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Optimal concentration of high thermal conductivity sensible storage materials (graphite) for performance enhancement of hemispherical distillers

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ABSTRACT

The present manuscript aims to obtain the optimum concentration of high thermal conductivity storage materials (graphite) that achieve the highest performance of the hemispherical distillers. In order to achieve the optimal graphite concentration, three hemispherical distillers were designed and built. The first is a conventional hemispherical solar still (CHSS) which represent the reference distiller and the second and third are modified hemispherical solar stills (MHSS) containing graphite in different concentrations of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 140 g/L. The pilot test was performed over 6 consecutive days, in each day two different concentration was tested in second and third MHSS and compared them with the reference distiller (CHSS) under the same ambient conditions. The experimental results show that the 35 g/L graphite concentration represents the optimum concentration that achieves the highest performance of hemispherical distillate. The use of graphite with a concentration of 35 g/L (MHSS-35) gives a cumulative yield of 7.37 L/m^2/d with an improvement of 93.94% compared to the reference distiller (CHSS). Also, the daily efficiency of (MHSS-35) is 72.12% with an improvement of 91.66% compared to the reference distiller (CHSS). The results concluded that when using storage materials sensitive to high thermal conductivity (graphite), their concentration should not exceed 35 g/L, so productivity would almost stabilize after this concentration, so there is no need to waste money and time.

Keywords: Hemispherical distiller; High thermal conductivity sensible storage materials; Graphite; Optimal concentration; Performance improvement

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1. Introduction

Algeria is considered one of the countries that adopted the technology of desalination of seawater to provide safe drinking water. Since 2005 ten stations were completed with a total capacity of about two million cubic meters per day, and additional five plants are preparing to launch soon. These stations have contributed to ensuring water security for 25% of Algerians [1–3]. However, isolated areas suffer from a scarcity of drinking water, the alternative that currently imposes itself is to use solar energy, as it is renewable, clean, and available energy throughout the year in Algeria in such areas [4–6]. Scientists and researchers have exploited the phenomenon of evaporation using solar energy in the discovery of a device to obtain safe drinking water called solar distillers, which depend mainly on the

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solar distillation process [7–9]. In this process, the water is evaporated using solar energy, and then the steam condenses again to obtain safe drinking water [10–12]. Among the problems that scientists encounter in the solar distillation process is low productivity. Researchers work in various ways in the possibility of improving the performance of solar stills by adding high thermal conductivity sensible storage materials [1], phase change materials (PCM) [13–18], fins [19,20], nanoparticle powders [21–24], floating sponge [25], sensible storage materials [26], hybrid storage materials [27–29], and parabolic trough collector [30,31] to enhance the performance of solar distillates. Kabeel et al. [32] theoretically studied the effect of stearic acid and capric-palmitic use on the daily productivity of the solar distiller. They concluded that the daily cumulative of distillate water was 100% improved with capric-palmitic and 65% using stearic acid. Attia et al. [33] added 25 cotton bags filled with sand, each bag was 4 cm in diameter and 4 cm high in the solar distillation basin to improve its performance. The results showed that sandbags were good and low-cost energy storage materials, and daily accumulation with or without sandbags was recorded as 5.09 and 3.71 kg/m^2/d, respectively. Khechekhouche et al. [34] added a layer of sand to the bottom of a solar distillery. They believed that the sand layer increases the productivity of distillation, but the opposite happened. The daily accumulation without and with the sand layer was recorded at 3.8708, 2.7352 kg/m^2/d, respectively. Attia et al. [35] added 42 aluminum balls with a diameter of 2 cm in the solar distillation basin to improve its performance. The results showed that the aluminum balls represent good energy storage materials and low cost, and the daily cumulative yield recorded with or without aluminum balls is 5.09 and 3.71 kg/m^2/d, respectively. Sharshir et al. [36] studied the effect of graphite and CuO at concentrations ranged from 0.125% to 2% to get the best concentration in enhancing the solar still. The obtained results show that the solar still productivity was enhanced by about 53.95% and 44.91% using the graphite and CuO, respectively, compared to the reference distiller. while the daily efficiency of the CSS was 30%, and the daily efficiencies of 40% and 38% were obtained when using graphite and CuO, respectively. Attia et al. [37] covered the inside surface of the solar distiller with an aluminum foil sheet as an absorber cover to increase daily productivity. They thought that covering solar still with aluminum foil sheets increased distillation productivity, but the opposite happened. Daily accumulation was recorded without and with aluminum foil sheet wrapping 1.528 and 1.004 kg/m^2/d, respectively. They concluded that the aluminum foil sheet cover harmed the productivity of the distillation apparatus, so they advised against using aluminum foil sheets in solar distillation. Arunkumar et al. [38] studied the influence of using various absorbing materials on a single slope solar distiller. The study showed that the productivity was 2.9 L/m^2 of single slope solar distiller with non-coated CuO absorber palates.

The present study aims to enhance the hemispherical distiller performance. This was done by the addition of sensible storage materials (graphite) with high thermal conductivity to improve the accumulative yield of hemispherical solar distillers. Various graphite concentrations of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 140 g/L were studied in order to obtain the optimal graphite concentration that achieves the highest performance of the hemispherical distillers. Three hemispherical distillers were designed, built, and tested under the same conditions to achieve this object. The first is a conventional hemispherical solar distiller (CHSS) and the second and third are modified hemispherical distillers (MHSS) which different concentrations of graphite, experiments were tested at El-Oued-Algeria (06°47′ E and 33°30′ N) in October 2020.

2. Experimental setup and procedure

A schematic presentation of the hemispherical solar still is depicted in Fig. 1. The hemispherical basin is a tray made of wood, 38 cm in diameter, 7 cm thick, and 3.5 cm deep. The inner surfaces of the basin are painted black silicone to increase the absorption of solar radiation, and the outer cover is made of transparent plastic 3 mm thick. The graphite specifications utilized in the present empirical work are shown in Table 1.

In the current practical study, the effect of graphite powder on the performance of solar distillates was tested, where eleven different concentrations of graphite powder (5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 140 g/L) were tested to reach the best concentration that achieves the highest performance. To achieve this goal, three distillers with the same dimensions were designed and manufactured. The first was used as a reference distiller and the second and third contained graphite powder with different concentrations. Fig. 2 shows a photograph of the experimental setup which contains a CHSS and two modified hemispherical solar stills (MHSS) with different graphite concentrations. The three hemispherical distillers are being tested under the same Algerian climatic conditions. The experimental study was carried out in six scenarios as explained in Table 2. For example, in the first scenario, the first distiller (CHSS) represents the reference distiller, the second distiller contained 5 g/L graphite (MHSS-5), and the third distiller contained 10 g/L graphite (MHSS-10), and the three hemispherical distillers are tested at the same climatic conditions.

The experiments were conducted in the southeast of Algeria on days 13, 14, 15, 16, 17, and 18 October 2020 (06°47′ E and 33°30′ N). The experimental data were recorded for 10 h starting from 8:00 a.m. till 6:00 p.m. Table 3 presents the specifications of measuring devices, their accuracy, and standard uncertainties.

3. Results and discussions

To illustrate the impact of the graphite powder on the performance of hemispherical solar distillers, the comparison between the performance of the reference distiller and modified hemispherical distiller with different graphite powder concentrations was investigated when exposed to the same climate weather conditions to makes the comparison more accurate. Fig. 3 shows the hourly variation of solar irradiation intensity and the ambient temperature for the 6 test days starting from 8:00 a.m. to 6:00 p.m. It is seen that the solar irradiation intensity of the 6 test days is almost similar and it goes up until its maximum value

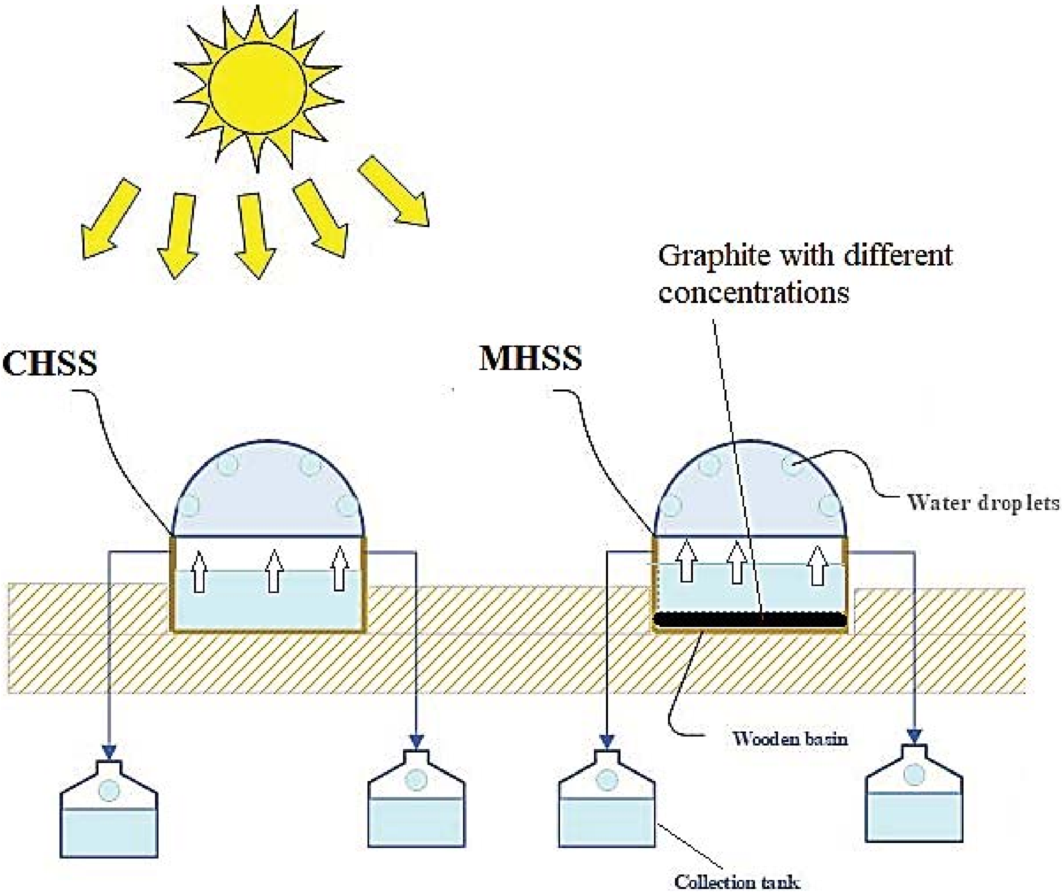

Fig. 1. Schematic presentation of hemispherical solar still.

Table 1
Graphite specifications

Properties	Graphite
Thermal conductivity [W/(m K)]	195
Apparent density (g/cm^3)	1.77
Apparent porosity (%)	13
Linear thermal expansion coefficient (µm/m K), (20°C–200°C)	3.2

at noon and it is then dramatically decreasing as the time proceeds until it gets its lower value near the time of sunset. Also, the maximum recorded ambient temperature was achieved during the period 1:00 p.m. to 3:00 p.m.

3.1. Hourly variation of water basin temperature for different graphite concentrations

A CHSS is built up and compared with an MHSS which contains different eleven concentrations of graphite 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 140 g/L. The experiments were performed in 6 consecutive days with almost similar solar intensity and climate conditions as shown in Fig. 3. Fig. 4 shows the hourly variation of water basin temperature for different graphite concentrations of hemispherical solar distiller from 8:00 a.m. to 6:00 p.m. on October 13, 14, 15, 16, 17, and 18, 2020.

It is seen that the hourly variation of water basin temperature increases with the increase of graphite concentration. However, the increment is very small after using graphite of 35 g/L concentration (MHSS-35). Also, at 2:00 p.m., the maximum water basin temperature of (CHSS), (MHSS-35), and (MHSS-140) reaches an average temperature of 48°C, 63°C, and 63°C, respectively.

3.2. Effect of graphite concentration on cumulative yield of hemispherical distiller

Fig. 5 indicates the hourly variation of accumulated water productivity for different graphite concentrations of hemispherical solar distiller from 8:00 a.m. to 6:00 p.m. on October 13, 14, 15, 16, 17, and 18, 2020. It is seen that the hourly variation of the accumulated water productivity of hemispherical solar distiller increases with the increase of graphite concentration till graphite concentration of 35 g/L (MHSS-35). After that concentration, there is no significant increase in the accumulated water productivity. Moreover, the average amount of the daily accumulated water productivity for (CHSS), (MHSS-35), and (MHSS-140) are 3.8, 7.37, and 7.39 L/m^2, respectively. Table 4 shows the accumulated productivity of CHSS, MHSS-5, MHSS-10, MHSS-15, MHSS-20, MHSS-25, MHSS-30, MHSS-35, MHSS-40,

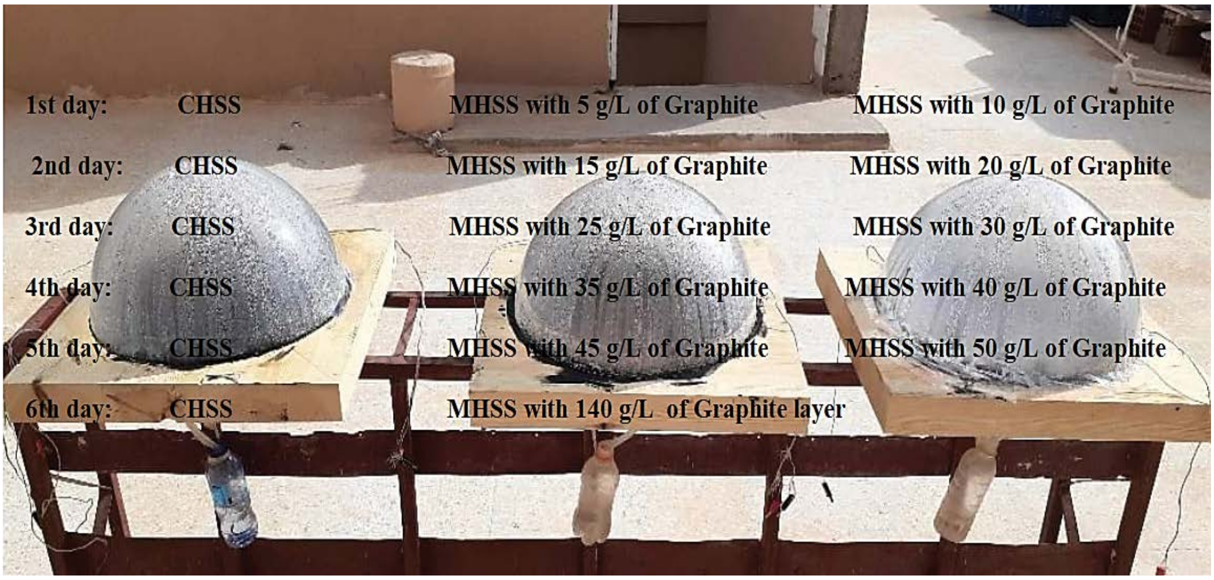

Fig. 2. Photograph of the experimental setup.

Table 2
Experiments four scenarios

Experiment	Distiller 1	Distiller 2	Distiller 3
One	CHSS	MHSS-5 (5 g/L)	MHSS-10 (10 g/L)
Two	CHSS	MHSS-15 (15 g/L)	MHSS-20 (20 g/L)
Three	CHSS	MHSS-25 (25 g/L)	MHSS-30 (30 g/L)
Four	CHSS	MHSS-35 (35 g/L)	MHSS-40 (40 g/L)
Five	CHSS	MHSS-45 (45 g/L)	MHSS-50 (50 g/L)
Six	CHSS	MHSS-140 (140 g/L)	

MHSS-45, MHSS-50, and MHSS-140 recorded on experiment days 13, 14, 15, 16, 17, and 18 October 2020 for a period of 10 h. Compared with (CHSS), It is seen that the maximum improvement in daily accumulative productivity reached 93.94% and it is accomplished by using a graphite concentration of 35 g/L (MHSS-35). The results concluded that when graphite powder is used as heat energy storage materials, the concentration of graphite powder should not exceed 35 g/L, because the productivity will almost stabilize after this concentration, so there is no need to waste money and time.

3.3. Effect of graphite concentrations on the efficiency of hemispherical distiller

Fig. 6 shows the variations of the hourly thermal efficiency of the hemispherical solar distiller with different graphite concentrations from 8:00 a.m. to 6:00 p.m. on Oct. 13, 14, 15, 16, 17, and 18, 2020. The hemispherical solar distiller efficiency depends on the distillate productivity, water latent heat, solar intensity, and the absorber area, it is can be calculated as:

$$\text{Hourly efficiency}, \eta(h) = \frac{\dot{m} \times \text{L.H.}}{I(t) \times A_{\text{SS}}} \tag{1}$$

$$\text{Daily efficiency}, \eta = \frac{\sum \dot{m} \times \text{L.H.}}{\sum I(t) \times A_{\text{SS}}} \tag{2}$$

where $\dot{m}$ is the distillate productivity (kg/s), L.H. is the latent heat (J/kg), $I(t)$ is the solar intensity (W/m^2), and A_{SS} is the solar still absorber area (m^2).

The latent heat of vaporization water L.H. is calculated by knowing the water basin temperature T_{WB} from Eq. (3) [39]:

Table 3
Instruments, accuracy, and standard uncertainties

Instrument	Accuracy	Range	Standard uncertainty
Solar power meter	±10 W/m^2	0–1,999 W/m^2	5.77 W/m^2
Thermocouple	±0.1°C	−100°C–500°C	0.06°C
Graduated cylinder	±1 mL	0–250 mL	0.6 mL

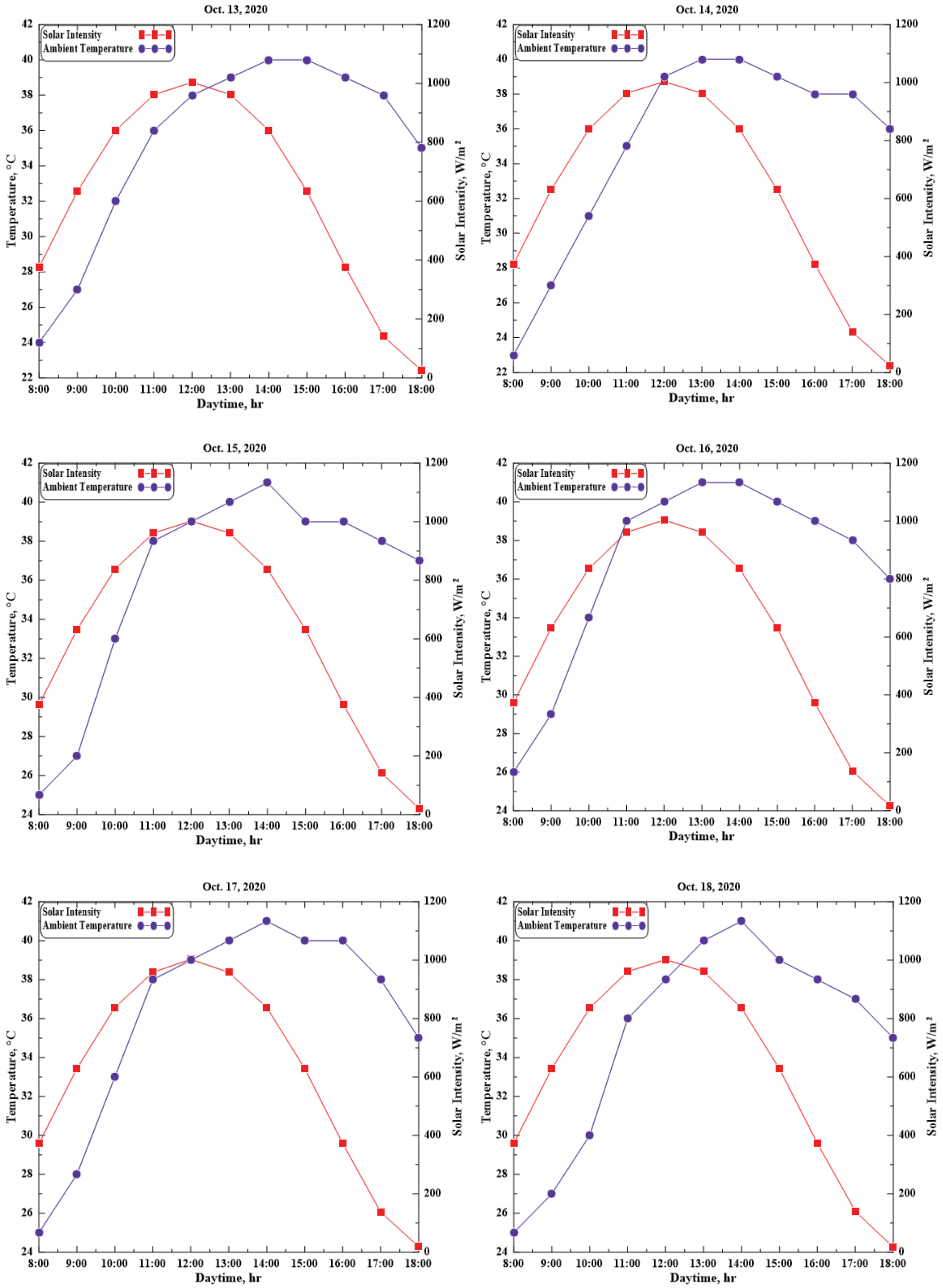
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Fig. 3 Variation of solar intensity and ambient temperature with daytime over six consecutive days.

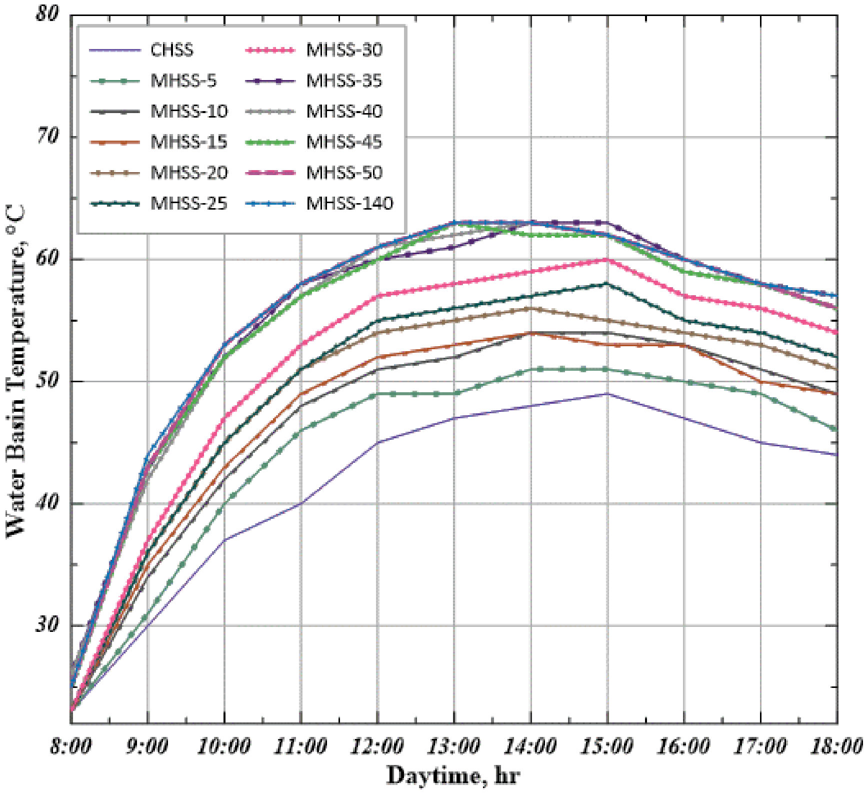

Fig. 4. Variation of water basin temperature with daytime for different graphite concentrations of the hemispherical solar distiller.

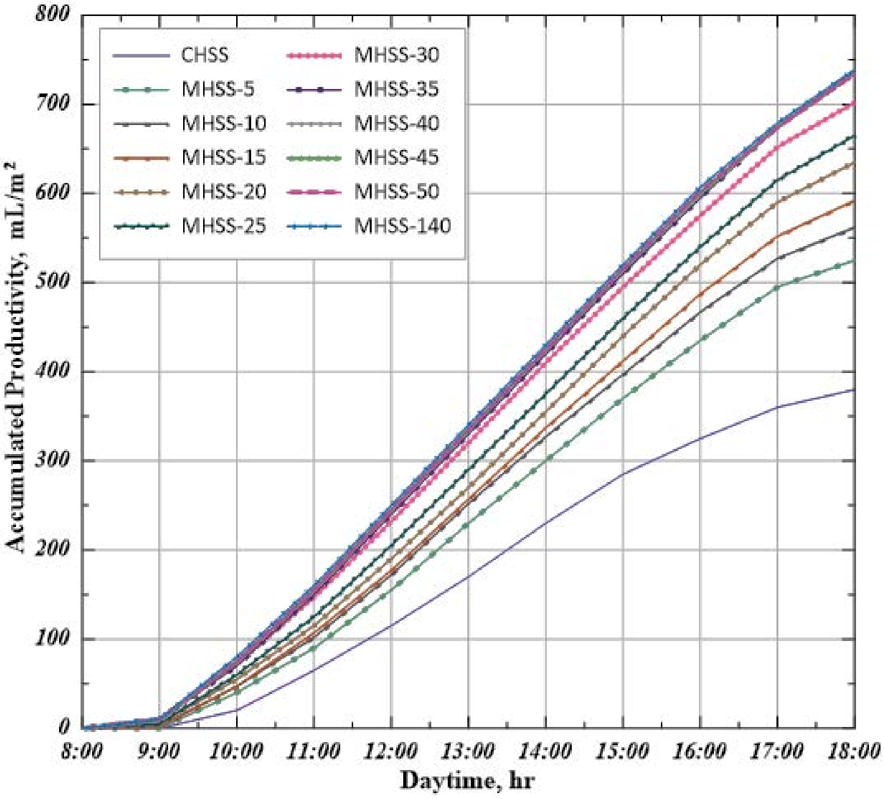

Fig. 5. Variation of accumulated productivity with daytime for different graphite concentrations of the hemispherical solar distiller.

Table 4
Daily productivity for conventional and modified hemispherical distillers recorded during six test days

Type	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Daily productivity rise %
	13 October	14 October	15 October	16 October	17 October	18 October	
CHSS (L/m^2)	3.80	3.82	3.80	3.80	3.80	3.82	–
MHSS-05 (L/m^2)	5.25	–	–	–	–	–	38.16
MHSS-10 (L/m^2)	5.62	–	–	–	–	–	47.90
MHSS-15 (L/m^2)	–	5.92	–	–	–	–	54.97
MHSS-20 (L/m^2)	–	6.35	–	–	–	–	66.23
MHSS-25 (L/m^2)	–	–	6.65	–	–	–	75.00
MHSS-30 (L/m^2)	–	–	7.02	–	–	–	84.74
MHSS-35 (L/m^2)	–	–	–	7.37	–	–	93.94
MHSS-40 (L/m^2)	–	–	–	7.35	–	–	93.42
MHSS-45 (L/m^2)	–	–		–	7.35	–	93.42
MHSS-50 (L/m^2)	–	–	–	–	7.34	–	93.16
MHSS-140 (L/m^2)	–	–	–	–	–	7.39	93.45

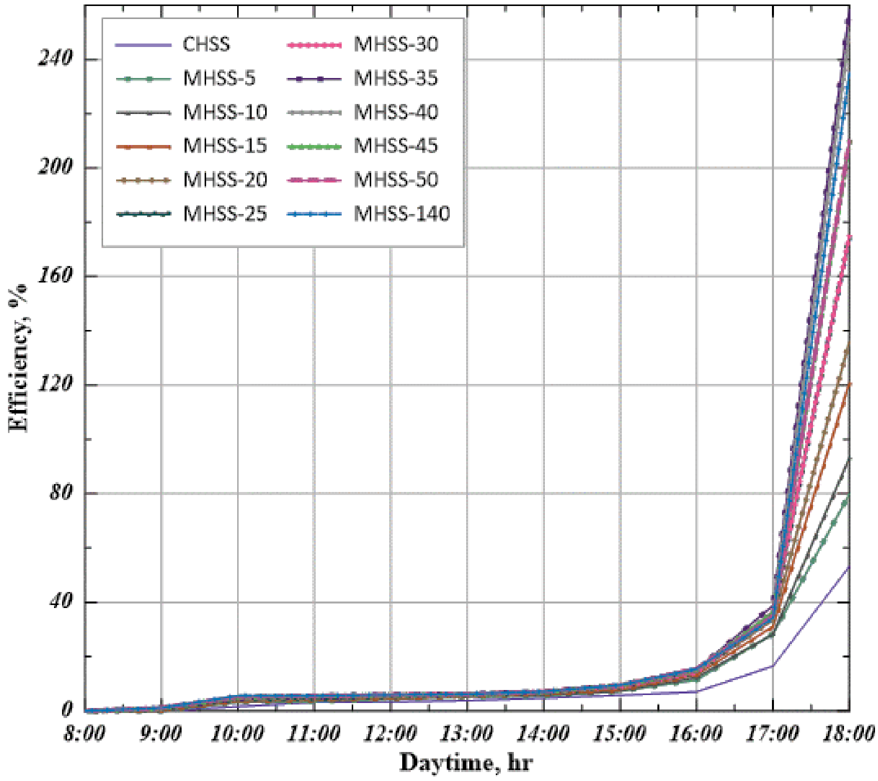

Fig. 6. Variation of hemispherical solar distiller efficiency with daytime for different graphite concentrations.

$$\text{L.H.} = 1{,}000\begin{bmatrix} 2{,}501.9 - 2.40706T_{\text{WB}} + 1.192217\times10^{-3}T_{\text{WB}}^2 \\ -1.5863\times10^{-5}T_{\text{WB}}^3 \end{bmatrix} \quad (3)$$

It is seen that the hourly variation of the efficiency of hemispherical solar distiller increases with the increase of graphite concentration to graphite concentration of 35 g/L (MHSS-35). After that concentration, there is no significant incensement in the solar distiller efficiency. Moreover, the average daily efficiency for (CHSS), (MHSS-35), and (MHSS-140) are 37.48%, 72.12%, and 72.32%, respectively.

Table 5 shows the daily efficiency of CHSS, MHSS-5, MHSS-10, MHSS-15, MHSS-20, MHSS-25, MHSS-30, MHSS-35, MHSS-40, MHSS-45, MHSS-50, and MHSS-140 recorded on experiment days 13, 14, 15, 16, 17, and 18 October 2020 for 10 h. Compared with the reference distiller (CHSS), it is seen that the maximum daily efficiency increase is 91.65%

Table 5
Daily efficiency of the conventional and modified hemispherical distillers

Type	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Daily efficiency rise (%)
	13 October	14 October	15 October	16 October	17 October	18 October	
CHSS (%)	37.48	37.76	37.55	37.63	37.65	37.82	–
MHSS-05 (%)	51.65	–	–	–	–	–	37.8
MHSS-10 (%)	55.16	–	–	–	–	–	47.17
MHSS-15 (%)	–	58.26	–	–	–	–	54.29
MHSS-20 (%)	–	62.38	–	–	–	–	65.2
MHSS-25 (%)	–	–	65.26	–	–	–	73.79
MHSS-30 (%)	–	–	68.78	–	–	–	83.17
MHSS-35 (%)	–	–	–	72.12	–	–	91.65
MHSS-40 (%)	–	–	–	71.94	–	–	91.18
MHSS-45 (%)	–	–	–	–	72.02	–	91.29
MHSS-50 (%)	–	–	–	–	71.88	–	90.92
MHSS-140 (%)	–	–	–	–	–	72.32	91.22

Table 6
Fabrication cost of the conventional and modified hemispherical distillers (1$ = 128.78 DZD, 1€ = 152.03 DZD)

	TCM (DZD)	PG (DZD)	MC (DZD)	TC (DZD)	AWPD (kg/m^2/d)	CLDWM (DZD)	PDWP (DZD)	RP (d)
CHSS	9,000	–	50	9,050	3.80	60	228	40
MHSS-05	9,000	5	50	9,055	5.25	60	315	29
MHSS-10	9,000	10	50	9,060	5.62	60	337.2	27
MHSS-15	9,000	15	50	9,065	5.92	60	355.2	26
MHSS-20	9,000	20	50	9,070	6.35	60	381	24
MHSS-25	9,000	25	50	9,075	6.65	60	399	23
MHSS-30	9,000	30	50	9,080	7.02	60	421.2	22
MHSS-35	9,000	35	50	9,085	7.37	60	442.2	20
MHSS-40	9,000	40	50	9,090	7.35	60	441	21
MHSS-45	9,000	45	50	9,095	7.35	60	441	21
MHSS-50	9,000	50	50	9,100	7.34	60	440.4	21
MHSS-140	9,000	140	50	9,190	7.39	60	443.4	21

TCM: Total cost of manufacture; PG: The price for 1 kg of graphite 1,000 DZD; MC: Maintenance cost; TC: Total cost; AWPD: The amount of water produced during the day; CLDWM: The cost per liter of distilled water on the market; PDWP: The price of daily water production; RP: Recovery period.

and it is achieved by using 35 g/L graphite concentration (MHSS-35).

4. Economic evaluation

A comprehensive economic analysis is performed to determine the period of time required to recover the total cost of CHSS, MHSS-5, MHSS-10, MHSS-15, MHSS-20, MHSS-25, MHSS-30, MHSS-35, MHSS-40, MHSS-45, MHSS-50, and MHSS-140. Table 6 indicates that the payback period required to recover the total cost of CHSS, MHSS-5, MHSS-10, MHSS-15, MHSS-20, MHSS-25, MHSS-30, MHSS-35, MHSS-40, MHSS-45, MHSS-50, and MHSS-140 are 40, 29, 27, 26, 24, 23, 22, 20, 21, 21, 21, and 21 d, respectively. This indicates that the best economic hemispherical solar still is MHSS-35 as the payback period is 20 d.

5. Conclusions

This manuscript aims to study the concentration effect of high thermal conductivity sensible storage materials (Graphite) and to obtain the optimal concentration that achieves the highest performance of hemispherical solar distillers. In order to determine the best concentration, different graphite concentrations of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 140 g/L are studied. The experiments were conducted for a period of 10 h over 6 consecutive days in October 2020. The following outcomes are concluded on the basis of experimental results:

- Sensible storage materials (graphite) with high thermal conductivity enhance the effectiveness of hemispherical solar distillers well.
- The accumulated productivity is 3.80, 5.25, 5.62, 5.92, 6.35, 6.75, 7.02, 7.37, 7.35, 7.35, 7.34, and 7.39 L/m^2/d for

CHSS, MHSS-5, MHSS-10, MHSS-15, MHSS-20, MHSS-25, MHSS-30, MHSS-35, and MHSS-40, MHSS-45, MHSS-50, and MHSS-140, respectively.

- The 35 g/L graphite concentration represents the optimal concentration for hemispherical solar still to achieve the highest performance.
- Using 35 g/L (MHSS-35) graphite concentration gives an accumulative yield of 7.37 L/m^2/d with an improvement of 93.94% compared to the reference distiller (CHSS).
- The daily efficiency of MHSS-35 reached 71.12% with an improvement of 91.66% compared to the reference distiller (CHSS).
- Daily productivity increases with increasing the concentration of graphite to a concentration of 35 g/L. Exceeding this concentration, no matter the graphite concentration, the daily yield is stabilized.
- Using high thermal conductivity (graphite) storage materials, their concentration should not exceed 35 g/L because the productivity will stabilize after this concentration, so there is no need to waste money and time.
- The payback period required to recover the total cost of (CHSS) is 40 d, while the required period for (MHSS-35) is 20 d. This indicates that the MHSS-35 is the best economical hemispherical solar distillers.

Finally, it can be concluded that the addition of sensible storage materials (graphite) with high thermal conductivity improves the performance of the hemispherical solar stills. The 35 g/L graphite concentration represents the optimal concentration for hemispherical solar still to achieve the highest performance and efficiency.

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