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Improving the performance of a pyramid solar still using different wick materials and reflectors in Iraq

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A B S T R A C T

As well-known, many rural communities suffer from water shortage in Iraq. Since there is an abundance of solar energy in these societies, it is preferable for them to use the solar desalination methods to overcome this problem. Solar still is one of these methods, but it suffers from the low productivity. In this paper, the performance of the pyramid solar still was investigated when using various types of wick materials to increase its productivity. So, two pyramid solar stills were fabricated and tested under the same environmental conditions: one is a conventional pyramid distiller (CPSS), and the other is a wick-type modified pyramid solar still (WPSS). The WPSS was investigated when using different wick materials such as light cotton cloth, heavy cotton cloth, jute fabric, and velvet fabric. Experimental results revealed that the light cotton fabric provided the best productivity of WPSS as compared to the other wick materials. The maximum efficiency and productivity of WPSS were obtained when using light cotton wick, where they were 55.3% and 1,476 mL/m^2·d, respectively. Using the light cotton wick improved the WPSS productivity by 11%, 24.2%, 76.7%, and 136.6% compared to that of WPSS with heavy cotton, jute fabric, velvet fabric, and CPSS, respectively.

Keywords: Wick-type; Light-cotton; Solar still; Basin; Velvet fabric

1. Introduction

In developing countries such as Iraq, the shortage of potable water is a big problem. Although Iraq is known for its many rivers, the potable water supply is only enough to feed 40% of Iraqi city dwellers, while those living in the countryside, deserts, and even city precincts, may not have access to water at all [1]. In all parts of Iraq, the north [2,3], central [4,5], and southern [6,7], getting portable water is a problem, where the distance to the nearest suitable water source is frequently a factor. In addition, since 2003, the water consumption has increased significantly as a result of both economic and social growth in Iraq (WHO) [8]. This issue can be remedied by constructing high-capacity distillation factories or, in some instances, by installing a standalone distillation machine in each family's home. The operation of distillation plants typically requires a significant quantity of fossil fuels, which might have a harmful impact on the surrounding environment. As a result, distillation systems that use solar energy and other renewable

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resources are recommended because they are the most beneficial to the environment. Iraq is one of the countries which have many hours of sunlight. During the summertime, the sun rays can reach a peak intensity of 1,250 W/m^2. In Iraq, there is an average of 333 clear days per annum [9].

Tables 1 and 2 show the number of sunny days and solar intensity over a 20-y period (1983–2012) for the city of Baghdad. This information was gathered by Baghdad's environmental station [10].

Solar energy can be used in the distillation process for both saltwater and brackish water, which can be found in marshes and wells in more remote regions. This provides a nearly cost-free supply of drinkable water [11]. A solar still is used for solar desalination in its most basic form. Heat collection and distillation is carried out within the same system in this method, using the greenhouse effect, solar energy is distilled directly. Water vapor condenses on the units' glass cover as it rises [12]. After being heated to specified temperatures, pure water vapor forms, leaving dissolved impurities at the bottom of the basin. It is then distilled, and the impurities sinking due to gravity [13]. Solar stills have been shown to be a highly effective method of obtaining clean drinking water [14].

Several considerations involving the salt-water depth, vapor drip, thermal isolation, covering slope, fabric material, and the surrounding environment have an impact on the solar still performance [15]. With a day-to-day production of roughly 3–4 L/m^2, the systems' efficiency is relatively low [16]. The productivity of the distiller is reliant on condensed water gathering on the glass cover. The productivity of the pudding basin is increased by intensifying evaporation from the basin and increasing condensation. Because of this, the area of evaporation and temperature difference between condensation and evaporation surfaces are the main parameters for increasing the productivity of the distiller. In addition to the temperature of the air that is around the glass, the warmth of the glass itself affects the condensation process. This is one of the factors that prevents the solar basin from being used in Iraq during the summer, because the air temperature, even in the shade, can exceed 50°C between 12 and 2 p.m. Under these conditions, condensation slows, and evaporation is increased when the temperature of the glass rises.

Many researchers have tried a variety of methods to chill the condensing surface, including running water over it to increase the temperature differential between the condensing surface and evaporated water [17]. The temperature of glass cover can be lowered by a continually flowing a cooling water layer over the glass [18,19]. The application of a pulsating stream of cooling water on the lid of the container [20,21] produces a similar effect. The speed of the wind has an additional influence on the temperature of the cover. When there is a greater amount of air movement, there is a greater amount of convective heat transmission from the cover to the ambience. This boosts the still's condensing and evaporation rates, as well as its production [22].

Moreover, scientists have developed solar stills with collectors [23], condensers, and PV panels with the goal of increasing production. However, due to their low productivity, solar distillers are still not commercially viable. The feasibility of using a phase-change material (PCM) has been investigated. PCMs have a high latent heat capacity and can absorb a lot of energy [24–27]. The larger temperature difference between the water and the glass lid allowed to raise the distillate production. However, the use of a straightforward solar distiller in conjunction with a PCM storage medium is not as commonplace as it might be [28]. Alawee et al. [29] improved the performance of a double basin distiller by raising its absorber. They achieved an improved distillate by 36.7%, where the productivity of the elevated-basin solar still were 4.37 L compared to 3.03 L for the conventional distiller. In addition, Kabeel et al. [30] proposed a rotating fan inside the solar still with various water depths and rotating speeds of the fan. The best results were obtained at 3 cm for the water depth and 45 rpm for the fan speed, where the yield was improved by 25%.

The current study involved the construction and testing of a pyramidal passive-type solar still using different wick materials in the basin, including thin cotton cloth, heavy cotton cloth, jute fabric and velvet fabric. The pyramid solar

Table 1
Numbers of sunny days per month in Baghdad between 1983 and 2012

Month	June	March	May	July	Sep.	Nov.	Average
Sunny days, h/d	5.5	8	8.3	11.5	11	8	
Month	Feb.	April	June	August	Oct.	Dec.	8.8
Sunny days, h/d	7	7.8	12	11.7	8	7	

Table 2
Monthly rates of solar intensity in Baghdad between 1983 and 2012

Month	June	March	May	July	Sep.	Nov.	Average
Solar intensity, W/m^2·d	333.1	469.1	726.8	731.6	560	289.1	
Month	Feb.	April	June	August	Oct.	Dec.	506.36
Solar intensity, W/m^2·d	348.2	541.4	732.4	861.2	435.4	245.1	

still was fitted with a wicked surface. The purpose of a wicked still design is to maximize still output by increasing evaporation rate.

2. Experimental work

At the University of Technology in Baghdad, Iraq, a testing rig was set up on the roof of the training and workshops building at 33.3° N, 44.5° E, 33 m above sea level.

2.1. Description of the experimental setup

Figs. 1 and 2 show the experimental setup for the two solar still models in this study: the conventional pyramid solar still (CPSS) and the wick-type pyramid solar still (WPSS). Their thermal performance was compared using identical dimensions and operating conditions. The dimensions of the feeding tank were 50 cm × 50 cm × 100 cm. Galvanized sheets, 1.5 mm thick were bent and welded together to make both solar distillers. As seen from Fig. 3 for the physical measurements, solar stills had an exterior size of 70 cm × 70 cm × 15 cm. Also, it is illustrated from Fig. 1 that the cover of the solar distillers was constructed from four triangle-shaped glass sheets.

The glass cover had a 49° inclination angle. A fiberglass (5 cm thick) was used to insulate the still basin body from the atmosphere. To collect and direct the condensed water to measuring jar, as can be seen in Fig. 1, the cover of the solar distillers was constructed from four triangle-shaped glass sheets. Silicone was utilized to seal the contact edges of the solar still to avoid leakage. The stills were supplied with saline water from the feeding reservoir, the freshwater distillate was collected in external flasks. The WPSS had the same size and surface area as the CPSS.

As shown in Fig. 3, the WPSS used four different types of wick materials in the experiment: light cotton, thick cotton,

Fig. 1. Solar stills system (a) without reflectors and (b) with reflectors.

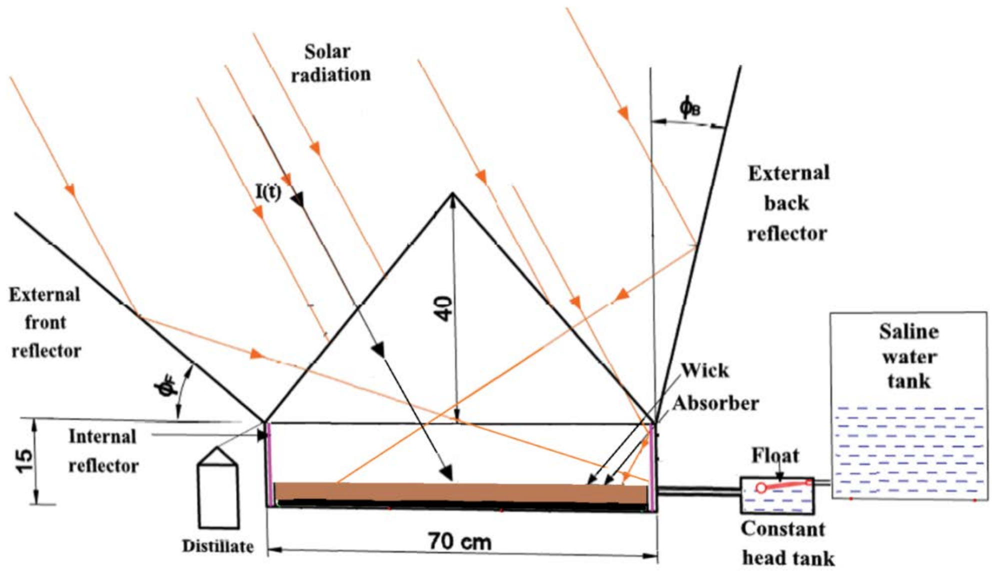

Fig. 2. Experimental test rig in two dimensions.

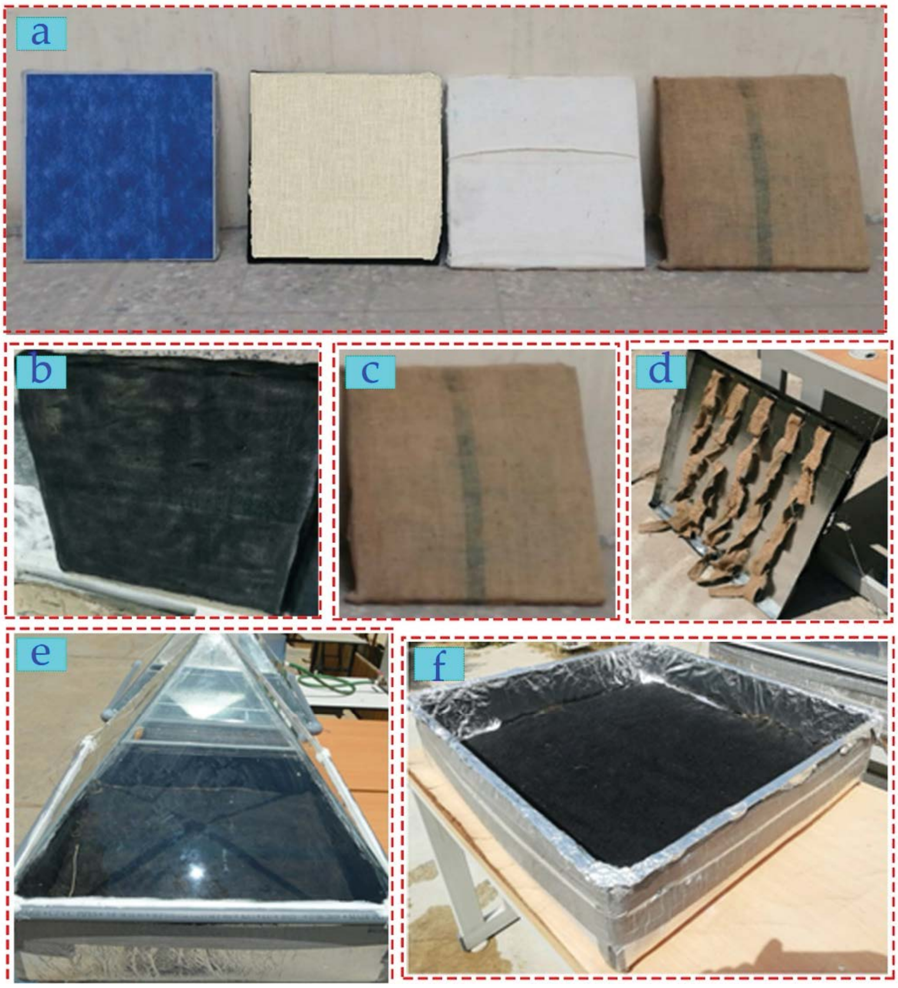

Fig. 3. Different arrangements of wick materials and cords (a) wick materials before the painting process, (b) black-painted jute wick, (c) jute wick, (d) back of jute wick, (e) wick inside SS, and (f) jute wick inside basin.

jute and velvet. Each wick was 68 cm wide and 68 cm long. To achieve optimum solar absorption, all wick materials fixed onto the basin water were painted by black. Also, it should be mentioned that all the wick materials were painted by black before conducting the experiments. To optimize incident solar radiation, two external mirrors were used. One mirror was mounted on the front of the distillers, while the other was installed on the back. Both mirrors were 70 cm × 70 cm in size. To maximize output throughout the year, it's important to modify the exterior reflector installation angle in step with the changing of the seasons. An exterior reflector is slanted either reverse or forward depending on the month of the year [31]. Based on the season, the upper mirror is angled either way around (or both). The mirror should be angled somewhat forwards in winter and in summer, angled slightly to the back. References [32,33] provide more information on reflector inclination angles. As a result, Table 3 obtains the best tilt angles for both mirrors through the year seasons.

Fig. 2 shows the inclination angles for the external top (Φ_B) and front reflectors (Φ_F). In all seasons, it is best to stretch the surface front mirrors from the stills' front side and slant them up from plane level to increase absorbed solar radiation (It) [34]. A metal strut that was adaptable enough to move closer to, or further away from the basin wall, was used to place the external mirrors at the desired angles. If the prop is located close to the basin wall, the slope angle will be greater. The tilt angle is small when the prop is a long way from the basin wall.

2.2. Measurement tools

The implementation of a solar still depends mostly on water temperature, solar irradiance, wind speed and the efficiency of water distillation. A Solarimeter was utilized to evaluate solar intensity, and *K*-type thermocouples were used to record temperature at various points of the still. Also, wind speed was recorded using a digital anemometer, and a sensitive scale was used to weigh the amount of freshwater produced every single hour throughout the investigation time. Table 4 shows the requirements of the measurement tools.

Table 3
Best reflector's tilt angles through the seasons of the year [33,34]

Angle of mirror	Spring	Summer	Autumn	Winter
Back reflector	7°	15°	8°	15°
	Forward	Backward	Backward	Forward
Front reflector	30°	50°	30°	20°
	Upward	Upward	Upward	Upward

Table 4
Accuracy and range of measuring instrument

No.	Instrument	Range	Accuracy	% Error
1	Thermocouple K-Type	0°C–100°C	±0.2°C	0.25%
2	Thermometer	0°C–100°C	±1°C	0.5%
3	Solarimeter	0–2,500 W/m²	±2 W/m²	2%
4	Measuring beaker	0–2,000 mL	±3 mL	1%

2.3. Uncertainty analyses

Holman's [35] approach was used to approximate experimental device uncertainty and calculation errors. The following equation can be used to estimate outcome errors:

$$S_R = \sqrt{\left(\frac{\partial R}{\partial X_1}S_1\right)^2 + \left(\frac{\partial R}{\partial X_2}S_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial X_n}S_n\right)^2} \tag{1}$$

where S_R denotes the result uncertainty and S_1, S_2, S_3, ..., S_n denote the uncertainty of the independent parameters. In Table 3, the errors in the device measurements are tabulated. The hourly output is a function of the basin water depth, as seen here: $m = (h)$. So, the question of how productive uncertain we'll really be:

$$S_m = \sqrt{\left(\frac{\partial m}{\partial h_1}S_h\right)^2} \tag{2}$$

Thermal efficiency (η) uncertainty is:

$$S_{\tau_{\text{th}}} = \sqrt{\left(\frac{\partial \eta_{\text{th}}}{\partial m}S_m\right)^2 + \left(\frac{\partial \eta_{\text{th}}}{\partial I_R}S_{I(t)}\right)^2} \tag{3}$$

Daily variations in solar stills' production and efficiency are roughly 1.4% and 2.5%, respectively.

2.4. Experiment procedure

Testing was carried out in January and February. Each solar still was fitted with different wick materials for a total of 10 d. The data was collected on days with the most hours of sunshine. At sunrise, the solar still's glass was cleaned, the trial set-up completed before 8 a.m. Before beginning to take measurements, the pyranometer, thermocouples, digital temperature indicator, and anemometer were all put through their places. Data on basin water temperature, ambient temperature, glass cover temperature, solar radiation intensity, wind speed, and productivity were accumulated experimentally every hour from 8 a.m. to 5 p.m. on all testing days. A trough is used to collect the condensate, which is then pushed out of the solar still and into a storage vessel.

3. Results and discussion

3.1. Wick solar stills' thermal performance

Fig. 4a–d show the hourly changes in temperature at different locations on the solar stills. To avoid repetition, the results from 1 d of tests for each type of wick used are presented here. It can be seen from Fig. 4 that the use of different wick materials improves the temperature in the WPSS compared to the conventional pyramid solar still (CPSS), no matter what of the type of wick used.

The temperature of the glass on the WPSS was greater than that of the CPSS by 0°C–14°C for LCWPSS, 0°C–9°C for HCWPSS, 0°C–5°C for JWPSS and 0°C–2°C for VWPSS. This is because the evaporation rate produced by the WPSS was greater than that of the CPSS. Consequently, the glass temperatures of the LCWPSS, HCWPSS, JWPSS, VWPSS, and CPSS were 41.6°C, 36°C, 32.8°C, 28.2°C and 27.1°C, respectively at 14:00.

As shown in Fig. 4, the WPSS had a higher water temperature than the CPSS by 0°C–18°C for four different wicks. This is because the basin water was exposed to more sunshine due to the convexity in the basin water. The temperature of the water in the LCWPSS, HCWPSS, JWPSS, VWPSS and CPSS were 47.9°C, 43.8°C, 37.1°C, 31.4°C and 30.1°C, respectively. Also, the air temperature and solar radiation was 24°C, and 1,150 W/m², respectively at 14:00.

Fig. 5a–d illustrate the variations in the hourly and cumulative yield of both solar stills when using four different wick materials. It is clear that LCWPSS productivity was improved rapidly as a result of the lower basin liner's high temperature. Comparatively, the CPSS requires more time to boil the water and vaporize. The HCWPSS, JWPSS, and VWPSS had higher freshwater productivity than the CPSS. Hourly distillation was greatest at 14:00, with 229, 218, 182, and 97 mL/m²·h for CWPSS, LCWPSS, HCWPSS, JWPSS, and CPSS, respectively.

The cumulative yield of WPSS was greater than that of CPSS. The LCWPSS, HCWPSS, JWPSS, VWPSS, and CPSS produced a total distillate of 1,461; 1,322; 1,181; 830 and 620 mL/m²·d, respectively. As a result, productivity increased by roughly 136.6%, 113%, 90.1%, and 33.8% for the LCWPSS, HCWPSS, JWPSS, and VWPSS. This increase in productivity is attributed to the higher rate of evaporation in the LCWPSS.

The solar still LCWPSS which had the maximum accumulated distillate, was selected to serve as a case study for the investigation into the impact of reflecting mirrors on a wick-type solar still. The purpose of the reflectors is to enhance the amount of solar energy received by the LCWPSS. This is accomplished by the CWPSS's front and rear exterior mirrors reflecting diffused sun rays, and this results in an increase

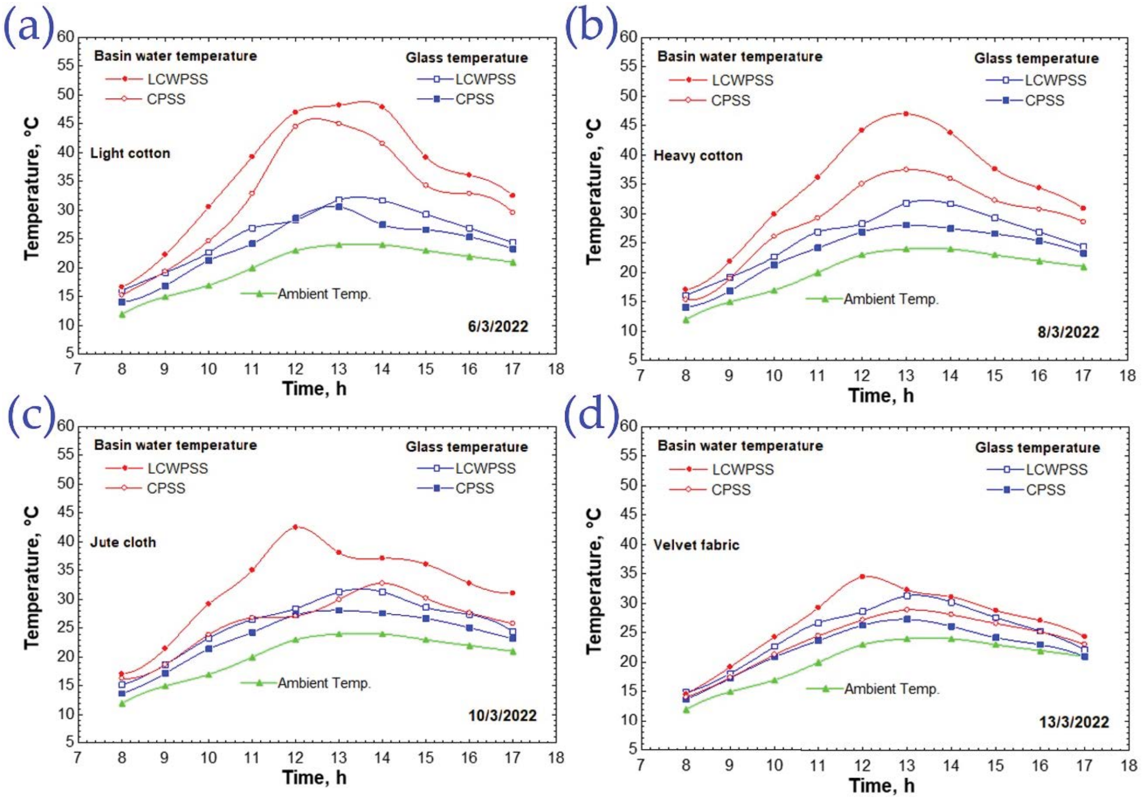

Fig. 4. Temperatures for the CPSS and WPSS with different wicks, (a) light cotton, (b) heavy cotton, (c) jute fabric, and (d) velvet fabric.

in the temperature of the water, glass and upper liner. As a result, evaporation and condensation rates within the CWPSS are increased. The interior mirrors limit thermal losses through the walls to which attached to the CWPSS's upper liner, they do it by reflecting part of the sun's intrinsic energy, raising the temperature of the upper liner, glass, and water. Evaporation and condensation are accelerated as a result.

Fig. 6 illustrates the variations in solar intensity and temperature at several sites (glass, water, ambient, and wash-basin liner) on the LCWPSS with external and internal mirrors. The temperature of the glass temperature was 0°C–8°C lower than the CPSS because the LCWPSS generates more evaporation than the CPSS. At 14:00, the LCWPSS and CPSS had glass temperatures of 45.8°C and 27.5°C, respectively.

At 14:00, the LCWPSS and CPSS had water temperatures of 53.6°C and 30.5°C, respectively indicating that using mirrors increased the difference water temperatures between the LCWPSS and CPSS.

According to the findings, there was a 0°C–16°C water temperature differential between the LCWPSS without mirrors and the CPSS, while the difference was approximately 0°C–22°C when mirrors were used. When mirrors are utilized, the basin liner heats up, which in turn raises the temperature of the LCWPSS's water. This result is contributed to the LCWPSS's superior evaporation rates. At 14:00, the sun intensity was 830 W/m^2 and the air temperature was 25°C.

Moreover, the reflectors work to increase the temperature of the glass opposing them, but not to a high degree, because there are other sides that are not exposed to solar radiation, and the presence of a small amount of water in the wick helps to quickly benefit from the solar radiation and not reflect a large part of it as it is brown in color and this is a different situation from the presence of water only that works relatively greater reflection of the radiation falling from the mirrors, which raises the temperature of the glass more. Thus, a difference is generated between the temperature of the glass in the pyramid distiller and the black cloth covering the base.

As projected, using mirrors with the solar still (both internal and external) significantly improves the CWPSS performance. Data from CPSS and LCWPSS with reflectors (internal and external mirrors) (experiment day 28/02/2022) are shown in Fig. 7 (hourly data) which clearly shows that the LCWPSS with mirrors produced more distillate than the CPSS. The LCWPSS and CPSS reached their maximum hourly productivity of 320 and 121 mL/m^2.h, respectively, at 13:00. The CPSS and LCWPSS with mirrors collected 1,525 and 620 mL/m^2 of freshwater every day, respectively.

Compared to the CPSS, using mirrors with the LCWPSS increased productivity by roughly 155% increasing its freshwater productivity by 136.6% over the CWPSS without reflectors. This increase in productivity is attributed to better condensation and evaporation processes within the CWPSS when reflectors are used.

In fact, the presence of wicks makes the water layer very small, only the cloth is wet, which increases the moisture and reduces the pressure, which works more on increasing the evaporation rate and releasing the steam from the surface of the wick material. With a large surface area of glass, good

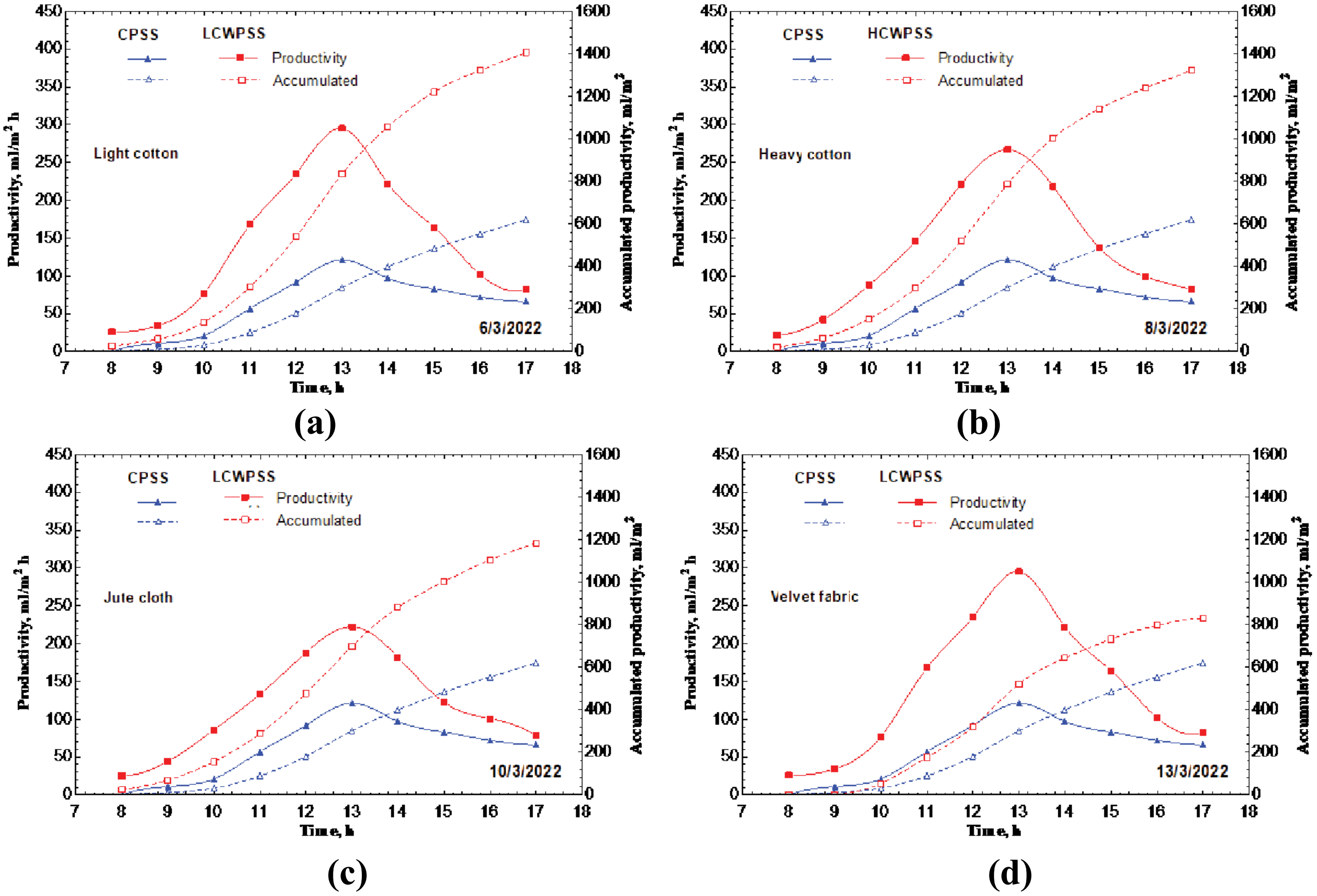

Fig. 5. Productivity hourly variation and overall cumulative productivity using different wicks, (a) light cotton, (b) heavy cotton, (c) jute fabric, and (d) velvet fabric.

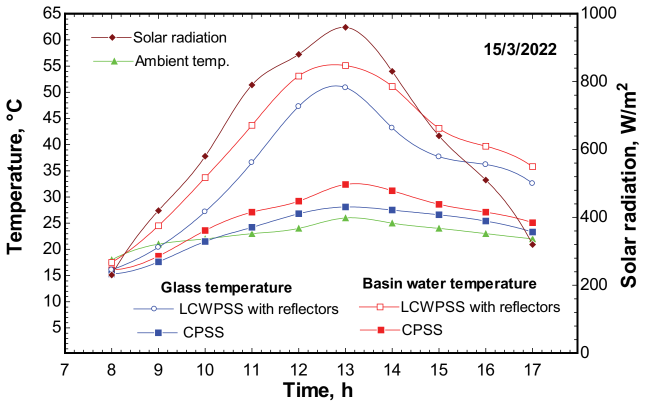

Fig. 6. Solar irradiation and temperature variations for the CPSS and LCWPSS with reflectors.

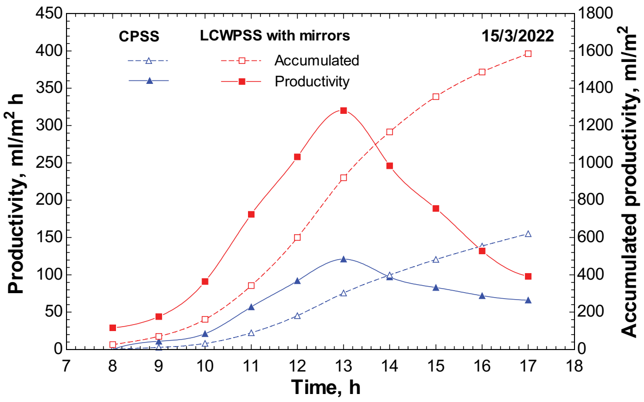

Fig. 7. The hourly variation in productivity and total accumulated productivity of both solar stills, CPSS and LCWPSS with reflectors.

condensation occurs. We find that the temperature of the outer surface of the glass depends greatly on the temperature of the outside air, as the lower the air temperature, the cooling of the glass occurred and at the same time, since the humidity is low in Baghdad, Iraq, which is the area under study, which is generally less than 20% throughout the year, so it does not depend on the temperature. The glass greatly increases the humidity of the surrounding air in the area under study. We find that the wicks that have a capillary property and a low conductivity have some dry points on the surface of the wick, especially at the time of high radiation intensity, which negatively affects its productivity.

3.2. The efficiency of solar stills

It was observed that both the thermal efficiency of the solar still and the daily productivity increased. It is possible to compute the daily productivity increase by:

$$\eta_d = \frac{\text{The daily productivity} \times \text{Vaporization latent heat}}{\text{The daily solar radiation}} \quad (4)$$

where η_d is thermal efficiency on a daily basis.

The daily thermal efficiency of the solar stills was used to compare their operation. Fig. 8 displays the daily efficiency of solar stills with and without reflectors for various wick materials. The thermal efficiency of the CPSS was nearly constant at 34.5%. The thermal efficiency of the WPSS, on the other hand, is dependent on the type of wick used and the work conditions, as shown in Fig. 8. The distillers with light cotton wicks, with or without mirrors, had the highest thermal efficiency, as shown in Fig. 8. The daily efficiency of the LCWPSS without mirrors was 36.5%. Using mirrors, on the other hand, resulted in a daily efficiency of 57%. A summary of the findings of the present study is tabulated in Table 5.

3.3. The comparison of this study to previous studies

A comparison of the current results with studies in the literature may be seen in Table 6. The goal of this comparison

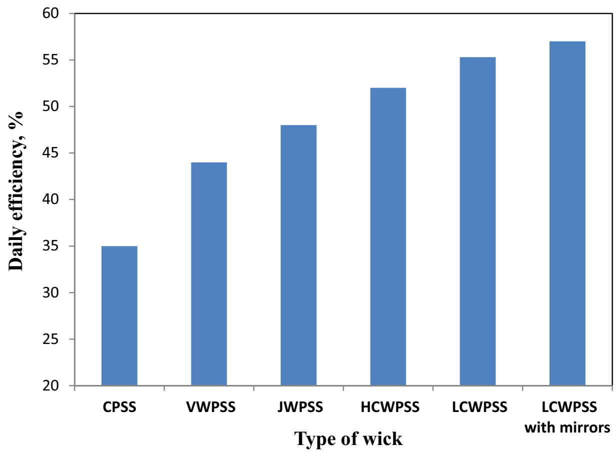

Fig. 8. Efficiency of CPSS and WPSS with different wick materials.

Table 5
Summary of the findings of the present study

Solar still	Productivity rise, %	Thermal efficiency, %	Productivity rise, %	Thermal efficiency, %
	Without mirrors		With mirrors	
Light cotton PSS	136.6	55	155	57
Heavy cotton PSS	113	52	129	53.3
Jute fabric PSS	90.1	47.5	104	49.6
Velvet fabric PSS	33.8	43	48	42

Table 6
Comparing the current findings with those of previous investigations

Reference	Modifications	Efficiency	Productivity improvement
Hamdan et al. [36]	Solar still with multiple basin having a square pyramid-shaped top cover	44%	24%
Kabeel [37]	Pyramid-type solar still with concave wick	30%	95%
Taamneh and Taamneh [38]	Pyramid-type solar still with forced convection	–	25%
Sathyamurthy et al. [39]	Triangular pyramid solar still with PCM	53%	20%
Senthil Rajan et al. [40]	Pyramid-type solar still with biomass heat source	–	84%
Prakash et al. [41]	Pyramid-type solar still with blackened blanket (wick)	50.25%	17.68%
Dhindsa [42]	Single slop solar still with paraffin wax and floating wicks	72.63%	31.36%
Modi and Modi [43]	Double slope solar still with wick pile of jute cloth	29.37%	23.71%
Bisht et al. [44]	Conventional solar still with floating wicks and solar pond	–	55%
Tuly et al. [45]	Double slope solar still with external condenser, paraffin wax, solid rectangular fin, and black cotton cloth	39.74%	22.33%
Agrawal and Rana [46]	Solar still with black jute cloth wick (V-shaped floating wicks)	56.62%	26%
Saravanan and Murugan [47]	Pyramid solar still with woollen cloth wick material	29.57%	40.3%
Present study	Pyramid solar still with four different wicks + internal and external mirrors	57%	155%

is to determine how much better the solar distiller will perform after the changes which have been made. Solar stills with a light cotton wick, as well as reflectors, were found to perform much better than those in other publications.

4. Conclusions and further work

- The CWPSS's thermal performance outperformed the CPSS's under all test conditions. This occurred as a result of the wick cords drawing water that was equivalent to the amount of water that evaporated while not drawing in surplus or hot water.
- The light cotton wick produced the best CWPSS performance without mirrors, with an increase in production of 136.6% and a daily thermal efficiency of 55.3% as opposed to 34.5% for the CPSS.
- Using mirrors enhanced the yield of the CWPSS by about 155% with light cotton wick, the efficiency of the distiller at 57%.

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