 0.3F per year without the price of PV system, then $C = 178 + 0.3 \times 118 \times 10 = 532$\$, where the minimum average daily productivity can be estimated 3.5 l/day, assume still operate 340 days in the year. The total productivity during the still life time Pn = 3.5 × 10 × 340 = 11,900 l. Then the cost of one liter from fan still = 532/11,900 = 0.0447\$.

6. Conclusions

From the recorded measurements and previous discussion concerning with the experimental investigation of still performance, the following important conclusions can be drawn:

- The performance of stills is strongly influenced by the fan rotational speed and depth of saline water.
- The daily productivity of still increases with increasing rotational speed of the fan and the maximum difference of daily productivity between fan and conventional solar stills is achieved at depth of saline water of 3 cm (with rotation).
- The difference in productivity between the fan solar still and the conventional still increases more from 1 p.m. to 7 p.m. Therefore, it is recommended to operate the fan only during this period to reduce the power consumed by the motor.
- The daily efficiency and estimated cost of 1 l of distillate for fan and conventional solar stills are approximately 38% – 0.0447\$ and 35.5% – 0.049\$, respectively, at H = 3 cm and N = 45 rpm.

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