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A. Kabeel
Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

A. Abdullah
Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt. Currently, Faculty of Engineering, Salman bin Abdulaziz University, KSA

Z. Omara
Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt

F. Essa
Mechanical Engineering Department., Faculty of Engineering., Kafrelsheikh University. Kafrelsheikh., Egypt.

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Corrugated solar still with wick and reflectors
المقطر الشمسي مموج القاعدة مع الفتائل والعواكس

A.E. Kabeel[a,*], A.S. Abdullah[a,b], Z.M. Omara[c], F.A. Essa[c]
[a]Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt.
[b]Currently, Faculty of Engineering, Salman bin Abdulaziz University, KSA,
[c] Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt.

الخلاصة
في هذا البحث تم تقديم دراسة عملية لأداء نظام تحلية مياة مكون من مقطر شمسي مموج القاعدة مع الفتائل (الخيش). لذا تم تصميم وتصنيع مقطران شمسيان لمقارنة أدائهما، الأول هو مقطر شمسي حوضي بسيط والثاني هو مقطر شمسي مموج القاعدة. تم دراسة أداء المقطر الشمسي مموج القاعدة مع الفتائل وبدونها وكذلك مع العواكس الداخلية وتم مقارنة الأداء مع المقطر الشمسي البسيط عند نفس الظروف.بلاضافة الي ذلك تم دراسة تأثير عمق المياة المالحة علي أداء المقطر المموج مع وبدون فتائل وعواكس عند أعماق مختلفة ١ ، ٢ ، ٣سم. وقد أظهرت النتائج أن إنتاجية المقطر المموج تتحسن مع الفتائل والعواكس. و أوضحت النتائج أنإنتاجية المقطر المموج (مع الفتائل والعواكس) أعلي من إنتاجية المقطر البسيط بحوالي 145.5% عند عمق ماء ا سم. وفي هذة الحالة تكون الكفاءة وتكلفة اللتر من المياه الناتجة من المقطر المموج والمقطر البسيط هي ٥٩% - 0.025$ و 33% - 0.048$ علي الترتيب.

Abstract
In this paper, an experimental attempt has been made to study the performance of the desalination system comprising of corrugated and wick absorbers of solar stills. Therefore, two solar stills are designed, fabricated and assembled to study and compare their performances. The first one is a conventional solar still (CSS) and the second is a corrugated solar still (CrSS). The performance of the CrSS with and without wick and reflectors is tested and compared with CSS at the same conditions. The influences of saline water depth (1, 2, and 3 cm) on the performance of the CrSS and its modifications have been investigated. Results showed that integrating wick and reflectors with corrugated still enhance the productivity. During experimentations, the productivities of CrSS with wick and reflectors are about 145.5% higher than that of the conventional still, at saline water depth of 1cm. In that case the daily efficiency and estimated cost of 1 l of CrSS (with wick and reflectors) and CSS are approximately 59%–0.025 $, and 33%–0.048 $, respectively.

Keywords**—Solar still desalination; Corrugated solar still; Wick solar still; Productivity enhancement; Efficiency and cost of solar still, Solar still with reflectors.**

1. Introduction
Freshwater is the main and primary requirement of life in the universe and without water, the life will be non-existent. However, while water covers about three quarters of the earth's surface, only 2.5% is gifted as freshwater in lakes, rivers, surface water, polar ice and ground water etc., and not all of this limited quantity is suitable for drinking because of the salt concentration and environmental pollution.

So, access to drinkable freshwater is a major problem everywhere in the world. Therefore, water treatment is usually needed, and water distillation and purification are always necessary to provide freshwater from brackish or seawater.

Solar desalination is one such technique which contributes as a part of the solution for drinking water shortages. However, distillation is energy intensive, and because of the scarce availability of wood and oil, solar desalination is the promise for a cost effective solution.

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Among other types of solar distillation, solar stills are adequate for providing freshwater from sea or brackish water for a single house or a small community. Although the production of basin type solar stills is low, they have the advantages of simple design, construction and less technology and are hence easy to maintain. A survey of various solar still desalination systems was made by Gang Xiao et al. [1] and Sivakumar and Sundaram [2]. Many attempts have been prepared and done to increase the yield of solar stills with lower costs. 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 surface areas of the solar still basin liner increases the productivity. To increase the basin area, fins, corrugated base and sponges [3,4,5] were used. Velmurugan et al. [3] investigated the integration of fins at the basin of the still and showed an increase of daily productivity from 1.88 to 2.8 kg/m^2 a day as compared to other types. The fin type solar still was modified with black rubber, sand, pebble and sponge for enhancing its productivity by Velmurugan et al. [4]. They also determined that the maximum increase in productivity of 75% occurred, when the fin type solar still was integrated with sand and sponge. Experimental investigation to study the effect of using finned and v-corrugated basin liners on the performance of solar stills was conducted by Omara et al. [6]. Their results obtained that the yield of the modified finned and corrugated solar stills was enhanced, at a constant quantity of saline water of 30 l, by 40% and 21% respectively. In addition, the daily efficiency reached about 47.5%, 41% and 35% for finned, corrugated and conventional solar stills respectively.

In addition, when the surface area of basin water is high, 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. As a result, the effects of increasing the surface area of evaporation of water on the performance of basin type solar stills by using different wick materials in the basin of a double slope solar still [7] or using a vertical jute cloth at the middle of the basin of a regenerative solar still [8] were investigated.

The advantage of the wick is to keep the brine as shallow as possible while avoiding dry spots. Sakthivel et al. [8] modified the solar still by keeping jute cloth in vertical position in the middle of the basin water and another row of jute cloth is attached with the wall of the still. They found that the efficiency increases by 8% and cumulative still yield with jute cloth increased by about 20%. Mahdi et al. [9] investigated experimentally a tilted wick-type solar still with charcoal cloth as an absorber/evaporator material and for saline water transport. It was concluded that increase of the input water mass flow rate leads to a reduction in the efficiency of the still where the representative daily efficiency of the still was 53% on a clear summer day. Kabeel [10] used a concave wick surface for evaporation, whereas four sides of a pyramid shaped still were used for condensation. The concave shaped wick surface increases the evaporation area due to the capillary effect. Results indicated that the average distillate productivity in daytime was 4.1 l/m^2 and its efficiency reaches about 45%. Omara et al. [11] conducted an experiment using a new hybrid system, which included the evacuated solar water heater, wicks still, and solar still. The following variables were studied: Single and double layers wick; plane wick, lengthwise and crosswise linen; and feeding hot water during night. Water productivity was increased by about 114% over conventional still for double layer square wick solar still.

Reflectors are used to enhance energy input to the solar still. Abdallah et al [12] enhanced the single sloped solar still performance through increasing the production rate of distilled water. Design modification was introduced to the conventional solar still, involving the installation of reflecting mirrors on all interior sides. The inclusion of internal mirrors improved the system thermal performance up to 30%. Tanaka [13] constructed a basin type solar still with internal and external reflectors. The daily productivity of a basin type still was increased by about 70% to 100% with a very simple modification using internal and external reflectors. The performance of the modified stepped solar still with internal and external (top and bottom) reflectors investigated by Omara et al. [14]. The results showed that, during experimentation the productivity of the modified stepped solar still with internal and an external reflector is higher than that of conventional still about by 125%. In this case the estimated cost of 1 l of distillate for stepped still with reflectors and conventional solar stills is approximately 0.031$ and 0.049$, respectively.

From the previous work, it is concluded that increasing the basin surface area, using the wick material, as well as using reflectors inside the basin still, leads to an increase in the overall productivity of the solar still. Therefore, the main objective of this experimental study is to enhance the yield of solar still by combining between changing the basin liner to be corrugated, using the double layer wick material and internal reflectors. In addition, the performances of conventional single basin solar still and the modified solar still were investigated and compared.

The performance of the corrugated still is experimentally investigated under three cases: corrugated still only, corrugated still with wick, and finally corrugated still with wick and reflectors. In addition, the corrugated still (with and without modifications) with three different depths of water (1, 2, and 3 cm) was also investigated to get the best water depth for maximum output of distilled water as compared to the conventional still.

2. Experimental setup

The investigated solar desalination system contains two solar stills. A cross-sectional view of solar stills is shown in Fig. 1. The first solar still is a conventional still and the second is a corrugated still. The basin area of the conventional still is 0.5 m^2. The still is made of iron sheets (0.0015 m thick). The whole surfaces of the still are coated with black paint to increase the absorptivity. The bottom and side walls of the basin were well insulated by fiberglass. The basin was covered by a glass sheet of 0.003 m thick inclined at nearly 30° horizontally, which is the latitude of Kafrelsheikh, Egypt. This tilt angle was designated to make the received insolation by the absorber to be maxima so as possible and to make the reflection losses to be minima so as possible. In addition, this angle is sufficient for all the water droplets to slip down to the collecting channel.

The corrugated still shown in Fig. 1b has the same dimensions of the conventional one except that the still base has a corrugated shape with a height of 50 mm with an angle of 80° between any two tops or any two bottoms. The space between any two tops is also taken as 0.1m, so the corrugated still base has nine tops and nineteen bottoms of corrugated form. The introduced modifications of the modified corrugated solar still is illustrated in Fig. 2b. Using the double layer wick material over the vees of the corrugated absorber is the first modification, as shown in Fig. 2c. While, the second modification is involving the installation of reflecting mirrors on the three shining walls inside the corrugated still, as shown in Fig. 2d. The feed and distribution of the saline water over the corrugated base form inside the corrugated still was done with the help of a perforated PVC tube, as shown in Fig. 2c.

3. Experimental Procedures

Experiments were conducted at the Faculty of Engineering, Kafrelsheikh University, Egypt

(Latitude 31.07°N and longitude 30.57°E) for twenty seven days from sunrise to sunset, during the period from May to July 2014. The performance of the different solar sills is experimentally investigated under three cases: corrugated still only, corrugated still with wick, and corrugated still with wick and reflectors. The performance of the corrugated still (with and without modifications) with three different depths of water (0.01, 0.02, and 0.03 m) was studied and compared with a conventional still, which has a constant water depth of 0.01 m. Each depth investigation was measured for three different days for each case, and then the average value was taken.

Atmospheric, basin and glass temperatures, distilled water productivity and the solar radiation were measured every one hour. In addition, the accumulated freshwater productivity during the twenty-four hours is measured in each experiment. During experimentations, the depth of water of conventional still is about 0.01 m (the quantity of saline water is about 5 l) and maintained approximately constant manually using the feed water tank and control valves. The experiments were conducted with saline water depths of 1, 2 and 3 cm for corrugated still; the quantity of saline water is about 2.40 l, 4.75 l and 7.10 l, respectively.

4. Error Analysis

Evaluation of the system performance needs several parameters to be measured during the experiments. These parameters are the inside brine temperature, the outer glass cover temperature, the surrounding temperature, the total solar radiation and the amount of output distilled water. The calibrated copper constantan type (K-type)thermocouples (± 0.5 K) were used to measure all temperatures. A data logging solar power meter with a range of 0-5000 W/m^2 and an accuracy of ±1 W/m^2 was used to measure the total insolation on the same level of stills glass covers. A regulated flask of 2 l capacity with an accuracy of 5 ml was used to measure the hourly productivity.

According to the accuracy of each measuring instrument, the estimation of the uncertainty in measurements has been calculated using the procedures explained by Kline & McClintock [15]. It has been carried out that the maximum uncertainty in the measurements is about 2.2 %.

5. Results and Discussion

5.1 Effect of solar radiation on the performance of the solar stills

Experimental investigations were implemented covering many operating conditions. For example, Fig. 3 shows the change in glass, basin water, and ambient temperatures and solar radiation for CrSS and CSS as affected by ambient and surrounding operating conditions during the time of the day.

As expected, it is observed that the brine and glass temperatures go up as the time growths to get a maxima value in afternoon and begin to decline after that. This is due to the increase of solar radiation intensity in the morning and its decrease in the afternoon.

Fig. 3 shows that the glass and basin water temperatures of CrSS with wick are higher than that of conventional still by about 0–1.5 °C and 0–2.5 °C, respectively. This may be due to the following: (1) the vees basin absorber has higher surface area (1.34 m^2) than the flat basin (1 m^2), thus consequently leads to raise the water temperature of the modified corrugated still more than that of the conventional type (2) The wick material has higher storage material properties than that of water only. For these reasons, the freshwater production rate from the modified still is more than that of the conventional type as the ability of evaporation and condensation rates are also higher in the modified still.

While results indicated that the glass and basin water temperatures of CrSS with wick and mirrors are higher than that of conventional still by about 0–3.5 °C and 0–4.5 °C. This is because using mirrors on the inside walls of the corrugated wick still (the three vertical shining sides of the basin still) makes the energy lost is minimal. In addition, the reflectors help in reflecting some of the incident solar radiation onto the basin water surface, thus consequently help to raise the water and glass temperatures of the modified solar still. So, the evaporation and condensation rates in modified solar still were greater than that of conventional still.

5.2 Water productivity

The hourly change in distillate yield for CrSS with wick and CSS at constant depths of saline water inside the basin still is revealed in Fig. 4. It can be concluded that many different measured parameters affect significantly the distilled water productivity (Fig. 3). In addition, observations show that the distilled water was minima during the morning period. This is because the water was not yet heated up. While the maxima productivity of distilled water was given around the afternoon, approximately at 1 p.m., and begins to decline after that. This is because the high incident solar radiation and the high ambient and surrounding temperature during this period of the day (Fig. 3). In addition, the feed water to the desalination system in the morning has low temperature and thus needs time to warm up. Also, it can be observed from Fig. 4 that the hourly distillate yield from modified still is greater than that of conventional type at all times.

Also, the figure shows that a wide productivity change was recorded. Fig. 4 shows that the output distilled water had a minima value in the early mornings at the startup of the desalination system, reaching up to 0.67 and 0.39 l/m^2h as a maximum productivity at 1 p.m. for corrugated still with wick and conventional still, respectively. Hence, at the mid-noon period, the thermal losses of the solar still were minimal, and the thermal performance is increased proportionally. This is attributed to the increase of the surrounding temperature of the still and higher incident solar radiation.

In addition, the modified corrugated still has smaller quantity of saline water (4.75 l/m^2) than that of conventional type. So, the productivity the modified still is higher than that of conventional still since it needs a short time for warming up, heating, evaporation and condensation. The corrugated surface based solar still shows a higher operating temperature for longer time than the plane surface (conventional still). While, the conventional still has higher quantity of water (10 l/m^2), therefore, it needs larger amount of energy to raise the water temperature and consequently takes longer time.

The average accumulated productivity and the percentage of increase in productivity of CrSS respect to CSS for the three tested modes at different water depths is showed in Table 1. Each depth at each case was repeated for three different days, and then the average value was taken.

As shown in Fig. 4 and Table 1, the productivity of the CrSS with wick is always higher than that of CSS either with or without the reflecting mirrors, all the time. This may be due to the negligible heat capacity of water mass in the CrSS (thin film of brine water). Using wick increases the heat transfer and evaporating surface area of the brine through base and vertical walls of solar still. In addition, it provides the still with a low thermal capacity and consequently faster response to incident solar radiation (compared with conventional basin type stills) which increase the absorber temperature (brine water) and yields higher evaporation rates [16].

The CrSS with wick has higher heat transfer area and bigger water surface exposed to incident solar radiation as compared to the CSS, 1.34 m^2 and 1 m^2 respectively. So, the heat transfer rate between the absorber surface and the water is got better in the modified still. The experimental measured data indicate that, as a result of area increase, the absorber plate temperature and saline water temperature were increased, and as the temperature difference between water and glass goes up, the distilled yield was augmented.

In addition, the CrSS with wick and reflecting mirrors has higher productivity than that of CSS. This is because the mirrors utilizes from the incident solar radiation as much as possible by redirecting some of the radiation onto the water surface, thus consequently the water and glass temperatures of the modified solar still are increased. So, the evaporation and condensation rates in modified solar still were greater than that of conventional still.

5.3 Daily productivity

Fig. 5 shows the hourly accumulative variations of freshwater productivity from 9 a.m. to sunset for the two tested stills. It is found that the amount of accumulated distillate for CrSS with wick is higher than that CSS at all times of experiments, where the hourly freshwater productivity is higher for modified solar still. But the accumulated distillate for the CrSS with wick and mirrors is greater than that of the CrSS with wick only and is higher than that of the CrSS only.

The average experimental data of daily accumulated water productivity for different days of testing for both conventional and modified corrugated stills are given in Table 1. Results demonstrated that the distillate production of CrSS only reached about 55.36% higher than that of CSS. In addition, the productivity of CrSS with wick was about 90% over the conventional still. And also, the productivity of CrSS with wick and mirrors reached approximately 145.5% higher than that of conventional still as shown in Table 1.

Efficiency, η_d, is obtained by the summation of the hourly condensate production $\dot{m}_{ew}$, multiplied by the latent heat h_{fg}, hence the result is divided by the daily average solar radiation $I(t)$ over the whole area A of the device:

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

In the current modes of operations, the daily average efficiency for the CrSSis approximately 40%. In addition, the daily average efficiency for the CrSS with wick is approximately 49.3% and equal 59% for the CrSS with wick and mirrors. While the daily efficiency for conventional solar still is approximately 33%. For conventional solar still, the same result was obtained by Omara et al. [11].

As the experimental data confirmed, using internal mirrors improved the performance of modified solar still. Al-Hayek and Badran [17] indicated that adoption of mirrors on the inside walls of the solar stills will enhance the production of distilled water and improve the efficiency through controlling the radiation losses from the still basin.

5.4 Effect of water depth on modified corrugated solar still

It can be indicated from Fig. 6 that the productivity decreases with increasing water depth for all tested modes. Also, Fig. 6 shows a comparison between using corrugated absorber only and supplying wick material at different depths of basin water with and without reflecting mirrors. It is seen from the figure that the more decrease in basin water depth, the more increase in productivity for all the three tested cases. In addition, it can be observed that the increase in productivity as a percentage for the corrugated wick still with mirrors is greater than that of the corrugated wick still without at the same water depth.

6. Cost Evaluation

The fixed cost of the CSS (1 m^2) is about F = 103 $. Assume variable costs V equal 0.3 F per year [6, 10], and C is the total costs, where, C = F + V and for the expected still life 10 years, then C = 103 + 0.3 × 103 × 10 = 412 $ where the minimum average daily productivity can be estimated from the analyses of different experimental data, and it is assumed that 2.5 l/day, Assume still operates 340 days in the year, where the sun rise along the year in Egypt. The total productivity during the still life =2.5x10x340=8500 l. Cost of distilled litter from the conventional still = 412/8500 = 0.048 $.

In addition, the fixed cost of a CrSS with wick (1 m^2) is about 122 $. Then, C = 122 + 0.3 × 122 × 10 = 488 $ where the minimum average daily productivity can be estimated at 5 l/day. The total productivity during the still life =4x10x340=13600 l. Cost of distilled litter from the conventional still = 488/13600 = 0.036 $.

Also, the fixed cost of a CrSS with wick and reflecting mirrors (1 m^2) is about 130 $. Then, C = 130 + 0.3 × 130 × 10 = 520 $ where the minimum average daily productivity can be estimated at 6 l/day. The total productivity during the still life =6x10x340=20400 l. Cost of distilled litter from the conventional still = 520/20400 = 0.025 $.

7. Conclusions

The performance of corrugated solar still in addition to a conventional still is investigated. The results showed that the distillate yield, as well as thermal performance, of a conventional still can be enhanced through the design modifications. The corrugated plate as a base increases the amount of distilled water produced by about 55.36% compared with the conventional still, at a saline water depth of 1 cm. While, adding wick to the corrugated plate as a base increases the amount of distilled water productivity by about 90% compared with the conventional still. Besides, water productivity of corrugated solar still with wick and internal reflecting mirrors is increased by about 145.5% over conventional still. In addition, the average daily efficiency for the corrugated solar still with wick is approximately 49.3%. While, the average daily efficiency is approximately 59% with wick and mirrors. And the daily efficiency for conventional solar still is approximately 33%.

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Table 1
Average accumulated productivity and the percentage of increase in productivity of CrSS respect to CSS for the three tested modes.

Mode 1			
Water depth (m)	H = 0.01		
Conventional still (l/m^2)	2.240	2.000	2.690
Water depth (m)	H = 0.01	H = 0.02	H = 0.03
Corrugated solar still only (l/m^2)	3.480	2.800	3.500
Increase in productivity (%)	55.36 %	40 %	30.11 %
Mode 2			
Water depth (m)	H = 0.01		
Conventional still (l/m^2)	2.000	2.360	2.640
Water depth (m)	H = 0.01	H = 0.02	H = 0.03
Corrugated still with wick (l/m^2)	3.800	4.320	4.600
Increase in productivity (%)	90 %	83.05 %	74.24 %
Mode 3			
Water depth (m)	H = 0.01		
Conventional still (l/m^2)	1.670	2.000	2.050
Water depth (m)	H = 0.01	H = 0.02	H = 0.03
Corrugated still with wick and reflectors (l/m^2)	4.100	4.400	4.000
Increase in productivity (%)	145.5 %	120 %	95.12%

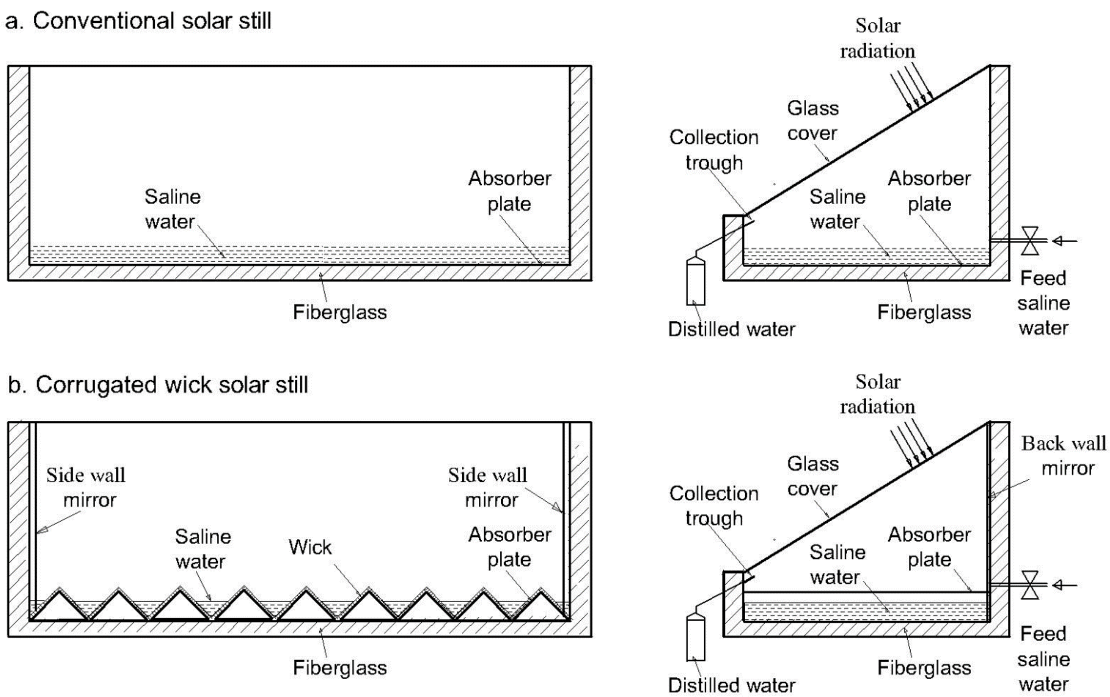

Fig. 1 Cross-sectional view of solar stills

a. Corrugated base

b. Corrugated solar still

c. Corrugated solar still with wick

d. Corrugated still with wick and reflectors

Fig. 2 Corrugated solar still

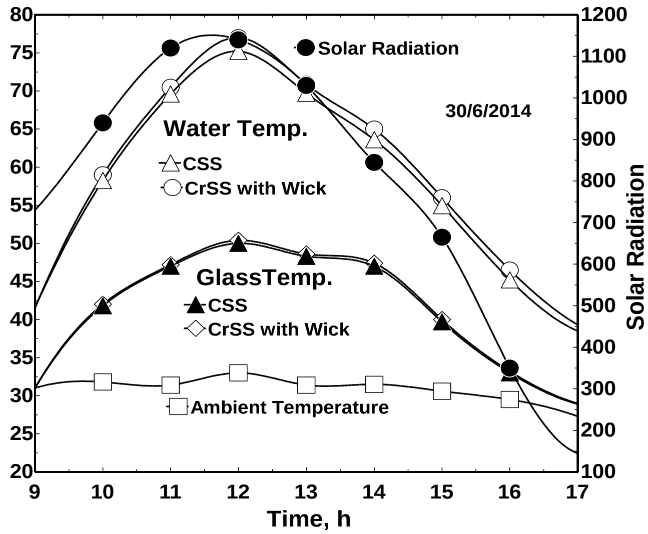

Fig. 3 Hourly temperature variation and solar radiation for CrSS with wick and CSS at saline water depth 0.01 m

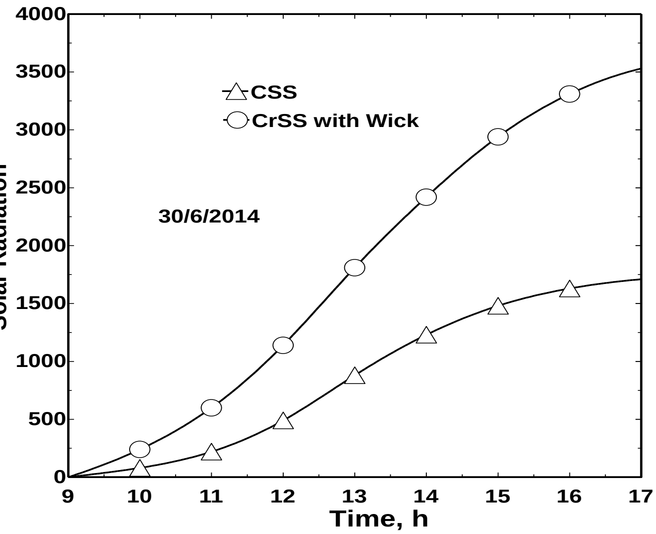

Fig. 5 Variation of accumulative water productivity for CrSS with wick and CSS at saline water depth 0.01 m

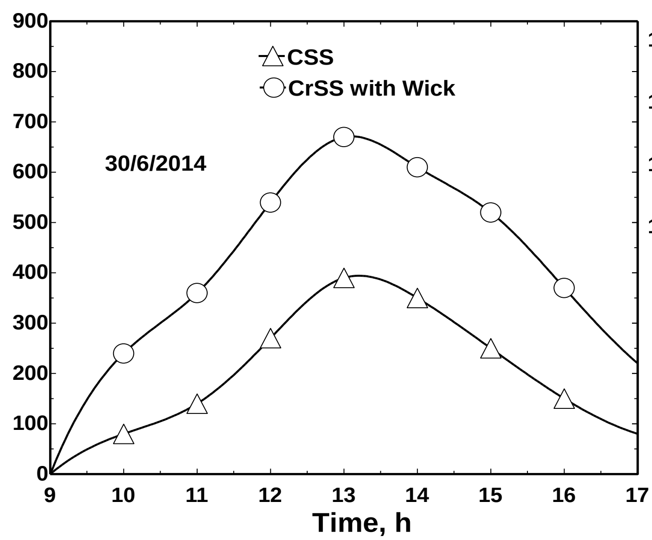

Fig. 4 Variation of Freshwater productivity for CrSS with wick and CSS at saline water depth 0.01 m

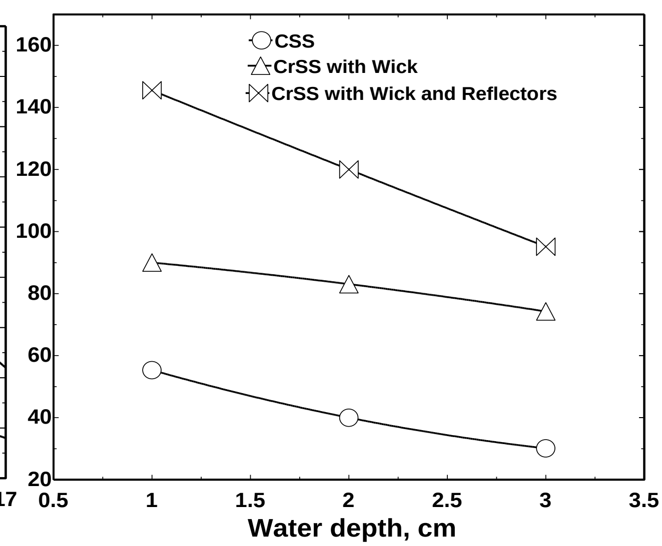

Fig. 6 Variations of increase in productivity for the CrSS and CSS for the three modes of testing at deferent saline water depths