Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28180

250 (2022) 16–26
February

Performance improvement of solar still using phosphate granules as energy storing materials: an experimental study

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Received 18 July 2021; Accepted 6 January 2022

ABSTRACT

There are many technologies that use solar energy to increase distilled water from salty water, using solar distillation. This article examines the performance improvement of solar still using phosphate granules with dimensions of 1.5–2 mm. All phosphate constituents have a high thermal conductivity, and this leads to the collection of thermal energy in solar utilization. In order to increase the yield in this experiment, modifications are made to traditional solar still using phosphate granules of 1%–2% (10–20 g/L) of varying concentration. The inclusion of phosphate granules enhanced the evaporation and condensation amounts as well as the daily yield. The total drinkable water production from the conventional solar distiller (CSD) and modified solar distillers with 1% and 2% of phosphate granules (MSDPG-1% and MSDPG-2%) are 3.5, 4.3 and 4.9 kg/m^2, respectively. Linked to the CSD, the daily drinkable water production was increased by 22.85%, 40% when using MSD with phosphate granules at a concentration of 1% and 2%, respectively.

Keywords: Conventional solar still; Phosphate granules; Energy storage; Desalination; Sustainable production

1. Introduction

There are various techniques for desalination such as filtration, sedimentation, disinfection, and distillation. Solar distillation is one way to purify salt water. Solar energy is the main factor in solar distillation, as it warms up the salt water in the solar basins, evaporates, then condenses on a glass surface and collects the distilled water. The design shapes of SD are many and varied, including conical, inclined, hemispherical and tubular, but conventional solar distiller (CSD) and dual slope SD have wide use [1,2]. The financial costs of SD is reasonable, their daily yield is acceptable, and they yield several liters of fresh water per square meter. This machine works for a long time about 20 years with an efficiency varying between 30% to 60% [3,4]. The yield of CSD provides a daily output between 2 to 4 L/m^2 according to climatic conditions. A lot of study was employed to enhance the daily output of CSD [5,6]. There are many factors that affect the increase in the daily output, including the intensity of solar radiation and temperature difference between the salty water and glass cover plate, thickness of glass cover, wind speed, area of the collector, absorption plate, depth of water and angle of

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inclination [7]. In order to increase the output of SD, many researchers have tried a number of wick materials (cotton, sponge and jute). Velmurugan et al. [8] added sponges as a wick material to traditional distillers to improve CSD yield. They concluded yield was enhanced by approximately 29% when spending sponge as a wick material linked to a CSD. Velmurugan et al. [9] published stepped SD using fins. Experimental outcomes revealed that when using 250 fins in 50 trays, it improves the daily yield by 76%. Arunkumar et al. [10] reported CSD with copper balls filled with paraffin wax. The outcomes show that the yield obtained was equal to 4.460 L/m²/d by using the paraffin wax with copper balls. However, without copper balls, a daily accumulation of 3.520 L/m²/d was obtained. Chaichan and Kazem [11] examined the effect of phase change material (PCM) paraffin wax in a conical SD integrated with concentrating dish. They concluded that the system yield was augmented by 307.54%. Kabeel et al. [12] published the impact of incorporating PCM and solar air collector in a CSD. It was concluded that daily production of the system was equal to 9.36 L/m²/d. However, without PCM the daily yield is equal to 4.51 L/m². Sathyamurthy et al. [13] published the impact of PCM in a triangular pyramid SD. The outcomes confirmed that with PCM the daily yield was equal to 5.5 L/m²/d. However, without PCM, the daily yield was equal to 3.5 L/m²/d. Gugulothu et al. [14] investigated effect of the dichromate of potassium and sulphate of sodium and acetate of sodium in a CSD. The authors confirmed that the sodium sulphate provided enhanced yield compared to the sodium acetate and potassium dichromate. Patel and Kumar [15] experimentally conducted studies on thermic fluids and the impact of the frontal height increase in a CSD with 2 cm of water depth. An experimental output shows that the yield increases by 11.24% with thermic fluids and the yield increases by 23% with the frontal height. Samuel et al. [16] used heat storage of spherical ball and sponge in a CSD. The result shows that yield presented 2.4 L/m²/d by using the CSD. However, by using spherical ball heat storage the daily accumulation is equal to 3.7 L/m², by using sponge, the daily accumulation is equal to 2.6 L/m². Shalaby et al. [17] used PCM and wick in a V-corrugated absorber SD. The experimental outcomes established that daily output was equal to 3.36 L/m² without PCM. However, by using the PCM, the daily accumulation is equal to 3.76 L/m² and to 2.6 L/m² by using PCM and wick. Deshmukh and Thombre [18] investigated the impact of the servo herm medium oil and sand in a CSD. Experimental results indicated that yield is equal to 4.734 L/m²/d by using CSD. The daily accumulation is equal to 4.778 L/m² by using servo herm medium oil. However, yield is equal to 4.566 L/m² by using sand. Dumka et al. [19] published CSD with and without cotton bags. The authors confirmed that the yield of 2.717 L/m²/d was obtained by using CSD. However, a daily accumulation of 3.493 L/m² was obtained when using sand cotton bags. El Hadi Attia et al. [20] published the influence of aluminum balls on a CSD output. It was stated that the yield of 3.71 L/m²/d was produced by using CSD. However, a daily accumulation of 5.09 L/m² was reported by using aluminium balls. Omara and Kabeel [21] studied the effect of yellow and black colour sand in a CSD. The researchers confirmed that yield was obtained 3.4 L/m²/d using CSD and the daily accumulation is equal to 3.98 L/m²/d by using yellow sand and yield is equal to 4.566 L/m²/d by using black sand. Several scholars have recently used waste/low-cost materials in SD [22–30], nano materials [31–36], nano fluids [37,38], SD integrated with concentrator integrated collectors [39,40], SD integrated with concentrator [41,42], and hybrid SD [43–48]. From the detailed literature it is found that only few research works were reported on phosphate granules as energy storage materials in SD. The first is the CSD, the second is MSDPG-1% (10 g/L), and the third is a MSDPG-2%) (20 g/L). The experiments was conducted at the El Oued University in Algeria in April 2020.

2. Experimental setup

A CSD was designed as presented in Fig. 1. The CSD basin has a size of 50 cm and a breadth of 50 cm. The inclination angle of the collector cover is equal to 10°. The basin was made of wooden of 2.5 cm thickness, having a height of 6 cm front side. Indeed, a PVC pipe was considered to gather

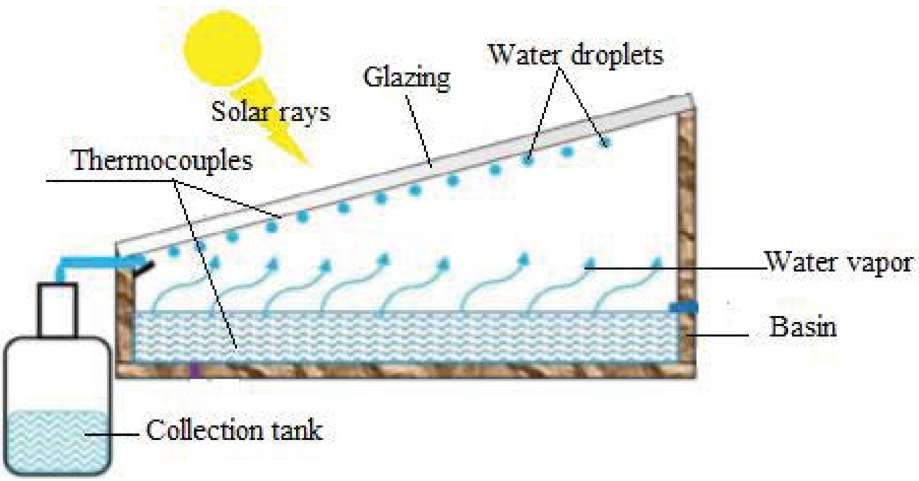

Fig. 1. Schematic diagram of the CSD.

the condensed water via the collector surface. By attaching a droplet PVC collection tube, a collector cover was used with a thickness of 3 mm.

Phosphates are found as raw materials in many regions of the world. The phosphate granules used in this experiment have dimensions approximately equal to 1.5–2 mm, as presented in Fig. 2.

Algeria ranked fifth in the world for export and tenth in the world for production, and the phosphate reserve in northeastern Algeria contains 2.2 billion tons. Also, several areas were discovered in southern Algeria containing phosphates that have not been exploited and have not been estimated yet [49,50].

Fig. 3 shows the complete preparation for the experimental test. The experiments were conducted on April 30, 2020 at El-Oued University in Algeria situated in 06° 47' E and 33° 30' N. Three water basins, that is, the CSD, the MSDPG-1% (10 g/L) and the MSDPG-2% (20 g/L) were tested for 16 h to observe the effect of the phosphate granules on daily accumulation day and night. Table 1 presents the meteorological conditions for the experiment day.

Solar stills were fabricated, experimented and the experimental data on April 30, 2020 was noted. The required temperatures were measured at various points of the considered basins corresponding to the CSD, MSDPG-1% and MSDPG-2%. The atmospheric temperature, the solar scale and the solar radiation for the day of the experiment are also measured. Table 2 recapitulates the used accuracy, range and uncertainties of the measuring apparatus.

3. Analysis

The energy efficiency of the CSD, MSDPG-1% and MSDPG-2% are found by Eq. (1), [56,57],

$$\eta_{\text{passive}} = \frac{\sum \dot{m}_{\text{ew}} L}{\sum I(t) A_s \times 3,600} \times 100 \quad (1)$$

The exergy efficiency of the CSD, MSDPG-1% and MSDPG-2% are given by [56,57],

$$\eta_{\text{exergy efficiency}} = \frac{E_{\text{out}}}{E_{\text{in}}} \times 100 \quad (2)$$

The exergy output per hour for the CSD, MSDPG-1% and MSDPG-2% are calculated by [56,57],

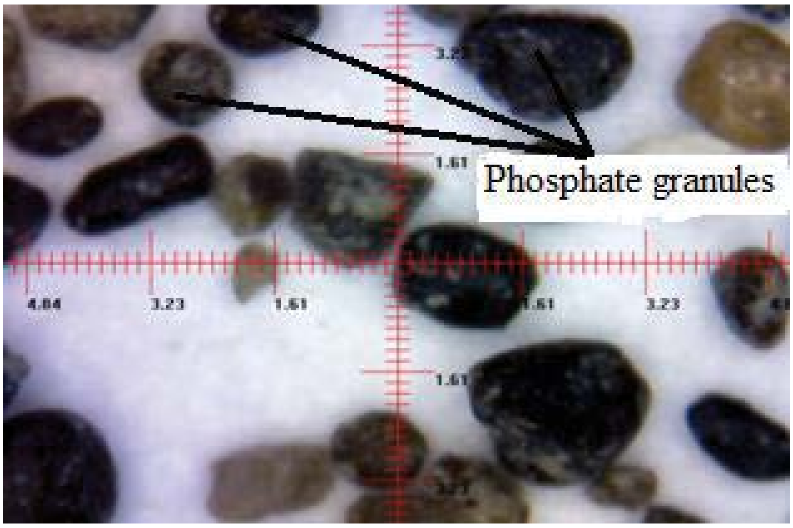

Fig. 2. Micrograph of phosphate granules.

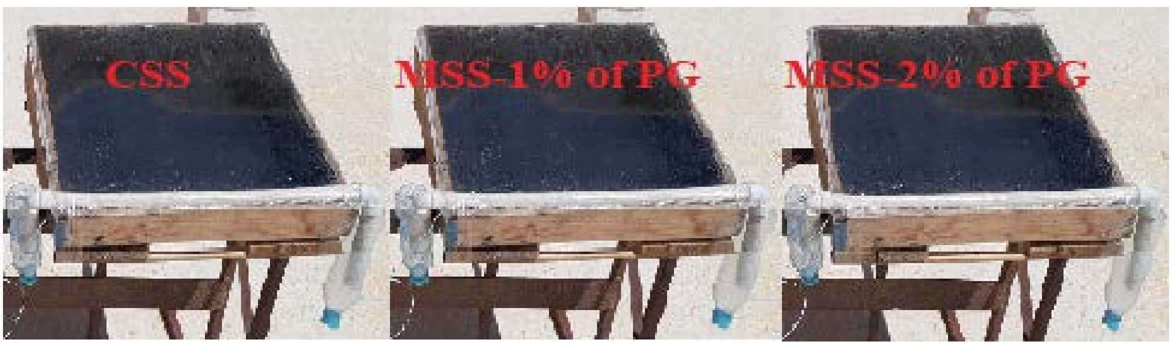

Fig. 3. Photograph of experimental setup.

$$E_{out} = E_{evaporation} = \frac{m_e}{3,600} \times A_w \times h_{fg} \times \left(1 - \frac{T_a}{T_w}\right) \quad (3)$$

The exergy input per hour for the CSD, MSDPG-1% and MSDPG-2% are calculated by [56,57],

$$E_{in} = E_{sun} = A_w \times I(t) \times \left[1 - \frac{4}{3}\left(\frac{T_a}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4\right] \quad (4)$$

4. Results and discussions

4.1. Time-wise distribution of various parameters

Figs. 4–6 present the hourly distribution of the solar irradiation $I(t)$, temperatures of ambient (T_a), salt water ($T_{s.w}$), and collector cover ($T_{c.c}$) for the CSD, MSDPG-1% and MSDPG-2%, respectively. From Fig. 4, it is identified that $I(t)$ increase in morning and recorded its highest value at 12:00 (1,040 W/m^2). Likewise, T_a increases in morning, recorded its highest value at 15:00 (34°C). The time-wise distribution of T_a have the similar trends like $I(t)$ as it is the source for variations of the ambient temperature T_a, water temperature $T_{s.w}$, and glass temperature $T_{c.c}$. The daily mean value of $I(t)$ and T_a during the investigational days is 725.45 W/m^2, and 29.3°C, respectively. From the graph, it is found that peak value of $T_{s.w}$ of the CSD is 70°C at 13:00, for the MSDPG-1% is 72°C at 15:00, and for the MSDPG-2% is 75°C at 15:00. The daily mean of $T_{s.w}$ of the CSD is 48.25°C, for the MSDPG-1% is 52°C and for the MSDPG-2% is 54.2°C. In the MSD, $T_{s.w}$ was improved by adding 1% and 2% of phosphate granules in the basin of the MSD. The $T_{s.w}$ of the MSDPG-2% is higher with the comparison to the MSDPG-1%. By placing 1% phosphate granules at basin, maximum $T_{s.w}$ of the MSD was improved by 2°C than the CSD. Similarly, by placing 2% phosphate granules at basin, maximum $T_{s.w}$ of the MSD was improved by 5°C than the CSD. An increasing the phosphate granules from 1 to 2%, $T_{s.w}$ of the MSD were improved by 3°C than the MSD at phosphate granules of 1%. In the 2% of phosphate granules, the weight of the granules is 100% higher than the 1% of phosphate granules. In the MSDPG-2%, phosphate granules are uniformly covered the basin of the MSD, whereas in the MSDPG-1%, phosphate granules are not uniformly covered the basin of the MSD. In the MSDPG-2%, all the phosphate granules are absorbing the heat energy and also it increases the basin surface area, so water gets easily heated as compared to the MSDPG-1% and the CSD. The MSDPG-1% expands the daily average $T_{s.w}$ by about 7.8% by comparison to the CSD. Similarly, the MSDPG-2% expands the daily average $T_{s.w}$ by about 12.3% by comparison to the

Table 1
Meteorological conditions

Date	April 30, 2020
Sunrise	05:45 AM
Sunset	07:15 PM
Ambient temperature	21°C–34°C
Humidity	26%
Wind speed	19 km/h

Table 2
Measuring apparatus

Instrument	Accuracy	Range	Uncertainty
Solar power meter	±10 W/m^2	0–1,999 W/m^2	5.72 W/m^2
Thermocouple	±0.1°C	−100°C–500°C	0.07°C
Graduated cylinder	±1 mL	0–250 mL	0.6 mL

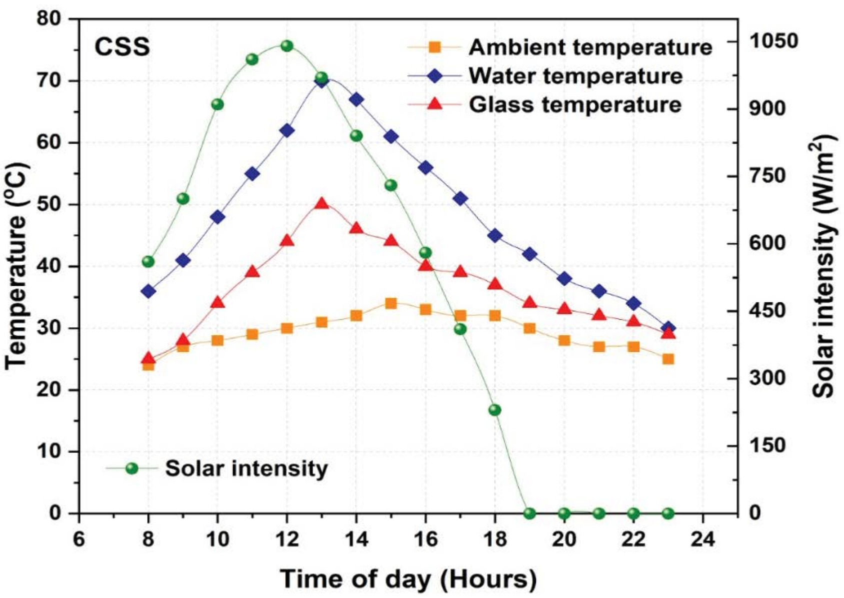

Fig. 4. Time-wise distribution of $I(t)$, T_a, $T_{s.w}$, and $T_{c.c}$ for the CSD.

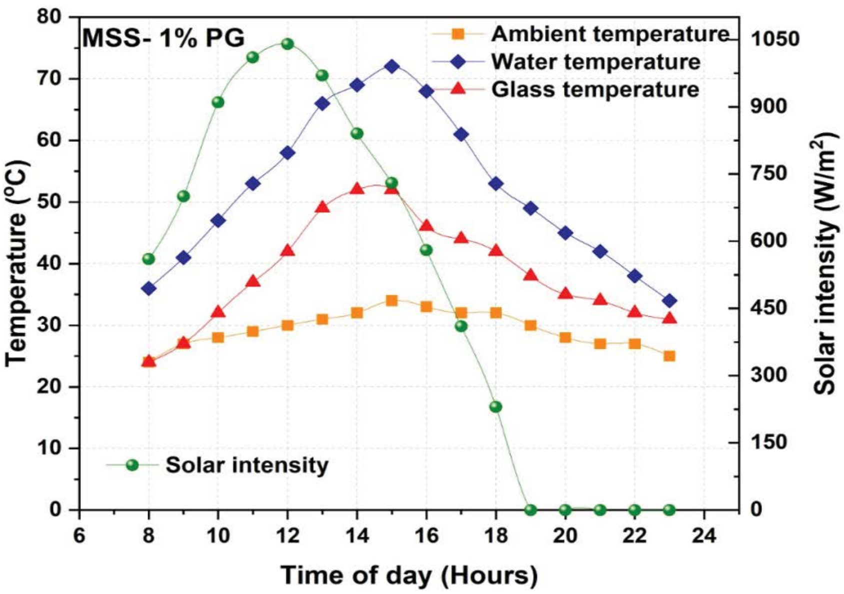

Fig. 5. Time-wise distribution of $I(t)$, T_a, $T_{s.w}$, and $T_{c.c}$ for the MSDPG-1%.

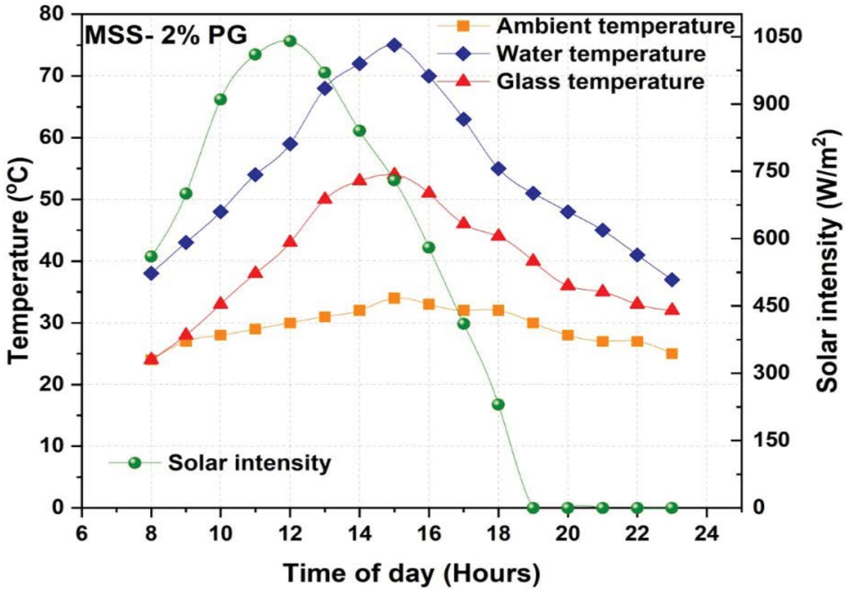

Fig. 6. Time-wise distribution of $I(t)$, T_a, $T_{s.w}$, and $T_{c.c}$ for the MSDPG-2%.

CSD. An increasing the phosphate granules weight from 1% to 2% increases the daily average $T_{s.w}$ by about 4.2%. In the MSDPG-1% and MSDPG-2%, phosphate granules were considered in the basin of the CSD to enlarge the surface area of the basin of MSD and also improve the $T_{s.w}$. The difference between $T_{s.w}$ and $T_{c.c}$ was higher by using phosphate granules in the MSD. The phosphate granules present in the MSD were used to reduce the heat losses to the environment through storing the heat energy, and this heat energy was used to augment the $T_{s.w}$ in the evening period. So, the phosphates granules enhances the $T_{s.w}$ by liberating the heat to the water when solar intensity is minimum.

The peak $T_{c.c}$ of 50°C, 52°C and 54°C was logged for the CSD, MSDPG-1% and MSDPG-2%, correspondingly. The daily mean $T_{c.c}$ of the MSDPG-1% and MSDPG-2% is higher than the CSD. The MSDPG-1% augments the daily mean $T_{s.w}$ by about 6.54% by comparison to the CSD. The higher alteration between $T_{s.w}$ and $T_{c.c}$ was achieved by using phosphate granules. The phosphates granules used in the MSD was used to slow down the heat losses to the atmosphere by collecting the thermal energy and this collected thermal energy was used to augment the $T_{s.w}$ throughout sunset hours. So presence of the phosphates granules augments the $T_{s.w}$ by providing the heat energy to the water during sunset hours.

4.2. Time-wise distribution of hourly and total drinkable water production

Fig. 7 displays the time-wise distribution of hourly and total production of drinkable water from the CSD, MSDPG-1% and MSDPG-2%. The maximum and total drinkable water production in hours of daylight from the CSD are 0.61 and 3.27 kg, from the MSDPG-1% are 0.71 and 3.9 kg and from the MSDPG-2% are 0.84 and 4.4 kg, respectively. The drinkable water production through the hours of daylight from the CSD is minimum as related to that of the MSDPG-1% and MSDPG-2%. The drinkable water production during hours of daylight from the MSDPG-1% and MSDPG-2% is 0.63 and 1.13 kg higher as related to the drinkable water production during hours of daylight from the CSD. Whereas MSDPG-2% (4.4 kg) has the 0.5 kg higher drinkable water production during hours of daylight as compared to the MSDPG-1% (3.9 kg). The drinkable water production through hours of daylight from the MSDPG-1% and MSDPG-2% are 19.4 and 33.5% higher as compared to the production of drinkable water during the daytime from the CSD. Likewise, the MSDPG-2% has 11.6% higher drinkable water production during hours of daylight as compared to the MSDPG-1%. The phosphate granules at 1% and 2% weight positioned on the basin has a larger surface area, so it improves the $T_{s.w}$, and drinkable water production from the MSDPG-1% and MSDPG-2% as compared to the CSD. By using phosphate granules in the MSDPG-1% and MSDPG-2%, the drinkable water production was increased by about 22.8% and 39.3% higher as compare than the CSD.

The highest and total yields after hours of daylight from the CSD are 0.07 and 0. 20 kg, from the MSDPG-1% are 0.141 and 0.36 kg and from the MSDPG-2% are 0.16 and 0.48 kg, respectively. The drinkable water production after hours of daylight from the CSD is minimum as related to that of the -1% and MSDPG-2%. The drinkable water production after hours of daylight from the MSDPG-1% and MSDPG-2% are 0.16 and 0.28 kg higher as related to the drinkable water production after hours of daylight from the CSD. Whereas MSDPG-2% (0.48 kg) has the 0.12 kg higher drinkable water production after hours of daylight as compared to the MSDPG-1% (0.36 kg). The phosphate granules inside the MSDPG-1% and MSDPG-2% stores heat energy and it was used for augmenting the drinkable water production after hours of daylight. However in the CSD, the total heat energy receiving in the basin constantly losses heat from the basin of the CSD to the ambience therefore the drinkable water produced after hours of daylight time from the MSDPG-1% and MSDPG-2% is for all time higher as compare than the CSD. The phosphate granules placed inside the MSD stores the heat energy which is used to enhance the yield after 4 P.M. While in the CSD, the amount of heat energy arriving the basin constantly transfers the heat from the basin to the atmosphere; therefore the yield from the MSD is higher than the CSD.

4.3. Energy and exergy efficiency of the CSD, MSDPG-1% and MSDPG-2%

Fig. 8 shows the daily energy efficiency of the CSD, MSDPG-1% and MSDPG-2% and enhancements in drinkable water production during hours of daylight, after hours of daylight and total days for the MSDPG-1% and MSDPG-2% as compare than the CSD. The daily efficiency of the CSD is 24.8%, for the MSDPG-1% is 34.1% and for the MSDPG-2% is 37.6%. From these results, it is clear that efficiency of the MSDPG-1% is 37.5% higher by the comparison to the

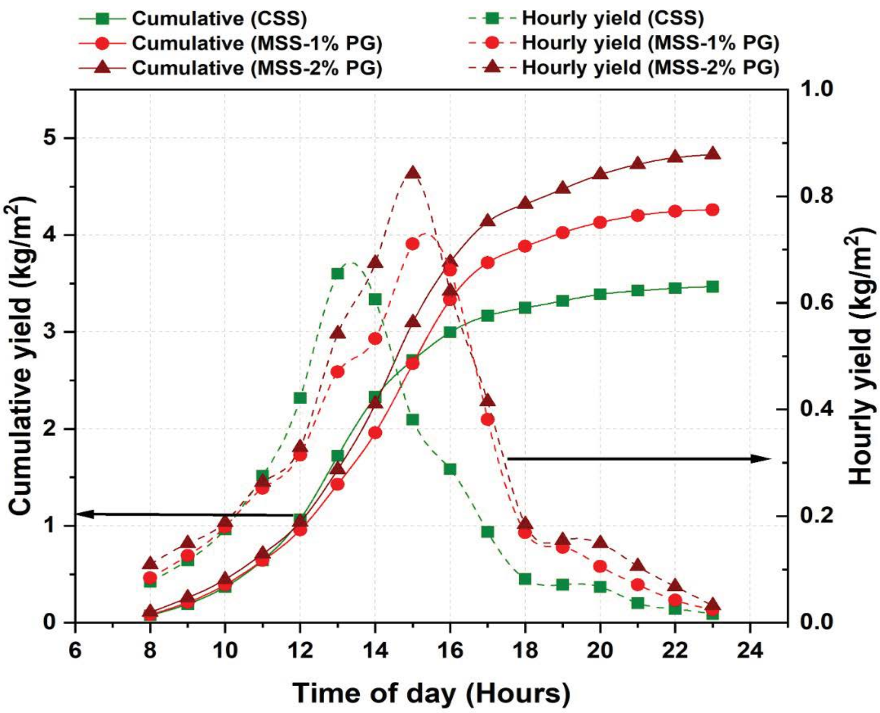

Fig. 7. Time-wise distribution of hourly and total yield from the CSD, MSDPG-1% and MSDPG-2%.

CSD and similarly, energy efficiency of the MSDPG-2% is 51.6% higher as compare than the CSD. The efficiency of the MSDPG MSDPG-2% was improved up to 10.3% as compared to the MSDPG-1%. Using phosphates granules, the daily energy efficiency of the MSDPG-1% and MSDPG-1% were improved by about 38% and 52% compared to the CSD. Fig. 9 shows hourly variations of exergy efficiency of the CSD, MSDPG-1% and MSDPG-2%. The daily exergy efficiency of the CSD is 1.77%, for the MSDPG-1% is 2.06% and for the MSDPG-2% is 2.49%. The exergy efficiency of the MSDPG-1% is 14.46% higher by the comparison to the CSD and similarly, exergy efficiency of the MSDPG-2% is 29% higher as compare than the CSD. The exergy efficiency of the MSDPG-2% was improved up to 17% as compared to the MSDPG-1%. Table 3 presents the daily output relative to the CSD, MSDPG-1% and MSDPG-2%.

4.4. Comparison of similar studies

Table 3 compares our outcomes with the daily yield of others study using sensible storage materials. During experimental outcomes, it has been noted that the daily yield of a MSD containing 1% (10 g/L) phosphate granules increased by 22.85% compared to the CSD. The daily yield was increased by 40% when using 2% (20 g/L) of the phosphate granules. Thus, the phosphate granules greatly augment the yield of the MSD and increase the efficiency and yield. So, the phosphates are excellent energy storage materials.

4.5. Daily yield

Table 4 displays the daily yield of CSD, MSDPG-1% and MSDPG-2% recorded in the day and night hours. During the 16 h of research on April 30, 2020, in weather conditions of El Oued Algeria, the cumulative yield is recorded for the CSD and MSD.

4.6. Economic analysis

Table 5 presents a cost analysis of CSD, MSDPG-1% and MSDPG-2%. From the economic study, it was determined that MSDPG-2% days of recovery were 164 d which is less than MSDPG-1% days that were 187 d, and both were less than CSD of 230 d.

Table 5: Cost examination of the CSD, MSDPG-1% and MSDPG-2% (1$ = 134.78 DZD, 1€ = 152.03 DZD).

Table 3
Comparison of daily yield of present experimental work with earlier reported work

Authors	Cases	Yield (L/m²/d)	% increase in cumulative yield
Present experimental work	CSD	3.5	–
	With 1% phosphate granules	4.3	22.85
	With 2% phosphate granules	4.9	40
Dumka et al. [19]	CSD	2.717	–
	With sandbags and 3 cm depth of basin water	3.493	28.56
Dumka et al. [19]	CSD	2.397	–
	With sandbags and 4 cm depth of basin water	3.140	31
Omara and Kabeel [21]	CSD	3.4	–
	With yellow sand	3.98	17
	With black sand	4.83	42
El Hadi Attia et al. [51]	CSD	3.76	–
	With sandbags	5.06	34.57
Sakthivel and Shanmugasundaram [52]	CSD	3.35	–
	With gravel	4.02	20
El Hadi Attia et al. [53]	CSD	3.04	–
	With phosphate bed	3.55	16.8
El Hadi Attia et al. [54]	CSD	3.8	–
	With phosphate bags and 1 cm depth of basin water	5.3	39
	With phosphate bags and 2 cm depth of basin water	4.9	28
Nafey et al. [55]	CSD	3.95	–
	With black rubber	4.7	20
Panchal et al. [58]	0.2% MgO nanofluids	3.5	–
	0.2% TiO_2 nanofluid	2.9	
Benoudina et al. [31]	Aluminum oxide	6.12	–

Total cost of CSD is given by, $TC = TCM + MC$ (5)

Total cost of MSD is given by, $TC = TCM + MC + PP$ (6)

$PDWP = YP \times CW$ (7)

Table 4
Cumulative distillate yield of CSD, MSDPG-1% with 1% of phosphate granules and MSDPG-2% with 2% of phosphate granules, recorded during day and nocturnal hours

CSD (kg/m^2)		MSDPG-1% (kg/m^2)		MSDPG-2% (kg/m^2)	
Day	Nocturnal	Day	Nocturnal	Day	Nocturnal
3.3	0.2	3.9	0.4	4.4	0.5

Table 5
Cost analysis of CSD, MSDPG-1% and MSDPG-2%

	CSD	MSDPG-1%	MSDPG-2%
Total cost of manufacture (DZD)	8,000	8,000	8,000
Price of phosphate	–	3	6
Maintenance cost (DZD)	50	50	50
Total cost (DZD)	8,050	8,053	8,056
Yield production (kg/m^2/d)	3.5	4.3	4.9
The cost of water per liter (DZD)	10	10	10
Price of daily water production (DZD)	35	43	49
Period (d)	230	187	164

$$P = \frac{TC}{PDWP} \quad (8)$$

where TCM: total cost of manufacture; PP: price of phosphate; MC: maintenance cost; TC: total cost; YP: yield production; CW: the cost of water per L; PDWP: price of daily water production; *P*: period.

5. Conclusions

A traditional CSD with phosphate granules was tested. A comparative investigation of the CSD, MSDPG-1% and MSDPG-2% performance was developed. The conclusions based on the solar stills performance are as follows:

- The efficiency of the MSD can be improved by adding the phosphate granules raising the thermal conductivity of the basin, temperature of basin water and hence drinkable water production.
- The amount of distilled water from the CSD during the daytime is equal to 3.3 kg/m^2 and nocturnal time is equal to 0.2 kg/m^2.
- The amount of distilled water from the MSDPG-1% during daytime is equal to 3.9 kg/m^2 and to 0.4 kg/m^2 during the nocturnal time.
- The amount of distilled water from the MSDPG-2% during daytime is equal to 4.4 kg/m^2 and to 0.5 kg/m^2 during the nocturnal time.
- The yield increases in the distillate MSDPG-2% was achieved with a higher rate of 13.95% compared to the distillate MSDPG-1%.
- Compared to the traditional distillation, the daily yield was improved by 22.85% and 40% by using 1% and 2% phosphate granules, respectively.
- The yield is directly proportional to the increase in the amount of phosphate granules in the solar distillery.

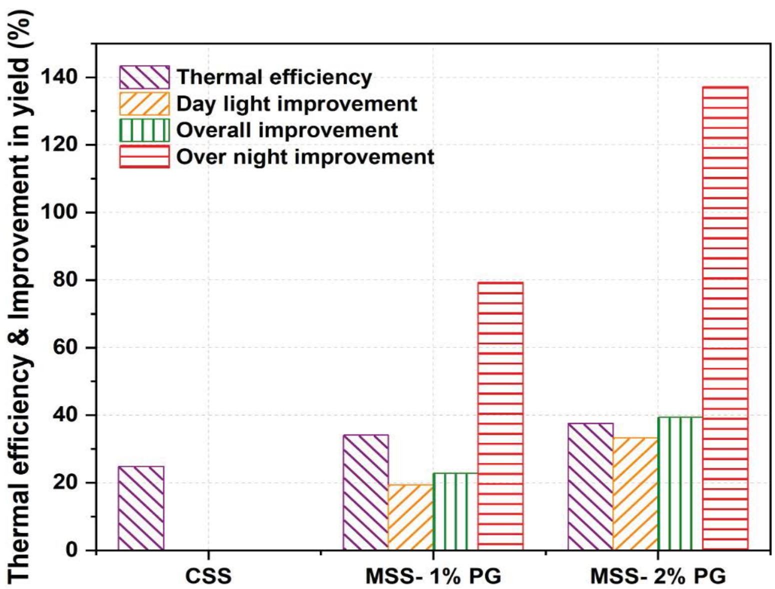

Fig. 8. Daily energy efficiency for the CSD, MSDPG-1% and MSDPG-2% and improvements in drinkable water production.

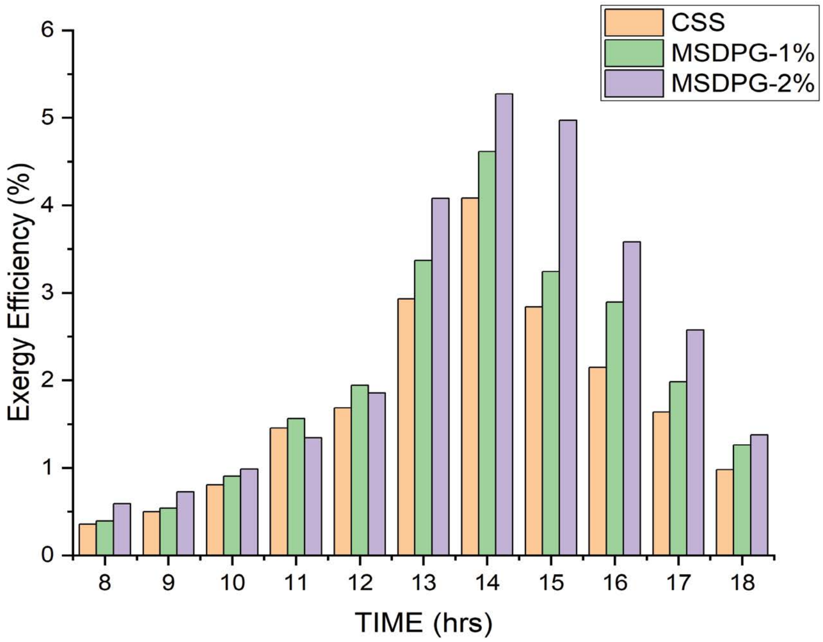

Fig. 9. Hourly exergy efficiency variations of CSD, MSDPG-1% and MSDP 2%.

Thus, it has been concluded that the phosphate granules greatly enhance the yield of the solar distillation and increases the yield and efficiency. Consequently, phosphate granules are excellent energy storage materials and are recommended in SD.

Symbols

CSD	—	Conventional solar distiller
$I(t)$	—	Solar intensity
MSDPG-1%	—	Modified solar distiller with 1% (10 g/L) phosphate granules
MSDPG-2%	—	Modified solar distiller with 2% (20 g/L) phosphate granules
PCM	—	Phase change material
T_a	—	Ambience temperature
$T_{c.c}$	—	Collector cover temperature
$T_{s.w}$	—	Saline water temperature

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