Hemispherical solar distiller with truncated circular cone-shaped reflector mirrors (TCC-RM): optimum inclination of reflector mirrors

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Abstract
The present study aims to achieve the highest cumulative yield of the hemispherical distillers, by designing and constructing new reflector mirrors, which are truncated circular cone-shaped reflector mirrors (TCC-RM). To obtain the optimum inclination of TCC-RM that achieves the highest hemispherical distiller’s performance, eight inclination angles (10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45° with vertical) were experimentally studied. To achieve this, a series of experimental tests were carried out on the three hemispherical solar distillers: the first represents the reference distiller (traditional hemispherical solar distiller (THSD)) and the other two devices are the hemispherical solar distiller with truncated circular cone-shaped reflector mirrors (HSD-TCCRM) with different inclination angles. The experimental results indicate that utilizing TCC-RM with a 25° inclination angle achieves the maximum cumulative yield of 8.35 L/m² with an improvement of 42.74% compared to THSD. While the utilization of TCC-RM with the inclination angles of 30°, 35°, 20°, 40°, and 15° achieves the cumulative yield of 7.9, 7.3, 7.05, 6.67, and 6.6 L/m² compared with 5.85 L/m² for THSD. On the contrary, adjusting the inclination angle of TCC-RM at 10° and 45° affects negatively the cumulative yield of the HSD with TCC-RM in comparison with THSD. Based on the data of cumulative yield, daily efficiency, and the economic analysis it is recommended to utilize TCC-RM with a 25° inclination angle to achieve the highest performance and minimum distillate cost of hemispherical solar distillers.

Keywords Hemispherical solar distiller · Truncated circular cone-shaped reflector mirrors · Optimal inclination angle · Economic analysis · Performance improvement

Introduction
Life on Earth is linked to the element of water. Water is essential to the life of all living and minute organisms. But many people do not have access to safe water to drink, with more than 5 million people dying each year from diseases transmitted through unclean water (Prasad et al., 2021; Dubey and Mishra, 2021; Arani et al., 2021). Population growth and pollution of natural resources are among the reasons for the scarcity of drinking water worldwide. The desert regions in Algeria, especially the city of El Oued, contain large quantities of saline groundwater, a large solar field, and long insolation period throughout the year (Sharshir et al., 2020; Kabeel and Abdelgaied, 2017; Natarajan et al., 2022; Azari et al., 2021). Saltwater affects the human body and machinery and factories as well because it contains salt. The solution is to remove the salts from the saltwater before using them. There are several ways to convert saltwater into safe water such as membrane distillation...
Solar distillation is an easy process that was utilized for this. In fact, solar distillation has played an important role to produce clean water in arid desert and dry regions. In the literature, many studies have focused on producing clean water from seawater by using the solar energy. Abd Elbar et al. (2019; Suraparaju and Hassan, 2020a,b) have studied the effect of internal reflectors (aluminum foil sheet and glass mirror) on single-slope solar distiller’s performance. They found that the optimal daily efficiency of the solar distillers with internal reflectors (aluminum foil sheet and glass mirror) was 48.57% and 68.57%, respectively, compared to classical still. Attia et al. (2021) analytically investigated the effect of internal reflectors (aluminum foil sheet and mirror) on the performance enhancements of hemispherical distillers. They conducted that the optimal daily efficiency of the hemispherical distillers with an internal reflector aluminum foil sheet was 30.53% and using an internal reflector mirror was 52.63%, compared to a classical hemispherical distiller. Khechekhouche et al. (2020) conducted that the impact of a single external refractor on a single-slope distiller productivity has been investigated, under the climatic conditions of El Oued, Algeria. From the information obtained, it was found that the technology achieves a performance improvement for the single-slope solar distiller, which amounted to about 45%, and the efficiency also draws 35%, and they also indicated that in a period of 23 days they can recover the amount of the cost and concluded that this technology is suitable for many regions in the world. Experimental work was conducted by Tanaka (2009) to obtain the enhancement of solar distillers by using basin liners with internal/external reflectors. They conducted an increase of 100% in the distillate yields on winter days. A numerical study was conducted by Tanaka and Nakatake (2006) to obtain the influences of applying the reflectors; they found that the yield improved by 48% on average over the year-round. A theoretical analysis was done by Tanaka and Nakatake (2007), to evaluate the performance of tilted wick solar distillers by modifying a vertical flat plate external reflector. They observed that increase in the daily productivity was 9% on a year-round average. Tanaka and Nakatake (2009) studied the effect of the length of inclined flat plate external reflector on tilted-wick distiller production. The results found that the distillate yield when using the length of the reflector that is half of the distiller’s length is 15% greater compared to the classical distiller and 27% greater when utilizing the length of the deflector that is equal to the length of the distillers compared to the classical distiller. Boubekri and Chaker (2011) performed a study on a single-slope solar distiller integrated with solar reflectors. They conducted that the efficiency of solar reflectors that still used single-slope solar distiller improves by 72.8%; for better output, the inclination angle must be less than 25°. Badran (2007) investigated the yield of a distiller active with a flat collector using the mirror. The percentage of improvement by using flat plate collectors and mirrors together is 36%. Hiroshi (2010) investigated the yield of distiller passive with external/internal reflectors. They found that the percentage of improvement is 48% when using external/internal reflectors. They concluded that using external/internal reflectors is very effective than the internal reflector only.

The comprehensive experimental study in this paper aims to overcome the disadvantages of the declining productivity of solar distillers. Since the design of the hemispherical distillers was characterized by having a large area of receiving and condensing, the utilization of truncated circular cone-shaped external reflector mirrors (TCC-RM) is very interesting to increase the intensity of solar rays falling on the receiving surface. To obtain the optimum inclination of TCC-RM that achieves the maximum hemispherical solar distiller’s performance, eight inclination angles of reflector mirrors (10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45° with vertical) were studied. To achieve this, a series of experimental tests were carried out on the three hemispherical solar distillers: the first represents the reference distiller (traditional hemispherical solar distiller (THSD)) and the other two devices are the hemispherical solar distiller with truncated circular cone-shaped reflector mirrors (HSD-TCCRM) with different inclination angles. In the first experiment, we studied the effect of TCC-RM with tilt angles of 10 and 15° on a yield of second and third hemispherical distillers and were compared to the first THSD. On the second experiment day, we change the tilt angles of TCC-RM to 20 and 25° in the second and third hemispherical distillers and were compared to the first reference distiller THSD. On the third experiment day, we change the tilt angles of TCC-RM to 30 and 35° in the second and third hemispherical distillers and were compared to the first reference distiller THSD. On the fourth experiment day, we change the tilt angles of TCC-RM to 40 and 45° in the second and third hemispherical distillers and were compared to the first reference distiller THSD. All experiments were conducted in the same weather condition in El Oued City, Algeria on August 5, 6, 7, and 8, 2021.

**Experimental setup procedure**

This study aims to achieve the highest cumulative yield of hemispherical distillers, by designing and constructing new reflector mirrors, which are truncated circular cone-shaped reflector mirrors (TCC-RM). Since the design of the hemispherical distiller was characterized by having a great area of receiving and condensing, the utilization of truncated
circular cone-shaped external reflector mirrors (TCC-RM) is very interesting to increase the solar rays falling on the receiving surface. To obtain the optimum inclination of TCC-RM that achieves a maximum hemispherical distiller’s performance, eight inclination angles of reflector mirrors \((10°, 15°, 20°, 25°, 30°, 35°, 40°, \text{and} \, 45° \text{ with vertical})\) were studied. To achieve this, three distillers were constructed with the same dimensions and tested in the Faculty of Exact Science, El Oued University-El Oued, Algeria during the month of August 2021. These three hemispherical distillers are made of a wooden basin with a circular inner diameter of 0.38 m \((0.11-\text{m}^2 \text{ absorber area})\), and the wooden basin is coated with the black silicone to absorb solar radiation and prevent water leakage. A vertical ruler is installed inside the basin of the hemispherical distiller to set the water depth constant at 1 cm throughout the test day. The feed water tank is placed 1 m above the hemispherical distiller to feed the saline water to the still basin. The feed water tank is connected to the basin of the hemispherical distiller by a water pipeline. A check valve is integrated at the pipeline entrance to regulate the saline water flow rate. The hemispherical distiller basin was covered with a transparent hemispherical plastic cap, 0.40 m in diameter, and 3 mm thick. A circular duct was formed on the entire circumference under the transparent plastic cover to collect the condensate and then collected in the distillate water tank. Figure 1 shows the schematic view of hemispherical solar distillers.

To study the effect of the angle of inclination of the truncated circular cone-shaped reflector mirrors (TCC-RM) with a vertical position on the hemispherical distillers and to obtain an optimum angle of inclination that achieves maximum performance, we made hemispherical solar distillers with the truncated circular cone-shaped reflector mirrors (TCC-RM) and changed the tilt angle from vertical each time \((\theta = 10, 15, 20, 25, 30, 35, 40, \text{and} \, 45° \text{ with vertical})\). The truncated circular cone-shaped reflector mirrors (TCC-RM) are designed at 0.30 m high, surrounding the hemispherical cover with a lower base with a fixed diameter of 0.41 m and an upper base whose diameter is changed according to the angle of inclination with the vertical position, as shown in Fig. 2.

The experiments were conducted on four tests, on days from August 5, 6, 7, and 8, 2021, throughout the day \((12 \text{ h})\). Experimental work has been extended to investigate the effect of truncated circular cone-shaped reflector mirror (TCC-RM) inclination angle on hemispherical distiller yield and obtain an optimal inclination angle that achieves a maximum cumulative yield of hemispherical distillers. To achieve this, eight inclination angles of reflector mirrors \((10°, 15°, 20°, 25°, 30°, 35°, 40°, \text{and} \, 45° \text{ with vertical})\) were studied as shown in Fig. 3.

Three hemispherical solar distiller modules are provided in each test. In the first test, the second and third hemispherical solar distiller’s units are provided by the truncated circular cone-shaped reflector mirrors (TCC-RM) with inclination angles \(\theta = 10\) and \(15°\) (HSD-TCC-RM10 and HSD-TCC-MR15), which were tested and compared to THSS. In the second test, the second and third hemispherical solar distiller’s units are provided by the truncated circular cone-shaped reflector mirrors (TCC-RM) with inclination angles \(\theta = 20\) and \(25°\) (HSD-TCC-RM20 and HSD-TCC-MR25), which were tested and compared to THSS. In the third test, the second and third hemispherical solar distiller’s units are provided by the truncated circular cone-shaped reflector mirrors (TCC-RM) with inclination angles \(\theta = 30\) and \(35°\) (HSD-TCC-RM30 and HSD-TCC-MR35), which were tested and compared to THSS. In the fourth test, the second and third hemispherical solar distiller’s units are provided by the truncated circular cone-shaped reflector mirrors (TCC-RM) with inclination angles \(\theta = 40\) and \(45°\) (HSD-TCC-RM40 and HSD-TCC-MR45), which were tested and compared to THSS. To maintain the same heat capacity of brine water, the same depth \((1 \text{ cm})\) of brine is maintained for each of the three units as shown in Fig. 3.

**Measuring instruments**

Thermocouples by \(\pm 0.1\) °C accuracy were placed at appropriate places in the hemispherical distillers to record a temperature at different segments. The basin water temperature, ambient temperature, and inner and outer cover temperature were measured. A solar power meter with \(\pm 10\)-W/m\(^2\) accuracy was used to record and log solar
radiation. A graduated cylinder with ±1 mL measuring is used to collect the freshwater from the strip. Table 1 summarizes the instruments used and their accuracy values. Based on the ranges, accuracy, standard uncertainty, and ranges of the instrumentations utilized in the present experimental test shown in Table 1, the uncertainties in the daily thermal efficiency and daily accumulative productivity are calculated using the procedure presented by Holman (2012) which reached to 2.37% and 1.32%, respectively.

**System performance**

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

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

(1)

Latent heat $h_{fg}$ can be calculated by (Kabeel and Abdel-gaied 2017; Kabeel et al. 2021)

$$
h_{fg} = 10^{3}[2501.9 - 2.40706 \times T_w + 1.192217 \times 10^{-3} \times T_w^2 - 1.5863 \times 10^{-5} \times T_w^3]
$$

(2)

where $A_s$ is the absorber area (m$^2$), $I(t)$ is the solar radiation (W/m$^2$), $T_w$ is the basin saltwater temperature (°C), $m_{\text{ev}}$ is the hourly distillate production (kg/m$^2$·h), and $h_{fg}$ is a latent heat (J/kg).

**Results and discussions**

The freshwater yield is the main goal of hemispherical distillers. This output is determined by the amount at which saline water evaporates and the rate at which evaporated water vapor condenses. The evaporation rate increases with argument saltwater temperature and the temperature difference between saltwater and internal glass. Furthermore, the increasing temperature differential between internal glass and external glass, the temperature difference between ambient air and external glass, and increasing outside wind speed all enhance the condensation rate. As a result, evaluating the still temperatures provides a clear picture of the still performance.

**Hemispherical solar still temperatures**

Figures 4, 5, 6, and 7 illustrate the temperature variations with time of the proposed hemispherical solar distiller.
components and the corresponding ambient temperature and solar rays within tested days. Figure 4 introduces the changes in temperature throughout time of saline water, internal glass, external glass, and ambient of hemispherical solar distiller with truncated circular cone-shaped reflector mirrors (HSD-TCC-RM) at inclination angles of 10 and 15° (with vertical) compared with traditional hemispherical solar distiller (THSD). However, all these temperature variations of HSD-TCC-RM20 and HSD-TCC-RM25 in comparison to THSD are presented in Fig. 5. Furthermore, Fig. 6 illustrates the changes in temperature with the time of HSD-TCC-RM30 and HSD-TCC-RM35 in comparison to THSD. Additionally, the changes in temperature with time of HSD-TCC-RM40 and HSD-TCC-RM45 and their difference with traditional solar still temperatures are displayed in Fig. 7.

As indicated from these Figs. 4, 5, 6, and 7 the solar intensity profile has the same trend during all tested days and its values have nearly the same values during the 4 days. This is because the cases studied were performed within four successive days in the period between 5/8/2021 and 8/8/2021 to avoid any variations in ambient conditions. It is clear from Figs. 4, 5, 6, and 7 that solar intensity values have a small value at the sunrise and rise gradually until it reaches their maximum value at noontime and then their values decline with time to hit the lowest value at the end of daytime. However, the solar intensity gets its maximum value at 12:00 am; it is noticed that the maximum values of all components for the proposed systems were obtained 3 h later at 3:00 pm. The reason for this time delay is that heat transferred through the solar radiation needs time to be absorbed by the hemispherical solar still components and to get warmer. Furthermore, it is obvious that the saline water temperatures for all studied cases have the maximum values, followed by the internal glass temperatures, and then the external glass temperatures which are always higher than the ambient temperatures. The reason of this is that the solar rays is transmitted through a still glass and absorbed by still absorber which is in contact with saltwater. Then, the water is heated and evaporated. The water vapor is condensed on the internal surface of the glass.

Figure 4 demonstrates the temperature variations of water, internal glass, external glass, and ambient over time for HSD-TCC-RM10, and HSD-TCC-RM15 compared with traditional hemispherical solar distiller (THSD). It is illustrated from Fig. 4 that the internal glass temperatures for any system are higher than the corresponding values of external glass temperatures due to the thermal resistance of glass and the latent heat of condensing absorbed by internal glass surface. It is revealed that using truncated circular cone-shaped
reflector mirrors (TCC-RM) with an inclination angle of 10° has a negative effect on the water temperature values. This is because TCC-RM with an inclination angle of 10° represents an obstacle to the solar rays falling on the absorbing surface, which causes a decrease in the rates of solar rays absorbed by the absorbing surface. However, using the TCC-RM with 15° enhanced the maximum water temperature by 2.78% compared with THSD; this is mainly due to increasing the incident solar radiation falling on the absorbing surface of the HSD-TCC-RM15.

The effect of using TCC-RM with inclination angles of 20 and 25 angles on the temperatures of HSD is introduced in Fig. 5. Results in Fig. 5 reveal that using TCC-RM20 and TCC-RM25 improves the maximum water temperature by 2.78% and 5.56%, respectively, compared to THSD. This is because with the addition of TCC-RM the intensity of solar rays falling on the absorbing surface increases with the increasing an inclination angle of TCC-RM, which causes an increase in the water temperature. The maximum difference in temperature between saltwater and an internal glass of THSD, HSD-TCC-RM20, and HSD-TCC-RM25 systems were 12, 14, and 15 °C, respectively. That means that the evaporation rate of HSD-TCC-RM20, followed by a traditional solar distiller (THSD). Furthermore, it is noticed in Fig. 5 that the maximum temperature difference between an internal and external glass of THSD, HSD-TCC-RM20, and HSD-TCC-RM25 systems were 6, 6, and 7 °C, respectively. This interprets that HSD-TCC-RM with a 25° inclination angle has the maximum condensation rate compared with other corresponding systems.

Figure 6 demonstrates the effect of using TCC-RM with inclination angles of 30 and 35° on THSD temperatures. It is

| Instrument          | Range        | Accuracy  | Standard uncertainty |
|---------------------|--------------|-----------|----------------------|
| Thermocouple        | −100–500 °C  | ±0.1 °C   | 0.08 °C              |
| Solar power meter   | 0–1999 W/m²  | ±10 W/m²  | 5.78 W/m²            |
| Graduated cylinder  | 0–500 mL     | ±1 mL     | 0.5 mL               |

in Fig. 5. Results in Fig. 5 reveal that using TCC-RM20 and TCC-RM25 improves the maximum water temperature by 2.78% and 5.56%, respectively, compared to THSD. This is because with the addition of TCC-RM the intensity of solar rays falling on the absorbing surface increases with the increasing an inclination angle of TCC-RM, which causes an increase in the water temperature. The maximum difference in temperature between saltwater and an internal glass of THSD, HSD-TCC-RM20, and HSD-TCC-RM25 systems were 12, 14, and 15 °C, respectively. That means that the evaporation rate of HSD-TCC-RM20, followed by a traditional solar distiller (THSD). Furthermore, it is noticed in Fig. 5 that the maximum temperature difference between an internal and external glass of THSD, HSD-TCC-RM20, and HSD-TCC-RM25 systems were 6, 6, and 7 °C, respectively. This interprets that HSD-TCC-RM with a 25° inclination angle has the maximum condensation rate compared with other corresponding systems.

Figure 6 demonstrates the effect of using TCC-RM with inclination angles of 30 and 35° on THSD temperatures. It is
concluded that using TCC-RM30 and TCC-RM35 improves the maximum water temperature by 4.23% and 2.82%, respectively, compared to THSD. This is because the addition of TCC-RM will increase the intensity of solar rays falling on the absorbing surface as the rate gradually decreases with the increasing an inclination angle of TCC-RM. The maximum difference in temperature between saltwater and internal glass of THSD, HSD-TCC-RM30, and HSD-TCC-RM35 systems were 12, 13, and 12 °C, respectively. The results of this figure presented that the evaporation rate in HSD-TCC-RM30 is higher as compared to HSD-TCC-RM35 and THSD systems.

The impact of using TCC-RM with inclination angles of 40 and 45° on HSD temperatures are shown in Fig. 7. It can be concluded from Fig. 7 that utilizing TCC-RM with 45° inclination angle has a negative impact on the water temperature compared with conventional distiller. This is because TCC-RM with an inclination angle of 45° represents an obstacle to the solar rays falling on the absorbing surface, which causes a decrease in the rates of solar rays absorbed by the absorbing surface. The maximum water temperatures obtained from THSD, HSD-TCC-RM40, and HSD-TCC-RM45 were 71, 71, and 69 °C, respectively.

By comparing the water temperatures of all proposed systems as shown in Fig. 8, it is revealed that utilizing TCC-RM with 10° and 45° inclination angles has a negative impact on the water temperature compared to the reference distiller THSD. This is because TCC-RM with an inclination angle of 10° and 45° represents an obstacle to the solar rays falling on the absorbing surface, which causes a decrease in the rates of solar rays absorbed by the absorbing surface. For utilizing TCC-RM with an inclination angle between 15° and 40°, the water temperature increase with an increase in the inclination angle of TCC-RM from 15° to 25°. This is because the intensity of solar rays falling on the absorbing surface increases with increasing the inclination angle of TCC-RM, which causes an increase in the water temperature. But with a continuous rise in the inclination angle of TCC-RM after 25°, the rate of improvement in the water temperature will be gradually decreased. This is because, with an increase in the inclination angle of TCC-RM from 25° to 40°, the
The intensity of solar rays falling on the absorbing surface gradually decreases with increasing an inclination angle of TCC-RM. This is mainly because of the rate of reflected solar rays from the TCC-RM to the outside increase with an increase in the inclination angle of TCC-RM from 25° to 40°. These results revealed that an optimal inclination of TCC-RM is 25°, which results in a maximum water temperature of 76 °C and a maximum difference in temperature between saltwater and internal glass (15 °C) compared to all other proposed inclination angles of TCC-RM. This means that HSD-TCC-RM25 has the maximum evaporation rate, and then maximum freshwater productivity.

**Hemispherical solar distiller freshwater yield**

Figure 9 depicts the effect of adjusting the inclination angle of the truncated circular cone-shaped reflector mirrors (TCC-RM) with the hemispherical solar distiller on the hourly yield. The hourly productivity of the traditional (THSD) and the hemispherical solar distiller with truncated circular cone-shaped reflector mirrors (HSD-TCC-RM) at various inclination angles are shown in this graph. Figure 9 depicts that the hourly production rises progressively from the morning until reaches the maximum value at 14:00 PM, which corresponds to nearly the time of maximum temperature as shown in Fig. 8. After that, as the solar intensity diminishes, the amount of freshwater produced decreases till the end of the day. Figure 9 indicates that using TCC-RM with 25° and 30° inclination angle achieves the maximum hourly yield of 1.1 L/m²·h for each system, followed by HSD-TCC-RM20 and HSD-TCC-RM35 with 1 L/m²·h, and HSD-TCC-RM15 and HSD-TCC-RM40 with 0.9 L/m²·h, compared with 0.85 L/m²·h for THSD. But for TCC-RM with 10° and 45° inclination angles, the maximum hourly productivity reached 0.8 L/m²·h; this is mainly because of the negative impact on the water temperature compared with THSD. Findings reveal that using TCC-RM with 25° and 30° inclination angles improves the maximum hourly productivity by 29.4% compared to THSD, followed by the use of TCC-RM with 20° and 35° inclination angles will improve the maximum hourly productivity by 17.6% compared to THSD, and the use of TCC-RM with 15° and...
Fig. 7 Temperature variations of THSD compared with HSD-TCC-RM at inclination angles of 40 and 45°.

Fig. 8 Water temperature variations of THSD compared with HSD-TCC-RM at inclination angles of 10, 15, 20, 25, 30, 35, 40, and 45°.

Fig. 9 Variation of hourly yield for all studied cases of THSD and HSD-TCC-RM.
40° inclination angle will improve the maximum hourly productivity by 5.8% compared to THSD. On the contrary, adjusting the inclination angle of TCC-RM at 10° and 45° has effects negatively on the hourly productivity of HSD-TCC-RM compared to the reference THSD.

Figure 10 shows how, till the sunset, the accumulated freshwater yield for all proposed solar stills grows. Furthermore, it results that using truncated circular cone-shaped reflector mirrors with an inclination angle of 15, 20, 25, 30, 35, and 40° enhanced the accumulated freshwater productivity of the traditional THSD by 12.82%, 20.51%, 42.74%, 35.04%, 24.79%, and 14.02%, respectively. However, the total accumulated yield of HSD-TCC-RM10 and HSD-TCC-RM45 declined by 11.97% and 6.84%, respectively, relative to the THSD system. Also, Table 2 shows the influences of the utilization of the truncated circular cone-shaped reflector mirrors with an inclination angle on the percentage improvement in cumulative yield of hemispherical solar distillers.

![Graph](image)

Fig. 10 Variation of accumulated yield for all studied cases of THSD and HSD-TCC-RM

From the findings presented in Fig. 10, for utilizing TCC-RM, the accumulated freshwater yield increases with increasing the inclination angle of TCC-RM from 15° to 25°. This is because the intensity of solar rays falling on the absorbing surface increases with increasing the inclination angle of TCC-RM, which causes an increase in the water temperature as shown in Fig. 8. But with continuous increases in the inclination angle of TCC-RM after 25°, the rate of improvement in the accumulated freshwater yield will be gradually decreased. This is because, with an increase in the inclination angle of TCC-RM from 25° to 40°, the intensity of solar rays falling on the absorbing surface gradually decreases with increasing the inclination angle of TCC-RM. This is mainly because of the rate of reflected solar rays from the TCC-RM to the outside increases with an increase in the inclination angle of TCC-RM from 25° to 40°. Otherwise, adjusting the inclination angle of TCC-RM at 10° and 45° has effects negatively on the accumulated freshwater yield of HSD-TCC-RM compared to the reference THSD. As a result, it is concluded that the optimum inclination angle for the truncated circular cone-shaped reflector mirrors used with a hemispherical solar distiller is 25°, which achieves the maximum accumulated freshwater yield among all other HSS proposed systems.

**Daily efficiency**

Figure 11 depicts the effect of adjusting the inclination angle of the truncated circular cone-shaped reflector mirrors (TCC-RM) on the cumulative yield and thermal daily efficiency of HSD. The results presented in Fig. 11 indicated that the optimum inclination angle for the truncated circular cone-shaped reflector mirrors used with a hemispherical solar distiller is 25°, which achieves the maximum accumulated freshwater yield and maximum thermal daily efficiency among all other HSS proposed systems.

**Economic evaluation**

To calculate the cost of 1 L of freshwater produced by distillers, we analyze and tabulate the cost details of the
hemispherical solar distiller’s devices with and without truncated circular cone-shaped reflector mirror (TCC-RM) inclination angle in Table 3.

The economic study was carried out to calculate the cost of distillate per liter (CPL) based on the equations mentioned by Attia et al. (2021) as follows:

The capital recovery factor (CRF) is calculated as follows:

\[
CRF = \frac{i(i + 1)^n}{i(i + 1)^n - 1}
\]  

(3)

Additionally, fixed annual cost (FAC) is calculated as follows:

\[
FAC = P \times (CRF)
\]  

(4)

where \(P\) is a distiller fixed cost.

Sinking fund factor (SFF) is calculated as follows:

\[
SFF = \frac{i}{(i + 1)^n - 1}
\]  

(5)

Also, salvage value (S) is calculated as follows:

\[
S = 0.17 \times P
\]  

(6)

Annual salvage value (ASV) is calculated as follows:

\[
ASV = S \times (SFF)
\]  

(7)

The annual maintenance cost (AMC) is calculated as follows:

\[
AMC = 0.05 \times (FAC)
\]  

(8)

The total annual cost (TAC) is calculated as follows:

\[
TAC = FAC + AMC - ASV
\]  

(9)

Then, the distilled cost per liter (CPL) is calculated as follows:

\[
CPL = \frac{TAC}{M}
\]  

(10)

where \(M\) is the average distillate yield per year.

| Material                  | THSD Cost (DZA) | THSD Cost ($) | HSD-TCC-RM Cost (DZA) | HSD-TCC-RM Cost ($) |
|---------------------------|-----------------|--------------|-----------------------|---------------------|
| Cover plastic             | 2000            | 14.787       | 2000                  | 14.787              |
| Reflective mirror        | -               | -            | 2000                  | 14.787              |
| Box of wooden             | 6500            | 48.0285      | 6500                  | 48.0285             |
| Accessories and workforce| 500             | 3.6945       | 500                   | 3.6945              |
| Maintenance               | 50              | 0.3694       | 50                    | 0.3694              |
| Total cost per m²         | 9050            | 66.8704      | 11,050                | 81.6484             |

Table 4 Daily productivity of hemispherical solar distillers with/without TCC-RM

| Distiller types             | Accumulative productivity (L/m²-day) |
|-----------------------------|-------------------------------------|
| THSD                        | 5.85                                |
| HSD-TCC-RM10                | 5.15                                |
| HSD-TCC-RM15                | 6.60                                |
| HSD-TCC-RM20                | 7.05                                |
| HSD-TCC-RM25                | 8.35                                |
| HSD-TCC-RM30                | 7.90                                |
| HSD-TCC-RM35                | 7.30                                |
| HSD-TCC-RM40                | 6.67                                |

Table 3 Effective cost analysis of components (1$ = 135.33 DZD)
Table 4 presents the daily productivity of hemispherical solar distiller use of truncated circular cone-shaped reflector mirrors (TCC-RM) with different inclination angles ($\theta = 10^\circ$, $15^\circ$, $20^\circ$, $25^\circ$, $30^\circ$, $35^\circ$, $40^\circ$, and $45^\circ$ with vertical).

The price of distilled water per liter in the Algeria market is 60 DZD ($ 0.4436), but the price of distilled water product per liter from THSD (reference unit) is 0.906 DZD ($ 0.0067) and product from hemispherical solar distillers with truncated circular cone-shaped reflector mirrors (TCC-RM) at inclination angle equal to $25^\circ$ is 0.771DZD ($ 0.0057) (Table 5).

| $N$ (year) | THSD | HSD-TCC-RM10 | HSD-TCC-RM15 | HSD-TCC-RM20 | HSD-TCC-RM25 | HSD-TCC-RM30 | HSD-TCC-RM35 | HSD-TCC-RM40 | HSD-TCC-RM45 |
|------------|------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| $I$ (%)    | 0.17 | 0.17         | 0.17         | 0.17         | 0.17         | 0.17         | 0.17         | 0.17         | 0.17         |
| $CRF$      | 0.21 | 0.21         | 0.21         | 0.21         | 0.21         | 0.21         | 0.21         | 0.21         | 0.21         |
| $P$ ($)    | 66.87| 81.65        | 81.65        | 81.65        | 81.65        | 81.65        | 81.65        | 81.65        | 81.65        |
| $S$ ($)    | 11.37| 13.88        | 13.88        | 13.88        | 13.88        | 13.88        | 13.88        | 13.88        | 13.88        |
| $FAC$ ($)  | 14.04| 17.15        | 17.15        | 17.15        | 17.15        | 17.15        | 17.15        | 17.15        | 17.15        |
| $SFF$      | 0.04 | 0.04         | 0.04         | 0.04         | 0.04         | 0.04         | 0.04         | 0.04         | 0.04         |
| $ASV$ ($)  | 0.455| 0.555        | 0.555        | 0.555        | 0.555        | 0.555        | 0.555        | 0.555        | 0.555        |
| $AMC$ ($)  | 0.702| 0.858        | 0.858        | 0.858        | 0.858        | 0.858        | 0.858        | 0.858        | 0.858        |
| $TAC$ ($)  | 14.287| 17.453      | 17.453       | 17.453       | 17.453       | 17.453       | 17.453       | 17.453       | 17.453       |
| $M$ (L/m$^2$ · yr) | 2135.3| 1879.8      | 2409         | 2573.3       | 3047.8       | 2883.5       | 2664.5       | 2434.6       | 1989.3       |

Table 5 Cost analysis of all distillers

- Whenever the angle of inclination was less than $25^\circ$, the productivity also decreased, and the improvement rates were $20.51$, $12.82$, and $-11.97\%$ at inclination angles of $20^\circ, 15^\circ$, and $10^\circ$ with vertical, respectively.
- Based on the data of cumulative yield, daily efficiency, and the economic analysis it is recommended to utilize TCC-RM with a $25^\circ$ inclination angle to achieve the highest performance and minimum distillate cost of hemispherical solar distillers.

We recommend using the truncated circular cone-shaped reflector mirrors (TCC-RM) with an ideal tilt angle of $25^\circ$ with vertical.

Nomenclature

THSD: Traditional hemispherical solar distiller; HSD-TCC-RM10: Hemispherical solar distiller with truncated circular cone-shaped reflector mirror inclination angle 10°; HSD-TCC-RM15: Hemispherical solar distiller with truncated circular cone-shaped reflector mirror inclination angle 15°; HSD-TCC-RM20: Hemispherical solar distiller with truncated circular cone-shaped reflector mirror inclination angle 20°; HSD-TCC-RM25: Hemispherical solar distiller with truncated circular cone-shaped reflector mirror inclination angle 25°; HSD-TCC-RM30: Hemispherical solar distiller with truncated circular cone-shaped reflector mirror inclination angle 30°; HSD-TCC-RM35: Hemispherical solar distiller with truncated circular cone-shaped reflector mirror inclination angle 35°; HSD-TCC-RM40: Hemispherical solar distiller with truncated circular cone-shaped reflector mirror inclination angle 40°; HSD-TCC-RM45: Hemispherical solar distiller with truncated circular cone-shaped reflector mirror inclination angle 45°

Conclusion

This paper studies the effect of truncated circular cone-shaped reflector mirror (TCC-RM) inclination angle on hemispherical distiller’s performance and obtains the optimal inclination angle. To obtain the optimum inclination of TCC-RM that achieves the highest hemispherical distiller’s performance, eight inclination angles ($10^\circ$, $15^\circ$, $20^\circ$, $25^\circ$, $30^\circ$, $35^\circ$, $40^\circ$, and $45^\circ$ with vertical) were experimentally studied. The yield of solar hemispherical distillation at the conditions of brine depth of 1 cm was studied, under the weather conditions of El Oued-Algeria City. The following points can be summarized from the experimental work:

- The use of truncated circular cone-shaped reflector mirrors (TCC-RM) within the hemispherical solar distillers increases the distillate yields.
- Optimal inclination angle of truncated circular cone-shaped reflector mirrors (TCC-RM) is $25^\circ$ with vertical; the corresponding improvement percentage is 42.74%.
- Whenever the tilt angle is greater than $25^\circ$, the productivity decreases, and the improvement percentages are $35.04$, $24.79$, $14.02$, and $-6.84\%$ at tilt angles of $30^\circ, 35^\circ$, and $45^\circ$ with vertical, respectively.

Author contribution

Mohammed El Hadi Attia: experimental work, writing — original draft, and preparation.

Abd Elnaby Kabeel: conceptualization, writing — review and editing, and supervision.

Mohamed Abdelgaied: conceptualization, methodology, and writing — review and editing.

Ayman Refat Abd Elbar and Abd Elkader Abdallah: formal analysis, investigation, and writing — review and editing.

Data availability

Not applicable.
Declarations

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Consent for publication Not applicable.

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References

Abd Elbar AR, Yousef MS, Hassan H (2019) Energy, exergy, exergo-economic and enviro-economic (4E) evaluation of a new integration of solar still with photovoltaic panel. J Clean Prod 233:665–680

AbdElbar AR, Hassan H (2020a) Energy, exergy and environmental assessment of solar still with solar panel enhanced by porous material and saline water preheating. J Clean Prod 277:124175

AbdElbar AR, Hassan H (2020b) An experimental work on the performance of new integration of photovoltaic panel with solar still in semi-arid climate conditions. Renew Energy 146:1429–1443

Abdelaied M, Zakaria Y, Kabeel AE, Essa FA (2021a) Improving the tubular solar still performance using square and circular hollow fins with phase change materials. Journal of Energy Storage 38:102564

Abdelaied M, Harby K, Eisa A (2021b) 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

Arani RP, Attia MEH, Al-Kouz W, Afzal A, Athikesavan MM, Sathyamurthy R (2021) Correction to: Energy and exergy efficiency analysis of solar still incorporated with copper plate and phosphate pellets as energy storage material. Environ Sci Pollut Res 28:48637

Attia MEH, Kabeel AE, Abdelaied M, Abdelaziz GB (2021) A comparative study of the effect of internal reflectors on a performance of hemispherical solar distillers: energy, exergy, and economic analysis. Sustain Energy Technol Assess 47:101-165

Azari P, Mirabdolah LA, Rahbar N, Yazdi ME (2021) Performance enhancement of a solar still using a V-groove solar air collector—experimental study with energy, exergy, environ-economic, and exergoeconomic analysis. Environ Sci Pollut Res 28:65525–65548

Badran OO (2007) Experimental study of the enhancement parameters on a single slope solar still productivity. Desalination 209:136–143

Boubekeur M, Chaker A (2011) Yield of an improved solar still: numerical approach. Energy Procedia 6:610–617

Chandrika VS, Attia MEH, Manokar AM, Márcuez FPG, Driss Z, Sathyamurthy R (2021) Performance enhancements of conventional solar still using reflective aluminum foil sheet and reflective glass mirror: energy and exergy analysis. Environmental Science and Pollution Research. 2021. https://doi.org/10.1007/s11356-021-13087-2

Dubey M, Mishra DR (2021) Correction to: Experimental analysis of double slope solar still augmented with dye, pebbles and metal chips. Environ Sci Pollut Res 28:22091

Gnanaraj SJP, Ramachandran S (2022) Identification of operational parameter levels that optimize the production in solar stills with plain, corrugated, and compartmental basin. Environ Sci Pollut Res 29:7096–7116

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

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

Kabeel AE, Abdelaied M (2017) Performance enhancement of modified solar still using multi-groups of two coaxial pipes in basin. Appl Therm Eng 118:23–32

Kabeel AE, Abdelaied M, Sathyamurthy R, Kabeel AA (2021) A comprehensive review of technologies used to improve the performance of PV systems in a view of cooling mediums, reflectors design, spectrum splitting, and economic analysis. Environ Sci Pollut Res 28(7):7955–7980

Khechekhouche A, Kabeel AE, Benhauoua B, Attia MEH, El-said EMS (2020) Traditional solar distiller improvement by a single external refractor under the climatic conditions of the El Oued region. Algeria, Desalination and Water Treatment 177:23–28

Manokar AM, Winston DP (2017) Experimental analysis of single basin single slope finned acrylic solar still. Mater Today: Proc 4(8):7234-7239

Natarajan SK, Suraparaju SK, Elavarasan RM, Pugazhendhi R, Hossain E (2022) An experimental study on eco-friendly and cost-effective natural materials for productivity enhancement of single slope solar still. Environ Sci Pollut Res 29:1917–1936

Prasad AR, Attia MEH, Al-Kouz W, Afzal A, Manokar AM, Sathyamurthy R (2021) Energy and exergy efficiency analysis of solar still incorporated with copper plate and phosphate pellets as energy storage material. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-14080-5

Sharshir SW, Elkadeem MR, Meng A (2020) Performance enhancement of pyramid solar distiller using nanofluid integrated with v-corrugated absorber and wick: an experimental study. Appl Therm Eng 168:114848

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

Thakur AK, Sharshir SW, Ma Z (2021) Performance amelioration of single basin solar still integrated with V-type concentrator: energy, exergy, and economic analysis. Environ Sci Pollut Res 28:3406–3420

Tanaka H (2009) Experimental study of a basinc 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

Tanaka H, Nakatake Y (2007) Improvement of the tilted wick solar still by using a flat plate reflector. Desalination 216:139–146

Tanaka H, Nakatake Y (2009) Increase in distillate productivity by inclining the flat plate external reflector of a tilted-wick solar still in winter. Sol Energy 83:785–789

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