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Performance of solar still with a concave wick evaporation surface

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ABSTRACT

Surfaces used for evaporation and condensation phenomenon play important roles in the performance of basin type solar still. In the present study, a concave wick surface was used for evaporation, whereas four sides of a pyramid shaped still were used for condensation. Use of jute wick increased the amount of absorbed solar radiation and enhanced the evaporation surface area.. A concave shaped wick surface increases the evaporation area due to the capillary effect. Results show that average distillate productivity in day time was 4.1 l/m^2 and a maximum instantaneous system efficiency of 45% and average daily efficiency of 30% were recorded. The maximum hourly yield was 0.5 l/h. m^2 after solar noon. An estimated cost of 1 l of distillate was 0.065 $ for the presented solar still.

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1. Introduction

The shortage of drinking water is expected to be the biggest problem of the world in the next years due to higher consumption rates and population growth. Pollution of fresh water resources (rivers, lakes and underground water) by industrial wastes has increased the problem.

The total amount of global water reserves is about 1.4 billion km^3. Seawater constitutes about 97.5% of this amount, and the remaining 2.5% fresh water is present in the atmosphere, surface water, polar ice and ground water. This means that only about 0.014% is directly available to human beings and other organisms [1]. Therefore, the provision of fresh water is becomes an increasingly important issue in many areas of the world. In arid areas, potable water is very scarce and the establishment of a human habitat in these areas strongly depends on how such water can be made available. The importance of supplying potable water can hardly be overstressed.

Solar desalination is suitable for remote, arid and semi-arid areas. Where drinking water shortage is a major problem and solar radiation is high. These places mostly suffer also from energy shortage. The limitations of solar energy utilization for desalination are the high initial cost for renewable energy devices and intermittent nature of the solar radiation. Due to these limitations the present capacity of solar desalination systems worldwide is only about 0.01% of the existing large-scale conventional desalination plants [2,3]. Therefore, efforts must be made to develop new technologies that can collect and use renewable energy more efficiently and cost effectively in the production of clean drinking water. Besides, developing better technologies to store this energy for use whenever it is not available is also required.

Solar stills are commonly used in arid coastal zones to provide low-cost fresh water from the sea. In the Northern Hemisphere, the still is placed due south with long axis facing East–West direction. The primary aim in solar still is to achieve as high productivity as possible. Total daily output of the solar still decreases with increasing water depth, but overnight output increases with an increase in water depth, which contributes considerably towards the total daily output [4]. Solar stills are usually classified into two categories [5]: a single-effect type and a multi-effect type. Solar stills made from waste materials were studied [6]. The still made from a polypropylene tray and polyethylene-wrapping sheets were subjected to laboratory tests at steady and unsteady states for heat and mass transfer analysis. The integration between flat plate solar collector and a solar still is classified into passive [7] and active [8] stills. Single-effect passive stills are composed of convectional basin, diffusion, wick and membrane types [9]. Using a still with cover cooling [10,11] and a still with a multi-effect type basin have been studied by Tanaka et al. [12]. Complicated systems with a variety of solar stills are not applicable to desert technology. A tube-type solar still is proposed to integrate a conventional still and a water distribution network suitable to our concept of desert plantation. This still is directly set up on ground-like pipelines connecting brackish water or seawater pond [13]. Solar distillation practice for water desalination systems was studied [14].

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Nomenclature

Q_{ev}	The rate of heat (energy) transfer by evaporation (W)
m_{ev}	Distilled water production rate (kg/m^2 h)
A_b	Still base area (m^2)
A	Still area (m^2)
H	Total solar radiation fall upon the still surface (W/m^2)
L	Latent heat of water (J/kg)
V	Variable cost (O&M), LE
C	Total cost, LE
n	Expected still life time, years
P_n	Total productivity during the economical still life (kg)
P	Accumulated productivity during the day (kg)
t	day time (h)
η_d	The solar still daily efficiency
η_i	The solar still instantaneous efficiency

However, various scientists have made attempts to maximize the daily yield per still area in a single basin solar still in a passive mode [15,16]. In the conventional still the transparent surface has the disadvantage of increase in its temperature due to solar radiation. Also, a part of radiation is absorbed in glass surface and increases its temperature, which results in decreasing the condensation rate.

It has been reported that tilted-wick type solar stills have some advantages over the basin type, especially their attractive performance in distillation. Conducting an experimental study on a tilted-wick type solar still, Tanaka et al. [17] found an increase in distillate output of 20–50% against basin types.

From the previous work, it has been observed that the daily yield per still area in the basin solar still mainly depends on the evaporative area and condensing surfaces [18,20]. Increasing the surface area or decreasing the cover temperature will enhance the distillate output. New approaches to enhance the performance of solar still are highly welcome.

This work presents an experimental investigation on a new design of solar still with wicked concave surface. The aim of using wick is to increase the solar radiation absorption area as well as the evaporation area. This is to increase the productivity of the still. Also, this concave still design reduces the shading effect than the conventional type because all sides are glass. The performance of the presented still was evaluated.

2. Experimental setup

Wick concave type solar still is designed and constructed for the purpose of experimental work. Fig. 1 shows a schematic diagram of the solar still and a photograph of this solar still is shown in Fig. 2. The basin of the solar still is concave with a square aperture of 1.2 m × 1.2 m. Its frame is fabricated from steel of 2 mm thickness. The still basin is made of galvanized steel. The bottom and sides of the basin are insulated by glass wool of 5 cm thick layer surrounded by a steel sheet 2 mm thickness. The wick surface takes the same shape of the concave surface and has a thickness of 5 cm covering the basin. The wick surface is black painted to absorb maximum solar radiation. The basin depth is 30 cm at the centre. The depth of saline water in the still is 10 cm at the centre. Glass cover is used at four sides of the solar still with ordinary window glass of 3 mm thickness and tilted at an angle of 45 degree to the horizontal surface [19]. The distillate is collected by a galvanized iron channel fixed on the sides at the lower end of the glass cover and is taken out through two PVC pipes to two graduated flash as shown in Fig. 1. The channels were inclined such that no accumulation of water was observed. The whole system is made vapor tight using silicone rubber as a sealant to prevent any vapor leakage. One of the four glass cover faces south direction.

The experimental setup is suitably instrumented to measure the temperatures at different points of the still (brine temperatures, wick temperatures and glass covers temperatures), total solar radiation and the amount of distillate. The temperatures have been measured using copper constantan thermocouples which were connected to a digital temperature indicator. Wick surface temperatures are measured at different points. The thermocouples for glass temperatures measurement at one third of the perpendicular distance from the triangle vertices. While for brine water the temperatures are measured at the water surface, 5 cm from surface and near the bottom at the centre. The solar radiation intensity is measured instantaneously by solarimultimeter. A part of wick surface is dipped into the water and another part absorbs water by capillary action. Use of glass covers at four sides of the still reduces the shading effect compared with that of conventional solar still.

3. Experimental procedure

Experiments were conducted at Tanta University, Egypt. Experiments were started at 8:00 a.m. and after one hour warm up

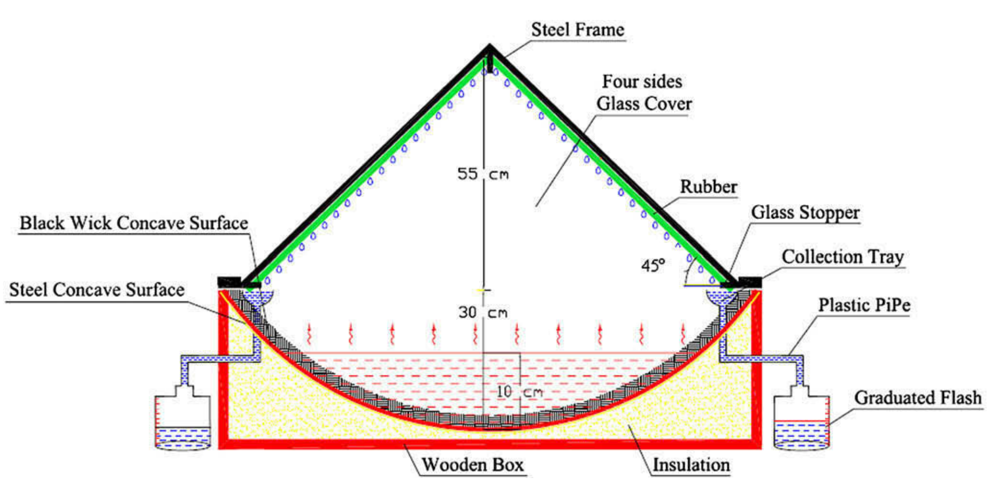

Fig. 1. Schematic diagram of concave wick solar still (drawn not to scale).

Fig. 2. A photograph of the fabricated concave wick solar still.

period hourly measurements of distillate had been recorded starting at 9.00 a.m. Experiments were conducted in a typical high solar insolation months of summer season, i.e. June and July. The data selected for the two months since the sky is clear during this period. Four days were chosen to represent the results. Experimental measurements were performed to evaluate the performance of the wick concave solar still under the outdoors of Tanta conditions. During that period, the ambient climatic conditions (solar radiation, ambient temperature and wind velocity) were measured. The depth of water at the centre of the basin was taken 10 cm for all experimental days. The evaporated water from the still during the day compared with that in the still was small that no significant change in the water level was observed.

In each run, water was fed into the basin to a specified depth in the morning which equals the amount of collected distilled water. This depth is enough to assure that the total wick surface in the still is saturated with water.

Each experiment is conducted in one day, during which the following measurements have been recorded every hour:

- Brine mean temperature.
- Glass cover's temperatures at four sides of the still.
- Distillate output in slight glass.
- Total solar radiation.
- Ambient air temperature.
- Wind speed.

The experimental data are collected at regular intervals of 1 hour, starting form about 9 a.m. to the sunset (the data are recorded after sunset in some days). However, the accumulated productivity during the 24 h has also been measured in each experiment.

4. Solar still efficiency

An instantaneous efficiency of a solar still η_i, defined as the ratio of the energy used for water production to the total solar radiation rate is given by:

$$\eta_i = \frac{Q_{ev}}{H\,A_b} \tag{1}$$

$$Q_{ev} = m_{ev}L \tag{2}$$

where Q_{ev} is evaporative heat transfer (W), m_{ev} is distilled water production rate (kg/m^{2}h), A_b is the still base area (m^2), H is the total solar radiation fall upon the still surface (W/m^2).

The solar still daily efficiency, η_d, is obtained by summing up the hourly condensate production multiplied by the latent heat of vaporization, and divided by the daily average solar radiation over the solar still area and calculated from the following equation:

$$\eta_d = \frac{\int_0^{24} m_{ev}L\,dt}{3600A\int_0^{24} H\,dt} \tag{3}$$

where t is the time.

5. Experimental uncertainty analysis

Uncertainty associated with the experimental measurements is shown in Table 1. The error is calculated for thermocouples, solarimeter anemometer and slight glass. The minimum error occurred in any instrument is equal to the ratio between its least count and minimum value of the output measured.

6. Experimental results and discussion

The experimental work was performed on the solar still during two months of the year 2007 (June and July) on different clear days. The experimental data presented in the following analysis are chosen for some clear sky days as example. Basin water temperature, surface temperature and ambient air temperature during the day time for the two considered days are shown in Fig. 3. It is observed that the temperatures at all points increase with time till maximum value around noontime before they start to decrease late in the afternoon. This is due to the increase of solar radiation intensity in the morning and its decrease in the afternoon.

The hourly temperature variation of the four glass sides is shown in Fig. 4. The system has four condensation glass surfaces. Temperature differences have been observed between all glass covers. The cold surfaces of glass covers are those which are not subjected to direct solar radiation. Wind direction also has a marked effect. Vapor condenses at the inner surfaces of the glass covers.

Fig. 5 shows the variation the total solar radiation intensity during the daytime. The amount of total solar radiation incident on the still surface depends on the time of the day. The solar radiation varies along the hours after sunrise till a maximum value at midday then decreases in the afternoon. These solar radiation data are used to calculate the solar still efficiency. These figures indicate that

Table 1
Experimental uncertainty errors.

Instrument	Accuracy	Range	% Error
Solarimeter	±1 W/m^2	0–5000 W/m^2	0.25
Thermocouple	±1 °C	0–100 °C	0.25
Graduated flash	±5 ml	0–1000 ml	5
Anemometer	±0.1 m/s	0–15 m/s	10

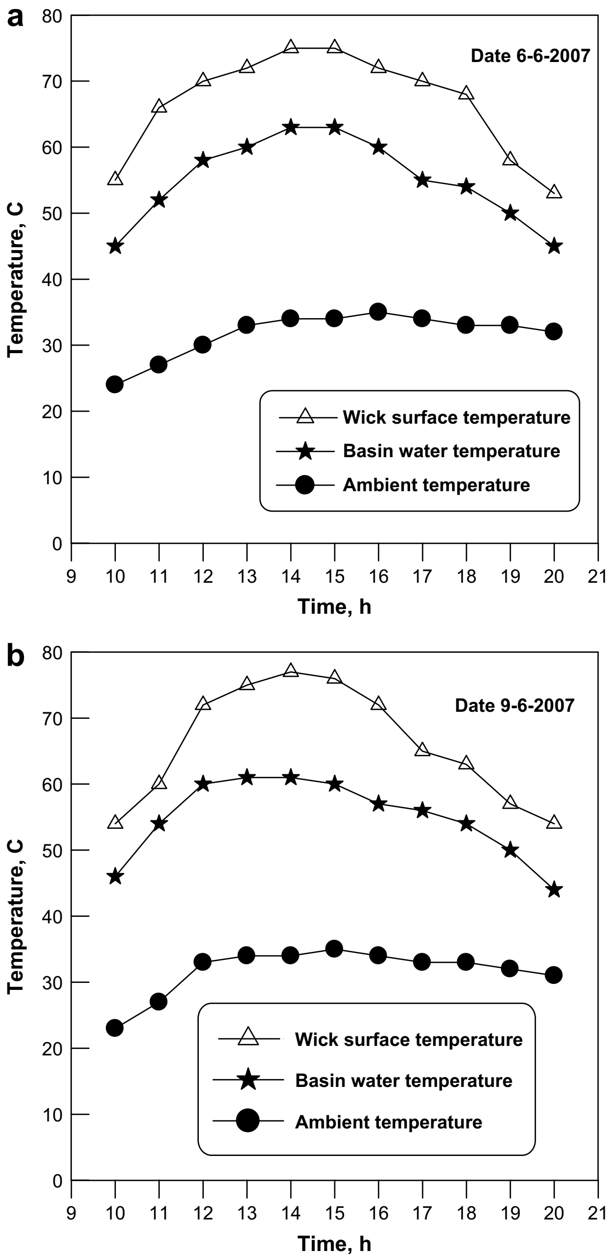

Fig. 3. Hourly variation of temperatures during the day.

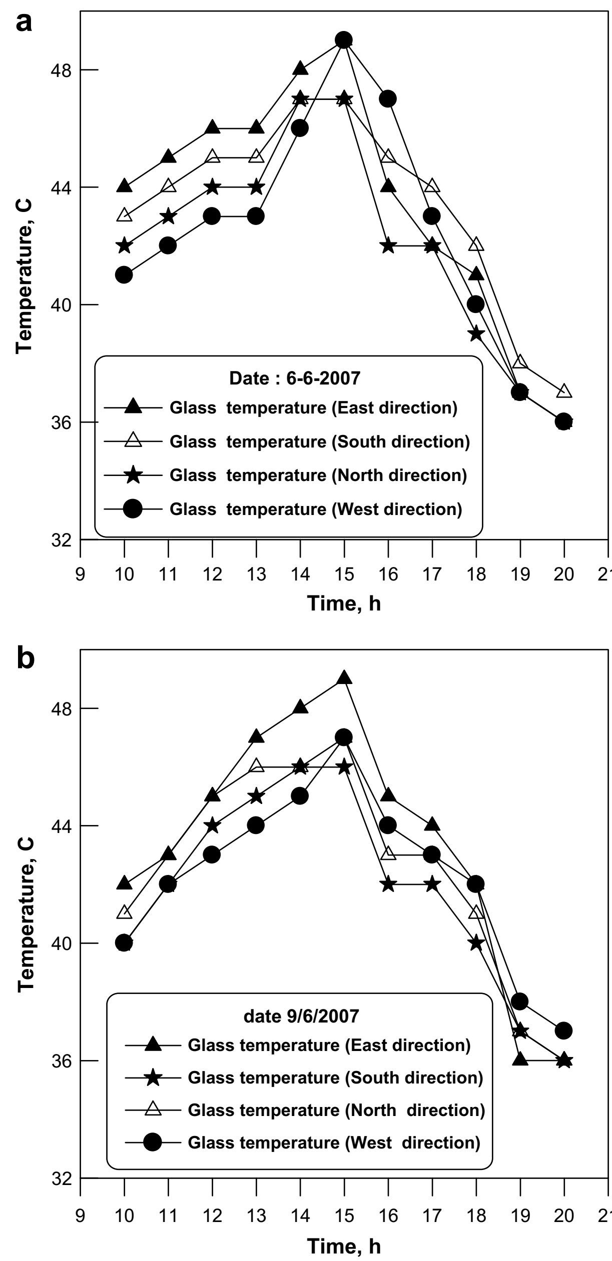

Fig. 4. Hourly temperature variation of the four side's glass covers.

the effect of solar radiation intensity on still productivity is pronounced.

Fig. 6 shows of distillate output for four different days. The distillate output of the solar still follows the total solar radiation intensity with about 2 h delay shift. It increases up to a maximum value at 3 p.m. and then decreases with time. The maximum yield reached is about 500 ml/m^2.

Variation of the accumulated distillate water during the day for different days is shown in Fig. 7. The accumulated water reached 3600 ml/m^2 at 20 h for day 6-6-2007, 2800 ml/m^2 for day 9-6-2007. The total accumulated water after 24 h operation reached 4000 ml/m^2 for day10-7-2007 and reached 4100 ml/m^2 for day 22-7-2007. These deferent values on the accumulated productivity may be due to the variation of climatic conditions. The present accumulated productivity is higher than the conventional type and roof type solar still with corrugated wick of clothes [20] with about 20–40%.

The hourly variation of instantaneous solar still efficiency calculated using Eq. (1) during the selected four different days of testing is shown in Fig. 8. The still efficiency profiles follow similar trends as of those for solar radiation and productivity. The instantaneous efficiency increases in the morning time until a maximum value after solar noon and then remains constant. It can be observed that the efficiency after 3 p.m. is nearly constant, this may be due to the method of calculation of the efficiency; where the input radiation decreases gradually but the stored energy in the still, which is not considered in calculation, may activate the evaporation process. The efficiency of the concave wick solar still reached about 0.45. The calculated daily efficiency from Eq. (3) equals 0.3. The present instantaneous efficiency is higher than the roof type solar still with corrugated wick of clothes [20] with about 20–40%. It also is higher than the tilted-wick type solar still with water flowing over the glass cover [21].

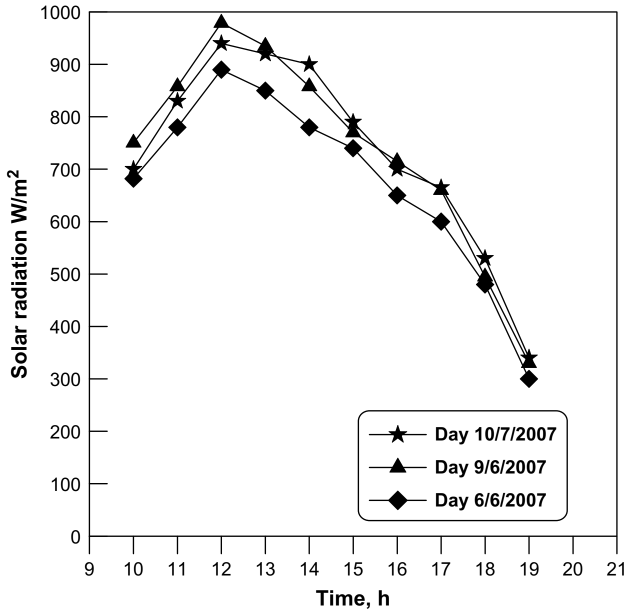

Fig. 5. Hourly variation of radiation intensity on three different days.

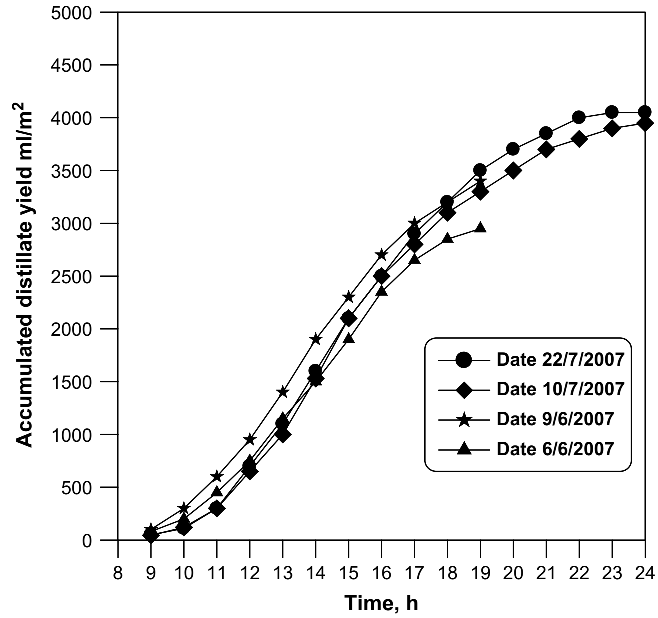

Fig. 7. Variation of the accumulated distillate water during the day for different days.

Comparison between the present solar still and the conventional type solar still [16] is presented in Table 2. It can be observed that the wick concave solar still output is about 200% of conventional type solar still. Also, the instantaneous efficiency is higher with about 50%

7. Cost evaluation

7.1. Cost estimated for present still

Typically, in designing a solar still for a primary application to provide a small scale of potable water needed in remote isolated locations, the objective is to maintain the cost minimal.

Cost estimation for various components used in the concave wick solar still is given in Table 3. The objective is to keep the cost low as possible. The total cost of fabricated still is about 145.5 $.

To obtain the average value of the cost of distillate output it is assumed: n is the expected still life time, V is the variable cost, C is the total cost

$$C = F + V \tag{4}$$

Assume variable cost V equals 0.3 F per year and for the expected still life 10 years, then

$$C = 145.5 + 0.3 \times 145.5 \times 10 = (582.3\$)$$

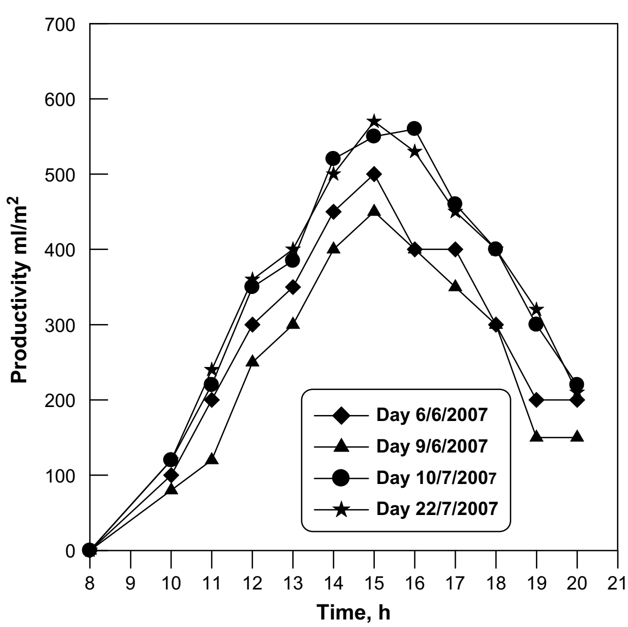

Fig. 6. Hourly variation of distillate output during different days.

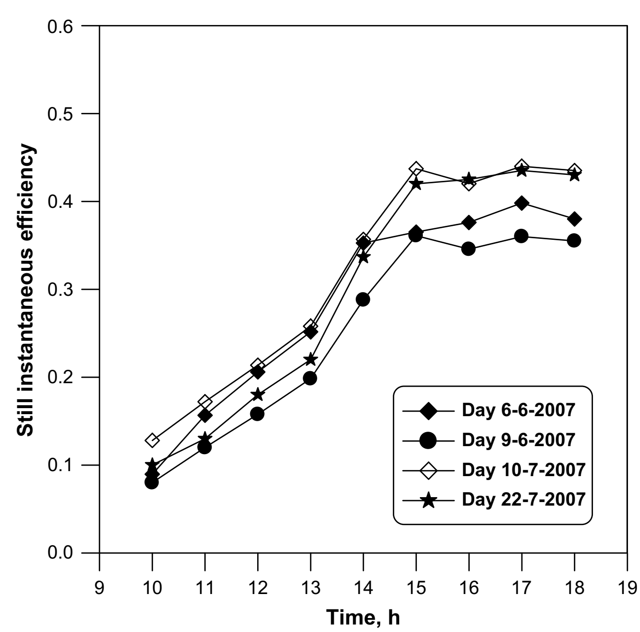

Fig. 8. The hourly variation of the instantaneous solar still efficiency during the different days.

Table 2
Comparison between present concave solar still and conventional solar still [16].

	Accumulated water output per day m^2	Instantaneous efficiency
Conventional type solar still [16]	2100 ml	30%
Present solar still	4100 ml	45%

Table 3
Cost of fabricated solar still in the present work.

Unit	Cost of present type solar still	Cost of conventional type solar still
Wooden box	27.3 $	25.6 $
GI linear	45.5 $	41.8 $
Glass cover	18.2 $	6.18 $
Inlet and outlet ducts	9.1 $	9.1 $
Paint	9.1 $	9.1 $
Insulation	9.1 $	9.1 $
Handles	9.1 $	9.1 $
Production	18.1 $	14.5
Total fixed cost (*F*)	145.5 $	124.5 $

where the minimum average daily productivity can be estimated from the analysis of experimental data, and it is evaluated as 3l/day, Assume still operate 300 days in the year. The total productivity during the still life $P_n = 9000$ l. Cost of litter from this still = 582.3/9000 = (0.065 $). From the previous analysis it can be found that the cost per liter is about 0.065 $.

7.2. Cost estimated for conventional type solar still

With using the previous analysis and assuming that the average productivity equals 2 l/day. It can be obtained that the cost of litter from the conventional type solar still equals 0.083 $ which higher than the concave solar still with about 28%.

8. Conclusions

Based on the results obtained from the experimental work, the following can be concluded.

1. The average distillate productivity of the proposed still during the 24 h time is about 4.0 l/m^2.
2. The proposed concave solar still efficiency reached about 45%.
3. The estimated cost of one litter from the present still equals (0.065 $).

In order to complete the whole picture of the present study, a future work is proposed in the following points:

1. Theoretical study of the system performance.
2. Studying the effect of glass tilt angles on the system performance.
3. Studying the effect of water depth in the still basin and different wick thickness on the still performance.

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