Experimental Investigation On a Novel Design of Hemispherical Solar Distiller With v-Corrugated Iron Trays And Wick Materials For Improving Freshwater Production

Mohammed El Hadi Attia
Universite d'El Oued
Mohamed Zayed
Tanta University
Mohamed Abdelgaied
Tanta University
Swellam Sharshir
Kafrelsheikh University
Abd Elnaby Kabeel (kabeel6@hotmail.com)
TANTA UNIVERSITY FACULTY OF ENGINEERING https://orcid.org/0000-0003-4273-8487

Research Article

Keywords: Hemispherical solar distiller, Flat trays absorber, V-corrugated trays absorber, Wick materials, Desalination, Solar energy

Posted Date: January 4th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1104835/v1

Abstract

The low energy efficiency of the solar distillers is one of the most key barriers to their effectual usage in the desalination domain. In this work, an experimental investigation was conducted to enhance the freshwater productivity of the hemispherical solar distiller. This was achieved by utilizing flat and v-corrugated iron trays configurations on the bottom of the distiller basin in order to increase the vaporization surface area for better heat transfer of saline water. Three distillers were designed and examined; namely, conventional hemispherical solar distiller (CHSD), hemispherical solar distiller with flat iron trays (HSD-FIT), and hemispherical solar distiller with v-corrugated iron trays (HSD-VIT). Moreover, the effects of using wick materials (WM) in the basin of HSD-FIT and HSD-VIT have been also investigated and compared to that of CHSD. A comparative thermo-economic analysis of HSD-VITWM, HSD-FITWM, HSD-VIT, HSD-FIT, and CHSD has been conducted to determine the better modification that maximizes the performance of hemispherical stills. Experiments were carried out at the desert climate conditions of El-Oued (33°27'N, 7°11'E), Algeria. The results showed that all modifications revealed good thermo-economic performance enhancements and the HSD-VITWM achieved the maximal improvement from both freshwater production and energo-economic performance. The freshwater productivity and energy efficiency of the HSD-VITWM were improved by 83.12 and 81.67%, respectively, relative to CHSD. Additionally, the cost of freshwater production was lowered by 41.72%.

Introduction

At present, increasing demand for drinking water is regarded as one of the main problems facing developing countries (Aboelmaaref et al., 2020). The World Health Organization (WHO) has referred to that more than 2.10 billion person currently have no access to a safe source of potable water, and nearly 40% of the world's people face squeaky freshwater deficiency (Abdelgaied and Kabeel, 2021). Besides, millions of humans annually perish from diseases associated with defective water supply. The increased level of potable water shortage is robustly related to the industrial revolution, population outgrowth, and increased pollution worldwide (Katekar and Deshmukh, 2020; Kabeel et al., 2021a). Currently, various common distillation technologies are obtainable to tackle the growing of water demand; including humidification dehumidification (Abdelgaied et al., 2021, 2019a; Kabeel et al., 2018a), reverse osmosis (Kabeel et al., 2017a), thermal vapor compression (Zayed et al., 2021), multi-effect evaporation (Darwish et al., 2006), multi-stage flash (Lv et al., 2009), solar distillation (Attia et al., 2021a, 2022), etc. Among these technologies, solar distillation is one of the most promising alternatives for supplying safe water with low energy and freshwater costs (Ahmed et al., 2019). Solar distiller (SD) is one of the simplest and cheap techniques for obtaining freshwater from saline/brackish water (Attia et al., 2021b). However, the low total freshwater production is represented as the essential drawback of any solar distiller system (Zayed et al., 2019).

Literature survey

Many previous attempts have been accomplished different types of distiller designs and diversified improved evaporation modifications to enhance the performance of SDs such as the usage of nanofluids (Elsheikh et al., 2018; Benoudina et al., 2021), the cooling of distiller glass cover (Bellila et al., 2021), the use of mirrors and reflectors (Kumbhar, 2019), sensible and latent storage materials (Attia et al., 2021c; Zayed et al., 2020), the insertion of fins (Attia et al., 2021d), nano-black coatings (Kabeel et al., 2017b), rotating drum (Abdullah et al., 2019), saline water preheating using solar water heaters (Morad et al., 2015; Patel et al., 2020), and so on.

Looking forward to previous designs for SDs that have been established to enhance the productivity of SDs. The basin of the distiller can be amended using several modulations such as the use of V-corrugated basin, doping of fins, basin coatings and wick materials, etc, for effective evaporation rate. In this research perspective, Hansen et al. (2015) investigated the influences of different wicks such as pulpwood paper, polystyrene sponge, and coral fabric wicks on the thermal performance of SDs with various basin configurations. It was unveiled that the coral fabric wick SD with a stepped absorber basin had the best freshwater productivity. Agrawal et al. (2018) studied the impact of jute cloth on the water distillate of the single-slope solar distillatory (SSSD). It was obtained an increase in the freshwater output of 62% compared to traditional SSSD. Kabeel et al. (2018b) analyzed the effect of jute cloth doped with sand sensible heat storage on the productivity of SSSD. It was observed that the usage of jute cloth mixed with sand thermal storage improved the productivity by 18.0% compared to references SSSD at 20 cm saline water depth. Subudhi and Sahoo (2019) analyzed the effect of jute cloth and internal reflectors on the SSSD performance. It was revealed that the accumulative yield was increased by 72.10% compared to the conventional SSSD. The effects of basin materials (steel, copper, and aluminum), as well as their metal chips, bandage on the total water output of wick type SSSD were experimentally investigated by Sharshir et al. (2020a). It was refereed that the SD with copper absorber integrated with wick-copper rings exhibited the maximal productivity improvement (62.30%) compared to all the other arrangements. In another effort, Sharshir et al. (2020b) studied the applicability of stepped double slope SD with carbon black nanomaterial and linen wicks. This combination resulted in an improvement in overall productivity and daily efficiency by 80.5 and 110.5%, respectively, over traditional SSSD. Omara et al. (2016) studied the performance of corrugated SSSD with wicks and internal reflectors. Results indicated the efficiency of the modified corrugated SSSD and conventional SSSD were approximately 59% and 33%, respectively. El-Sebaii and Shalaby (2014) numerically studied the performance of v-corrugated basin SSSD. The numerical results showed that the corrugated basin improved the productivity by 24.0% compared to the flat basin SSSD. Shalaby et al. (2016) researched experimentally the impact of corrugated basin with wicks and phase change material (PCM) on the energetic performance of the SSSD. It was deduced that the modified SSSD with wicks ad PCM improved the productivity by 12.0% when compared to classical SSSD. Kabeel et al. (2021b) mathematically and experimentally studied the effect of using v-corrugated absorber and wick materials on the tubular solar still performance. The results show that the average daily efficiency and accumulated yield for the tubular still were improved by 47.0% and 44.8% compared to the conventional distiller. Elshamy and El-Said (2018) analytically analyzed the effects of the geometry of the absorber basin on the productivity of tubular solar distiller. They inferred that the utilization of a semi-circular corrugated basin ameliorated the distilled output by 26.5% compared to the other studied basin geometries. Kabeel et al. (2016) carried out experiments on the impact of tilt angles of glass cover surface on the productivity of square pyramid solar distillery (SPSD). Three similar SPSD with several cover angles of i.e. 50.0°, 40.0°, and 30.5° were examined. It was obtained that distilled yields of 2.94, 3.50, and 4.30 were attained at tilt cover angles of i.e. 50.0°, 40.0°, and 30.5°, respectively. In a later effort, a pyramid SD with TiO_2 nano/black paint was designed and fabricated by Kabeel et al. (2019b). They showed that the usage of TiO_2 nano mixed with black paint limitedly enhanced the overall productivity of the pyramid SD by 6.10%, respectively, compared to the uncoated distiller at 1.0 cm water depth.

Recently, one of the used tools for augmenting productivity and decreasing the losses of the solar distillers is a promising design, which is defined as a trays solar distiller (TSD). The thermo-economic performance of TSD was theoretically and experimentally proposed by Abdallah et al. (2020a). The design of TSD was made via modifying the traditional SSSD by inserting internal metal trays at the interior sides of the distiller as well as utilizing exterior and interior mirrors at the bottom and top. The results indicated that the proposed TSD achieved a 95.0% increment in the distilled yield over the conventional SSSD. In a consecutive effort (Abdullah et al., 2020b), they experimentally studied the effect of coating the TSD surfaces with the black paint mixed CuO nanopowder. Moreover, paraffin wax doped with nano CuO was added below the distiller basin as a TES material. It was shown the freshwater distillate was increased by 108% compared to the conventional SSSD.

Novelty and objectives of the current study

From the aforementioned survey, it is inferred that there are diverse types of SD designs such as a traditional single slope, tubular, pyramid, stepped, trays, and wick type solar distillers. Several studies have been introduced different modifications to improve the productivity of conventional SDs. The reviewed results summarized that the maximization of seawater vaporization from the basin of the distiller is achieved by either implementing porous materials such as (cotton, jute, linen) wicks; or integrating TES materials such as sensible heat storage/pure PCMs or nano-composite PCMs. Moreover, the reviewed studies showed that the corrugated wick absorber basins have an effective influence on augmenting the vaporization rate and thus maximizing the freshwater yield of conventional SSSDs. Additionally, it is revealed that there are few studies on the effect of using metal trays of the thermal performance solar distillers. Besides, it is also found that there are no particular studies that investigated the dual combination of utilizing v-corrugated absorber basin with metal trays and wick materials for augmenting the surface evaporation area of saline water for the solar distiller.

The present work aims to improve the performance of hemispherical cover solar still through an experimental study of proposed modulations applied to the traditional hemispherical solar still. The modification was fulfilled by using the V-corrugated absorber basin with iron trays and wicks to maximize the vaporization rate, in order to attain the maximal conceivable usage of the large condensing surface area, which characterize the hemispherical solar stills to ameliorate the total distilled yield and daily efficiency. Therefore, the innovation for this study targets to develop an improved design of a hemispherical solar distiller that could supply a significant amount of freshwater using a novel v-corrugated basin hemispherical solar distiller embedded with iron trays and wick materials, which has not yet been studied. Hence, the hemispherical solar distillers with flat and v-corrugated trays configurations were studied. Three distillers were designed, examined, and compared. The tested solar distillers were conventional hemispherical solar distiller (CHSD), hemispherical solar distillery with, with V-corrugated iron trays (HSD-VIT), and hemispherical solar distiller with flat iron trays (HSD-FIT). Moreover, the effects of using a double wick layer in the basin of HSD-VIT and HSD-FIT have been also investigated and compared with that of the CHSD. Experiments were carried out at the outdoors conditions of El-Oued (33°27'N, 7°11'E), Algeria. In addition, a cost analysis is also conducted to estimate the freshwater unit cost for the five studied hemispherical distillers.

Experimental Methodology

This experimental work targets to achieve the highest performance in hemispherical solar distillers. The experimental apparatus is clearly schematized in Fig. 1 (a) and photographically displayed in Fig. 1 (b) and Fig. 1 (c). The whole experimental apparatus is mainly composed of a feed saline water tank, wooden groove supporting base, and three hemispherical solar distillers. The three solar hemispherical distillers are conventional hemispherical solar distiller (CHSD), V- hemispherical solar distillery with, with V-corrugated iron trays (HSD-VIT), and hemispherical solar distiller with flat iron trays (HSD-FIT). All three stills have a projected area of 0.11 m^2. The three hemispherical stills are carried on a wooden groove base of 2.50 cm deep and 38.0 cm diameter. The CHSD has a traditional circular solar basin fabricated from wood with 38.0 cm diameter, 2.50 cm thickness, and 4.0 cm depth edge. The bottom and interior sidewalls of the basin are painted with mat black rubber silicone to maximize the absorbtivity of incident solar energy. While the exterior sides walls are properly insulated with a polyester wrap of thickness 4.0 cm to minimize the heat losses to the surrounding. Moreover, the basin is covered by a hemispherical glass cap as a condensing surface with a 0.30 cm thickness and a diameter of 40.0 cm. On the second hand, the modified HSD-FIT is also technicality designed with the same dimensions as CHSD with adding new flat iron trays on the bottom of the solar still instead of the conventional basin to increase the evaporation area of the hemispherical solar distiller in order to maximize the heating of the water in the basin. The flat iron trays are designed with a circular area of 0.10 m^2, 3.0 cm height edge, and 0.30 cm thick. Thirdly, the HSD-VIT has also the same dimensions as CHSD, besides we used circular v-corrugated iron trays on the bottom of the basin of the still to further maximize the vaporization surface area for better evaporation. All the angles of v-corrugated bends are 60°, and the spacing between any two tops is 4.40 cm. The base of the corrugated basin has 7.0 bottoms and 7.0 tops of corrugated shape. In addition, a circular channel is installed at the down end of the glass cover for each distiller to collect the condensed water vapor, and thereafter a water bottle for collecting the distillate water yield. Experiments have been carried out on the proposed three hemispherical distillers under the same hot outdoors conditions of El-Oued (33°27'N, 7°11'E), Algeria in two consecutive days in October 2021 from 8:00 a.m. to 6:00 p.m. To fulfill the best amending that obtains the maximum freshwater productivity, the experiments were carried out in two experimental manners. To fulfill the best amending that reaches the maximum freshwater productivity, the experiments were carried out in two experimental manners. In the first manner, the thermal performance of the three distillers (CHSD, HSD-FIT, and HSD-VIT) has been tested and compared without using wick materials. In the second manner, the influences of flat and v-corrugated iron trays with wick materials on hemispherical still performances were investigated. Hence, in the 2nd testing manner, a double wick layer was added in the basin of HSD-FIT and HSD-VIT as seen Fig. 2, to maximize the vaporization rate in order to attain the maximal conceivable usage of the large condensing surface area, to further ameliorate the total distilled yield and daily efficiency of the distiller. Where the 2nd distiller became a hemispherical solar distiller with flat iron trays and wick materials (HSD-FIT & WM), and a 3rd became a hemispherical solar distiller with v-corrugated iron trays and wick materials (HSD-VIR & WM).

For each testing scenario, the temperatures and freshwater productivities of the modified hemispherical distillers have been measured and compared with that of the CHSD. During the experimentations, the amount of saline water in the basin of all tested distillers was set at 1.50 cm depth. K-type thermocouples (±0.10°C accuracy) have been attached at suitable positions in the three solar stills to measure the absorber basin, saline water, and glass cover temperatures as well as the ambient temperature was also monitored. Moreover, a data logging solarimeter (±10.0 W/m^2 accuracy) has been also utilized to record the total solar radiation. Furthermore, a graduated cylinder (accuracy ± 1.0 ml) was also used to measure the volume of hourly distillate. All measurements have proceeded on an hourly essential. The measuring accuracy, creative range, and uncertainty for the measuring instrumentations are summarized in Table 1. Based on the uncertainty, accuracy, and range of the measuring devices depicted in Table 1, the relative errors in the overall freshwater production and daily energetic efficiency are computed using the analysis described by Holman (2012), which are predestined to be 1.17% and 2.28%, respectively.

Table 1
Technical specifications for the utilized measuring devices.

Device	Accuracy	Range	Uncertainty
Solarmeter	± 10.0 W/m^2	0.00 - 1999 W/m^2	5.780 W/m^2
Thermocouple	± 0.10°C	−100 - +500°C	0.080°C
Graduated cylinder	± 1.00 ml	0.00 - 500 ml	0.5000 ml

Results And Discussion

The current investigation aimed to augment the distilled water production of the hemispherical solar distiller by implementing flat and v-corrugated iron trays absorber basins. To fulfill the optimal modification that reaches the maximum freshwater productivity, the experiments were carried out under the outdoors desert conditions of El-Oued (33°27'N, 7°11'E), Algeria in two typically consecutive days in October 2021 based on two experimental manners. In the 1st manner, the effects of using flat and v-corrugated iron trays absorber basins on the performance of hemispherical distillers were studied. Wherefore, three solar distillers were fabricated and examined; namely, conventional hemispherical solar distiller (CHSD), hemispherical solar distillery with V-corrugated iron trays (HSD-VIT), and hemispherical solar distiller with flat iron trays (HSD-FIT). In the 2nd manner, the impacts of utilizing flat and v-corrugated iron trays with wick materials on hemispherical still performances were investigated. Hence, a double wick layer was added in the basin of HSD-FIT and HSD-VIT in the 2nd testing manner, where the 2nd distiller became a hemispherical solar distiller with flat iron trays and wick materials (HSD-FIT & WM), and the 3rd still became a hemispherical solar distiller with v-corrugated iron trays and wick materials (HSD-VIR & WM).

Figure 3 displays the hourly fluctuation of total solar intensity and weather temperature as a function of local time for two of the typical test days for the two experimental sceneries of the proposed hemispherical distillers in October 2021 (07-10-2021 & 08-10-2021) from 8:00 a.m. to 6:00 p.m. It can be observed in Fig. 3 that the trends of solar irradiance within the two experimented days are the same which increments gradually to the maximum value in midday's and slightly reduces till afternoon time. It is recorded that the average and maximum solar intensity values are found to be 619.3 and 1006.0 W/m^2, respectively. While the averagely and maximal ambient temperatures are recorded to be 38.2 and 44.0 ^oC, respectively.

The thermal performance of HSD-VIT and HSD-FIT have been examined with and without using wick materials (WM) and compared with CHSD. The measured values for basin water temperature of the five studied distillers (HSD-VIR&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD) at constant saline water level (1.50 cm) are presented in Fig. 4. It indicates that HSD-VIR&WM has the maximal saline water temperatures, followed by HSD-FIT&WM, HSD-VIT, and HSD-FIT, respectively, whereas the CHSD has the minimal saline water temperatures. It is found that the water temperatures of the basin for HSD-VIR&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT show about 0 – 8°C, 0 – 6°C, 0 – 5°C, and 0 – 2°C greater than that for CHSD, respectively. The significant increase in water basin temperature of the HSD-VIR&WM compared to the CHSD is due to the combined utilization of v-corrugated iron trays and wicks with the absorber basin, which remarkably maximized the vaporization surface area and thus, the condensation and evaporation rates in HSD-VIR&WM were higher than that of CHSD, especially that the temperatures of glass cover were almost the same for the HSD-VIR&WM and the CHSD. It is found that the mean and maximum water temperatures of the HSD-VIR&WM are recorded to be 69.0 and 59.2 ^oC, respectively, whereas they are obtained to be 61.0 and 51.54 ^oC, respectively, for the CHSD.

Figure 5 illustrates the hourly fluctuation of the temperature of exterior and interior cover surfaces of the hemispherical still under the diverse modified cases (HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD). It is obvious that the temperatures of the inner surface of the glass cover surface are higher than that of the outer cover surface, as a result of the distilled content collected on the inner surface of the glass casing of the distiller. Also, as shown in Fig. 5, the HSD-VIR&WM indicated a higher glass temperature than CHSD by about 0 – 1.0°C. The increment in the cover temperature of the HSD-VIR&WM is due to higher condensation and vaporization rates than CHSD as a result of a larger vaporization area for HSD-VIR&WM. The difference between the interior surfaces temperatures of the glass of all studied solar stills was about 0.0–1.5°C.

The diurnal changes in hourly freshwater productivity for all investigated cases of hemispherical distillers (HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD) at a saline water depth of 1.5 cm inside the distillers are displayed in Fig. 6. As respected, it is clear that at all times the HSD-VIT&WM inhibited the highest distilled water productivities, followed by HSD-FIT&WM, HSD-VIT, and HSD-FIT, respectively, whereas the lowest distilled water productivities are obtained by the CHSD. The latter result is due to that the use of v-corrugated iron trays basin in the HSD-VIR&WM remarkably increased the saline water temperature and thus augmented the rates of distilled vapor generation and freshwater productivities as a result of the larger vaporization area for HSD-VIR&WM. Besides the utilization of wick materials acts as a thermal moderator by further increasing the water heating in the v-corrugated iron trays basin by the heat energy transferred by radiation and convection from the pores of wick materials. Figure 5 indicates that the hourly output freshwater had low values in the morning at the outset of the solar distiller and progressively increases with time attaining maximal productivity midday, and afterward it gradually decreases till late evening. The experimental findings unveiled that the hourly distillate was maximum at 02:00 pm, where it was recorded to be 1.0, 0.95, 0.85, 0.65, and 0.60 kg/m^2.h for HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD, respectively.

Figure 7 demonstrates the accumulative amounts of freshwater for the five investigated cases of hemispherical solar distillers. It is obvious from Fig. 7 that the v-corrugated basin hemispherical solar distiller embedded with iron trays and wick materials outperformed the best accumulative productivity compared with other modifications of hemispherical distiller arrangements and traditional hemispherical distiller, for the same above-previously mentioned reasons. The maximum accumulated water distillate was found to be 7.05 kg/m^2.d, for the HSD-VIT&WM, while the corresponding for the HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD were about 5.95, 5.50, 4.40, and 3.85 kg/m^2.d, respectively. This refers to that the total accumulative productivity of modified hemispherical distiller with v-corrugated iron trays and wicks are enhanced by 83.12% more than that for CHSD.

The performance of the five investigated hemispherical distillers has been compared and assessed in terms of the daily energy efficiency and total distillate production and of the distiller. The daily efficiency of the still η, is a vital parameter to figure out the actual improvement in the performance of solar distiller from the perspective of the total energy received by the distiller. It accounts on the entirety of hourly yield Σm_w, latent heat of the vaporization h_l, daily solar intensity $\Sigma I_s(t)$, and surface area of the basin A_s, as described in the following equation;

$$\eta = \frac{\sum h_l \times m_w}{\sum A_s \times I(t) \times 3600}$$

1

Figure 8 demonstrates a bar chart of the total cumulative yield and daily thermal efficiency along with their amelioration percentages for the four modified hemispherical distillers (HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT) compared to the CHSD. It is reported that the HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT obtained an enhancement in the total cumulative yield of 83.12% (7.05 kg/m^2.day), 54.55% (5.95 kg/m^2.day), 42.85% (5.50 kg/m^2.day), and 14.30% (4.40 kg/m^2.day), respectively, over the CHSD at a constant saltwater deepness of 1.5 cm over day cycle. Moreover, the daily efficiency of CHSD, HSD-FIT, HSD-VIT, HSDFITWM, and HSDVITWM has been computed to be 33.94, 38.72, 48.28, 52.16, and 61.67%, respectively. It is obviously confirmed that employing flat iron trays and v-corrugated iron trays improves the daily efficiency of the hemispherical distiller by about 14.06 and 42.23%, respectively, over that of CHSD. While, the addition of wick materials to the flat iron trays and v-corrugated iron trays further enhances the daily efficiency of the hemispherical distiller by about 53.66 and 81.68%, respectively, over that of CHSD. Accordingly, the latter results inferred that the amalgamation between two those efficacious modifications (v-corrugated iron trays and wick materials) regards as the best choice among the different investigated modifications for augmenting the freshwater productivity and daily efficiency of the hemispherical solar distillers.

Comparison with other published designs of solar stills

To clarifier the significance of utilizing the proposed V-corrugated iron trays and wick materials in ameliorating the performance of solar stills. A comparison between the results of recent work with these of other relevant studies established in solar stills has been demonstrated in Table 2. The obtained enhancements in both daily efficiency ad total water production exhibited a good performance compared to those revealed by other previous works.

Table 2
Comparison between the results of the current work and previous relevant studies in performance improvement of solar distillers.

Ref	**Design of solar distiller**	**Additives and modifications**	**Daily productivity (kg/m^2.day)**	**Daily Eff. (%)**	**Productivity increase (%)**
Kabeel et al., (2018b)	Single slope solar distiller	Jute cloth wicks mixed with sand	5.90	56.0	18.0
Sharshir et al., (2020a)	Single slope solar distiller	Copper absorber with wicks and copper chips	6.30	60.9	62.30
Sharshir et al., (2020b)	Stepped double slope distiller	Carbon black nanoparticles and linen wicks	4.46	60.2	80.5
Shalaby et al., (2016)	Single slope solar distiller	V-corrugated basin and PCM	3.76	37.1	12.0
Kabeel et al., (2021b)	Tubular solar still	V-corrugated basin and wicks	4.15	51.4	44.82
Elshamy and El-Said, (2018)	Tubular solar still	Semicircular corrugated absorber	3.40	34.1	26.47
Kabeel et al., (2019b)	Pyramid solar distiller	TiO_2 nano mixed with black paint	6.60	-	6.10
Abdullah et al., (2020a)	Single slope solar distiller	- Flat steel trays at the basin sides - Flat trays with internal mirrors - Flat trays with internal and bottom exteral mirrors - Flat trays with internal and (bottom+top) exteral mirrors	2.95 3.40 4.05 4.20	41.0 42.0 44.0 50.0	45.0 57.0 84.0 95.0

Ref	Design of solar distiller	Additives and modifications	Daily productivity (kg/m^2.day)	Daily Eff. (%)	Productivity increase (%)
This study	Hemispherical solar distiller	- Basi with flat iron trays - Basi with corrugated iron trays - Basi with flat iron trays and wicks - Basi with corrugated iron trays and wicks	4.40 5.50 5.95 7.05	38.72 48.2852.16 61.67	14.30 42.85 54.55 83.12

Economic analysis

In this section, an economic analysis is conducted to assess the economic feasibility of the developed modifications applied for the proposed hemispherical distiller to determine and compare the cost per unit of distilled water produced of all studied distillers. The daily freshwater productivity for HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD were 7.05, 5.95, 5.50, 4.40, and 3.85 kg/m^2.d respectively. The cost analysis is accomplished accounting on Eqs. (2-8) that were described by (Attia et al., 2021e; Kabeel and Abdelgaied, 2017);

The cost per freshwater liter (C_W) can be calculated as follows:

$$C_W = \frac{TAC}{M_{W,\,annual}} = \frac{TAC}{M_{W,\,daily*N}}$$

2

Where TAC is the sum of total annual cost, M_{daily} is the daily accumulative yield, and N refers to the number of operating days of still over the year, which is assumed to be 270 days to attain reliable water cost results and consider the scarcity of solar energy through the seasons of the year (Kabeel and Abdelgaied, 2019). TAC can be computed as follows;

$$TAC = AFC + AMOC - ASV$$

3

Where AFC is the yearly fixed cost that is described by Eq. (4), whereas $AMOC$ is the annual maintenance and operating cost which is computed by Eq. (6) (Kabeel and Abdelgaied, 2019); While ASV depicts the yearly salvage value which is represented by Eq. (7);

$$AFC = TCC * CRF$$

4

Where *TCC* is the total capital cost of the distiller system and *CRF* is the capital recovery factor that is represented by Eq. (5);

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

5

Where K_d is the yearly discount rate (12%), and *i* refers to the lifetime of the still (10 years).

$$AMOC = 30\% * TAC$$

6

$$ASV = S * SFF$$

7

The salvage value of the distiller (*S*) is considered 20% of the total capital cost (Kabeel and Abdelgaied, 2019). While the sinking funding index (*SFF*) can be represented as:

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

8

Table 3 demonstrates the findings of the cost analysis of the proposed hemispherical distillers. The economical findings revealed that the cost per litre of freshwater for the HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT were lower than CHSD by 41.72% (0.0081 $/L), 33.81% (0.0092 $/L), 25.18% (0.0104 $/L), and 10.79% (0.0124 $/L), respectively.

Table 3
Economic assessment for the proposed hemispherical distillers.

Financial Parameter	**CHSD**	**HSD-FIT**	**HSD-VIT**	**HSD-FIT&WM**	**HSD-VIT&WM**
Total capital cost of the still, *TCC* ($)	66.16	67.63	70.55	67.63	70.55
Annual fixed cost, *AFC* ($)	11.71	11.97	12.486	11.97	12.486
Annual maintenance and operating cost, *AMOC*, ($)	3.513	3.591	3.746	3.591	3.746
Salvage annual value, *ASV* ($)	0.754	0.771	0.804	0.771	0.804
Total annual cost, *TAC* ($)	14.47	14.79	15.43	14.79	15.43
Distillate productivity per year, (L/m^2.year)	1039.5	1188	1485	1606.5	1903.5
Cost per litre of freshwater productivity, C_w **($/L)**	**0.0139**	**0.0124**	**0.0104**	**0.0092**	**0.0081**

Conclusions

This study aims to enhance the energy and economic performance of hemispherical cover solar distillers using v-corrugated and flat iron trays materials. The iron trays were used on the bottom of the distiller basin in order to increase the vaporization surface area for better heat transfer of saline water. Three hemispherical distillers namely, conventional hemispherical solar distiller (CHSD), hemispherical solar distillery with flat iron trays (HSD-FIT), and hemispherical solar distiller with v-corrugated iron trays (HSD-VIT) were tested and compared at the outdoors conditions of El-Oued (33°27'N, 7°11'E), Algeria. Moreover, the effects of using wick materials (WM) in the basin of HSD-FIT and HSD-VIT have been also investigated and compared to that of CHSD. The key conclusions were deduced as follows:

- The utilization of v-corrugated iron trays within the basin of hemispherical distiller remarkably increased the saline water temperature and thus augmented the rates of evaporation as a result of the larger vaporization area. Besides the usage of wick materials acts as a thermal moderator by further increasing the water heating in the v-corrugated iron trays basin by the heat energy transferred by radiation and convection from the pores of wick materials.
- The HSD-VITWM achieved the maximal improvement from both freshwater production and thermo-economic performance among the different modifications applied to hemispherical distillers.
- The HSD-VITWM, HSD-FITWM, HSD-VIT, and HSD-FIT obtained an enhancement in the total cumulative yield of 83.12% (7.05 kg/m^2.day), 54.55% (5.95 kg/m^2.day), 42.85% (5.50 kg/m^2.day), and 14.30% (4.40 kg/m^2.day), respectively, over the CHSD.
- Utilizing flat and v-corrugated iron trays improved the daily efficiency of the hemispherical distiller by about 14.06% and 42.23%, respectively, over that of CHSD. While, the addition of wick materials to

the flat and v-corrugated iron trays further enhanced the daily efficiency of the hemispherical distiller by about 53.66% and 81.68%, respectively, over that of CHSD.

- Cost analysis indicated the economic feasibility of the different modulations applied to hemispherical stills as the cost per liter of freshwater for the HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT were lower than CHSD by 41.72% (0.0081 $/L), 33.81% (0.0092 $/L), 25.18% (0.0104 $/L), and 10.79% (0.0124 $/L), respectively.
- It can be inferred that the inclusion of v-corrugated iron trays ad wick materials in the basin of hemispherical solar distillers is a highly effective choice for augmenting the freshwater productivity and daily efficiency of the hemispherical solar distillers.

Declarations

Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

Author’s full name Authors Contributions

1 *Mohammed El Hadi Attia,* Expermental work, , Writing - original draft*,* preparation.

2 *Abd Elnaby Kabeel,* Swellam Sharshir, Conceptualization, Writing – Review &Editing.Supervisor

3-*Mohamed Abdelgaied,* Conceptualization, Me 441 thodology, Writing -,Review &

Editing.

4 Mohamed Zayed, Formal analysis and investigation. Writing -Review & Editing.

Funding

No any funding used in this paper

Competing Interests

No competing interests

Availability of data and materials

Not applicable

References

1. Abdelgaied M, Kabeel AE (2021) Performance improvement of pyramid solar distillers using a novel combination of absorber surface coated with CuO nano black paint, reflective mirrors, and PCM with pin fins. Renewable Energy 180:494–501
2. Abdelgaied M, Kabeel AE, Kandeal AW, Abosheiasha HF, Shalaby SM, Hamed MH, Yang N, Sharshir SW (2021) Performance assessment of solar PV-driven hybrid HDH-RO desalination system integrated with energy recovery units and solar collectors: Theoretical approach. Energy Conv Manag 239:114215
3. Abdelgaied M, Kabeel AE, Zakaria Y (2019a) Performance improvement of desiccant air conditioner coupled with humidification-dehumidification desalination unit using solar reheating of regeneration air. Energy Conv Manag 198:111808
4. Abdullah AS, Essa FA, Omara ZM, Rashid Y, Hadj-Taieb L, Abdelaziz GB, Kabeel AE (2019) Rotating-drum solar still with enhanced evaporation and condensation techniques: Comprehensive study. Energy Convers Manage 199:112024
5. Abdullah AS, Younes M, Omara ZM, Essa FA FA (2020a) New design of trays solar still with enhanced evaporation methods–Comprehensive study. Sol Energy 203:164–174
6. Abdullah AS, Essa FA, Bacha HB, Omara ZM (2020b) Improving the trays solar still performance using reflectors and phase change material with nanoparticles. J Energy Storage 31:101744
7. Aboelmaaref MM, Zayed ME, Zhao J, Li W, Askalany AA, Ahmed MS, Ali ES (2020) Hybrid solar desalination systems driven by parabolic trough and parabolic dish CSP technologies: Technology categorization, thermodynamic performance and economical assessment. Energy Conv Manag 220:113103
8. Agrawal A, Rana RS, Srivastava PK (2018) PK Application of jute cloth (Natural fibre) to enhance the distillate output in solar distillation system. Mater. Today Proc., 5: 4893-4902
9. Ahmed FE, Hashaikeh R, Hilal N (2019) Solar powered desalination – technology, energy and future outlook. Desalination 453:54–76
10. Attia MEH, Kabeel AE, Elaloui E, Abdelgaied M, Abdullah A (2022) Experimental study on improving the yield of hemispherical distillers using CuO nanoparticles and cooling the glass cover. Sol Energy Mater Sol Cells 235:111482
11. Attia MEH, Kabeel AE, Abdelgaied M, Abdel-Aziz MM, Bellila A, Abdullah A (2021a) Optimal size of black gravel as energy storage materials for performance improvement of hemispherical distillers. Journal of Energy Storage 43:103196
12. Attia MEH, Kabeel AE, Abdelgaied M, Abdullah A (2021b) 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 47:101465

13. Attia MEH, Driss Z, Kabeel AE, Alagar K, Athikesavan MM, Sathyamurthy R (2021c) Phosphate bags as energy storage materials for enhancement of solar still performance. Environ Sci Pollut Res 28(17):21540–21552
14. Attia MEH, Kabeel AE, Abdelgaied M, El-Maghlany WM, Bellila A (2021d) Comparative study of hemispherical solar distillers iron-fins. J Clean Prod 292:126071
15. Attia MEH, Kabeel AE, Bellila A, Manokar AM, Sathyamurthy R, Driss Z, Muthusamy S (2021e) A comparative energy and exergy efficiency study of hemispherical and single-slope solar stills. Environ Sci Pollut Res 28:35649–35659
16. Benoudina B, Attia MEH, Driss Z, Afzal A, Manokar AM, Sathyamurthy R (2021) Enhancing the solar still output using micro/nano-particles of aluminum oxide at different concentrations: An experimental study, energy, exergy and economic analysis". Sustainable Materials and Technologies 29:00291
17. Bellila A, Attia MEH, Kabeel AE, Abdelgaied M, Harby K, Soli J (2021) Productivity enhancement of hemispherical solar still using Al_2O_3–water–based nanofuid and cooling the glass cover. Applied Nanoscience 11:1127–1139
18. Darwish MA, Al-Juwayhel F, Abdulraheim HK (2006) Multi-effect boiling systems from an energy viewpoint. Desalination 194(1):22–39
19. El-Sebaii AA, Shalaby SM (2014) Parametric study and heat transfer mechanisms of single basin v-corrugated solar still. Desalination Water Treat 55(2):285–296
20. Elsheikh AH, Sharshir SW, Mostafa ME, Essa FA, Ali MKA (2018) Applications of nanofluids in solar energy: a review of recent advances. Renew Sustain Energy Rev 82:3483–3502
21. Elshamy SM, El-Said EMS (2018) Comparative study based on thermal, exergetic and economic analyses of a tubular solar still with semi-circular corrugated absorber.J. Cleaner Prod 195:328–339
22. Hansen RS, Narayanan CS, Murugavel KK (2015) Performance analysis on inclined solar still with different new wick materials and wire mesh. Desalination 358:1–8
23. Holman JP (2012) Experimental Methods for Engineers. Eighth ed., McGraw-Hill Companies, New York (2012)
24. Kabeel AE, Harby K, Abdelgaied M, Eisa A (2021a) Performance improvement of a tubular solar still using V-corrugated absorber with wick materials: Numerical and experimental investigations. Sol Energy 217:187–199
25. Kabeel AE, Abdelgaied M, Feddaoui MB (2018a) Hybrid system of an indirect evaporative air cooler and HDH desalination system assisted by solar energy for remote areas. Desalination 439:162–167
26. Kabeel AE, Abdelgaied M, El-Said EMS (2017a) Study of a solar-driven membrane distillation system: Evaporative cooling effect on performance enhancement. Renewable Energy 106:192–200
27. Kabeel AE, Omara ZM, Essa FA, Abdullah AS, Arunkumar T, Sathyamurthy R (2017b) Augmentation of a solar still distillate yield via absorber plate coated with black nanoparticles. Alexandria

Engineering Journal 56(4):433–438

28. Kabeel AE, El-Agouz SA, Sathyamurthy R, Arunkumar T (2018b) Augmenting the productivity of solar still using jute cloth knitted with sand heat energy storage. Desalination 443:122–129
29. Kabeel AE, Harby K, Abdelgaied M, Eisa A (2021b) Performance improvement of a tubular solar still using V-corrugated absorber with wick materials: Numerical and experimental investigations. Sol Energy 217:187–199
30. Kabeel AE, Abdelgaied M, Almulla N (2016) Performances of pyramid-shaped solar still with different glass cover angles: experimental study. 2016 7th International Renewable Energy Congress (IREC), pp. 1-6
31. Kabeel AE, Sathyamurthy R, Sharshir SW, Muthumanokar A, Panchal H, Prakash N, Prasad C, Nandakumar S, El Kady MS (2019b) Effect of water depth on a novel absorber plate of pyramid solar still coated with TiO_2 nano black paint. J Cleaner Prod 213:185–191
32. 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
33. 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
34. Katekar VP, Deshmukh SS (2020) A review of the use of phase change materials on performance of solar stills. J Energy Storage 30:101398
35. Kumbhar SV (2019) Double slope solar still distillate output data set for conventional still and still with or without reflectors and PCM using high TDS water samples. Data in Brief 24:103852
36. Lv H, Wang Y, Wu L, Hu Y (2019) Numerical simulation and optimization of the flash chamber for multistage flash seawater desalination. Desalination 465:69–78
37. Morad MM, El-Maghawry HAM, Wasfy KI (2015) Improving the double slope solar still performance by using flat-plate solar collector and cooling glass cover. Desalination 373:1–9
38. Omara ZM, Kabeel AE, Abdullah AS, Essa FA (2016) Experimental investigation of corrugated absorber solar still with wick and reflectors. Desalination 381:111–116
39. Patel M, Patel C, Panchal H (2020) Performance analysis of conventional triple basin solar still with evacuated heat pipes, corrugated sheets and storage materials. Groundwater for Sustainable Development 11:100387
40. Sahoo BB, Subudhi C (2019) Performance enhancement of solar still by using reflectors-jute cloth-improved glass angle. J Eng Res 16:1–10
41. Shalaby SM, El-Bialy E, El-Sebaii AA (2016) An experimental investigation of a v-corrugated absorber single-basin solar still using PCM. Desalination 398:247–255
42. Sharshir SW, Peng G, Elsheikh AH, Eltawil MA, Elkadeem MR, Dai H, Zang J, Yang N (2020a) Influence of basin metals and novel wick-metal chips pad on the thermal performance of solar desalination process. J Clean Prod 248:119224

43. Sharshir SW, Eltawil MA, Algazzar AM, Sathyamurthy R, Kandeal AW (2020b) Performance enhancement of stepped double slope solar still by using nanoparticles and linen wicks: energy, exergy and economic analysis. Appl Therm Eng 174:115278
44. Zayed ME, Zhao J, Elsheikh AH, Li W, Sadek S, Aboelmaaref MM (2021) A comprehensive review on Dish/Stirling concentrated solar power systems: Design, optical and geometrical analyses, thermal performance assessment, and applications. J Clean Prod 283:124664
45. Zayed ME, Zhao J, Du Y, Kabeel AE, Shalaby SM (2019) Factors affecting the thermal performance of the flat plate solar collector using nanofluids: A review. Sol Energy 182:382–396
46. Zayed ME, Zhao J, Li W, Elsheikh AH, Elbanna AM, Jing L, Geweda AE (2020) Recent progress in phase change materials storage containers: Geometries, design considerations, and heat transfer improvement methods. Journal of Energy Storage 30:101341

Figures

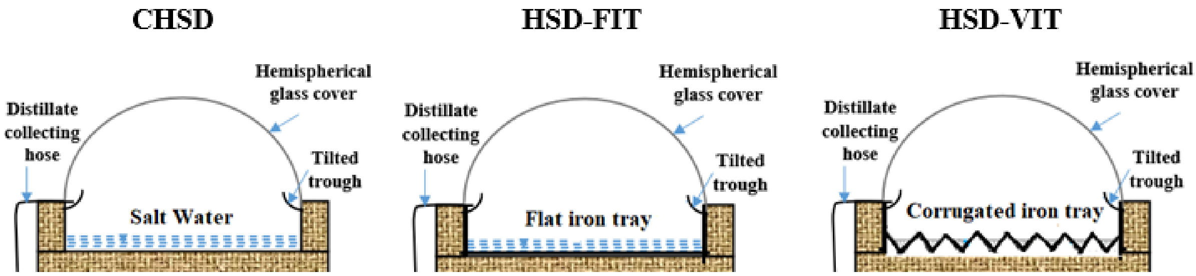

Figure 1

(a) Schematic diagram of the three proposed hemispherical distillers; (b) Photographic view of the developed absorber basins; (c) Photographic view of the experimental test rig.

wicks.

Figure 2

Schematic and photographic view; (a) Flat iron tray basin with wicks; (b) V-corrugated iron tray basin with wicks.

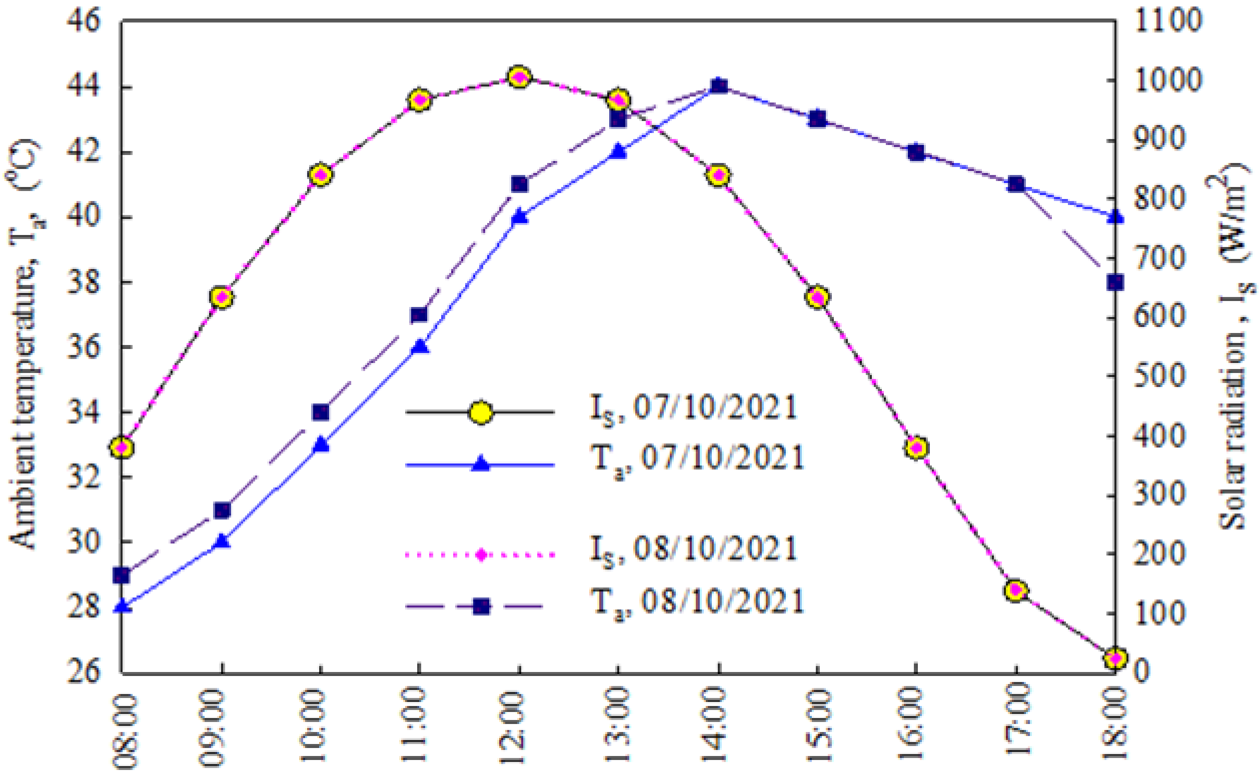

Figure 3

Hourly change of ambient temperature and total solar irradiance the different two testing days.

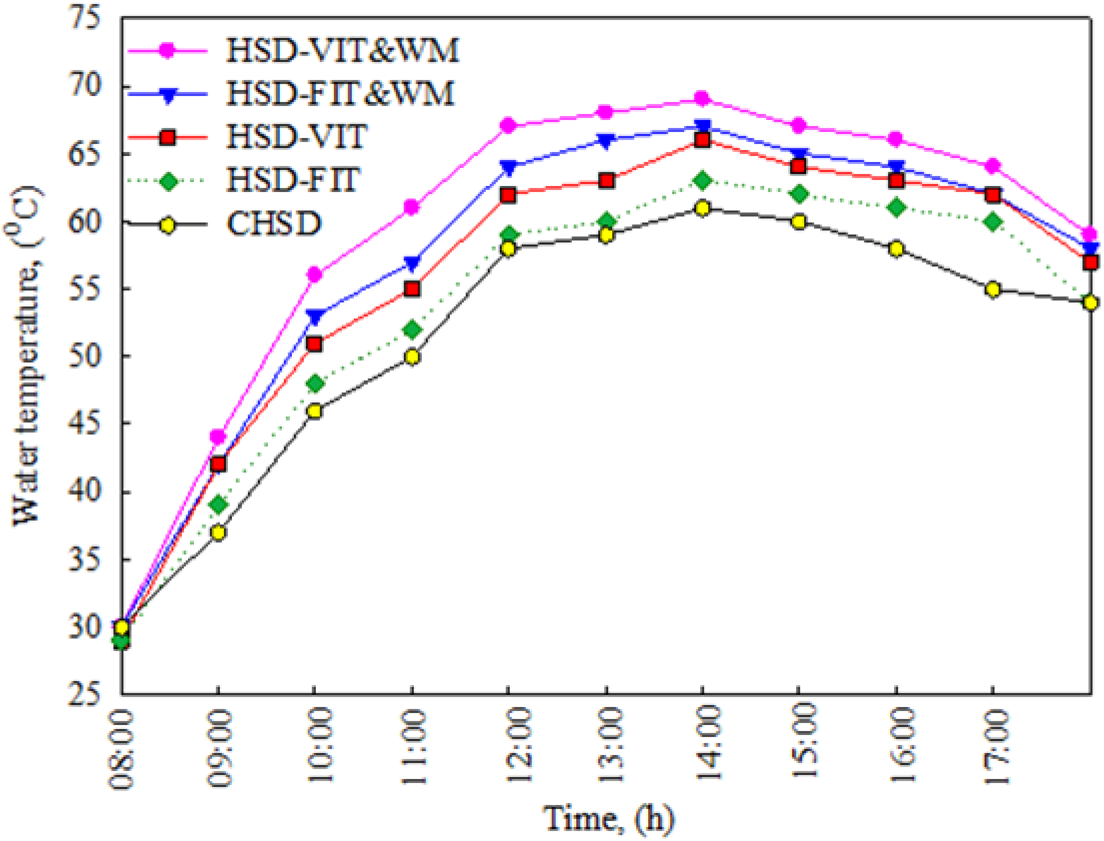

Figure 4

Hourly variation of saline water temperature for the proposed hemispherical distillers.

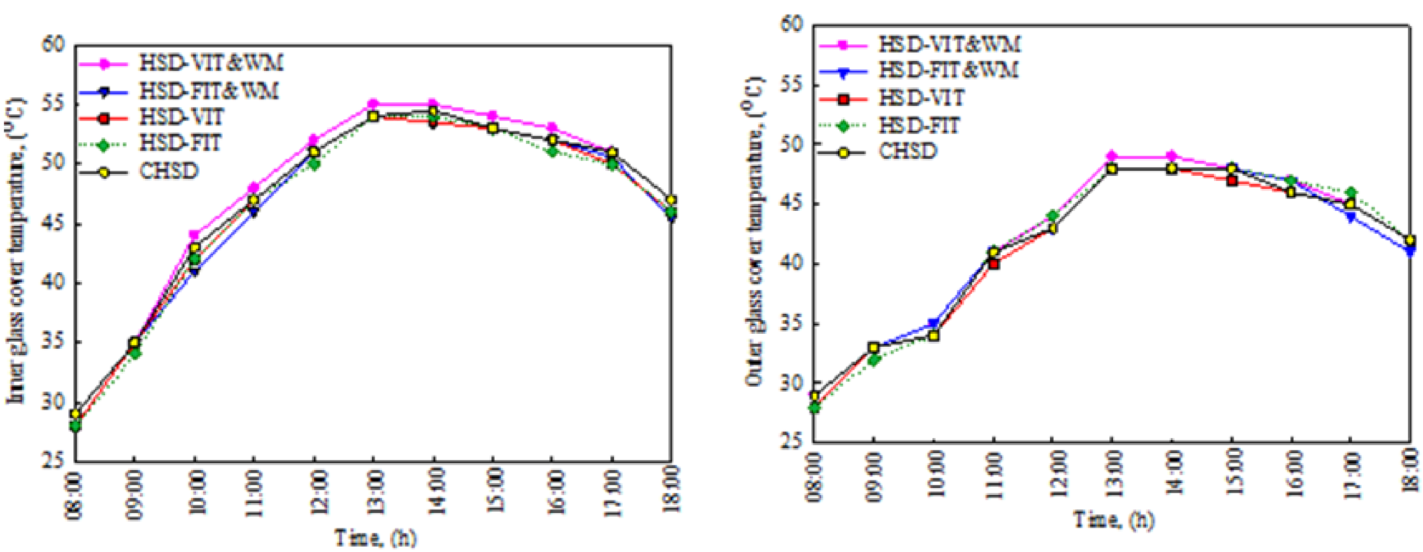

Figure 5

Hourly changes of exterior and interior surface temperatures of the glass cover for the proposed hemispherical distillers.

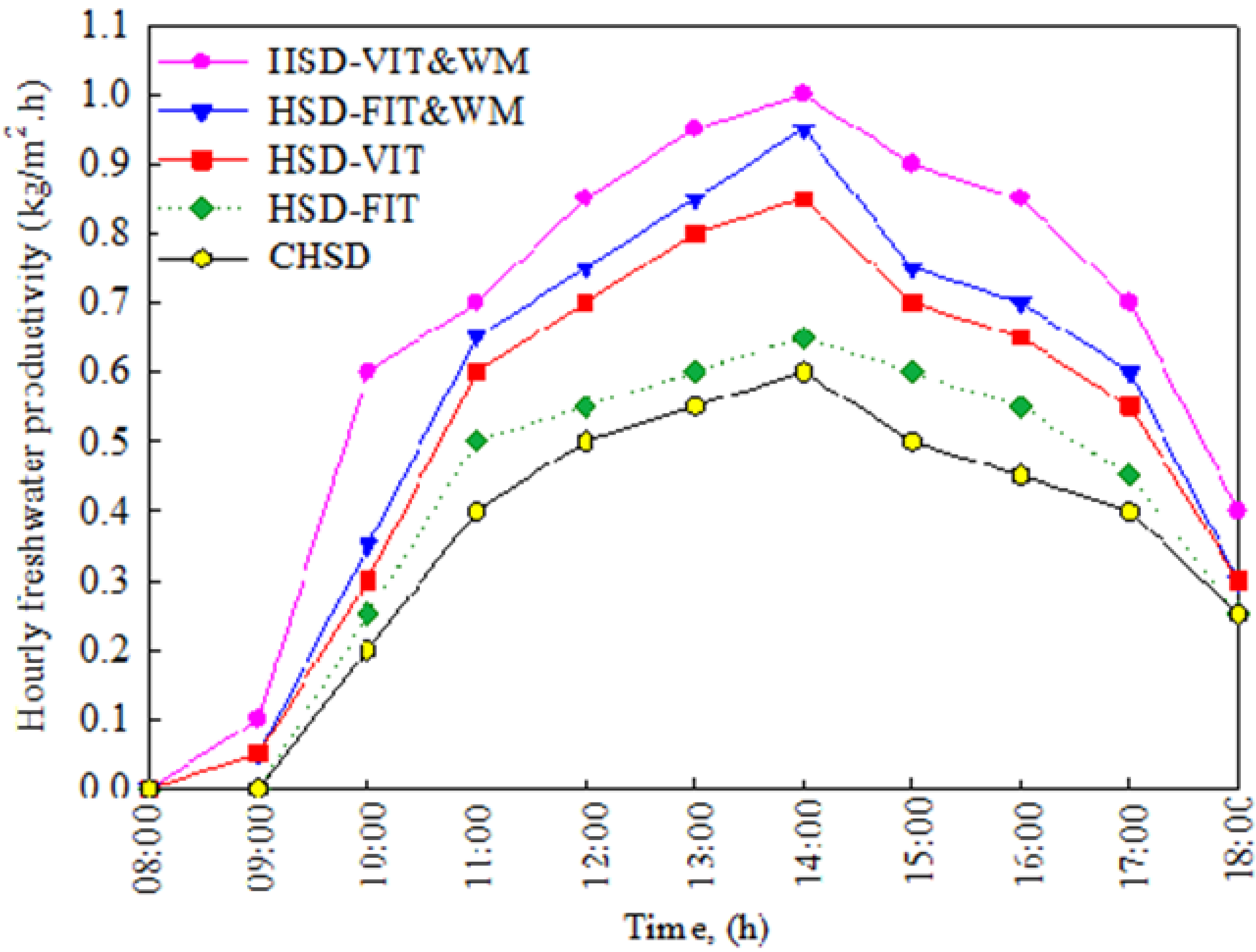

Figure 6

Change of the hourly freshwater production of the proposed hemispherical distillers.

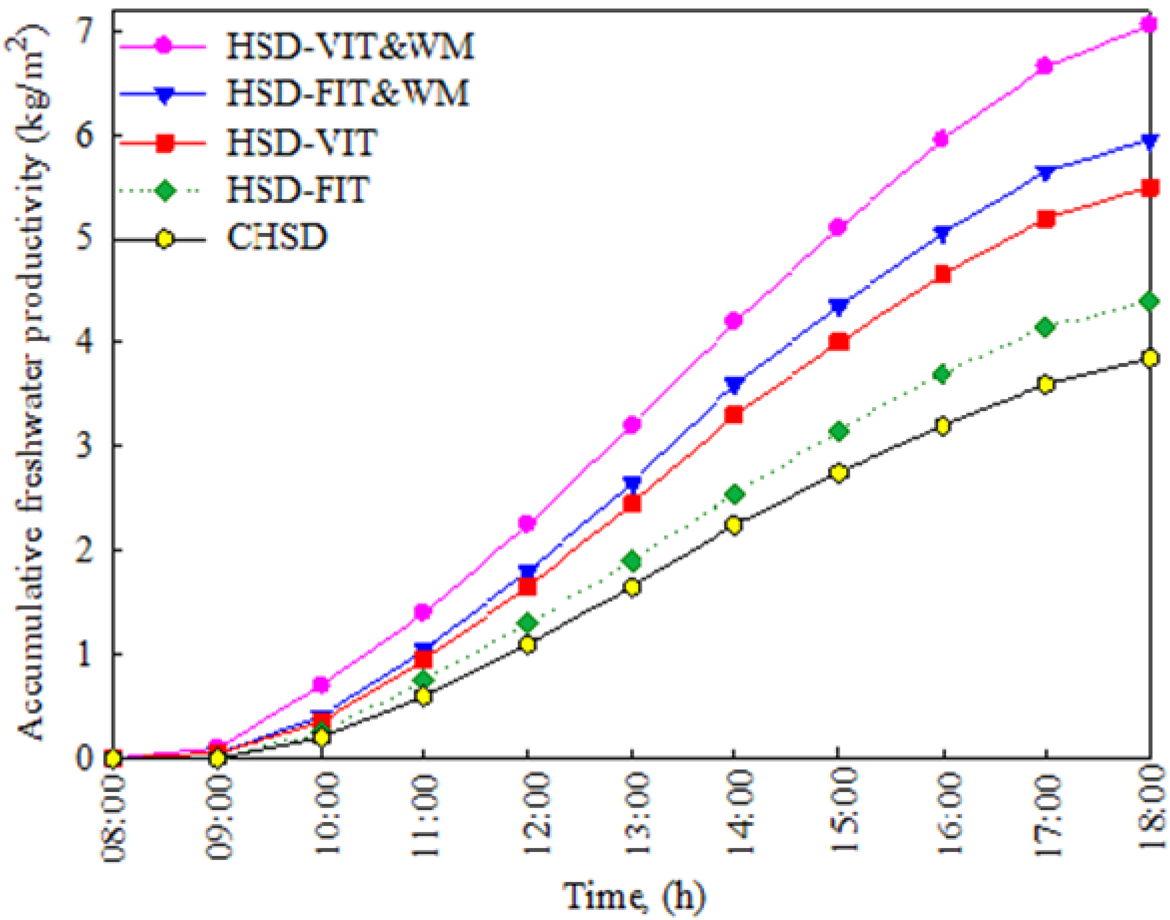

Figure 7

Hourly variations of the cumulative freshwater productivity of the proposed studied hemispherical distillers.

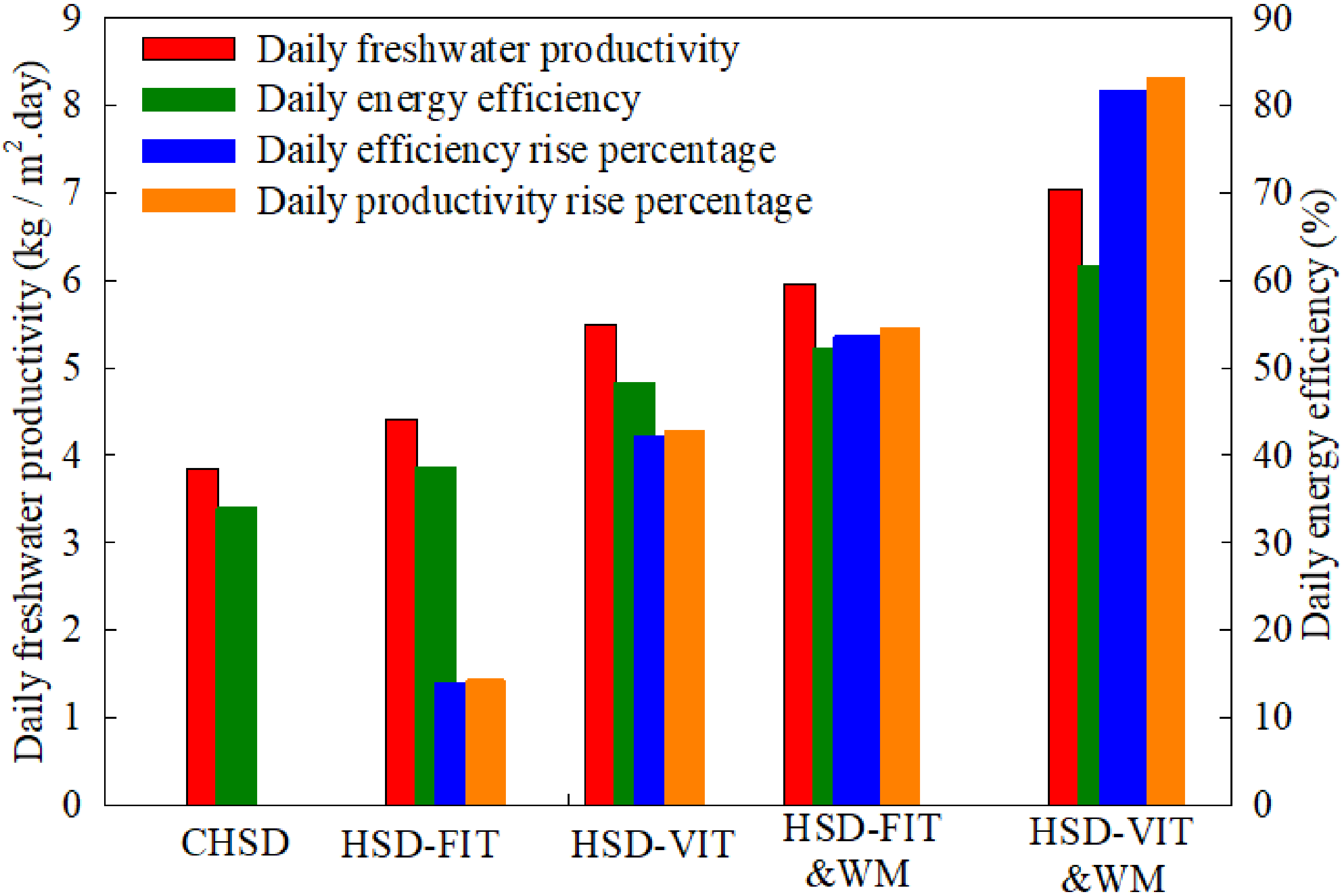

Figure 8

Total cumulative yield and daily thermal efficiency along with their amelioration percentages for the four modified hemispherical distillers (HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT) compared to the CHSD.