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Enhancing hemispherical solar still yield via wick materials and glass cover cooling

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ABSTRACT

Hemispherical solar still with 8 mm thick wick materials at the bottom of its basin increases freshwater yield. Three 0.1 m^2 hemispherical solar devices were utilized for the experimental study. The system was experimentally tested in three ways for consecutive days. The first basin was a traditional one (THSS), the second basin was completely covered with a wick with 8 mm thickness (THSS-W), and the third basin was completely covered with the wick with a thickness of 8 mm and the glass cover cooling at a rate of 2 L/h (THSS-WC). The results showed that the wick utilization in the hemispherical basin gave high production compared to the traditional one. However, the glass surface cooling in addition to the wick utilization gave the best yield enhancement. The system with a traditional hemispherical basin provided a distillate of 3.25 L/m^2, the system with a hemispherical basin covered with a wick provided a distillate of 4.55 L/m^2, while the system with a hemispherical basin covered with a wick and the glass cover cooling produced a distillate of 5.5 L/m^2. Accordingly, THSS-W and THSS-WC yields increased by 40% and 69.23%, respectively, when compared to THSS yield. The economic feasibility presented that the dual utilization of the wick and the glass cover cooling (THSS-WC) reduced the total cost of distillates produced from hemispherical solar distillers by 38.4% compared to THSS.

Keywords: Solar energy; Hemispherical solar still; Wick; Glass cover cooling

1. Introduction

Lack of freshwater is a problem that people all over the world suffer from. Potable water represents only 3% of the total water on Earth [1,2]. Solar distillation is one of the techniques used to desalinate salt/seawater in the world, especially in regions that suffer from a severe shortage of drinking water, including arid and arid regions [3–5]. This method is economical, easy, and environmentally friendly. Besides, it is suitable for places with high solar radiation and has continuous water resources. Traditional solar distillation is the easiest and simplest way to provide fresh water to isolated populations in arid and remote locations. Conventional solar distillates are low, and scientists are eager to think about improving yield [6,7]. Several scientists have improved solar stills performance using wick

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systems [8–12]. Hansen et al. [13] studied the influence of water coral fleece material on the performance of tilted type solar stills with a gradient mesh absorber plate. The results displayed that when using water coral wool as wick material, the distillate achieved a maximum of 4.28 L/d. Omara et al. [14] conducted a study on the performance of corrugated solar distillation using a double-layer wick material. They deduced that the daily accumulation of corrugated solar still using the wick was much higher than that of conventional solar still. Alaian et al. [15] experimentally examined the role of a vertical pin-finned wick on a steel wire basin on solar still performance. They concluded that yield improved when the finned wick was applied in the solar still. Akash et al. [16] studied the effect of using a black rubber mat absorber, black ink, and black dye absorber in a SS solar still to enhance the yield. Experimental results showed yield enhancement by 38%, 45%, and 60% for using black rubber mat absorber, black ink and, black dye absorber, respectively. Mahdi et al. [17] conducted experiments using the charcoal cloth in the tilted wick. They concluded that the charcoal cloth is a superb technique for increasing the yield of the tilted solar still because it is a water transport medium to be used as an absorbent/evaporator. Suneesh et al. [18] studied the use of an inclined wick with or without cooling a cotton gauze over an intense glass cover with a regenerative effect. The results showed that the yield of the system using an inclined wick with cotton gauze was about 6,300 L/m^2, while it was 5,600 L/m^2 without cotton gauze. Ayoub et al. [19] introduced a simple modification to solar distillation to enhance its yield, by introducing a slowly rotating drum enabling the formation of thin aqueous films that were constantly replenished and rapidly evaporated. The researchers concluded that when the drum was added to the system, the daily production increased by around 200% compared to the daily yield of the reference solar distiller.

The hemispherical distiller has the maximum surface area to volume ratio compared to all distiller geometries. From the previous literature, the enhancement of the hemispherical distiller via both wick utilization and glass cover cooling has not been investigated. In this paper, the wick with 8 mm thickness coverage of the hemispherical solar distillation basin, with and without glass cover cooling was studied experimentally with a cooling water flow rate of 2 L/h. Three hemispherical solar devices (THSS, THSS-W, and THSS-WC) were tested within the same days. The system was tested in three ways for consecutive days: (i) the first basin was a traditional one that did not contain the wick (THSS), (ii) the second basin was completely covered with the wick (THSS-W), and (iii) the third basin was completely covered with the wick, with the glass cover cooling at a rate of 2 L/h (THSS-WC).

2. Experimental setup and procedure

The hemispherical solar distiller is a very simple device with available and inexpensive components. The cycle of producing distilled water uses the principle of evaporation/condensation. This simple device converts salt/seawater into drinking water in isolated areas. The experiments were conducted on three consecutive days at November 2020 from 8:00 am to 5:00 pm, i.e. 9 h of sunlight. The test setup was established in the Algiers Valley with latitude 33.3676°N and longitude 6.8516°E. Fig. 1 shows a schematic presentation of hemispherical solar still. In this experiment, we made three solar distillation basins of 0.1 m^2 of wood with a thickness of 2.5 cm and a depth of 2.5 cm. We coat the base and the inner sides with black silicone, which is considered an absorbent material. The wick piece is installed at the bottom of the second and third distillation basin to absorb the largest number of sunlight. As we cool the glass cover of the third hemispherical distiller, the temperature of the water increases according to the incident radiation. The water evaporates and condenses into drops, the droplets slide to collect in a tank. Fig. 2 shows the hemispherical solar still with a wick and glass cover cooling. By using these devices, the experiments were conducted for 3 d in a row: 1, 2, and 3 November 2020 for 9 h in the city of El Oued Algeria. In our experiments, three water basins were used. The first distiller is a traditional hemispherical solar still (THSS), the second is a modified

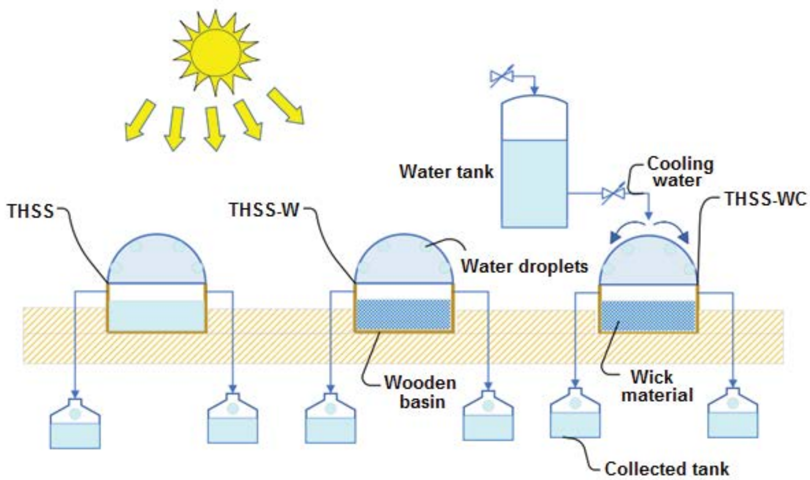

Fig. 1. Schematic presentation of hemispherical solar still configurations.

hemispherical solar basin with an 8 mm wick (THSS-W), and the third is a modified hemispherical solar basin with wick (a thickness of 8 mm) and glass cover cooling (THSS-WC).

The considered parameters are measured within the thermocouples, the solar power meter, and the graduated cylinder. The uncertainties of these measuring devices are listed in Table 1.

3. Results and discussions

Experiments were performed in three ways for three consecutive days: (i) the first basin was a traditional one that did not contain the wick (THSS), (ii) the second basin was completely covered with the wick (THSS-W), and (iii) the third basin was completely covered with the wick, with the glass cover cooling at a rate of 2 L/h (THSS-WC). Figs. 3–5 show the hourly variation in solar intensity and the temperatures of (the cooling water, ambient, and the wick material) from 8:00 am to 5:00 pm on Nov. 1, 2, and 3, 2020. It is seen that the solar intensity goes up until its maximum value at noon and it is then dramatically decreasing as the time proceeds until it gets its lower value near the time of sunset. Also, at nearly 2:00 pm, the maximum temperatures of the cooling water, ambient, and the wick material were about 34°C, 38°C, and 61°C, respectively.

3.1. Hourly temperature variation of water basin for the three configurations

Figs. 6–8 show the hourly variation of water basin temperature from 8:00 am to 5:00 pm on Nov. 1, 2, and 3, 2020 for three different configurations. It is seen that the hourly temperature variation of the second basin (THSS-W), and the third basin (THSS-WC) are greater than the hourly temperature variation of the first traditional basin that did not

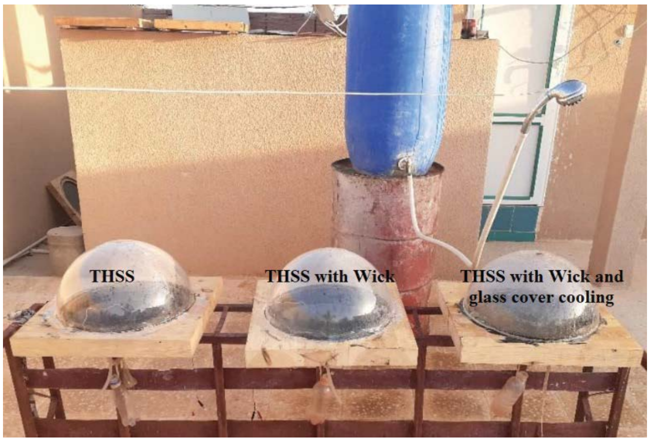

Fig. 2. Hemispherical solar still with a wick and glass cover cooling.

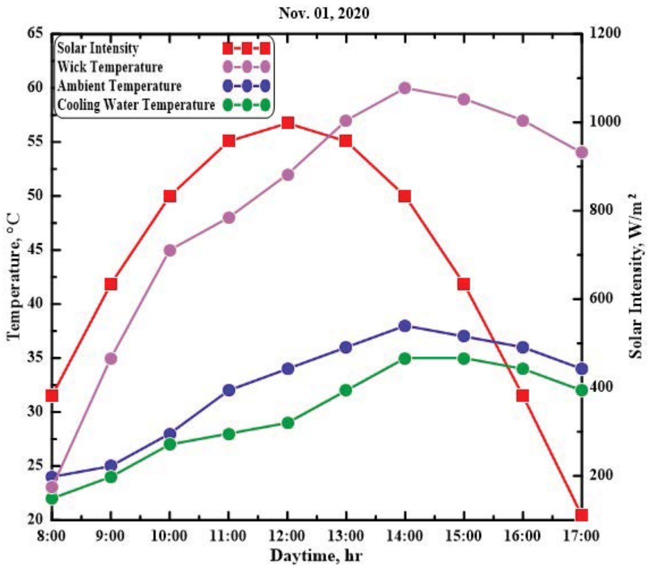

Fig. 3. Variation of solar intensity and temperature with daytime for the first day.

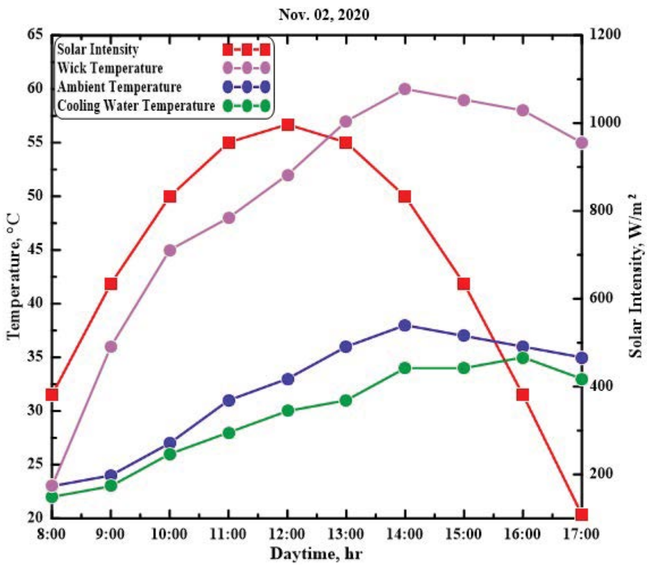

Fig. 4. Variation of solar intensity and temperature with daytime for the second day.

Table 1
Uncertainties of the measuring devices

Instrument	Accuracy	Range	Standard uncertainty
Solar power meter	±10 W/m²	0–1,999 W/m²	5.72 W/m²
Thermocouple	±0.1°C	−100°C to 500°C	0.07°C
Incremental cylinder	±2 mL	0–250 mL	0.6 mL

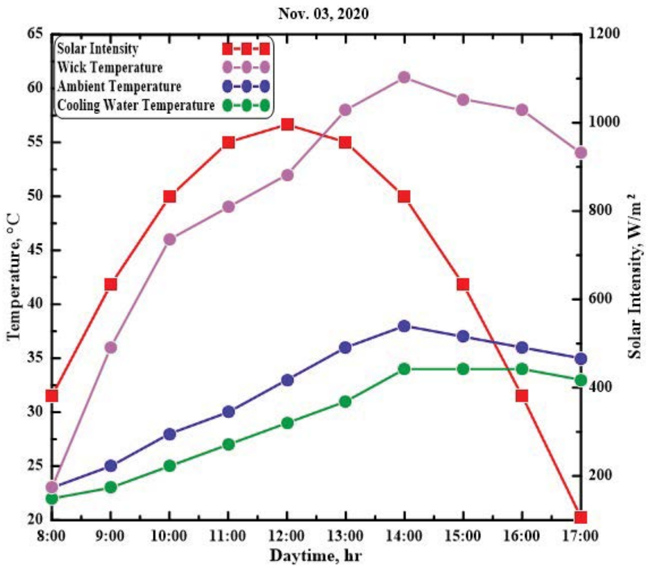

Fig. 5. Variation of solar intensity and temperature with daytime for the third day.

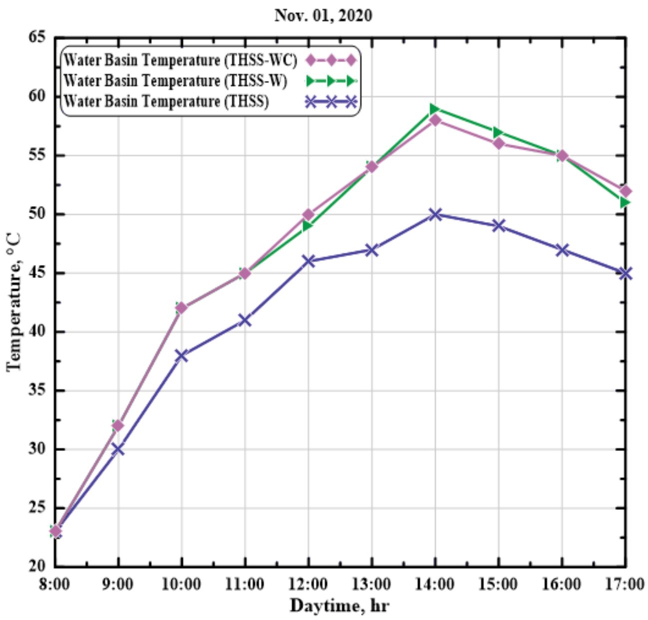

Fig. 6. Variation of water basin temperature with daytime for the first day.

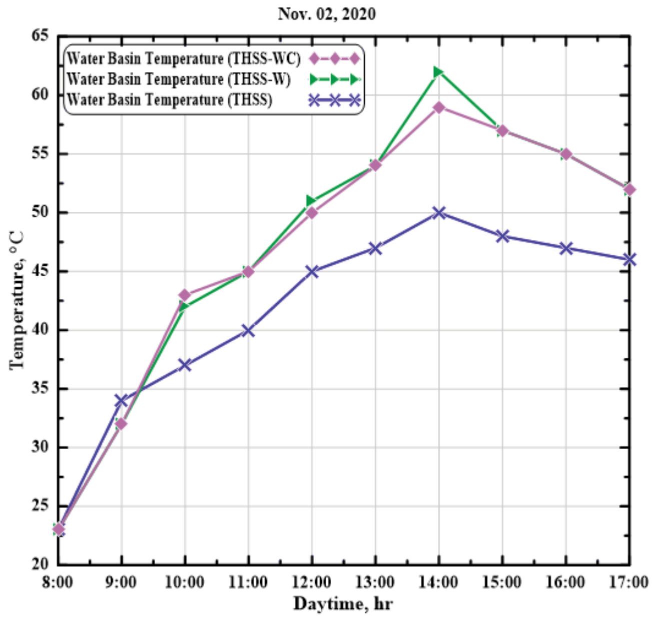

Fig. 7. Variation of water basin temperature with daytime for the second day.

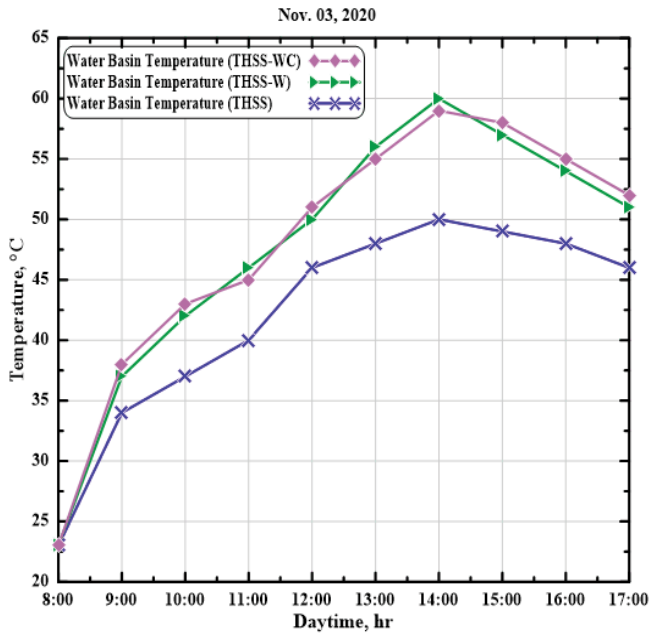

Fig. 8. Variation of water basin temperature with daytime for the third day.

contain the wick (THSS). Also, at 2:00 pm, the maximum water basin temperature of (THSS-W), (THSS-WC), and (THSS) reached an average temperature of 60°C, 57°C, and 50°C, respectively.

3.2. Hourly temperature variation of glass covers for the three configurations

Figs. 9–11 show the hourly variation of external glass temperature from 8:00 am to 5:00 pm on Nov. 1, 2, and 3, 2020 for three different configurations. It is seen that the external glass temperature variation of the third basin (THSS-WC) is lower than the external glass temperature variation of the first traditional basin that did not contain the wick (THSS) and the second basin that was completely covered with the wick (THSS-W). Also, it is seen that the maximum glass cover temperature of (THSS-WC), (THSS-W) and (THSS) reached an average temperature of 38.5°C, 37.5°C, and 34°C, respectively.

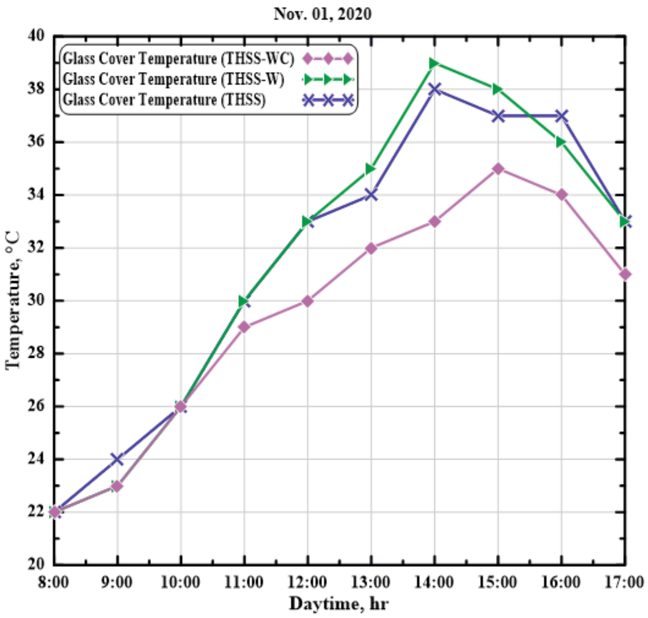

Fig. 9. Variation of glass cover temperature with daytime for the first day.

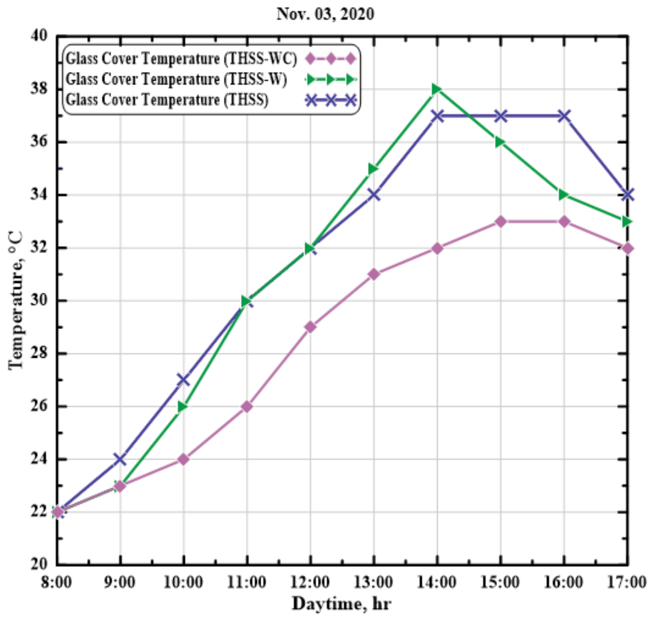

Fig. 11. Variation of glass cover temperature with daytime for the third day.

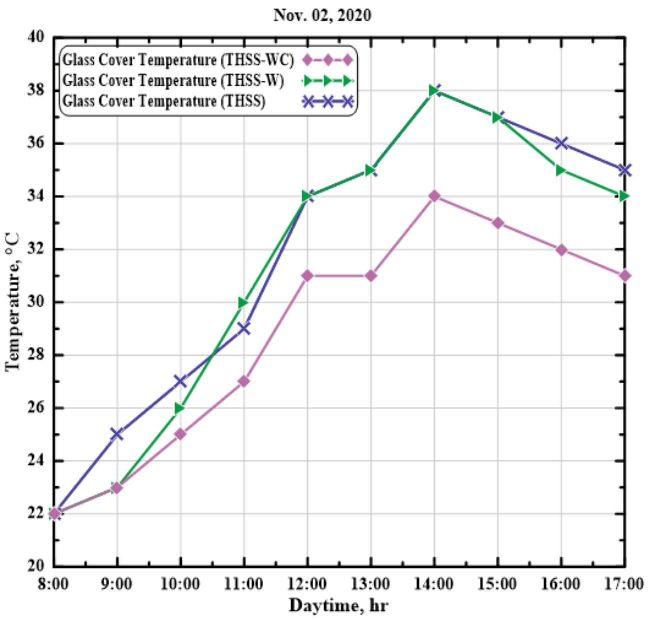

Fig. 10. Variation of glass cover temperature with daytime for the second day.

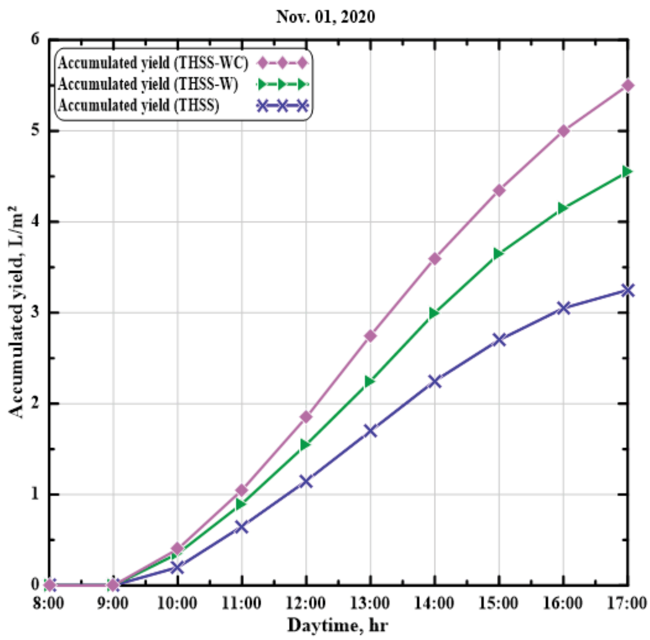

Fig. 12. Variation of the accumulated yield with daytime for the first day.

3.3. Effect of wick materials and glass cover cooling on the accumulated yield of hemispherical solar still

Figs. 12–14 indicate the hourly variation of accumulated water yield from 8:00 am to 5:00 pm on Nov. 1, 2, and 3, 2020 for three different configurations. It is seen that the accumulated yield of the distillate with wick and glass cover cooling (THSS-WC) is much better than the distillate with a wick material (THSS-W) and the distillate without a wick material (THSS). The average amount of the accumulated water yield at 5:00 pm for (THSS-WC), (THSS-W), and (THSS) were 5.50, 4.55, and 3.25 L/m^2, respectively.

3.4. Effect of wick materials and glass cover cooling on the hemispherical solar still efficiency

Figs. 15–17 indicate the hourly variation of hemispherical solar still efficiency from 8:00 am to 5:00 pm on Nov. 1, 2, and 3, 2020 for three different configurations. The solar still

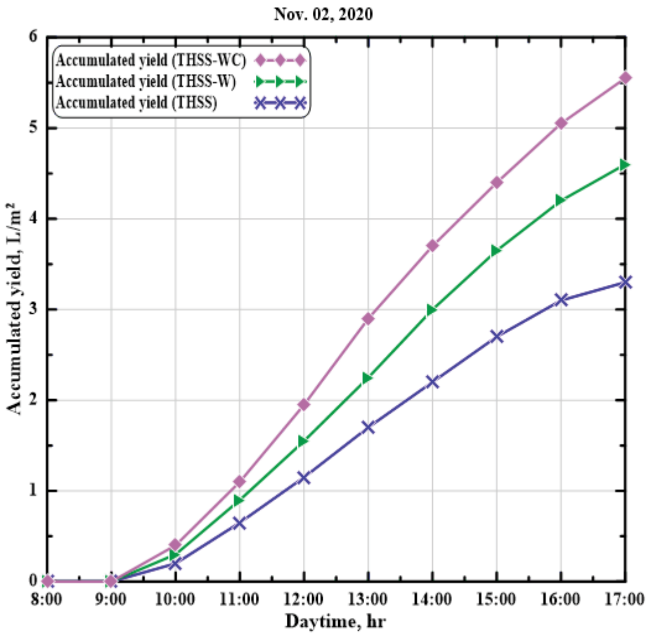

Fig. 13. Variation of the accumulated yield with daytime for the second day.

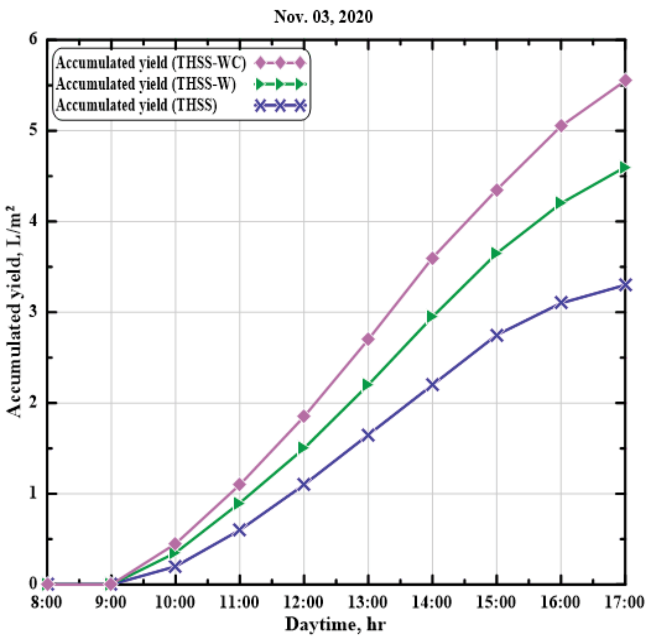

Fig. 14. Variation of the accumulated yield with daytime for the third day.

efficiency depends on the distillate yield, water latent heat, solar intensity, and the solar still absorber area, it is can be calculated as;

Instantaneous efficiency is given by:

$$\eta(t) = \frac{\dot{m} \times \text{L.H.}}{I(t) \times A_{ss}} \quad (1)$$

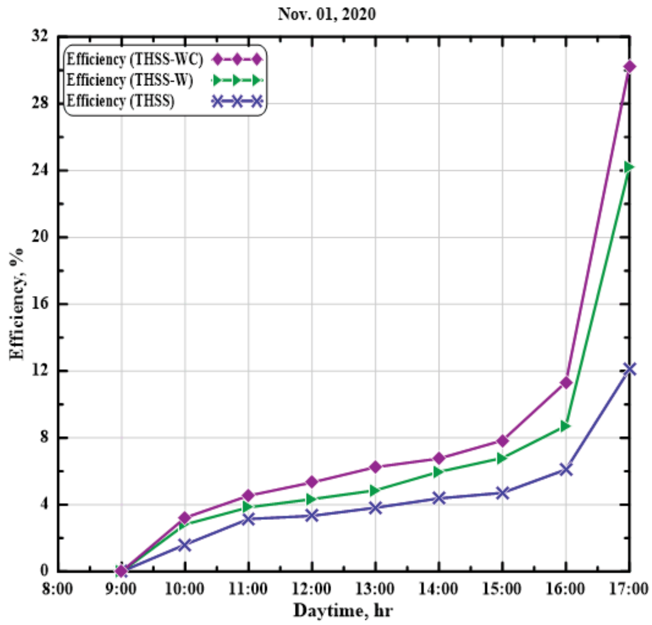

Fig. 15. Variation of solar still efficiency with daytime for the first day.

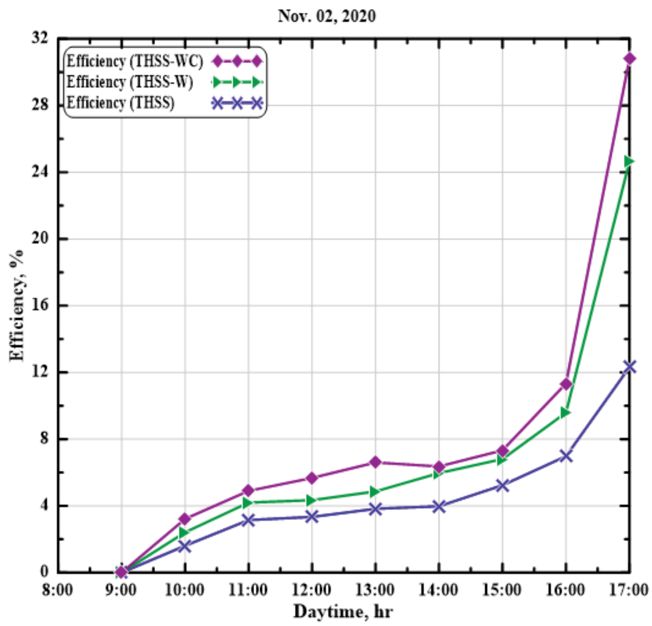

Fig. 16. Variation of solar still efficiency with daytime for the second day.

While the daily efficiency is given by:

$$\eta = \frac{\sum \dot{m} \times \text{L.H.}}{\sum I(t) \times A_{ss}} \quad (2)$$

where $\dot{m}$ is the distillate yield (kg/s), L.H. is the latent heat (J/kg), $I(t)$ is the solar intensity (W/m²), and A_{SS} is the solar still absorber area (m²).

The latent heat of vaporization water L.H. is calculated by knowing the water basin temperature T_w from Eq. (3) [20]:

$$\text{L.H.} = 10^3 \times \begin{bmatrix} 2501.9 - 2.40706T_w + 1.192217 \times \\ 10^{-3}T_w^2 - 1.5863 \times 10^{-5}T_W^3 \end{bmatrix} \quad (3)$$

It is seen that the efficiency of the distillate with wick and glass cover cooling (THSS-WC) is much better than the distillate with wick material (THSS-W) and the distillate without wick material (THSS). The average amount of daily efficiency for (THSS-WC), (THSS-W), and (THSS) were 54.57%, 45.35%, and 32.65%, respectively.

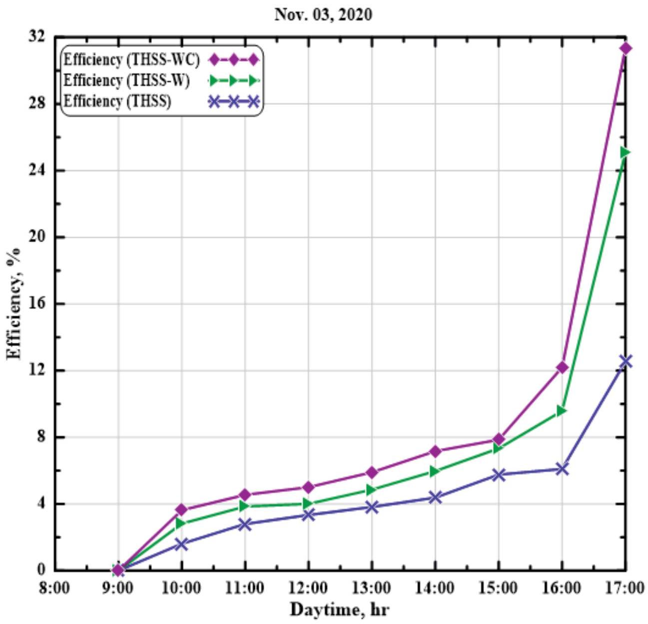

Fig. 17. Variation of solar still efficiency with daytime for the third day

4. Comparison between the present study and similar published works

Table 2 shows a comparison between the current study with similarly published works. Through the results, it has been noted that the accumulated yield of hemispherical solar still containing wick (THSS-W) increases by 40% compared to the THSS, and cumulative yield increases by 69.23% when using wick and glass cover cooling (THSS-WC) compared to the THSS. Thus, wick greatly enhances the yield of hemispherical solar distillation. From Table 3, it can be noticed that the yield of double slope single-wick solar still, with various wicks [23] is minimum with a value equal to 20%. However, for the tilted wick solar still, with wick materials with glass cooling, it is maximum with a value equal to 278.4% [22].

5. Economic evaluation

A comprehensive economic analysis was investigated to demonstrate the economic feasibility of using wick (THSS-W) and dual use of the wick and glass cover cooling (THSS-WC) and the extent of their impact on the total cost of distillates produced from hemispherical solar distillers. Economic analysis was performed using the equations shown as follows:

The distillate water cost per liter (C_W) calculated as follows [27–30]:

$$C_W = \frac{\text{TAC}}{M_{d,\text{annual}}} \quad (4)$$

where $M_{d,\text{annual}}$ is annual distillate water productivity and TAC is the total annual cost which calculated as [28–30]:

$$\text{TAC} = \text{AFC} + \text{AMOC} - \text{ASV} \quad (5)$$

where ACC is the annual capital cost, AMOC is the annual maintenance and operating cost, and ASV is the annual salvage value.

Table 2
Comparison between the yields

Reference	Solar still type	Enhancement techniques	Yield enhancement
Haddad et al. [21]	Conventional wick type solar still	- Vertical rotating wick	51.1%
Sharshir et al. [22]	Tilted wick solar still	- Wick materials	210.2%
		- Wick materials with glass cooling	278.4%
Rajaseenivasan et al. [23]	Double slope single-wick solar still	- Various wicks	20%
Samuel Hansen et al. [24]	Stepped wick solar still	- Coral fleece wick over	71.2%
		- Wire-mesh, stepped	57.2%
		- Flat plate absorbers	45.4%
Omara et al. [25]	Corrugated wick solar still	- Double-layered wicks	90%
		- Wicks escorted by reflectors	145.5%
Alaian et al. [26]	Finned wick solar still	- Pin-finned wicks fixed	23%
Present work	Hemispherical wick solar still	- Wick materials	40%
		- Wick materials with glass cooling	69.23%

Table 3
Cost details of THSS, THSS-W, and THSS-WC

	THSS	THSS-W	THSS-WC
Capital cost (P), $	69.88	71.13	72.83
Annual capital cost (ACC), $	12.37	12.59	12.89
Annual maintenance and operating cost (AMOC), $	3.71	3.78	3.87
Annual salvage value (ASV), $	0.79	0.81	0.83
Total annual cost (TAC), $	15.29	15.56	15.93
Annual productivity ($M_{d,\text{annual}}$), L/m²/y	891	1,242	1,499
Distilled water cost per liter (C_W), $/L	0.0172	0.0125	0.0106

Annual capital cost (ACC) calculated as follows [27–30]:

$$\text{ACC} = P \times \text{CRF} \quad (6)$$

where P is the capital cost.

The capital recovery factor (CRF) expressed as,

$$\text{CRF} = \frac{K_d\left(1+K_d\right)^i}{\left(1+K_d\right)^i - 1} \quad (7)$$

The yearly discount rate (K_d) and system life years (i) are assumed to be 12% and 10 y.

Annual maintenance and operating cost (AMOC) calculated as follows [28–30]:

$$\text{AMOC} = 30\% \times \text{ACC} \quad (8)$$

Annual salvage value (ASV) calculated as follows [28–30]:

$$\text{ASV} = S \times \text{SFF} \quad (9)$$

The salvage value of the distiller (S) is considered 20% of the capital cost [30]. While the sinking funding index (SFF) can be represented as:

$$\text{SFF} = \frac{K_d}{\left(K_d+1\right)^i - 1} \quad (10)$$

Table 3 details the cost analysis, showing that the estimated total cost per one liter of distillate water produced comes to about 0.0172, 0.0125, and 0.0106 $/L for THSS, THSS-W, and THSS-WC, respectively. The economic feasibility presented that the dual utilization of the wick and the glass cover cooling (THSS-WC) reduced the total cost of distillates produced from hemispherical solar distillers by 38.4% compared to THSS.

6. Conclusions

This experimental work highlights the positive impact of wick materials with and without glass cover cooling on the yield of hemispherical wick solar still. This simple technique involves placing a wick with a thickness of 8 mm on the bottom of the basin solar distillate, and glass cover cooling at a rate of 2 L/h. This technique is simple, inexpensive, and effective. Also, it has no negative impact on the environment. This newly proposed solution provides significant improvement rates compared to other researches. The obtained conclusions can be written as follows:

- The wick material enhances the cumulative yield of hemispherical solar still distillation by 40% compared to the THSS.
- Cooling of the glass cover increases the cumulative yield of hemispherical solar distillation by 69.23% compared to the THSS.
- The water production from the distiller THSS during the day is equal to 3.25 kg/m². However, it is equal to 4.55 kg/m² from the distiller THSS-W and 5.50 kg/m² from the distiller THSS-WC.
- Compared to the distillate THSS-W, the yield increase in the distillate THSS-WC is achieved with a higher rate of 20.88%.
- The daily efficiency of the distiller THSS is equal to 32.65%. However, it is equal to 45.35% for the distiller THSS-W and 54.57% for the distiller THSS-WC.
- The estimated total cost per one liter of distillate water produced comes to about 0.0172, 0.0125, and 0.0106 $/L for THSS, THSS-W, and THSS-WC, respectively.
- The economic feasibility presented that the dual utilization of the wick and the glass cover cooling (THSS-WC) reduced the total cost of distillates produced from hemispherical solar distillers by 38.4% compared to THSS.
- Wick with glass cover cooling greatly improves the yield of the hemispherical solar still and increases yield and efficiency. Therefore, a wick with glass cover cooling is recommended to be considered in such applications.

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