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An Experimental Investigation of the Effect of Phase Change Material and External Reflectors on the Performance of a Single Slope Still

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ABSTRACT

Solar stills are widely recognized as a cost-effective and eco-friendly solution for transforming brackish water into potable water. Although solar energy shows promise, it has yet to be widely adopted due to its lower productivity. This paper presents an experimental investigation to enhance the performance of a single slope solar still using phase change material (PCM) and external reflectors. Many outdoor experiments have been conducted for three cases including: solar still without PCM, Solar still with PCM, and solar still with PCM with external reflectors. Also, the effect of water depth inside the still is examined. The performance of the four cases is evaluated and compared under the meteorological conditions of Baghdad City, Iraq. The results showed that using the PCM improved the Accumulated yield of the conventional solar still by 23% and 14 % for water depths of 2 cm and 3 cm, respectively. Also, the results revealed that using the external reflectors improves the Accumulated yield by 15% for the still with PCM, respectively.

1. Introduction

The worldwide growth in population and industrialization is disrupting the balance between the availability and demand for fresh water and energy resources. On the earth, 70% of water is salty, 29% is brackish, and only 1% is potable [1]. Various methods exist for purifying water. However, most of them depend on conventional energy sources. Globally, the application of solar energy for water purification is crucial due to its abundant supply, nonpolluting characteristics, and low operating expenses [2,3]. Solar stills are valuable apparatus for purifying salt water by using solar energy. However, its effectiveness could be improved under cloudy conditions and after sunset [4-6].

Various improvements have been implemented to the design and operating features of solar distillation systems to increase their efficiency. Various supplementary components, such as nanoparticles, colourants, energy storage materials (ESM), concentrators, absorbent materials, and wicks, significantly enhanced the efficiency of solar distillation [7-11]. Utilizing energy storage

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materials in solar stills is an economically efficient approach that improves the production of distilled water and extends the operational duration [12]. Energy storage materials are used to store additional heat during system operation and, after that, release it gradually during periods of absence of direct sunlight [13]. Phase change materials (PCMs) have shown to be very practical and economically advantageous in enhancing the performance of solar distillation, surpassing alternative options of energy storage materials (ESMs). During solar distillation, PCM undergoes a physical state change as it absorbs energy during sunny hours. Subsequently, when the stored energy is released, the PCM returns to its initial state [14]. PCMs often utilized in solar stills are paraffin wax, beeswax, stearic acid, lauric acid, capric palmitic acid, and calcium chloride hexahydrate.

Since the main drawback of solar stills is their low productivity, numerous researchers worldwide have conducted many studies on increasing their productivity. The influence of some crucial factors, such as operating conditions, climate, and geographic location, has been assessed [15]. Researchers revealed promising results in improving the performance of solar stills. Most of them discovered that the productivity of the still is influenced by the absorption area, water depth, and temperature of the glass cover.

Furthermore, they improved the efficiency of the still by including an additional layer of heat-absorbing material, such as gravel, sawdust, and sand, in the base of the still. Furthermore, additional components such as sponges, rubber, aluminum plates or fins, heat pipes, and solar collectors were included to enhance the absorption of solar energy and augment water evaporation [16,17]. Recently, researchers have turned to using heat storage to improve solar still production. Storage materials can store energy in the form of either sensible heat or latent heat. Latent thermal energy is accumulated during the process of charging and then released to the water during the process of discharging [18].

Numerous numerical and experimental investigations were conducted to examine the impact of utilizing phase change materials (PCM) as a storage system on the productivity of solar stills. Ghadamgahi *et al.,* [19] experimentally investigated the effect of using a phase change material on the performance of a multi-stage solar still. The impact of using paraffin wax at the back of the absorber surface on productivity was investigated for 25mm and 50mm water depths. The results revealed that using paraffin wax with a thickness of 25 mm augments freshwater productivity by 15%. Also, it was found that increasing the paraffin thickness from 25mm to 50 mm decreases productivity by 36%. The maximum efficiency was reported at 38%, 32%, and 53% for the cases without PCM, with 50mm thickness PCM and 25mm thickness PCM, respectively. Grewal *et al.,* [20] experimentally investigated the influence of using a phase change material on the performance of a stepped solar still. Paraffin wax is loaded in metal tubes and fixed on the absorber plate. Also, the effect of preheating the feedwater using an evacuated tube collector was investigated. The results showed that introducing the PCM tubes increases freshwater productivity by 20% while using the evacuated tube preheater increases productivity by 30% compared to traditional stepped solar still. Integrating the paraffin wax tubes and the preheater into the solar still augmented the productivity by 98% and achieved a maximum efficiency of 46.9%. Also, the results indicated that using pcm increases the working time of the still by 3 hours. Cheng *et al.,* [21] investigated experimentally and theoretically the effect of using shape-stabilized phase change material (SSPCM) as an absorber plate on the performance of a pyramid solar still. The SSPCM is composed of paraffin wax and 5% graphite. The experimental results indicated an enhancement of 43% in productivity when using SSPCM. The theoretical results revealed that increasing the thermal conductivity of the SSPCM from 0.2 W/m.K to 4 W/m.K augments the productivity by 75%. Also, it was found theoretically that increasing the melting point of the SSPCM from 34 °C to 50 °C improves the productivity by 3%. Essa *et al.,* [22] investigated the impact of using paraffin wax PCM mix with Ag-Nano particles under the absorber surface on the productivity of a pyramid solar still. The absorber surface was pyramidal to increase the exposed surface area to the radiation and evaporation surface area. The experiment's results demonstrated that using PCM-Ag resulted in a 36% increase in the daily productivity of the pyramidal absorber PSS. Kumar *et al.,* [23] investigated experimentally the performance of single-slope solar still under the effect of using paraffin wax phase change material (PCM) and silica-paraffin nano phase change material (n-PCM). The results revealed 51.22% and 67% enhancement in the productivity when using PCM and n-PCM. Moreno *et al.,* [24] investigated numerically, using Ansys-Fluent, the influence of adding different PCMs, including RT45 HC, RT62 HC, RT70 HC, and RT80 HC, on the performance of a single-slope solar still. The results revealed an enhancement in productivity by 10.82%, 13.23, and 4.86% when adding RT80 HC, RT70 HC, and RT62 HC, respectively, while adding RT45 HC reduced the productivity by 2.95%. Furthermore, decreasing the thickness of RT70 HC from 10 mm to 2.5 mm improved the productivity by 5.6%. For the sun-off operation, it was indicated that the lower temperature PCM gave higher productivity. Mousa *et al.,* [25] experimentally investigated the impact of using candle wax encapsulated in tubes as a PCM on the performance of a single-slope solar still. The effect of the mass ratio of PCM to water was investigated in the range from 0 to 0.51. The results indicated that the relation between the productivity and the mass ratio of PCM to water is inversely proportional during the daytime and directly proportional during the nighttime. Increasing the mass ratio from 0 to 0.51 decreases the productivity during the day by 26% while increasing it in the nighttime by 100%. Other work investigated the impact of incorporating phase change materials and other techniques such as water preheater, reflectors, fins, glass cover cooling, heat exchanger and collectors. Abdullah *et al.,* [26] experimentally investigated the performance of a single slope solar still with two spiral water heaters in series that preheat the feed water. Furthermore, the effect of using an internal mirror and nanophase change material was tested. The results indicated that preheating the feed water augments the productivity and the efficiency of the traditional solar still by 66% and 44%, respectively, while using the internal mirror with preheating the feed water improves the productivity and the efficiency by 81% and 46%, respectively. The maximum enhancements in productivity and efficiency were reported as 115% and 51.3%, respectively. They were achieved using the nanophase change material with the internal mirror and preheating the feed water. Abdullah *et al.,* [27] improved the productivity of a tray solar still (TSS) and compared it with a conventional single-slope solar still (CSS). The investigated designs of the TSS are TSS with finned trays covered with jute wick (FTSS), FTSS with heaters inside the basin (FTSS-H), FTSS with a layer of a nanophase change material at the back of the trays (FTSS-PCM) and FTSS-PCM with heaters inside the basin (FTSS-PCM-H). All the tray solar designs were still tested with a vertical mirror inside. The reported productivity in enhancement was 56%, 95%, 168%, and 136% for FTSS, FTSS-H, FTSS-PCM, and FTSS-PCM-H. Al-Harahsheh *et al.,* [28] improved the productivity of a double glass single-slope solar still using different modifications. The modifications include placing metal tubes loaded with PCM (Sodium Thiosulfate Penta hydrate) inside the basin, cooling the glass cover by passing water between the glass layers, and submerging a coil heat exchanger inside the basin connected to an external solar collector. Also, the effect of the water level inside the basin was investigated. The results indicated that using PCM improves the productivity by 23%. Also, increasing the flow rate inside the coil heat exchanger from 2 ml/s to 30 ml/s increases the productivity by 300%, while the glass cooling water flow rate from 6 ml/s to 10 ml/s increases the productivity by 110%. Furthermore, increasing the water level inside the basin from 5 cm to 10 cm improves the productivity by 112.5%. Kabeel *et al.,* [29] investigated the effect of preheating the feed water of a stepped-solar still loaded with pcm using an evacuated tube collector and internal reflectors. Paraffin wax and graphite are mixed and used as a hybrid PCM. The results revealed that using the hybrid PCM improves the productivity and efficiency by 21%. Also, it was found that increasing the feed water flow rate inside the evacuated collector by 133% increases productivity by 12.5%. Hameed [30] experimentally improved the productivity of single-slope solar still by adding paraffin wax as PCM, using hollow square fins on the basin bottom, and cooling the glass cover using water spray. The results showed that using paraffin wax and fins augments the productivity by 40 %, while using them with water spray augments the productivity by 63%.

The shortage of water around the globe, especially in the Middle East region, has prompted many researchers to study the implementation of solar energy in water desalination. Although much research dealing with enhancing the performance of the single slope is presented in the literature, new techniques can be investigated or tested in different conditions and climates. To the best of the authors' knowledge, no work incorporates PCM and external reflectors with solar stills. Therefore, the present work investigates the experimental impact of experimentally utilizing Paraffin wax and external reflectors on the performance of a single slope still in Baghdad climates. It also investigates the effect of water depth.

2. Experimental Setup

The experimental setup of the present work was located at the College of Engineering, Baghdad University, Iraq (latitude 33.3152, longitude 44.361488). The experiments were conducted in February. Figure 1 and Figure 2 show a photo and schematic of the experimental setup for the three investigated cases. The experimental setup consists of two identical single-slope solar stills. The basin area of each still is 1 m2 (1 m x 1 m). The low sidewall height is (250) mm, and the high side wall is (900) mm. The still is fabricated from galvanized steel sheets with (1) mm thickness. The surfaces of the basin are coated with black paint to improve the absorptivity. The bottom and sides of the still are insulated with a cork of (50) mm and plywood of (10) mm to minimize the heat loss from the still to the ambient. The glass cover is fabricated from clear glass sheets (3) mm thick with an inclination angle (33o) horizontally, which is the latitude of Baghdad, Iraq [31]. The experimental setup is oriented in the south direction to receive the maximum solar radiation throughout the year. A small electric pump supplies saline water to the basin from a reservoir. An electric level controller controls the operation of the pump. The controller has three probes fixed inside the basin at the desired water level. Tanaka [32] mentioned that the upper reflector can be tilted forward or backward in accordance with the changing seasons. During winter, the sun altitude angle decreases, causing a significant portion of the reflected light from the vertical reflector to miss the still and reach the ground. Therefore, it is recommended to tilt the upper reflector slightly forward. Conversely, the altitude angle of the sun rises throughout the summer, making it difficult for the vertical reflector to redirect sunlight to the stationary position efficiently. Hence, it is recommended to have a modest backward tilt for the upper reflector, with an inclination angle of less than 25° consistently throughout the year. Tanaka [33] indicated that adding a flat bottom reflector to the still, which extends from the lower edge and slopes horizontally upwards, would enhance the absorption of solar radiation and raise the productivity of the distillate. So, in the present study (the experiments in the summer season), the angles of the top and bottom external reflectors were set at 15° and 50°, which was predicted as an optimum reflector angle in the summer season.

Paraffin wax is used as a thermal storage material and introduced below the basin bottom of the still. A holder basin holds 20 kg of paraffin wax between the water basin and the insulation. The thermal properties of the paraffin wax are presented in Table 1. The thickness of the paraffin wax is 5 cm.

Table 1
Thermal properties of Paraffin wax

Property	Value
Melting temperature	48 °C
Density of liquid/solid	830/930 kg/m^3
Latent heat of fusion	190000 J/kg
Thermal conductivity	0.21 W/m °C
Specific heat	2100 J/kg °C

Fig. 1. Photo of the still

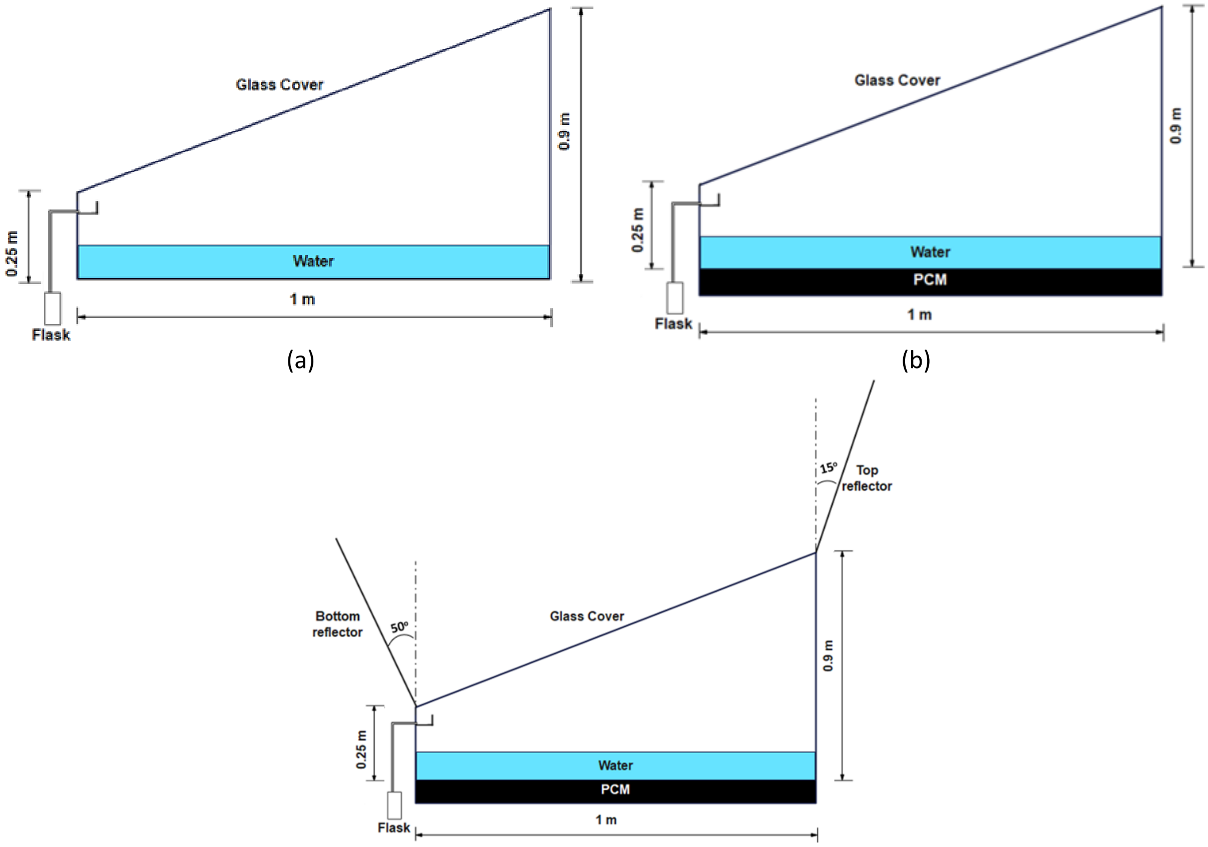

Fig. 2. Schematic of the still

The experiments were conducted according the following procedures:

i. Conducting a preliminary experiment to assess the reliability of the still.
ii. Conducting experiments to choose the optimum water depth.
iii. Conducting experiments in the presence of PCM.
iv. Conducting experiments in the presence of PCM and external reflectors.

3. Measurements and Uncertainty

Table 2 presents all of the measurement instruments and their features. The measured quantities are solar radiation, wind speed, and still temperatures. The irradiance is measured and recorded using a digital datalogger (SPM 1116SD). The wind speed is recorded using a digital anemometer (UT361). Eighteen calibrated type-K thermocouples are used to measure the temperatures of glass, vapor, saline water basin walls, and paraffin wax. The thermocouples are distributed as 3 at the glass outer surface, 2 at the inner glass surface, 2 for the vapor, 3 inside the saline water, 4 at the basin side walls, and 4 inside the paraffin wax. the readings of the thermocouples are monitored and recorded using a digital data logger (Lutron BTM-4208). A flask of (1000) ml capacity is used to measure the yield. The uncertainty is computed based on the nominal accuracy reported by the instrument manufacturer. Standard uncertainties are estimated by dividing the titular accuracy by 1.7302.20 [34]. The accumulated uncertainties are calculated using Eq. (1) [35]. The results of all uncertainties for standard and accumulated quantities utilized in this study are detailed in Table 3.

$$u_R = \pm\sqrt{(\frac{\partial R}{\partial x_1}\, u_{x_1})^2 + (\frac{\partial R}{\partial x_2}\, u_{x_2})^2 + \cdots\cdots + (\frac{\partial R}{\partial x_n}\, u_{x_n})^2} \tag{1}$$

where $R = f(x_1, x_2, x_3 \ldots \ldots, x_n)$.

Table 2
Details of all measuring instrumentations used

Parameter	Instrument	Model	Accuracy
Temperature	Thermocouple	K-Type	±1%
Solar radiance	Solar power meter	SPM 1116 SD	±5%
Water yield	Graduated cylinder	EISCO	1%
Wind speed	Anemometer	UT361	±3%

Table 3
Standard and accumulated uncertainties

R	S	u_x	U_R
Temperature	T	±1%	±1%
Solar radiance	I	±5%	±5%
Water yield	m_w	1%	1%
Wind speed	V	±3%	±3%

4. Performance Metrics

The daily efficiency is calculated by summing the hourly condensate output m_w and multiplying it by the latent heat. so, the result is divided by the daily average solar radiation I(t) over the whole area [36]:

$$\eta_d = \frac{\sum_{i=1}^{24} m_w h_{fg}/3600}{\sum A\, I(t)} \tag{2}$$

Where m_w is the mass of condensed water (kg), η_d is still efficiency, A is the basin area (m^2), I is the solar irradiation (W/m^2), h_{fg} is the latent heat of water vaporization (J/kg), it is calculated as:

$$h_{fg} = 2.4935\,(10^6 – 947.79\,T_i + 0.13132\,T_i^2 – 0.0047974\,T_i^3) \tag{3}$$

for $T_i \leq 70\ ^oC$

$$h_{fg} = \ 3.1615\,(10^6\ –\ 761.6\,T_i) \tag{4}$$

or $T_i > 70\ ^oC$

where T_i is the mean temperature of the glass cover and saline water (K):

$$T_i = \frac{T_g + T_w}{2} \tag{5}$$

5. Economic Analysis

There are several factors that influence the cost of distillate derived from a solar desalination plant. Both the initial investment and ongoing operational expenses are affected by factors such as the size of the unit, the location of the site, the characteristics of the feed water, the quality of the needed product water, and the availability of competent personnel. Solar desalination offers significant economic benefits that may be achieved without the need for extensive infrastructure. Additionally, it is characterized by its ease of local design, implementation, operation, and maintenance.

The optimal economic return on investment is contingent upon the manufacturing cost of the distilled water and its suitability for various applications. The CRF (capital recovery factor), the FAC (fixed annual cost), the SFF (sinking fund factor), the ASV (annual salvage value), average annual productivity (M) and AC (annual cost) are the main calculation parameters used in the cost analysis of the desalination unit. The annual maintenance operating cost (AMC) of the solar still is necessary to provide the regular replenishment of brackish water, the collection of distilled water, the cleaning of the glass cover, and the removal of accumulated salt (in the form of scaling). The maintenance requirements for a system tend to escalate as its lifespan progresses.

Hence, maintenance costs have been allocated at a rate of 10% of the net current cost. The cost per liter (CPL) of distilled water may be determined by dividing the yearly cost of the electrical system (AC) by the annual production of the solar still (M). All of the aforementioned computation parameters may be represented as [37]:

$$CRF = \ i\,(1+i)^n\ /[(1+i)^{n-1}] \tag{6}$$

$$FAC = P(\mathrm{CRF}) \tag{7}$$

$$SFF = \ i/[(1+i)^{n-1}] \tag{8}$$

$$S = 0.2\ \mathrm{P} \tag{9}$$

$$ASV = (\text{SFF})\text{S} \tag{10}$$

$$AMC = 0.15\ \text{FAC} \tag{11}$$

$$AC = 0.15\ \text{FAC} \tag{12}$$

$$CPL = \text{AC}/\text{M} \tag{13}$$

where P is the present capital cost of desalination system; i is the interest per year, which is assumed as 12%; n is the number of life years, which is assumed as 10 years in this analysis. The prices of raw materials, according to the Iraqi market in study.

6. Results

6.1 The Effect of Solar Intensity on the Behavior of Solar Still

The performance of the solar still is mainly affected by the intensity of solar radiation absorbed by the basin. It can be observed from Figure 3 and Figure 4 that both solar radiation intensity and ambient temperature rise to peak value at midday and decline gradually after that. Also, Figure 3 and Figure 4 show the temperature variation with time for still of water depth H=2 cm with and without phase change material (PCM), including glass, vapor, water, basin, and PCM. Figure 3 shows that the maximum water temperature for the solar still without PCM is about 50 °C, while the glass and vapor temperature is in the range of (12-25) and (18-40) °C. On the other hand, for the still with PCM, the maximum water temperature is 49 °C, and the PCM, glass, and vapor temperatures are in ranges (20-48), (11-25) and (20-40), respectively.

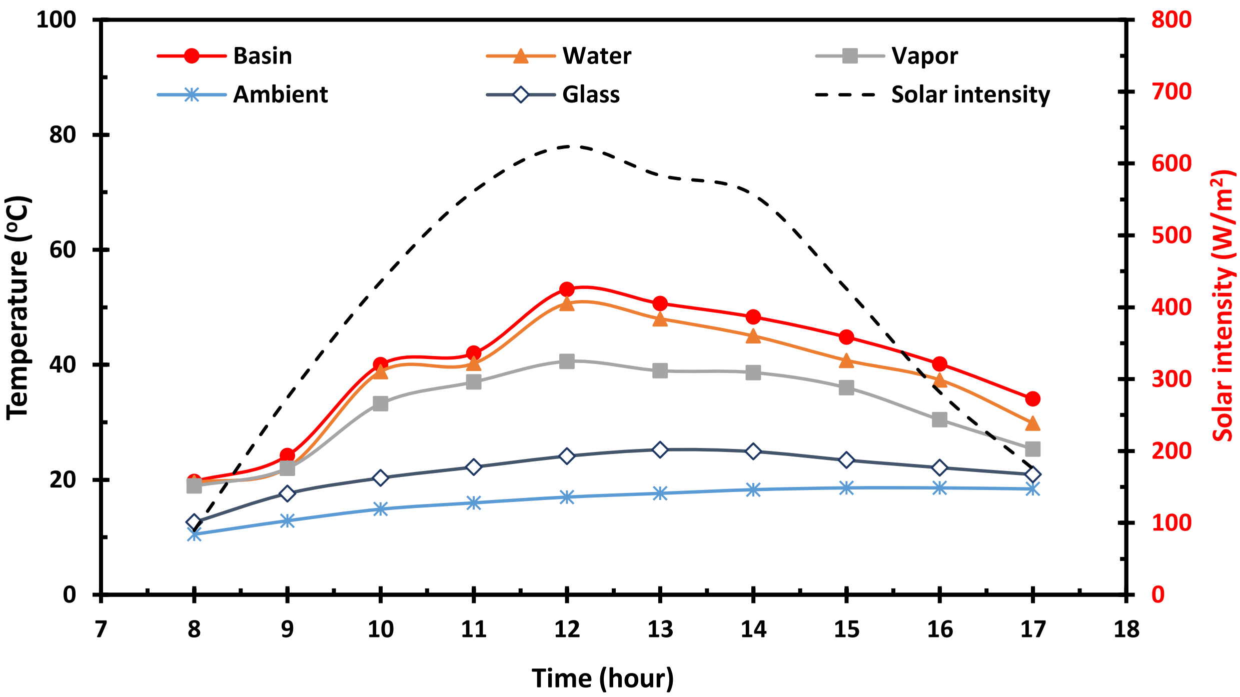

Fig. 3. Hourly solar radiation and temperature variations for the solar still without PCM, H=2cm 19-2-2023

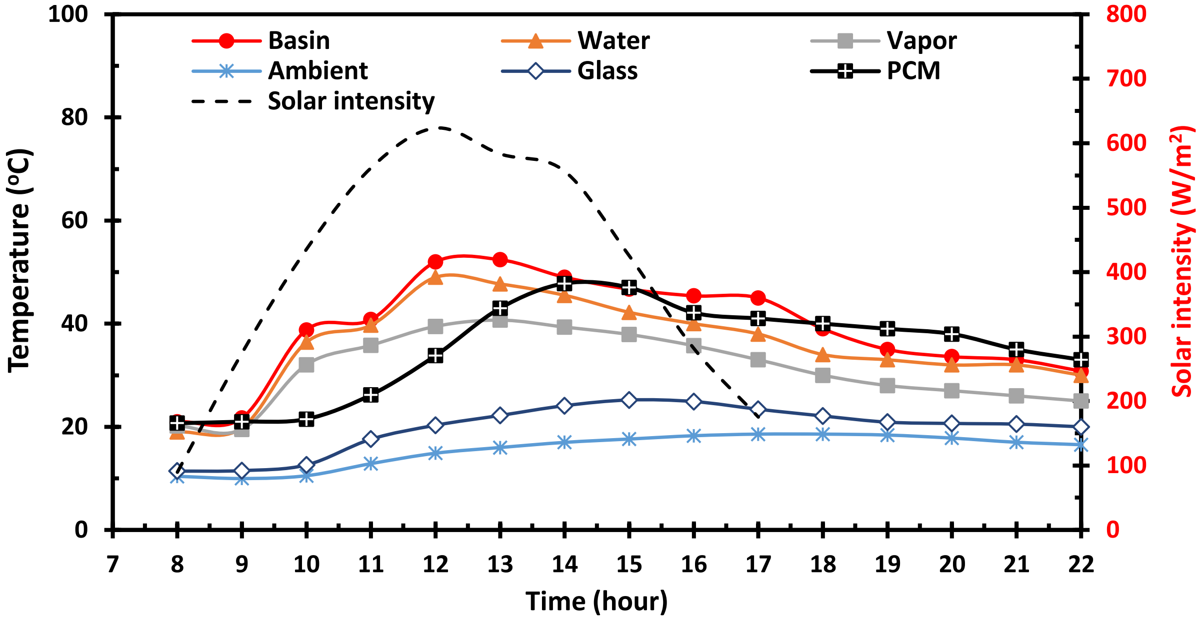

Fig. 4. Hourly solar radiation and temperature variations for the solar still with PCM, H=2cm 19-2-2023

For another test day for still of water depth H=3 cm, Figure 5 shows that the maximum water temperature for the still without PCM is about 53 °C, and the glass and vapor temperature is in ranges (18-39) and (18-43) °C. On the other hand, for the solar still with PCM, as shown in Figure 6, the maximum water temperature is 51 °C, while the PCM, glass, and vapor temperatures are in the ranges (18-48), (18-40) and (23-43) °C, respectively. The temperature of the phase change material (PCM) rises over time as the rate of heat transfer through conduction from the basin liner to the PCM increases with the intensity of solar radiation. The PCM started to melt after 7 hours, from the beginning of still exposure to solar radiation, for the summer and winter days, respectively [38]. Afterwards, it decreases slowly with time after sunset when the discharging process of the heat stored within the PCM begins. The water temperature of the still with PCM is lower than that of the still without PCM; this is because the PCM absorbs parts of the heat absorbed by the basin liner during the charging period. The water temperature in the presence of PCM is higher than without PCM after midday. This is because the PCM acts as an additional heat source during the discharging process.

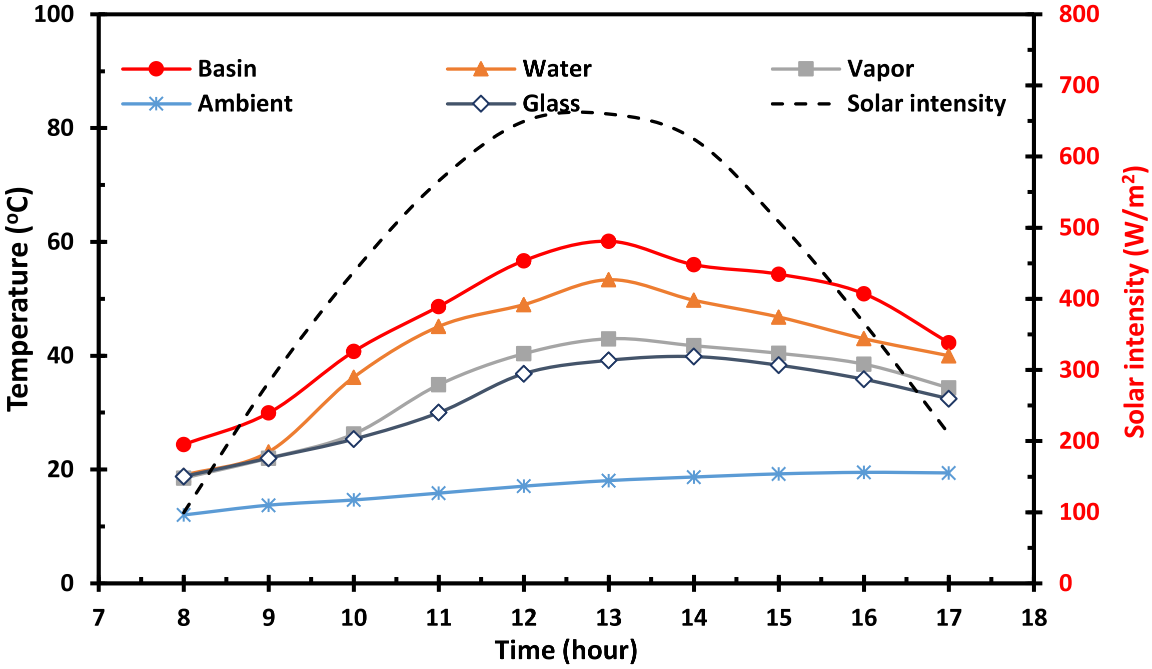

Fig. 5. Hourly solar radiation and temperature variations for the solar still without PCM, H=3 cm 22-2-2023

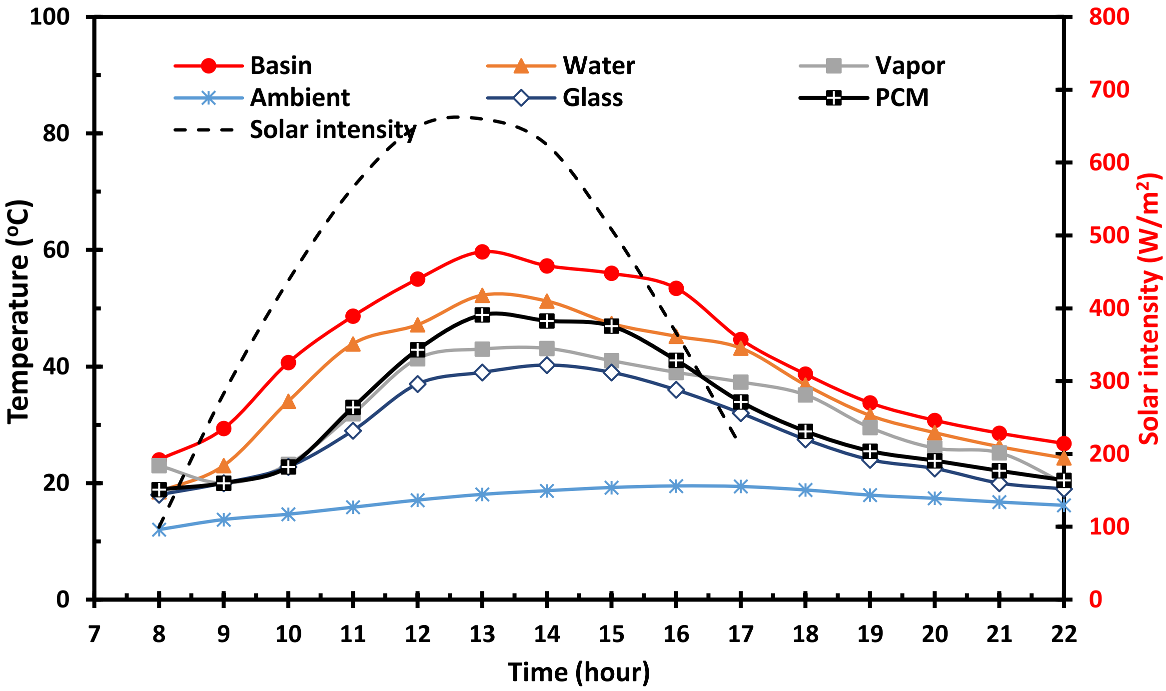

Fig. 6. Hourly solar radiation and temperature variations for the solar still with PCM, H=3 cm 22-2-2023

Figure 7 presents the temperature variation over time for the still with PCM in the presence of an external mirror. It was found that using reflectors increased the maximum water temperature by 8% and the ranges of PCM, glass and vapor temperatures by 6%, 20% and 12%, respectively. This is due to the increased solar energy received by the still.

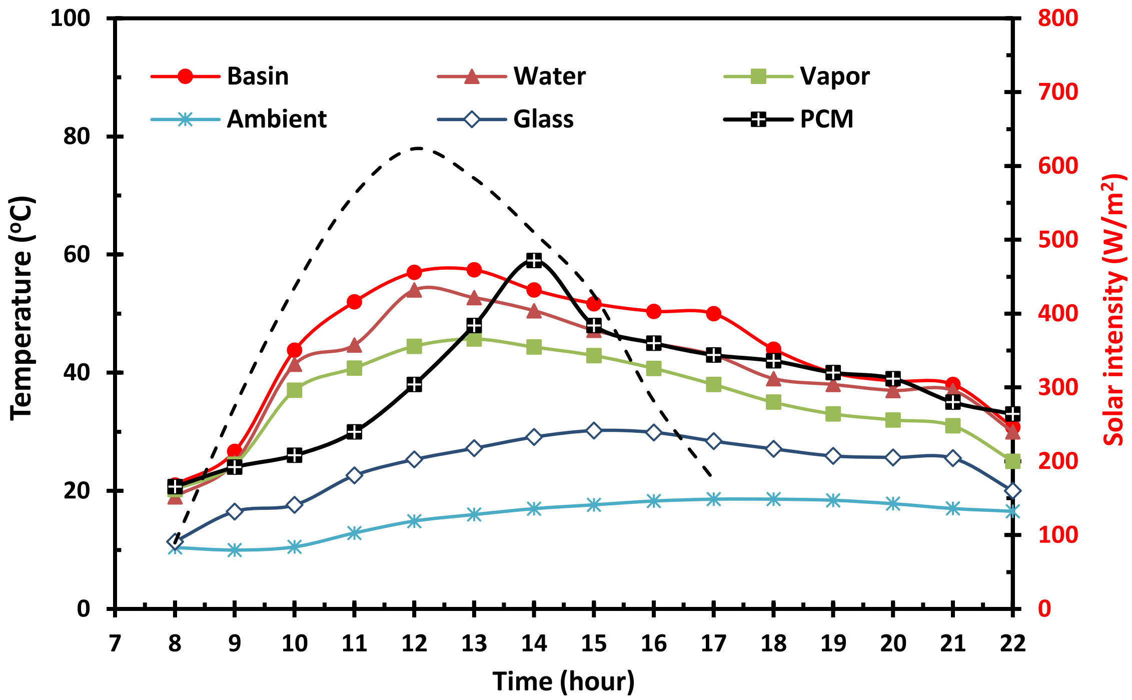

Fig. 7. Hourly solar radiation and temperature variations for the solar still with PCM with reflectors, H=2cm 20-2-2023

6.2 Hourly Yield

Figure 8 illustrates the hourly freshwater yield for both stills with and without PCM during the period from 8 am to 10 pm for water depth H=2 cm. The hourly productivity varies from zero at 7 pm to achieve the peak value at 1 pm. The hourly yield of the sill without PCM is higher than that with PCM in the period from 8 am to 1 pm. After that, the yield of the still with pcm becomes higher than that without pcm. This sudden increase in yield is due to the fact that the PCM represents a source of heat for the basin water in the periods when the intensity of solar radiation tends to decrease and during the night; and by following, the solar still with PCM continues to produce the freshwater after sunset due to the effect of the PCM. The maximum hourly yield achieved is 0.67 Liter and 0.66 Liter for still without and with PCM. Figure 9 exhibits the hourly yield for the still with and without PCM for water depth H=3 cm. Regardless of the little difference between the solar radiation intensity between the test days, it can be seen that increasing the water depth from 2 cm to 3 cm decreases the maximum hourly yield by 34 % and 40 % for the still without and with PCM, respectively. Increasing water depth decreases the hourly yield due to the increased quantity of water inside the still, which requires more energy to evaporate, leading to a decrease in the evaporation rate. Incorporating PCM with solar still is found to extend the operation of the still by 5 hours after sunset.

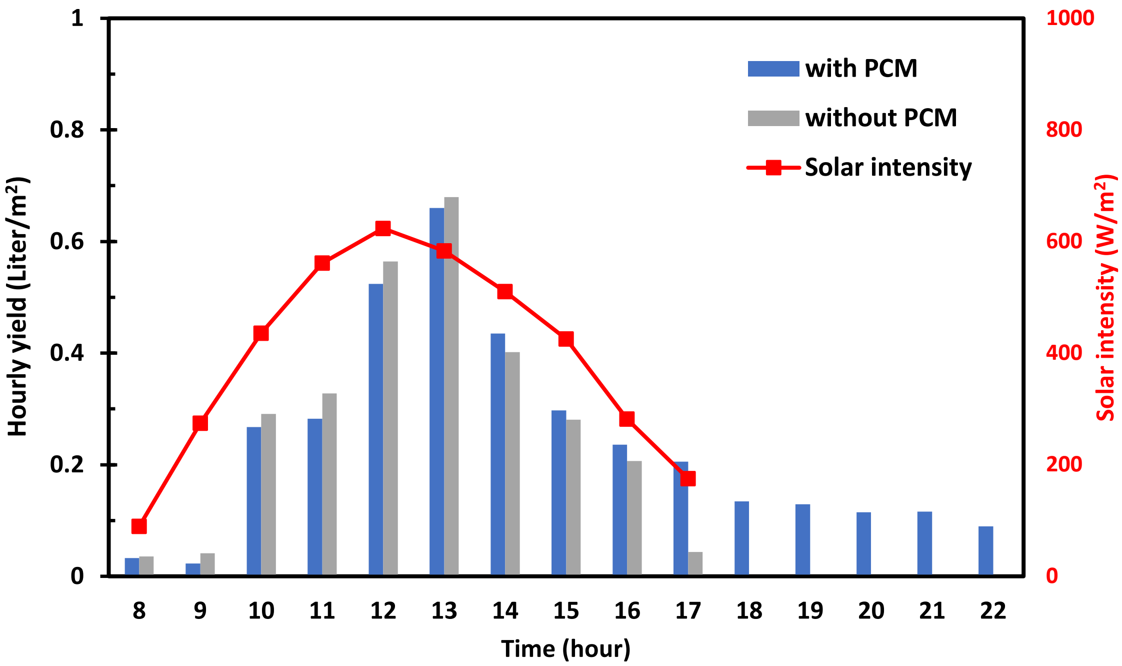

Fig. 8. Hourly yield variation for the solar still, H=2 cm,19-2-2023

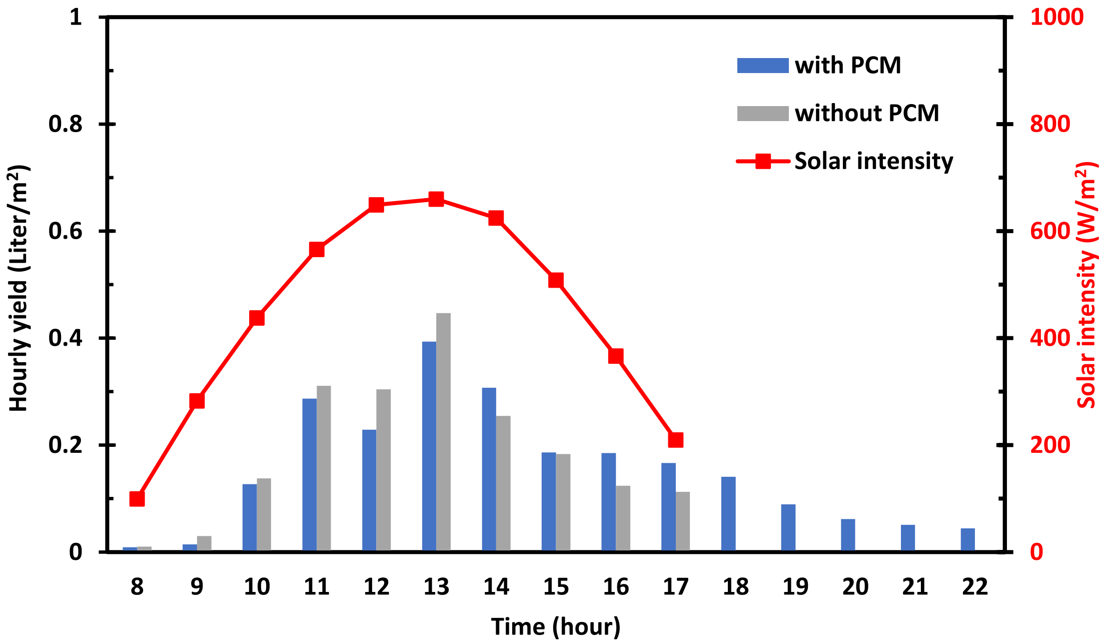

Fig. 9. Hourly yield variation for the solar still, H=3 cm,22-2-2023

Figure 10 shows the hourly yield variation along with time for the still with PCM in the presence of the reflectors and the hourly yield of the still without PCM and reflector. The reflectors significantly increase the hourly yield due to the increased solar energy received by the solar still, which increases the temperature inside.

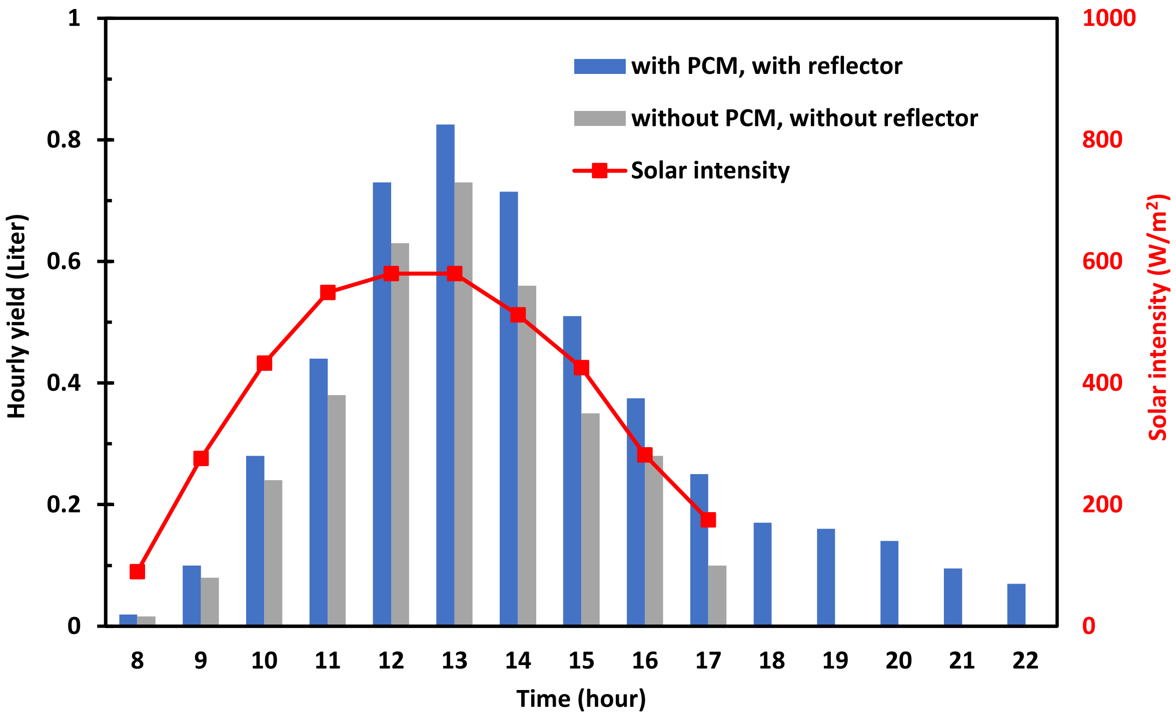

Fig. 10. Hourly yield variation for the solar still with PCM with reflector, H=2 cm,20-2-202

6.3 Accumulated Yield

Figure 11 summarizes the accumulated freshwater yield for both stills with and without PCM during the period from 8 am to 10 pm for water depth H=2 cm. The results from this figure show that the accumulated yield of the still without PCM is higher than that of one with PCM until 4 pm. After that, the still with PCM exhibits a higher accumulated yield due to the effect of the discharging process. The accumulated yield of the still without PCM is about 2.87 (Liter/m^2.h); in the presence of the PCM, it rises to about 3.54 (Liter/m^2.h). The presence of the PCM augments the Accumulated yield of conventional still by 23.34%. Also, the Accumulated yield for still with water depth H=3 cm is shown in Figure 12 for both stills with and without PCM. The Accumulated yield of the still without PCM is higher than that of one with PCM before 4 pm, which is the same as in the case of still. water depth H=2 cm. The accumulated yield of the still without PCM is about 1.9 (Liter/m^2.h); in the presence of the PCM, it rises to about 2.19 (Liter/m^2.h). The still with PCM has a higher Accumulated yield by 15.2%.

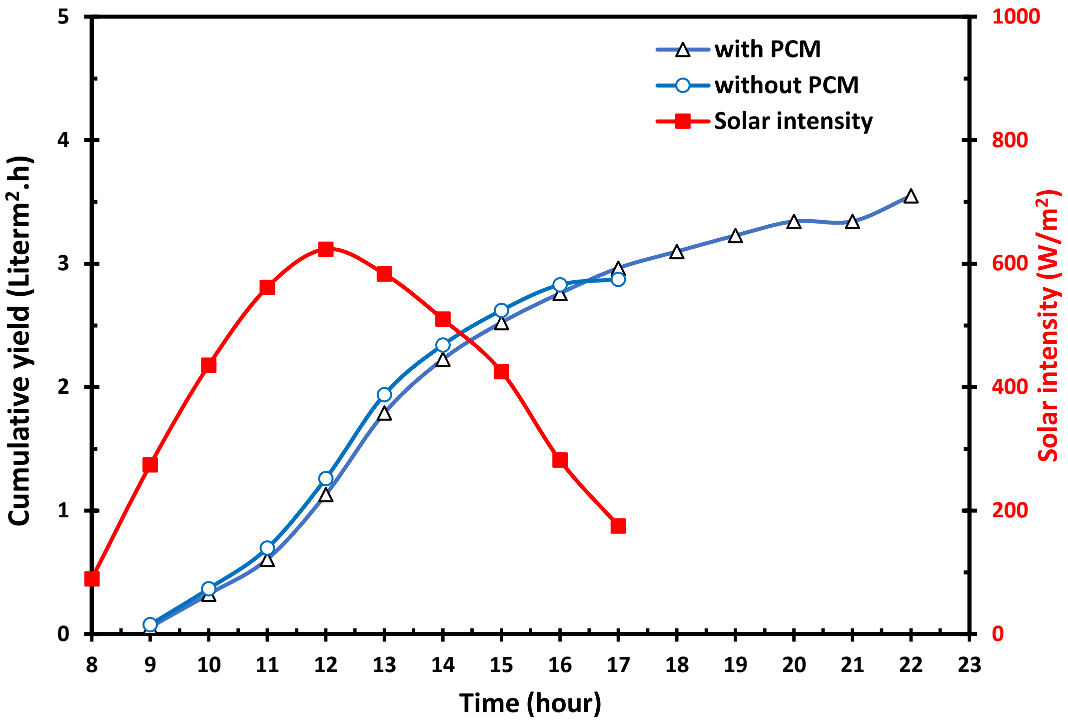

Fig. 11. Accumulated yield for both solar stills, H=2 cm,19-2-2023

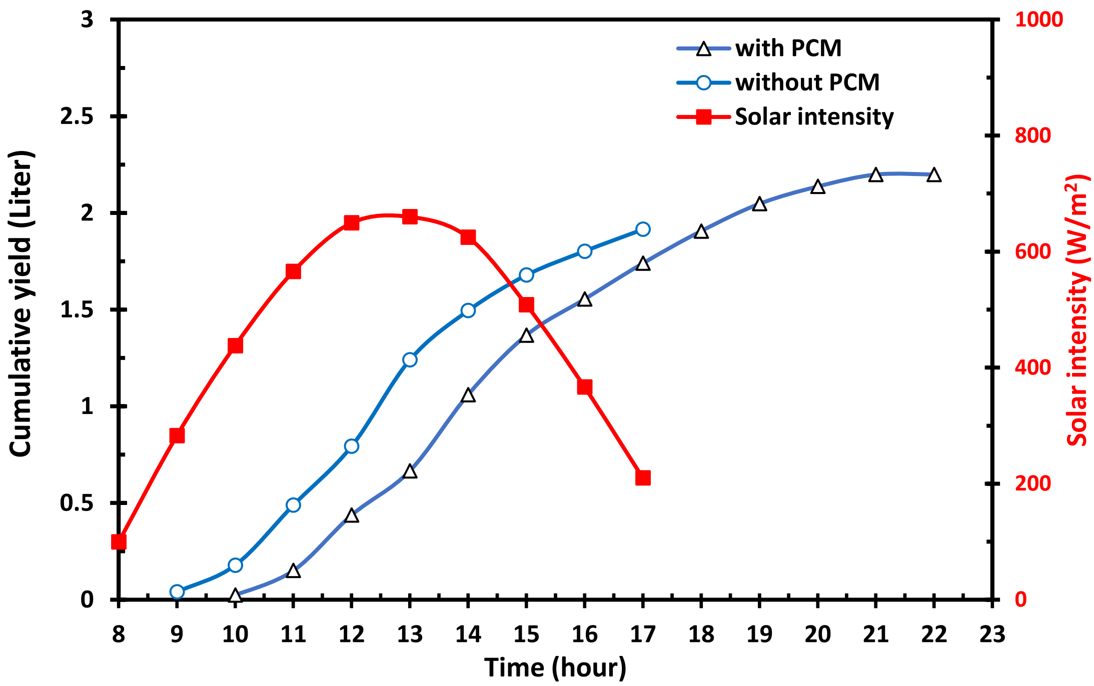

Fig. 12. Accumulated yield for both solar stills, H=3 cm,22-2-2023

Regardless of the little difference in solar intensity, which is less than 7%, it can be said that increasing the depth of the water inside the still from 2 cm to 3 cm decreases the Accumulated yield by 33% and 38% for the case with and without PCM, respectively. Figure 13 shows the Accumulated yield for the still with PCM with reflectors and conventional still for water depth H=2 cm. It can be observed that the accumulated yield increased from 3.33 (Liter/m^2.h) to 4.87 (Liter/m^2.h) when using PCM and reflectors. Also, from Figure 14, the effect of using PCM and reflectors on the still productivity is 45%.

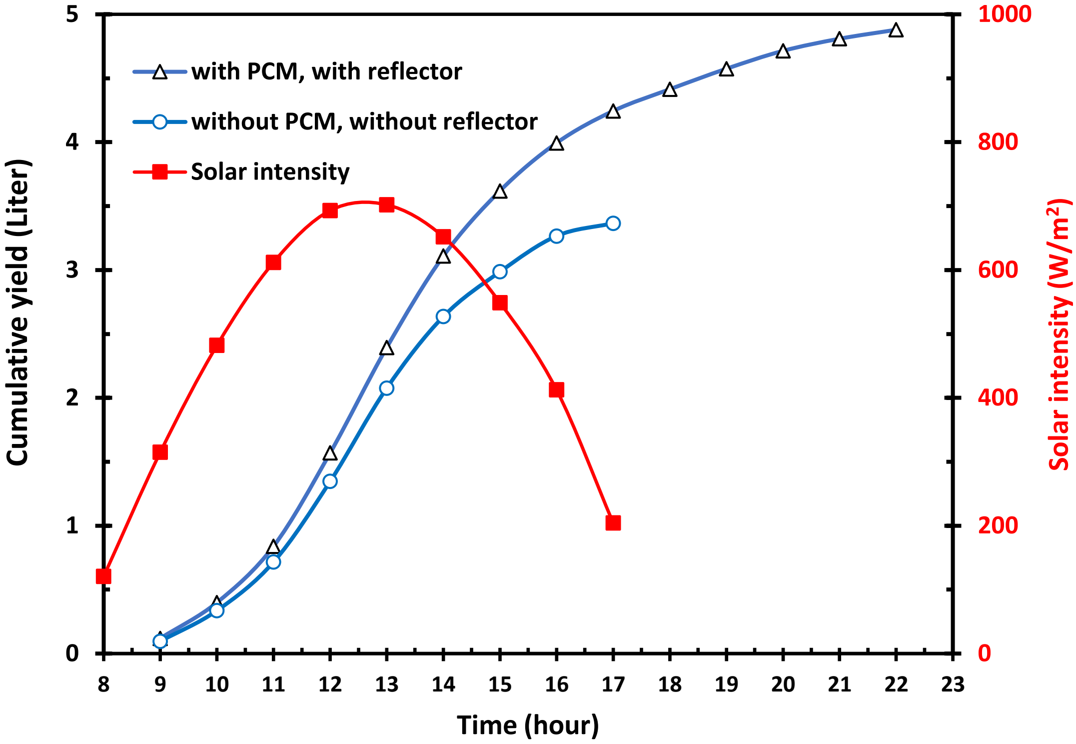

Fig. 13. Accumulated yield for solar still with PCM with reflectors, H=2 cm,20-2-2023

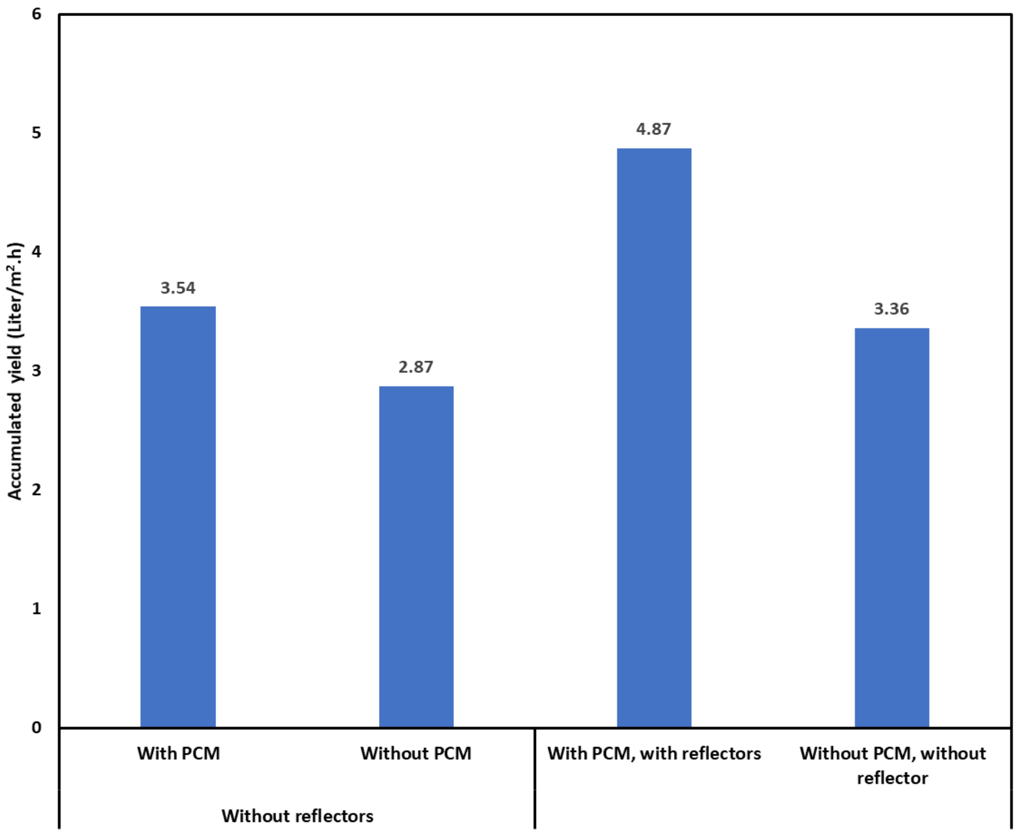

Fig. 14. Effect of reflectors on accumulated yield for both solar stills, H=2 cm

6.4 Efficiency

Figure 15 and Figure 16 display the variation of hourly efficiency with time for the still with and without PCM for water depth H=2 cm and H=3 cm, respectively. As time passes, all efficiencies rise progressively until they reach a maximum value at midday for still without PCM and then decline until the end of the day. In the presence of the PCM, the efficiency achieves peak value at 5 pm due to the effect of the discharging process of the PCM. The results reveal that the maximum efficiency for the still without and with PCM is 54% and 67%, respectively, for the water depth H=2 cm. Increasing the water depth from 2 cm to 3 cm decreases the maximum efficiency for the still without and with PCM to 47% and 54%, respectively. The average efficiency for the still without and with PCM is 31% and 40% for a water depth of 2 cm, respectively, while 27% and 34% for a water depth of 3 cm, respectively. The efficiency is lower for higher water depths due to the increased water mass inside the still, which leads to a decrease in the temperatures inside the still, eventually decreasing productivity and efficiency.

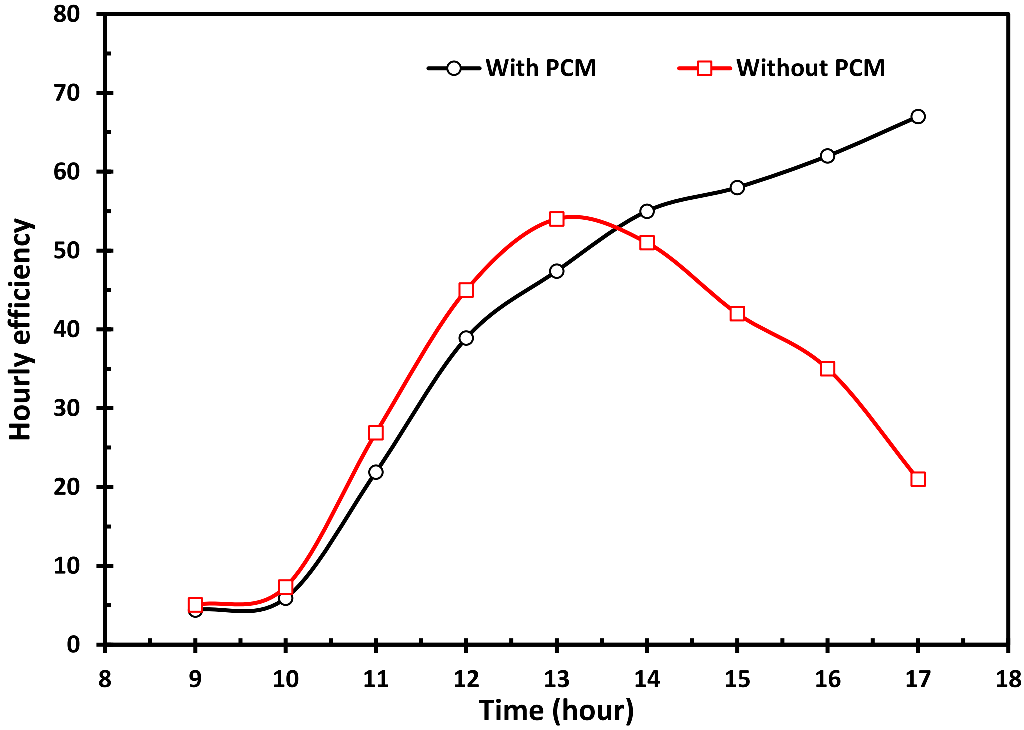

Fig. 15. Hourly efficiency for both solar stills, H=2 cm,19-2-2023

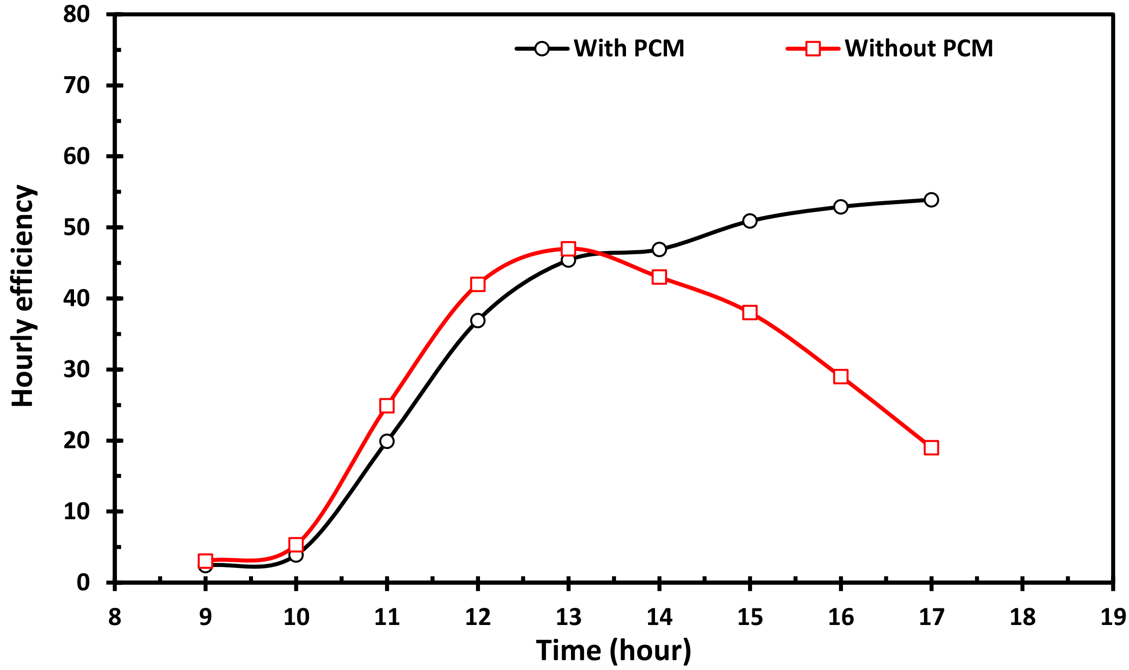

Fig. 16. Hourly efficiency of both solar stills, H=3 cm,22-2-2023

6.5 A Comparison with Previous Work

The results of the present work are compared with those of previous research discovered in the literature in order to evaluate the performance of the solar stills tested in the present work. Table 4 lists several solar stills use, wick, phase change materials, and reflectors.

Table 4
Comparison with previous works

Authors	Solar still	Productivity improvement %
Kumar *et al.,* [23]	CSS+PCM-nanoparticles	67
Younes *et al.,* [39]	CSS + corrugated wick + PCM-CuO	134
Omara and Kabeel [40]	CSS + different sand beds	17
Abdullah *et al.,* [41]	CSS + trays + PCM-nanoparticles	94
Present work	CSS + PCM + External reflectors	49

6.6 Economic Cost

Figure 17 shows the average costs of distilled water for different types of solar stills. The results obtained show that best water production cost for a solar still having a capacity of 1511 Liter/m^2 as average annual yield, while the water production cost of the present work (CSS + PCM + External reflectors) is higher by 20% for annual production of 1266 Liter/m^2. It can be said that the water production cost of the present work is reasonable.

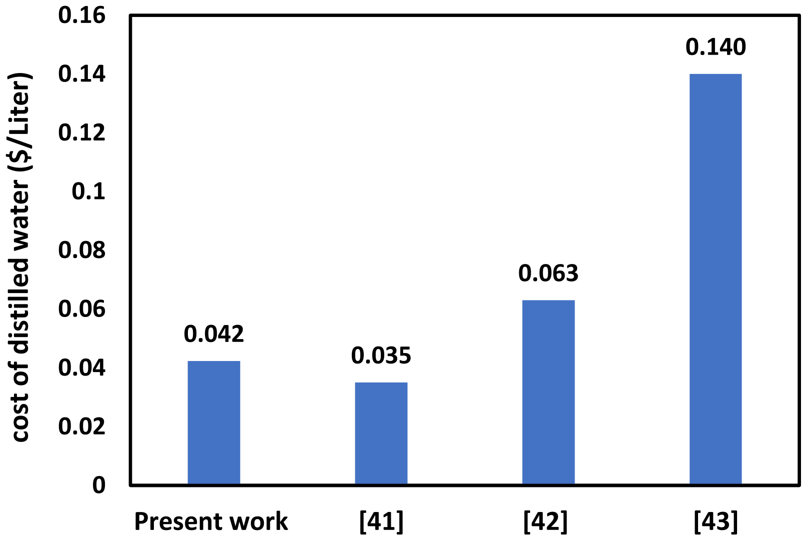

Fig. 17. The average costs of distilled water

7. Conclusions

The present work investigates the effect of using Parrafin wax as a thermal storage medium and external reflector on the performance of a single slope still in the climate of Baghdad in February 2023. The main findings can be summarized as:

i. During the early hours of the day, the overall productivity and device efficiency were lower compared to the still without PCM. This is because the PCM stores some sun heat that would have been lost through evaporation if the PCM wasn't used.
ii. The solar still shows 23% and 14% Accumulated yield enhancement for a 2cm and 3 cm water depth, respectively, by adding 20 kg of the PCM.
iii. The performance difference due to the PCM's presence is recorded after 2 p.m. until 10 p.m. The PCM also extends the still's operation time by five hours.
iv. Using external reflectors augments the Accumulated yield by 15% for the still with PCM.
v. Increasing the water depth inside the still from 2 cm to 3 cm diminishes the Accumulated yield by 33 % and 38 % for stills without and with PCM, respectively.

8. Recommendations

Many factors can be investigated to enhance the yield of solar stills through the flowing research lines:

i. Using PCM along with corrugated absorber plate.
ii. Using nano-PCM as a thermal storage material.
iii. Adopting a spraying cooling technique for the glass cover.
iv. Inserting a mesh inside the PCM.

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