Enhancing the hemispherical solar distiller performance using internal reflectors and El Oued sand grains as energy storage mediums

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Abstract
This paper presents a comprehensive experimental study of some effective modifications which aim to improve the cumulative productivity of solar distillers, in order to reach the best modification that achieves the highest cumulative productivity of hemispherical distillates. The experimentations were carried on the hemispherical distillers which are characterized by a large area of receiving and condensation. To obtain the best modification that achieves the highest cumulative productivity, the present comprehensive studies were conducted on two experimental scenarios. In the first scenario, the influences of internal reflective (Reflective Mirrors and Reflective Aluminum Foil) on hemispherical distillers performance was studied. In the second scenario, the influences of internal reflective with El-Oued sand grains as the energy store mediums on hemispherical distiller performances was studied. To achieve this goal, we designed and fabricated three hemispherical distillers, the first distiller represents the reference case (Conventional Hemispherical Solar Still—CHSS), the second is the Hemispherical Solar Still with Internal Reflective Mirrors (HSS-IRM), and a third is the Hemispherical Solar Still with Internal Reflective Aluminum Foil (HSS-IRAF). In the second experimental scenario, the El-Oued sand grains were added to the basin of the second and third distillers as follows; where the second distiller became a Hemispherical Solar Still with Internal Reflective Mirrors and El-Oued sand grains (HSS-IRM & SG), and a third distiller became a Hemispherical Solar Still with Internal Reflective Aluminum Foil and El-Oued sand grains (HSS-IRAF & SG). The results presented that the cumulative production of reference distiller (CHSS) up to 4750 mL/m², while use of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) increases the production to 9400 mL/m² day. The maximum improvement in cumulative distillate production, exergy efficiency, and thermal efficiency was recorded for utilization of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) which reached 98, 200.9, and 96%, respectively, compared to reference case (CHSS). The economic feasibility indicated that the utilization of HSS-IRM & SG represent the good modification which reduced the cost of freshwater productivity by 49.1% compared to CHSS.

Keywords Hemispherical solar distillers · Internal reflectors · El-Oued sand grains · Energy storage · Performance improvement

Nomenclature

\( A_s \)
Absorber area, m²

\( \text{Ex}_{\text{input}} \)
Input exergy energy, W

\( \text{Ex}_{\text{output}} \)
Output exergy energy, W

\( h_{fg} \)
Latent heat, J/kg

\( I(t) \)
Solar radiation, W/m²

\( \dot{m}_{ev} \)
Hourly distillate production, kg/m² h

\( T_a \)
Ambient temperature, °C

\( T_w \)
Basin saltwater temperature, °C

\( \eta_{\text{daily,exe}} \)
Daily exergy efficiency, %

\( \eta_{\text{daily,th}} \)
Daily thermal efficiency,

Abbreviations

SS
Solar still

CHSS
Conventional Hemispherical Solar Still
HSS-IRM  |  Hemispherical Solar Still with Internal Reflective Mirrors
HSS-IRA  |  Hemispherical Solar Still with Internal Reflective Aluminum Foil
HSS-IRM & SG  |  Hemispherical Solar Still with Internal Reflective Mirrors and El-Oued Sand Grains
HSS- IRAF & SG  |  Hemispherical Solar Still with Internal Reflective Aluminum Foil and El-Oued Sand Grains

**Introduction**

Algeria produces more than two million cubic meters per day of potable water using desalination plants, which is nearly a fifth it consumes. The main problem with desalination technologies is their high cost because they consume great energy. Desalinating one cubic meter consumes approximately 4 kilowatt hours (Kabeel et al. 2020; Attia et al. 2020a; Abdelgaied et al. 2021a, b; Al-Molhem and Eltawil, 2020). Therefore, the continuous reduction in the production of electricity from solar energy will directly affect the cost of desalination. The Dubai Water and Electricity Agency recently announced the achievement of the world record for the lowest price per cubic meter of water produced with desalination technology, which is 0.277 $ per cubic meter, less than a third of a dollar (Attia et al. 2020b, 2021a; Kabeel et al. 2017, 2018; Chandrika et al. 2021; Mohammed et al. 2021). The location of Algeria is important as it is located in the sunbelt. It is among the regions in the world that have the largest amount of solar energy. From this, Algeria can benefit from this site and these resources (renewable energy, especially solar energy and the development of desalination technologies) and can be transformed into productive economic sectors that create revolution and contribute to economic growth (Ramalingam et al. 2021; Suraparaju and Natarajan, 2021a; Bellila et al. 2021; Kabeel and Abdelgaied, 2019; Attia et al. 2016). One of the strategic areas for research and development is desalination of saline water with solar energy, because we are concerned with economic and climate change and its dangerous effects.

Attia et al. (2021b) compared a modified single-slope solar distillation device (completely wrapped on the inside with aluminum foil sheets as an absorbent cover) to a conventional distillation device. They found that the productivity of a modified distillation device (1004 ml/m²) was much lower than that of a conventional distillate (1528 ml/m²). An experimental work was conducted by Mu et al. (2019) they have incorporated the Fresnel lens (FRL) was integrated with a single-basin to improve its performance. Due to effect the FRL, there is increase in basin temperature and thus it was found increase of 467% in distillate yield by the conventional system with FRL. Plus an 84.7% improvement in daily efficiency, compared to the traditional system without FRL. Srivastava and Agrawal (2013) conducted a single basin solar still coupled with the porous absorbers (blackened jute cloth), with the two plane reflector mirrors. The porous absorbers acted as energy source for basin to warm. In addition, the difference in temperature between basin water and glass became greater because a plane reflector mirrors. The productivity of the system increased 68 and 79% without and with the twin reflector mirrors, respectively. Tanaka (2009) designed a modified distillation basin with internal/external reflectors. Reflectors were added to introduce more solar radiation into the modified still and compare of conventional still. He conducted experiments every day of the year and found that the daily productivity increased by 70–100% on winter days. Tanaka and Nakatake (2006) conducted theoretical analyzes on the same experiment (modified distillation basin with internal/external reflectors) and over the course of the year, they observed that the average increase in daily productivity was about 48%. Dev et al. (2011) experimentally studied the inverted distillers consists of (curved shaped reflector and traditional solar distiller). The result concluded that the inverted solar still yielded 6.302 l/m²/day. Abdul-Wahab and Al-Hatmi (2012) tested an inverted still with refrigeration cycle. A refrigeration cycle was added for increase the temperature gradient between the absorber and the condenser. The productivity of the inverted still was 10 l/m²/day at the feed temperature of 35 °C. Khalifa and Ibrahim (2011) tested a conventional solar still without and with reflectors mirrors (of thickness 4 mm). A refrigeration cycle was added for increase the temperature gradient between the absorber and the condenser. The productivity of the solar still was 6.26 and 6.70 l/m²/day when using external reflector and internal and external reflector together, respectively. While the maximum productivity without reflector was 6.08 l/m²/ day. Hiroshi (2010, 2011) conducted experiments in a single-basin still with mirrors. The use of reflectors increases the amount of solar energy that reaches the basin still to improve distillation productivity. Also, studied the placed the reflector during the days of the year. It was found that the crop of distillate products increased by tilting the external reflector backward when used in the summer and by tilting it forward when used in the remaining seasons. Boubekri and Chaker (2011) numerically studied the effect of adding internal and external reflectors on the productivity of solar still. They concluded that the increase in productivity was 72.8% when using internal and external reflectors. They also found that the optimum inclination angle for external reflectors should be less than 25° and that the optimum inclination angle for the (condensed) glass cover ranges between 10 and 50° depending on the season. Chandrika et al. (2021) experimentally studied the effect of using different reflectors
The current study aims to reach the best modifications that achieve the highest productivity of fresh water produced from hemispherical solar distillers, which characterized by the presence of a large area for receiving and condensation. So, this comprehensive study presented the results of two experimental scenarios to illustrate the influences of internal reflective (Reflective Mirrors and Reflective Aluminum Foil) on hemispherical distiller’s performance in the first scenario. In the second scenario, the influences of internal reflective with El-Oued sand grains as heat storage medium on a performance of hemispherical solar distillers was studied. Two experimental scenarios aim to achieve the best modifications that achieve the highest hemispherical distillers’ performance. To achieve this goal, we designed and fabricated the three hemispherical distillers, the first distiller represents the reference unit (Conventional Hemispherical Solar Still—CHSS), second is a Hemispherical Solar Still with Internal Reflective Mirrors placing on the inner vertical surfaces (HSS-IRM), and the third is the Hemispherical Solar Still with Internal Reflective Aluminum Foil sheets placing on the inner vertical surfaces (HSS-IRAF) in the first experimental scenario. In the second experimental scenario, we added the El-Oued sand grains as the energy store medium to the basin of the second and third distillers; where the second distiller became a Hemispherical Solar Still with Internal Reflective Mirrors and El-Oued sand grains (HSS-IRM & SG), and a third distiller became a Hemispherical Solar Still with Internal Reflective Aluminum Foil and El-Oued sand grains (HSS-IRAF & SG). The three hemispherical distillers (CHSS, HSS-IRM, and HSS-IRAF) in the first experimental scenario, and (CHSS, HSS-IRM & SG, and HSS-IRAF & SG) in the second experimental scenario were tested at the same Algerian weather conditions in from 7 AM to 7 PM, during August 2020 to get the best modification that achieves the highest accumulative productivity along the day.

This manuscript gives good knowledge and understanding of all modifications to illustrate the best modifications of hemispherical solar distillers that gives the highest accumulative productivity of fresh water. So, this manuscript includes five sections, which are as follows: “Experimental work”; “System performance”; “Results and discussions”; “Comparison of present study with published similar works”; and “Conclusions”. Moreover, the economic studies of these modifications are presented to demonstrate their economic feasibility.

**Experimental work**

**Experimental setup and description**

The present empirically test rigs were constructed for two experimental scenarios with the aim of achieves the maximum possible hemispherical solar distillers performances. In the first experimental scenario, effect of utilizing the internal reflective (Reflective Mirrors and Reflective Aluminum Foil) on the performance of hemispherical solar distillers was investigated. In the second experimental scenario, the effect of utilizing the internal reflective and El-Oued sand grains as heat storage medium on a performance of hemispherical solar distiller were investigated. To achieve this goal, we designed and fabricated the three hemispherical solar distillers, the first distiller represents the reference case (Conventional Hemispherical Solar Still—CHSS), second is the Hemispherical Solar Still with Internal Reflective Mirrors placing on the inner vertical surfaces (HSS-IRM), and the third is the Hemispherical Solar Still with Internal Reflective Aluminum Foil sheets placing on the inner vertical surfaces (HSS-IRAF) as shown in Fig. 1. The three hemispherical solar stills fabricated in this work has the same dimensions, which consisted of a wood circular basin 38 cm in diameter and 4 cm depth, this wood circular basin covered by a transparent hemispherical cover 40 cm in diameter. The inner surface of the basin was painted with black silicon to increase the intensity of absorption solar rays and to prevent water leakage from the basin. An annular duct was formed on the inner perimeter connected to the distillate water tank.
to collect condensed water on the inner surface of the hemispherical cover. The aluminum foil sheet has a shiny side and a matte side. The reflectivity of bright aluminum foil utilized in HSS-IRAF is 88%. The thickness of aluminum foil is about 0.2 mm. While the reflectivity of mirrors utilized in HSS-IRM is 99% (Chandrika et al., 2021). The location of reflective placing on the inner vertical surfaces inside basin of hemispherical solar still is shown in Fig. 2.

In the first experimental scenario, the influences of utilizing the Reflective Mirrors and Reflective Aluminum Foil was tested at a same Algerian weather conditions in from 7 AM to 7 PM, during August 2020. Fixed marked was placed on the vertical surface of the water basin for three hemispherical distillers (CHSS, HSS-IRM, and HSS-IRAF) to maintain the constant amount of seawater inside the basin at 2.25 kg throughout the test day using makeup system connected between the basin distillers and feed seawater tank as shown in Fig. 1.

In the second experimental scenario, to achieve the maximum benefit from the high intensity of solar rays falling on a surface of basin saltwater resulting from use of internal reflective, the El-Oued sand grains were added to basin saltwater where it is used as energy storage materials to store part of the heat energy in a period of high solar intensity and is recovery it in the periods of lower solar radiation, El-Oued sand grains are also used to increase a solar radiation absorption rates.

To achieves the influences of the El-Oued sand grains and internal reflective on cumulative yield of hemispherical distillers, we added the El-Oued sand
grains as the energy storage medium to the basin of the second and third distillers; where the second distiller became a Hemispherical Solar Still with Internal Reflective Mirrors and El-Oued sand grains (HSS-IRM & SG), and a third distiller became a Hemispherical Solar Still with Internal Reflective Aluminum Foil and El-Oued sand grains (HSS-IRAF & SG) as shown in Fig. 3. In the second experimental scenario, the CHSS, HSS-IRM & SG, and HSS-IRAF & SG were tested at a same Algerian weather conditions in from 7 AM to 7 PM, during August 2020. The fixed marked was placed on the vertical surface of the water basin of CHSS, HSS-IRM & SG, and HSS-IRAF & SG to maintain the constant amount of seawater inside the basin at 2.25 kg throughout the test day using make up system as shown in Fig. 3. The El-Oued sand grains concentration utilized in this study is 3%. Sand is available in several countries of a world, as it is an energy storage material thanks to its components and properties. The color of sand depends on its region. The Algerian El Oued City is distinguished by its sand dunes. The sands of the valley are distinguished by yellow color. In Fig. 4, a micrograph of sand grains exposing size between 1.5 and 2 mm. Table 1 presented the Algerian sand grains characteristics (Meftah and Mahboub, 2020). Figure 5 views a photographic of test bench.
Measurements

To achieve the influences of using the internal reflector, as well as, the influences of using the internal reflector and El-Oued sand grains as the heat storage medium on the cumulative production of the hemispherical distillers. In the first experimental scenario, the CHSS, HSS-IRM, and HSS-IRAF where tested at a same Algerian weather conditions in from 7 AM to 7 PM, during August 2020. In the second experimental scenario, the CHSS, HSS-IRM & SG, and HSS-IRAF & SG where tested at a same Algerian weather conditions in from 7 AM to 7 PM, during August 2020. The specifications and standard uncertainty of the measuring instrumentation utilized in the present experimentations are presented in Table 2. The uncertainty was calculated using the procedure listed by Holman (2012). Consequently, the errors of the exergy efficiency, thermal efficiency, and cumulative productivity reached 2.23%, 2.12%, and ± 1.37%, respectively.

System performance

The exergy efficiency and thermal efficiency of the CHSS, HSS-IRM, HSS-IRAF, HSS-IRAF & SG and HSS-IRAF & SG are calculated as follows:

The exergy efficiency $\eta_{\text{daily,exe}}$ can be calculated by (Manokar et al. 2018);

$$\eta_{\text{daily,exe}} = \frac{\sum Ex_{\text{output}}}{\sum Ex_{\text{input}}} \times 100\%;$$ (1)

The input exergy energy $Ex_{\text{input}}$ can be calculated by (Manokar et al. 2018);

$$Ex_{\text{input}} = A_s I(t) \times \left[1 - \frac{4}{3} \left(\frac{T_w + 273}{6000}\right)^3 + \frac{1}{3} \left(\frac{T_w + 273}{6000}\right)^4\right] \times (W)$$ (2)

The output exergy energy $Ex_{\text{output}}$ can be calculated by (Manokar et al. 2018);

$$Ex_{\text{output}} = \frac{m_{ev} h_{fg}}{3600} \left[1 - \frac{T_w + 273}{T_a + 273}\right] \times (W)$$ (3)

Thermal efficiency $\eta_{\text{daily,th}}$ can be calculated by:

$$\eta_{\text{daily,th}} = \frac{\sum m_{ev} h_{fg}}{\sum I(t) A_s \times 3600} \times 100\%;$$ (4)

Latent heat $h_{fg}$ can be calculated by (Kabeel and Abdel-gaied, 2017);

$$h_{fg} = 10^{3} \left[2501.9 - 2.40706 \times T_w + 1.192217 \times 10^{-3} \times T_a^2 - 1.5863 \times 10^{-5} \times T_a^4\right]$$ (5)

where $A_s$ is absorber area ($m^2$); $I(t)$ is solar radiation ($W/m^2$); $T_w$ is basin saltwater temperature ($^\circ$C); $T_a$ is ambient temperature ($^\circ$C); $m_{ev}$ is hourly distillate production ($kg/m^2 h$); $h_{fg}$ is a latent heat (J/kg).

Results and discussions

The test days for the first and second experimental scenarios was starting from 7:00 am till 7:00 pm, and Fig. 6 depicts the hourly variation of ambient temperature and solar intensity. The solar intensity of the two test days
(19 August 2020 and 20 August 2020) is almost identical, which increases until it reaches the maximum value at noon, then dramatically decreases until it reaches its lowest value near sunset. Also, the highest recorded ambient temperature was recorded between 1:00 pm and 5:00 pm. This means that all cases of CHSS, HSS-IRM, HSS-IRAF, HSS-IRM & SG, and HSS-IRAF & SG can be compared to one another because all was exposed to very similar ambient climate conditions, allowing for a more accurate comparison.

Figure 7 shows the influences of utilizing the internal reflective, as well as, the internal reflective and the El-Oued sand grains on basin saltwater temperature of the distillers from 7:00 am to 7:00 pm on 19 and 20 August 2020. The highest basin saltwater temperature was recorded for utilization of the internal reflective mirrors and the El-Oued sand grains (HSS-IRM & SG). The maximum recorded basin saltwater temperature was reached to 68, 72, 74, 78, and 80 °C for CHSS, HSS-IRAF, HSS-IRM, HSS-IRAF & SG, and HSS-IRM & SG respectively, between 2:00 pm and 3:00 pm. This because that the increases the intensity of absorbed solar rays filling on the basin saltwater for utilization internal reflective mirrors, as well as, use El-Oued sand grains as energy storage material. Figure 8 shows glass cover temperature of different distillers (CHSS, HSS-IRAF, HSS-IRM, HSS-IRM & SG, and HSS-IRAF & SG) from 7:00 am to 7:00 pm on 19 and 20 August 2020.
HSS-IRAF & SG, and HSS-IRM & SG) through the period 7:00 am to 7:00 pm on August 2020.

In the solar distillers, the convection heat transfer represents the main driven in the distillation field. Whereas, the temperature difference between the saltwater and glass (Tw-Tg) is a measure of natural buoyancy inside solar distillers. With increasing the temperature difference, the buoyancy force will be increases, and thus will be improving the rate of distillate production inside the hemispherical solar distillers. Figure 9 shows the variations of the temperature difference (Tw-Tg) within the different cases of hemispherical distillers (CHSS, HSS-IRM, HSS-IRAF, HSS-IRM & SG, and HSS-IRAF & SG). As shown in Fig. 9, in the reference case (CHSS) the temperature difference ranged between 1 and 19 °C, while the use of internal reflective aluminum foil (HSS-IRAF) increases this difference to 1–23 °C, with the average improvement of 25.8%. While the use of internal reflective mirrors (HSS-IRM) increases this difference to 1–24 °C, with the average improvement of 48.1%. While the use of internal reflective aluminum foil and El-Oued...
sand grains (HSS-IRAF & SG) increases this difference to 1–26 °C, with the average improvement of 61.9%. While the use of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) increases this difference to 1–28 °C, with the average improvement of 83.8%. The results of temperature analysis evident that the use of internal reflective mirrors and El-Oued sand grains (HSS-IRAF & SG) represents the good modification to achieve the highest distillate production of hemispherical solar distiller.

Based on the recorded data of the hourly distillate production of the different cases of hemispherical distillers presented in Fig. 10, it is found that the hourly distillate production has the same trend for CHSS, HSS-IRAF, HSS-IRM & SG, and HSS-IRAF & SG, but with the higher rates for utilizing of the internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG). The recorded peak hourly distillate production which reached 750, 800, 900, 1100, and 1150 mL/m² h for CHSS, HSS-IRAF, HSS-IRM & SG, and HSS-IRAF & SG, respectively was recorded within the period 2:00 pm till 3:00 pm. It is evident from this that the use of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) represent the good option to achieve the highest instantaneous distillate production of hemispherical solar distillers.

To get the influences of the internal reflective and the El-Oued sand grains on cumulative distillate production of the hemispherical distillers, Fig. 11 shows cumulative distillate production of five hemispherical solar distillers (CHSS, HSS-IRAF, HSS-IRM, HSS-IRAF & SG, and HSS-IRM & SG). As presented in Fig. 11, the cumulative distillate production of reference unit (CHSS) reached 4750 mL/m², while use of internal reflective aluminum foil (HSS-IRAF) increases the cumulative distillate production to 6200 mL/m² day, with the improvement of 30.5%. While the use of internal reflective mirrors (HSS-IRM) increases the cumulative distillate production to 7150 mL/m² day, with an improvement of 50.5%. While the use of internal reflective aluminum foil and El-Oued sand grains (HSS-IRAF & SG) increases the cumulative distillate production to 8350 mL/m² day, with an improvement of 75.8%. While the use of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) represent the optimal design configuration to achieve the highest cumulative distillate production of hemispherical solar distillers.

Figure 12 shows the exergy efficiency and daily thermal efficiency of CHSS, HSS-IRAF, HSS-IRM, HSS-IRAF & SG, and HSS-IRM & SG. As shown, the exergy efficiency and thermal efficiency of the reference distiller (CHSS) reached 2.2% and 38.9%, respectively. While the use of internal reflective aluminum foil (HSS-IRAF) increases the exergy and thermal efficiencies to 3.44% and 50.65%, respectively. While the use of internal reflective mirrors (HSS-IRM) increases the exergy and thermal efficiencies to 4.4% and 58.3%, respectively. While the use of internal reflective aluminum foil and El-Oued sand grains (HSS-IRAF & SG) increases the exergy and thermal efficiencies to 5.4% and 67.9%, respectively. While the use of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) increases the exergy and thermal efficiencies to 6.62% and 76.3%, respectively.

![Fig. 10](https://example.com/image10.png) Instantaneous hourly variations of distillate production for the five different cases of hemispherical distillers.
Figure 13 show the influences of the internal reflective, as well as, the internal reflective and the El-Oued sand grains on hemispherical distillers performance improvement. The results presented that the maximum improvement in cumulative distillate production, exergy efficiency, and thermal efficiency was recorded for utilization of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) which reached 98, 200.9, and 96%, respectively, compared to reference case (CHSS). This is mainly because of the higher reflectivity of the mirrors utilized in this empirically work as well as the good thermal properties of El-Oued sand grains, and then the utilization of the both internal reflective mirrors and El-Oued sand grains together (HSS-IRM & SG) represent the good options to achieves a highest hemispherical distillers performances.
Comparison of present study with published similar works

In Table 3, we compared our results with published similar works. Through the results, compared to the reference distiller (CHSS), it has been noted that the yield of hemispherical solar still containing internal reflective aluminum foil (HSS-IRA) increases by 30.5%, the yield of hemispherical still containing reflective mirrors (HSS-IRM) increases by 50.5%, the yield of hemispherical still containing internal reflective aluminum foil and El-Oued sand grains (HSS-IRAF & SG) increases by 75.8%, the cumulative yield of hemispherical solar still containing internal reflective mirrors and El-Oued sand grains increases by 98%.

Economic study

Comprehensive economic studies of these modifications are presented to prove their economic feasibility and the extent of their impact on the total cost of distillates produced from containing internal reflective aluminum foil and El-Oued sand grains (HSS-IRAF & SG) increases by 75.8%, the cumulative yield of hemispherical solar still containing internal reflective mirrors and El-Oued sand grains increases by 98%.

Table 3 Comparison between our experimental results and previously published results

| Author name          | Classification | Modifications                                                                 | Gain in distillate production (%) |
|----------------------|----------------|-------------------------------------------------------------------------------|-----------------------------------|
| Our results          | Hemispherical SS | - Internal reflective aluminum foil - Internal reflective mirrors - Internal reflective aluminum foil and El-Oued sand grains - Internal reflective mirrors and El-Oued sand grains | 30.5 50.5 75.8 98                  |
| Chandrika et al. (2021) | Single slope SS | - Reflective glass mirror - Reflective aluminum foil sheet | 68.57 48.57                       |
| Attia et al. (2021d) | Hemispherical SS | - 10 g/L of phosphate granules - 20 g/L of phosphate granules | 33.7 47.9                        |
| Attia et al. (2021e) | Single slope SS | - Bed phosphate granules - Mirror - Mirror and charcoal | 16.8 11.92 14.11                 |
| Selva et al. (2008)  | “V” type SS     | - Mirror - Mirror and charcoal | 11.92 14.11                      |
hemispherical solar distillers represented in (CHSS, HSS-IRM, HSS-IRAF, HSS-IRM & SG, and HSS-IRAF & SG). A comprehensive economic analysis was performed to calculate the total distillate cost per liter based on the equations mentioned by Kabeel and Abdelgaied (2017). Table 4 shows a detailed statement of costs for the five cases covered by the current practical study in order to show the total cost of distillates per liter of different cases (CHSS, HSS-IRM, HSS-IRAF, HSS-IRM & SG, and HSS-IRAF & SG). As shown in the Table 4, the total cost of distillate per liter was 0.0114, 0.0076, 0.0087, 0.0058, and 0.0065 for cases CHSS, HSS-IRM, HSS-IRAF, HSS-IRM & SG, and HSS-IRAF & SG, respectively. The economic feasibility indicated that the utilization of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) represent the good modification which reduced the cost of freshwater productivity by 49.1% compared to CHSS.

**Conclusions**

This study presented the results of two experimental scenarios to illustrate the influences of internal reflective (Reflective Mirrors and Reflective Aluminum Foil) on the performance of hemispherical solar still in the first experimental scenario. In the second experimental scenario, the influences of internal reflective with El-Oued sand grains as the energy storage medium on hemispherical solar still performances was studied. The two experimental scenarios aim to reach the best configuration that achieves highest hemispherical solar stills performance. The obtained conclusions can be written as follows:

- The cumulative distillate production of the reference (CHSS) reached 4750 mL/m² day, while use of internal reflective aluminum foil (HSS-IRAF) increases the cumulative distillate production to 6200 mL/m² day. Also, the use of internal reflective mirrors (HSS-IRM) increases the cumulative distillate production to 7150 mL/m² day.
- The improvement in cumulative distillate production reached to 30.5% and 50.5% for use the internal reflective aluminum foil and internal reflective mirrors, respectively.
- Use the internal reflective aluminum foil and El-Oued sand grains (HSS-IRAF & SG) increases the cumulative distillate production to 8350 mL/m² day, with an improvement of 75.8%.
- Use the internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) increases the cumulative distillate production to 9400 mL/m² day, with an improvement of 98%.
- The exergy and thermal efficiencies of the reference distiller (CHSS) reached 2.2% and 38.9%, respectively. While the use of internal reflective aluminum foil (HSS-IRAF) increases the exergy and thermal efficiencies to 3.44% and 50.65%, respectively. While the use of internal reflective mirrors (HSS-IRM) increases the exergy and thermal efficiencies to 4.4% and 58.3%, respectively.
- Use the internal reflective aluminum foil and El-Oued sand grains (HSS-IRAF & SG) increases the exergy and thermal efficiencies to 5.4% and 67.9%, respectively.
- Use the internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) increases the exergy and thermal efficiencies to 6.62% and 76.3%, respectively.
- The results presented that the maximum improvement in cumulative distillate production, exergy efficiency, and thermal efficiency was recorded for utilization of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) which reached 98, 200.9, and 96%, respectively, compared to reference case (CHSS).
- The economic feasibility indicated that the utilization of internal reflective mirrors and El-Oued sand grains (HSS-IRM & SG) represent the good modification which reduced the cost of freshwater productivity by 49.1% compared to CHSS.

**Authors’ contributions**  Mohammed El Hadi Attia: formal analysis and investigation, and writing—original draft preparation. Abd Elnaby Kabeel: conceptualization, writing—review, and editing. Mohamed Abdelgaied: conceptualization, methodology, writing—review, and editing. All authors read and approved the final manuscript.
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References

Abdelgaied M, Harby K, Eisa A (2021) Performance improvement of modified tubular solar still by employing vertical and inclined pin fins and external condenser: an experimental study. Environ Sci Pollut Res 28:13504–13514

Abdelgaied M, Harby K, Eisa A (2021a) Experimental investigation on the performance improvement of tubular solar still using floating black sponge layer. Environ Sci Pollut Res (2021)https://doi.org/10.1007/s11356-021-13187-z

Abdul-Wahab SA, Al-Hatmi YY (2012) Study of the performance of the inverted solar still integrated with a refrigeration cycle. Procedia Eng 33:424–434

Al-Molhem YA, Eltawil MA (2020) Enhancing the double-slope solar still performance using simple solar collector and floatable black wicks. Environ Sci Pollut Res 27:35078–35098

Arani RP, Sathyamurthy R, Chamkha A, Kabeel AE, Deverajan M, Kamalakannan K, Balasubramanian M, Manokar AM, Essa F, Saravanan A (2021) Effect of fins and silicon dioxide nanoparticle black paint on the absorber plate for augmenting yield from tubular solar still. Environ Sci Pollut Res 28:35102–35112

Attia MEH, Kabeel AE, Abdelgaied M, Essa F, Omara ZM (2016) Enhancement of hemispherical solar still productivity using iron, zinc and copper trays. Sol Energy 216:295–302

Attia MEH, Driss Z, Manokar AM, Sathyamurthy R (2020) Effect of Aluminum Balls on the productivity of Solar Distillate. J Energy Storage 30:101466

Attia MEH, Karthick A, Manokar AM, Driss Z, Kabeel AE, Sathyamurthy R, Sharshir SW, Essa FA, Arun V R, Abdul-Wahab SA, Tiwari GN (2011) Performance study of the inverted absorber solar still with water depth and total dissolved solid. Appl Energy 88:252–264

Dev R, Abdul-Wahab SA, Tiwari GN (2011) Performance study of the inverted absorber solar still with water depth and total dissolved solid. Appl Energy 88:252–264

Dhivagar R, Mohanraj M (2021) Performance improvements of single slope solar still using graphite plate fins and magnets. Environ Sci Pollut Res 28:20499–20516

Hiroshi T (2010) Monthly optimum inclination of glass cover and external reflector of a basin type solar still with internal and external reflector. Sol Energy 84:1959–1966

Hiroshi T (2011) A theoretical analysis of basin type solar still with flat plate external bottom reflector. Desalination 279:243–251

Holman JP (2012) Experimental Methods for Engineers, 8th edn. McGraw-Hill Companies, New York

Kabeel AE, Abdelgaied M (2017) Observational study of modified solar still coupled with oil serpentine loop from cylindrical parabolic concentrator and phase changing material under basin. Sol Energy 144:71–78

Kabeel AE, Abdelgaied M (2019) Performance enhancement of a photovoltaic panel with reflectors and cooling coupled to a solar still with air injection. J Clean Prod 224:40–49

Kabeel AE, Omara ZM, Essa FA, Abdullah AS, Arunkumar T, Sathyamurthy R (2017) Augmentation of a solar still distillate yield via absorber plate coated with black nanoparticles. Alex Eng J 56(4):433–438

Kabeel AE, Abdelgaied M, Essa A (2018) Enhancing the performance of single basin solar still using high thermal conductivity sensible storage materials. J Clean Prod 183:20–25

Kabeel AE, Sathyamurthy R, Manokar AM, Sharshir SW, Essa FA, El shiekh AH (2020) Experimental study on tubular solar still using Graphene Oxide Nano particles in Phase Change Material (NPCM’s) for fresh water production. Journal of Energy Storage 28:101204

Khaliha AJ, Ibrahim HA (2011) Experimental study on the effect of internal and external reflectors on the performance of basin type solar stills at various seasons. Desalination Water Treat 27:313–318

Manokar AM, Winston DP, Kabeel AE, Sathyamurthy R (2018) Sustainable fresh water and power production by integrating PV panel in inclined solar still. J Clean Prod 172:2711–2719

Mefnah M, Mahboub MS (2020) Spectroscopic Characterizations of Sand Dunes Minerals of El-Oued (Northeast Algerian Sahara) by FTIR, XRF and XRD Analysis. Silicon 12:147–153

Mohammed AH, Attalla M, Shmroukh AN (2021) Performance enhancement of single-slope solar still using phase change materials. Environ Sci Pollut Res 28:17098–17108
Mu L, Xu X, Williams T, Debroux C, Gomez RC, Park YH, Kuravi S (2019) Enhancing the performance of a single-basin single-slope solar still by using Fresnel lens: Experimental study.”. J Clean Prod 239:118094
Ramalingam VK, Karthick A, Jayalekshmi MPV, Decruz AMMAJ, Manokar AM, Sathyamurthy R (2021) Enhancing the fresh water produced from inclined cover stepped absorber solar still using wick and energy storage materials. Environ Sci Pollut Res 28:18146–18162
Selva KB, Kumar S, Jayaprakash R (2008) Performance analysis of a “V” type solar still using a charcoal absorber and a boosting mirror. Desalination 229(1–3):217–230
Srivastava PK, Agrawal SK (2013) Experimental and theoretical analysis of single sloped basin type solar still consisting of multiple low thermal inertia floating porous absorbers. Desalination 311:198–205
Suraparaju SK, Natarajan SK (2021) Productivity enhancement of single-slope solar still with novel bottom finned absorber basin inserted in phase change material (PCM): techno-economic and enviro-economic analysis. Environ Sci Pollut Res 28:45985–46006
Suraparaju SK, Natarajan SK (2021) Experimental investigation of single-basin solar still using solid staggered fins inserted in paraffin wax PCM bed for enhancing productivity. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-11980-w
Tanaka H (2009) Experimental study of a basin type solar still with internal and external reflectors in winter. Desalination 249:130–134
Tanaka H, Nakatake Y (2006) Theoretical analysis of a basin type solar still with internal and external reflectors. Desalination 197:205–216
Vaithilingam S, Muthu V, Athikesavan MM, Afzal A, Sathyamurthy R (2021) Energy and exergy analysis of conventional acrylic solar still with and without copper fins. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-16124-2

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