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Improving the productivity of a single-slope solar still using Fresnel lenses under Iraq climatic conditions

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ABSTRACT

The present work highlights the importance of using the Fresnel lens technique to enhance the productivity of a conventional solar still (CSS). In this regard, the effect of using Fresnel lenses to improve the productivity of a CSS is investigated experimentally under the climate conditions of Basra city (30.5258°N latitude and 47.7738°E longitude), Iraq. The Fresnel lenses integrated conventional single-slop-basin type solar still (CSS_{FL}) adjustable to be rotated manually at different angles was examined, compared to the CSS which showed a remarkable enhancement of producing output. The study concerned the variation of daily solar radiation and temperature effect on the distillate output and the efficiency of both the conventional and modified solar stills at 1 and 2 cm saline water depths during July and September of the year 2019. The experimental results showed better performance during July where it has been found that the productivity of the CSS_{FL} improved over the CSS by about 68.6% at 1 cm depth and about 59.3% at 2 cm depth. Moreover, the average daily thermal efficiency of the CSS and the CSS_{FL} at 1 cm depth was 21% and 36%, respectively. Several conclusions and recommendations are presented for future work.

Keywords: Solar still; Fresnel lenses; Water purification; Single-slope basin still; Productivity enhancement

1. Introduction

Water purification has become one of the urgent requires of modern life due to the increase of the human population and the variety of contaminant sources. The wastewater produced by industrial processes and other natural activities has increased dramatically, which threatens the existence of people and nature, eventually. Task 62 of IEA SHC provides the most effective possibilities, technically and economically, for decontaminating and treating industrial wastewater using solar thermal energy aiming to reduce CO_2 emissions and save energy [1]. Solar stills are among the technologies that attracted the researchers due to its simple construction and viable for using different energy sources and thus, many methods have been applied to improve the performance to produce more freshwater.

The single-slope basin type solar still, despite its simplicity, has the lowest productivity compared to the other distillation methods. Geothermal energy can be used to improve the productivity of solar still by shortening the time required for condensation. Danish et al. [2] built a solar still integrated geothermal cooling system and a vacuum pump. The cooling effect was obtained from circulating fluid within the underground and later, transfers it to

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the shell and tube heat exchanger contains the water vapor produced from the solar still. The vacuum pump is necessary to maintain a certain pressure level inside the still. The productivity of the modified still was increased by 305% taking into consideration the effect of vacuum pressure, ambient temperature and wind speed. Reflectors were used in many research works to enhance the yield of solar still by increasing the amount of solar radiation reflected in the basin. Mulyanef et al. [3] tested a solar still equipped with a reflector placed on the top of the still with an angle of 30°. The daily produced water was improved by 16.8% compared to the still without reflectors. Omara et al. [4] used reflectors along with double layer wick material inside conventional single slope solar still to increase freshwater productivity. The experiments have made for 1, 2, and 3 cm saline water depths and the results indicated productivity increment up to 145.5% by using this technique and the daily efficiency was increased by 26% at the depth of 1 cm. Gugulothu et al. [5] introduced the reflectors with the sodium sulfate and white Paraffin wax as phase change materials (PCMs). They found that Paraffin wax is the best for more yield of the solar distillation. The use of PCM as heat storage was also studied experimentally by Kabeel et al. [6]. Double passes solar air collector was coupled with a phase change material inside conventional solar still (CSS) for better freshwater productivity. The productivity was enhanced by 108% where the modified solar still reached 9.36 L/m^2 d compared to 4.5 L/m^2 d obtained by the still without using this technique under the same weather conditions.

Gupta et al. [7] modified a CSS by adding a sprinkler attachment flowing water over the top cover of the still, and mixed nanoparticles (cuprous oxide) with the saline water to accelerate the evaporation rate in the basin. This technique produced 4,000 mL/m^2 d of freshwater compared to 2,900 mL/m^2 d obtained from the CSS. The efficiencies for the modified and conventional stills were 34% and 22%, respectively. Omara et al. [8] used a water fan powered by wind turbines to enhance the daily productivity of a CSS. The fan was fixed inside the still basin at 1, 2, 3 and 4 cm water depths and operated under different rotational speeds. The results showed that better productivity was collected at 1 cm water depth and less than 22 rpm rotational fan speed. Further, the daily freshwater productivity is enhanced by 17% at depth of 3cm and fan speed of 30 rpm. Ketabchi et al. [9] proposed several modifications to get maximum productivity from the inclined basin solar still. Angled bars were placed in the basin, a cooling system was fixed on the glass cover and an external flat-plate reflector was installed on the top and bottom of the basin which constructed adjustable to achieve the highest solar radiation in each season. The maximum productivity achieved was 4.2 kg/m^2 with a still efficiency of 36.7% at a basin inclination angle of 25° and top and bottom reflector angles of 10° and 45°, respectively.

The use of PCMs to improve the productivity of solar stills was reviewed comprehensively by Omara at al. [10]. They reported that the use of PCM as a latent heat storage system can enhance the productivity of passive and active solar still by up to 120% and 700%, respectively compared with a solar still without PCM. Moreover, the productivity of freshwater increased as the mass of PCM increased and the mass of saline water decreased inside the basin. In the same direction, Vigneswaran et al. [11] designed and tested three models of PCM-assisted solar stills with equal dimensions for yield enhancement. A CSS (*A*) was used for comparison with the still (*B*) which has 16 tubes of 25.4 mm diameter filled with the paraffin and placed at the basin, while the PCM was incorporated in between the annulus of the outer tube (31.75 mm diameter) and the inner tube (6.35 mm diameter) of the third still (*C*). The obtained daily productivity was 2.228, 2.592 and 2.832 L/m^2/d for the still (*A*), (*B*) and (*C*), respectively. Further, the still (*A*) enhanced productivity by 27% and 6% higher than the stills (*A*) and (*B*). Amarloo and Shafii [12] utilized the potential of radiative cooling at night using PCM material to enhance the water productivity of a desalination system in the day-time. Two condensers were used for this purpose, a PCM-condenser to store cooling effect at night and, an air-condenser used to condensate the vapor generated from evaporative tank-solar collector arrangement. The results showed that the daily yield and efficiency of the system were increased from 2.139 kg/m^2 and 23.9% to 2.805 kg/m^2 and 30.7%, respectively. Bhalavi et al. [13] used cylindrical cement blocks as a sensible heat storage medium in the basin of single slope solar still compared to another CSS that has the same size under the same weather conditions. The experiment was done for different saline water depths ranging from 2–5 cm to identify the best level for water yield. The results showed enhancement in the efficiency by up to 67% at 2 cm depth in the modified solar still using this technique compared to the conventional one. In the same direction, Deshmukh and Thombre [14] utilized the sensible heat transfer medium to enhance the nighttime yield. They used sand and servo-therm material as a heat transfer medium (oil medium) under the basin of single slope solar still to store the heat during the day. The study concluded that productivity was increased during the night period and it was directly proportional to the size of the storage and water mass. Moreover, the productivity during the day period was decreased and the relative humidity has impacted productivity. The role of nanoparticles to enhance the performance of solar stills was extensively reviewed by Rashidi et al. [15]. They concluded that the daily productivity of both active and passive solar stills has enhanced when the nanoparticles have adapted with higher solid fraction, furthermore, the SiC is the better option of nanoparticles due to its excellent stability and high thermal conductivity. Many other techniques such as the use of photovoltaic thermal compound parabolic concentrator water collectors, developing of a hybrid system of mini solar pond combined with the still, adding of square pipes as fins attached to the basin, etc. were carried out by the researchers aiming at increasing the productivity of the single-slope basin type solar still where the results showed obvious enhancements [16–21].

The use of Fresnel lenses to concentrate the sunlight on the saline water is a modern method adapted to speed up the rate of vaporization and produce more freshwater along with the improvement of the overall thermal efficiency of solar still [22]. Sriram et al. [23] built multi slope solar still to purify the polluted industrial wastewater. The four sides of a still were made in such a way acting as Fresnel lenses and the results showed that the wastewater was converted to drinkable water with optimal ph and total dissolved values. El-Agouz [24] modified a CSS using a convex lens on the glass cover of the still and later, a black stone was added to the modified solar still to enhance the performance of produced water at 30 and 20 kg of water mass. The results showed that the productivity of the modified still with the convex lens has improved by 26.64%, and improved more by 35.55% using black stone along with the convex lens at a water mass of 30 kg. Moreover, productivity has been enhanced by 51.85% at 20 kg mass of water. In the same direction, Sathyamurthy and El-Agouz [25] investigated the exergy analysis of a CSS modified with convex lenses as the first step, and adding bluestone (as energy material placed inside the basin) secondly at 30 kg mass of water. The results showed good improvement in the exergy efficiency of the modified CSS with convex lenses by about 4% while, it was 11.7% using bluestone along with the convex lenses modified solar still. This study indicated the good quality of the produced water according to the standards of the world health organization. Mu et al. [26] investigated the augmentation in productivity of a single-basin, single-slop solar still using a Fresnel lens of (0.75 m × 1 m). The study considered the water depth inside the basin and the forced air as operational parameters which successfully reported an improvement of 467% in the produced pure water and daily efficiency of 84.7% was obtained. Abdelsalam and Abdel-Mesih [27] used four Fresnel lenses of (400 mm × 320 mm) dimensions to focuses the solar beam aiming at heating the main feeding saline water pipe of a solar still. The results indicated that the use of Fresnel lenses accelerated the start of evaporation and resulted in an enhancement of productivity by 231.17% and increasing the thermal efficiency by 68.76%. Muraleedharan et al. [28] investigated the performance of solar still connected with a combined solar collector bases Fresnel lenses. The collector was provided with an evacuated receiver tube and heat exchanger of the serpentine loop type. Nanofluid based Al_2O_3-Therminol-55 was used as a heat transfer fluid flowing inside the loop to exchange the heat between the still and the collector. The influence of saline water temperature, hourly and total productivity was studied as performance parameter. The results showed that at 0.1% nanofluid concentration the hourly efficiency of the modified still was increased by 45%–250.27% over the conventional still. Moreover, the productivity of the modified solar still was improved by 12.190 L/m^2 d compared with 3.48 L/m^2 d for the conventional one. The study also stated that the maximum daily efficiency of the modified still reached 53.55% over the CSS.

In the present work, the effect of the Fresnel lenses-based modification, as well as the saline water depth, on the productivity and thermal efficiency of solar still were experimentally studied under the climatic conditions of Basra city, Iraq. The lenses are fixed on an adjustable lever and tracked manually to concentrate the solar radiation at different times of the day for better productivity.

2. Methodology

2.1. Experimental set-up

Two identical single-slope basin type solar stills, a CSS and a modified one with Fresnel lenses (CSS_{FL}), were used in the study. Fig. 1 shows a detailed photo of the stills and measuring devices used in the experiments. The stills are made mainly of a local clear glass of 6 mm thickness and all four sidewalls and bottom are covered with a blacked-insulation sheet to minimize heat losses from the stills. The bottom of each still is rectangular with (50 cm × 40 cm) dimensions while, the elevation of the highest and lowest side walls are 32 and 22 cm, respectively. The top glass cover is inclined by about 11.3°to the horizontal to gain the highest beam solar radiation at different times considering the best inclination angle at the studied location. The basin is made from a galvanized iron sheet of 2 mm thickness with dimensions of 30 cm × 20 cm × 5 cm for length, width and height, respectively.

Three-electrically operated thermocouples are used to measure the inlet water temperature (*T*1) provided to each still (tank water temperature), outer glass cover temperature (*T*2) and the temperature of the water inside the basin

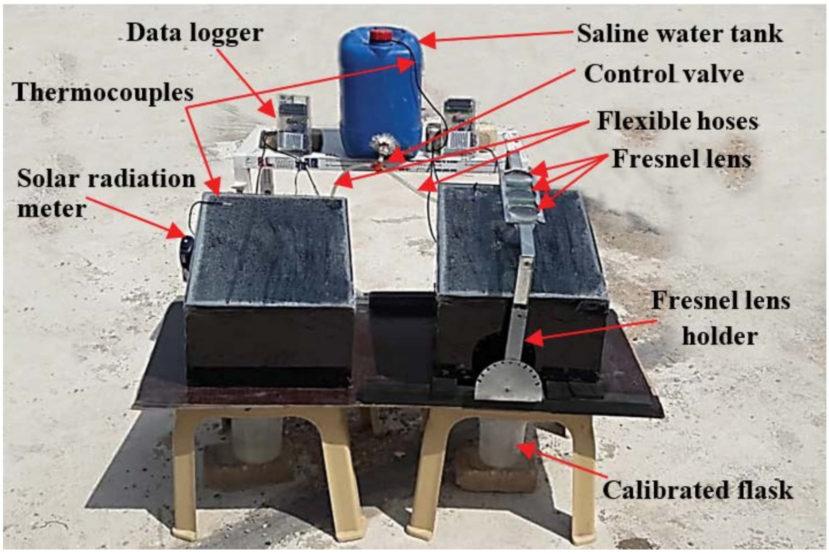

Fig. 1. Photo of CSS and CSS_{FL}.

($T3$). The used thermocouples were manufactured and calibrated by a local specialized company and tested in different experiments giving good results compared to standard ones. A solar power meter device used to measure the solar radiation over the studied period. Saline water obtained from a salty well-known river called Shatt Al-Arab was used in the study. The saline water is fed into the stills from an external tank (quantity of 20 L) kept at a level of 1 m above the ground via flexible tubes provided with a control valve to keep the water inside the basin at a suitable level (1 and/or 2 cm). The freshwater produced from each solar still is collected by a calibrated flask placed beneath each still.

The modified solar still is provided with an adjustable lever has three Fresnel lenses of 9 cm diameter for each with a distance of 2 cm between each two, as shown in Fig. 2. The lever is fixed aside from the still and rotatable in different angles ranging from 0° to 180°. The arm of the lever can be adjusted to get the best focal length between the lenses and the saline water. The base of the lever has 11 holes with an angle step of 15° between each two, to position and manually fix the lenses at the optimal track to the sun. Table 1 shows the best angles fixed in each time for the CSS_{FL} considering the orientation of the sun.

2.2. Experimental procedure

The measurements were carried out on the rooftop of the department of mechanics/Southern Technical University, Basra (30.5258°N and 47.7738°E), Iraq. The stills were tested in the first week of July 2019 to maintain any technical issues that may take place during the days of the experiment. The measured data was recorded during the whole day long of two hottest months in Iraq, July and September 2019, starting from 6:00 to 18:00. All necessary data of produced freshwater, ambient temperature, $T1$, $T2$, $T3$, and solar radiation were collected every 30 min. The experiment started by opening the control valve attached to the flexible tubes joined the tank with solar stills. The saline water was poured into the basin slowly by controlling the level of water at 1 and 2 cm every 30 min in the days of the experiment. The direct solar radiation is heating the saline water inside the basin of CSS and CSS_{FL}. The vaporized water droplets were formed continuously on the inner glass cover surface due to the temperature difference of cover sides and then, the accumulated freshwater is collected into the calibrated flasks coming out from the stills, continuously.

2.3. Instrumentation

The realistic results usually depend on the accuracy of the instruments and tools used in the study. The measurements were carefully recorded for the main parameters (the inlet of saline water temperature, glass cover temperature, basin temperature, and solar radiation) and the results were quite logical. Table 2 shows the specifications of the main measuring devices used in the study.

3. Results and discussions

3.1. Impact of solar radiation

Solar radiation has a significant influence on the variation of solar still temperatures, which impacts its productivity, later on. Figs. 3 and 4 show the relation of solar radiation with the variation of ambient temperature, $T1$, $T2$ and $T3$ for CSS and CSS_{FL} at 1 and 2 cm of saline water depths in every 30 min of experiment days.

On the day of the experiment, 8/7/2019, the recorded values of solar radiation ranged from 357 W/m^2 in the early morning at 6:00 to the highest value in the mid-day at 13:00 which was 1,221 W/m^2. The lowest and highest values of solar radiation ranged from 445 W/m^2 at 6:00 to 1,268 W/m^2 at 13:30 on 21/7/2019. Ambient temperature is linked to solar radiation, it was increasing as the solar radiation increase and reached the highest value of 46.6°C and 50.8°C in the first and second days of the experiment. The temperature of inlet saline water started to increase steadily as the radiation increase and reached the maximum value at the midday, and then it decreased in the late afternoon. The values of inlet water temperature should be fixed constant during the experiment to record precise data but they showed such variation because the saline water was contained in a tank exposed to the solar radiation directly all day long.

For September days, the solar radiation was lower than July which ranged between 387 and 1,229 W/m^2 and that affects the ambient temperatures and produced water eventually. The temperature of the outer glass cover surface in both stills had somehow a close temperature behavior during the day with a slight increase in the modified still.

Table 1
Angles of inclination fixed for lenses in each time

Time (h)	Angle
6:00–7:30	60°
8:00–10:30	75°
11:00–12:30	90°
13:00–14:30	105°
15:00–16:30	120°
17:00–18:00	135°

Table 2
Specifications of instruments and devices used

Instrument	Model	Range	Resolution	Accuracy
Solar power meter	SM206	0.1~399.9 W/m^2	0.1 W/m^2	±10 W/m^2
Thermocouples	DS18B20	–55°C~+125°C	9 to 12 bits	±0.5°C from –10°C to +85°C
Graduated flask	–	0~1,000 mL	2 mL	±1 mL

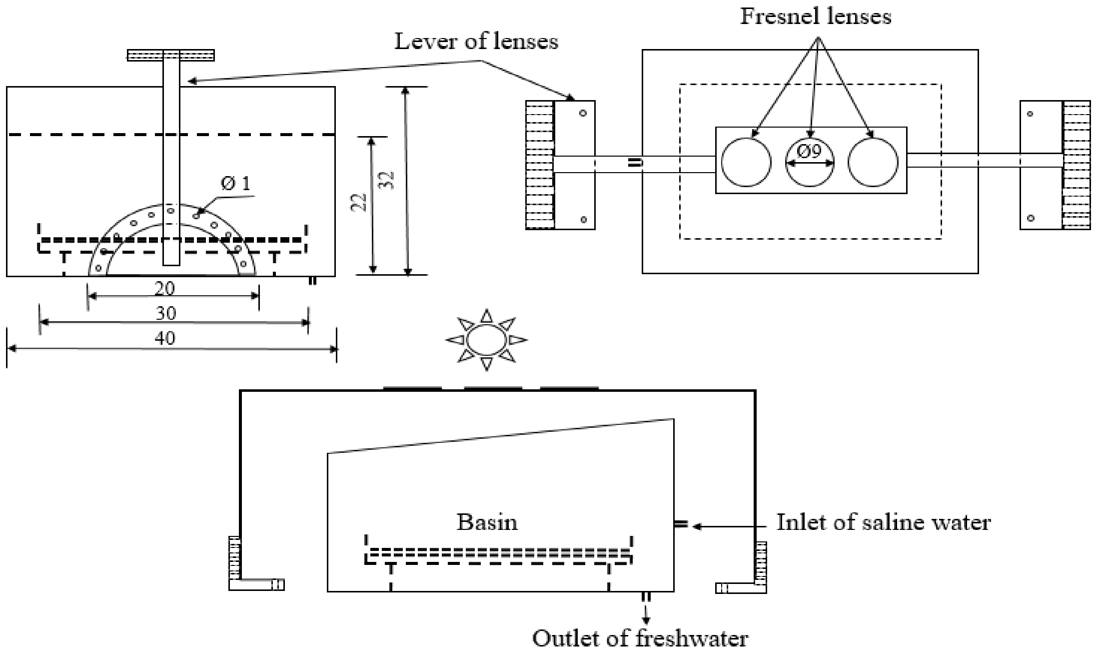

Fig. 2. 2D schematic view of the modified solar still.

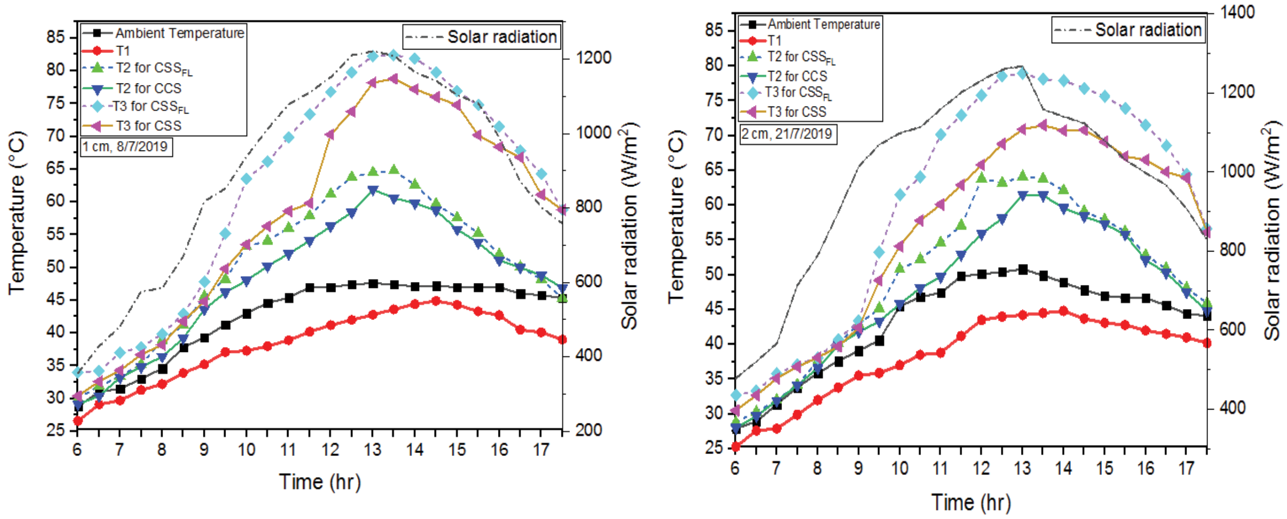

Fig. 3. Temperature variation for CSS and CSS$_{FL}$ at 1 and 2 cm depth in July 2019.

This increases due to the concentration of solar radiation by the lenses which leading to heat the outer surface of the glass cover of CSS$_{FL}$. The most important benefit of modifying the still with Fresnel lenses is to reach the evaporation for saline water in a time shorter than that taken by the conventional still. Moreover, the use of lenses increases the temperature difference between water vapor generated inside the still and the ambient air surrounding the still which increases the condensation significantly. This can be shown in the above figures where the basin temperatures of CSS$_{FL}$ are quite higher than that of CSS in both levels of saline water.

3.2. Productivity of freshwater

The relation between solar radiation and the productivity of freshwater for CSS$_{FL}$ and CSS at different levels and times can be seen in Fig. 5. The curves indicated zero productivity from both stills in the early morning where the solar radiation was low and the heat collected by the stills was not enough to heat the saline water inside the basins. The modified solar stills, at 1 and 2 cm levels, started to produce freshwater earlier than the conventional stills with small quantity because the lenses accelerated the time needed to reach evaporation. Later, both stills produced more and more fresh water and reached the maximum

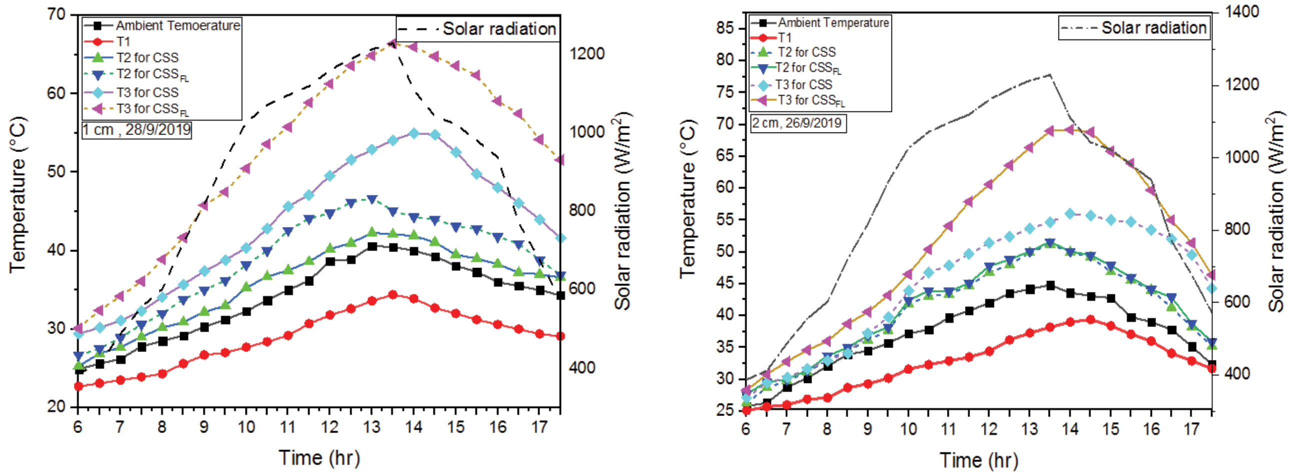

Fig. 4. Temperature variation for CSS and CSS$_{FL}$ at 1 and 2 cm depth in September 2019.

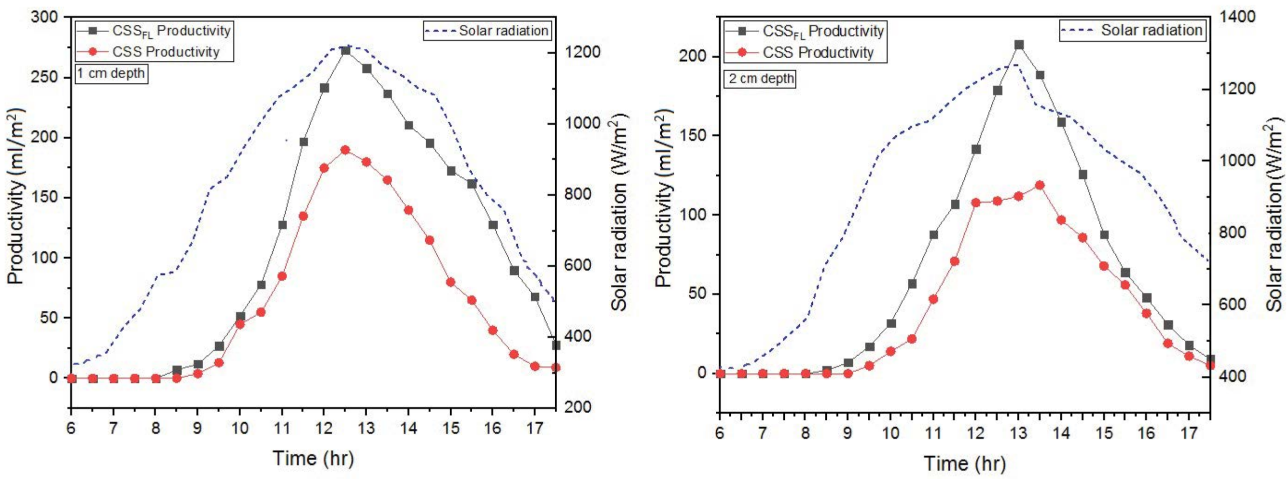

Fig. 5. Productivity at 1 and 2 cm depths in July month experiments.

values in the mid-day, as expected, due to the high solar radiation incident on them. The productivity declined after that as the solar radiation decrease and it was obvious that the productivity of CSS$_{FL}$ is higher than CSS at all times. The stills at 1 cm saline water depth produced more freshwater than the stills at 2 cm depth although the solar radiation was higher. The reason for that is the saline water at 1 cm depth needs a shorter time to be heated up and reach evaporation less than that needed to heat the saline water at 2 cm depth.

Fig. 5 shows that the difference between productivity curves at 1 cm depth remained large in the late afternoon and this is due to the following reasons: first, the solar radiation incident is continued high in the second part of the day and this is the nature of Iraqi summer days and the lenses benefit by this property. Secondly, the tank contains saline water that was exposed to solar radiation all times which warming the water more and more during the day and fed it at high temperature to the stills. Meanwhile, the relatively high quantity of saline water at 2 cm depth made these reasons less affect and kept the curves of productivity closed.

The total cumulated distillate water of CSS$_{FL}$ and CSS for July and September experiments can be seen in Table 3 and Fig. 6, where the highest values were recorded at a depth of 1 cm in the months of the experiments.

3.3. Efficiency

The efficiency of conventional and modified solar stills are calculated using the method introduced by [29] in which the hourly thermal efficiency in each time of the experiments calculated by Eq. (1):

$$\eta_{th.} = \frac{\sum P \times L}{\sum I \times A \times 3,600} \tag{1}$$

where P is the hourly freshwater productivity (kg); L is the latent heat of vaporization (kJ/kg); $L = 3.1615 \times 10^6 [1 - (7.616 \times 10^{-4} T3)]$.

For $T3 > 70°C$ and $L = 2.4935 \times 10^6 [1 - 9.4779 \times 10^{-4} T3 + 1.3132 \times 10^{-7} T3^2 - 4.7974 \times 10^{-9} T3^3]$. For $T3 < 70°C$; I is the hourly solar radiation (W/m^2); A is the area of the cover (m^2).

Fig. 7 shows the variation of solar still efficiency at different water depths during the day. The efficiency started with zero value in the early morning until 8:30 h and reached higher values in the mid-day. The modified still recorded the highest values at 1 and 2 cm depths compared to the conventional still at the same depths. The hourly thermal efficiency of CSS_{FL} at 1 cm depth shows optimal values at all times and indicated a ratio of about 97% at 12:30.

For the July experiments, the results showed that the daily average thermal efficiency of CSS and CSS_{FL} at 1 cm depth is approximately 21% and 36%. While, the daily average thermal efficiency at 2 cm for CSS and CSS_{FL} is 15% and 26%, respectively.

Table 3
Total distilled freshwater in July and September

Date of experiment	Saline water depth (cm)	Distillate water (mL)	
		CSS	CSS_{FL}
8 July 2019	1	1,528	2,578
21 July 2019	2	988	1,574
26 Sep. 2019	2	1,073	1,457
28 Sep. 2019	1	949	1,370

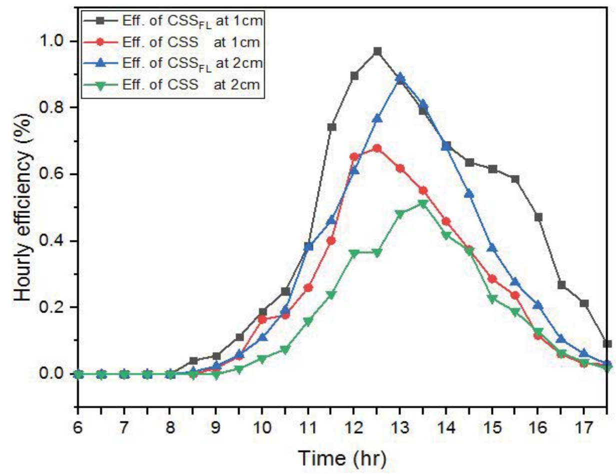

Fig. 7. Variation of hourly thermal efficiency of CSS and CSS_{FL} at different depths (July experiments).

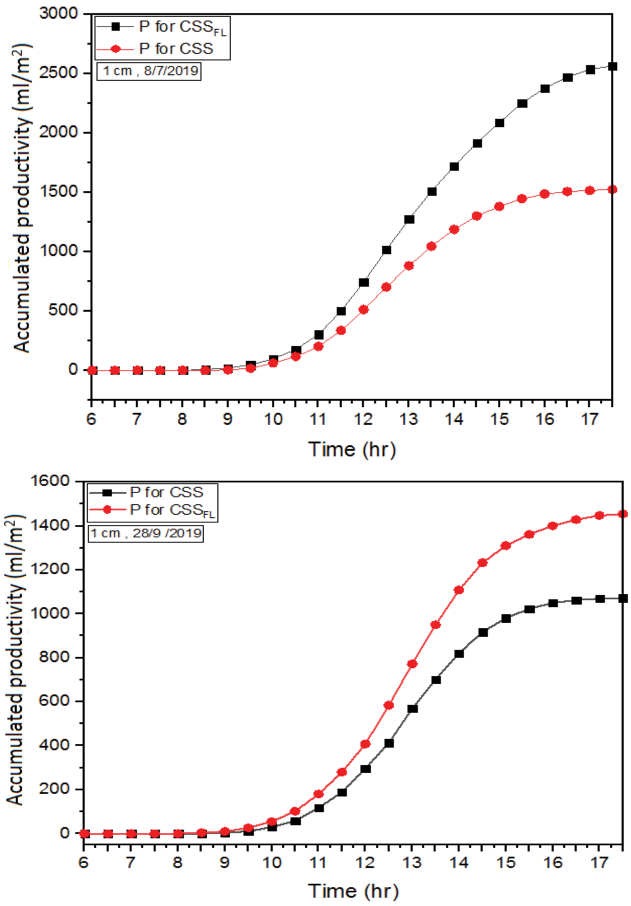

Fig. 6. Accumulative produced freshwater at 1 and 2 cm depths.

4. Conclusions

Fresnel lenses integrated single-slope solar still to improve the productivity of freshwater was investigated experimentally. The prototype was fabricated and tested under weather conditions of Basra city, Iraq in the hottest two months of the summer, July and September. The study concerned the variation of solar radiation and temperature effect on the distillate output and the efficiency of the conventional and modified solar stills at two different depths. Based on the previous discussions, several conclusions have been drawn as follows:

- Modified solar still with Fresnel lenses has a better performance compared to the one without Fresnel lenses under the same climatic conditions.
- Modified solar still increases the productivity of freshwater by about 68.6% at 1 cm depth and, about 59.3% at 2 cm depth over the CSS (July experiments).
- Daily average thermal efficiency increases by about 71% at 1 cm depth.
- Performance of solar stills at a depth of 1 cm is better than that at 2 cm even though the solar radiation values are higher in the day of experiments of 2 cm depth.
- Accumulated freshwater and thermal efficiency of still are higher in July compared to the September experiments.

5. Recommendations for future work

The use of Fresnel lenses showed good results of solar still performance based on productivity and efficiency. Such a method can be developed more to enhance the distillate freshwater and below several recommendations can be considered for future work:

- The above study considered only the direct solar radiation incident on glass cover by insulating the sides of solar still. Considering the reflected solar radiation, removing the insulator, may increase the temperature exposed by the basin and then, the time needed for evaporation will decrease and the distilled fresh water will increase.
- Designing a suitable mechanism to track the lever of lenses automatically.
- Number of lenses, the most effective area and configuration should be investigated.
- Using another heat source inside the basin can overcome the shortage of solar radiation during the winter season and, increasing productivity in the summer.
- Heat sink material can be placed inside the basin to receive the concentrated solar beam by lenses and transfer it extensively to the saline water inside the basin.

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