

STRUCTURE AND EXPERIMENTAL ANALYSIS OF A SOLAR-POWERED WATER DESALINATION SYSTEM ENHANCED WITH REFLECTORS

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Abstract. This study presents the structural design and experimental evaluation of a portable water desalination system equipped with crystalline solar cells serving as a photothermal absorber, and enhanced with lateral and bottom reflectors. Experiments were conducted under real open-sky conditions in Tashkent during the spring and summer seasons of 2025. The use of reflectors increased the solar radiation flux incident on the heat collector surface by 40–60%, reaching values exceeding 1500–1550 W/m² in the full-reflector configuration. As a result, the maximum working water temperature rose to 90–95°C, significantly accelerating the evaporation and condensation processes. Consequently, the overall thermal efficiency of the system increased to 55–65%, while the hourly and daily freshwater productivity improved by 45–50% and 35–40%, respectively.

Key words: solar radiation, solar cell array, reflector, heat collector, cooling system, conventional solar still.

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СТРУКТУРА ТА ЕКСПЕРИМЕНТАЛЬНИЙ АНАЛІЗ СИСТЕМИ ОПРИСНЕННЯ ВОДИ НА СОНЯЧНІЙ ЕНЕРГІЇ З ВИКОРИСТАННЯМ ВІДБИВАЧІВ

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У цьому дослідженні представлено конструкцію та експериментальну оцінку портативної системи опріснення води, оснащеної кристалічними сонячними елементами як фототермічним абсорбером, з додатковими бічними та нижніми відбивачами. Експерименти проводились у реальних умовах відкритого неба в Ташкенті протягом весни та літа 2025 року. Використання відбивачів збільшило потік сонячного випромінювання, що падає на поверхню теплоаккумулятора, на 40–60%, досягаючи понад 1500–1550 Вт/м² у конфігурації з повним набором відбивачів. Внаслідок цього максимальна

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робоча температура води підвищилась до 90–95 °С, що значно прискорило процеси випаровування та конденсації. Відповідно, загальна теплова ефективність системи зростає до 55–65 %, а годинна та добова продуктивність прісної води підвищилась на 45–50 % та 35–40 % відповідно.

Ключові слова: сонячне випромінювання, масив сонячних елементів, відбивач, теплоакумулятор, система охолодження, звичайний сонячний випарник.

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1. Introduction of research work

At present, the rapid increase in the demand for potable water has led to a global water scarcity issue. This situation is also evident in the Central Asian region, where expert forecasts indicate that by 2050, water resources in the Syr Darya basin may decrease by up to 5%, and in the Amu Darya basin by up to 15%. Moreover, due to population growth, the total water demand in Uzbekistan is expected to reach 7 billion m³ by 2030, with the possibility of doubling by 2050. Uzbekistan is among the countries with high solar radiation, experiencing an average of 270 days of clear and sunny weather annually. During the summer months, solar radiation flux density can reach up to 1000 W/m². Among the most convenient and sustainable energy sources, solar energy stands out and is currently widely utilized in various sectors serving human needs. One of these applications is the desalination of saline water to produce freshwater, which remains one of the simplest and most widespread methods [1]. In general, solar water desalination systems exhibit a variety of structural configurations, each demonstrating specific characteristics and efficiency performance [2].

The configurations shown in Fig. 1 include single-slope [4], single-basin [5], double-slope [6], stepped [7], V-type [8], cylindrical [9], hemispherical [10], double-basin [11], inclined [12], conical [13], multi-effect [14], triangular [15], desalination tower [16], multi-stage tubular [17], pyramid-shaped [18], tubular [19], and oval-shaped [20] systems. Despite numerous experimental studies conducted on solar water desalination units with diverse structural configurations, the identification of the most optimal design remains a complex and unresolved issue. This complexity arises from a combination of interrelated factors, including meteorological conditions, operational modes, geographical location, system operating duration, and the varying properties of materials used in fabrication.

Compared to other technologies, reverse osmosis (RO) is widely employed due to its high efficiency; however, it requires substantial energy consumption and complex maintenance [21]. Similarly, Multi-Stage Flash (MSF) distillation is effective for large-scale water production but demands very high energy input [22]. Membrane distillation (MD) offers an alternative approach that utilizes a temperature gradient and consumes relatively less energy, although its scalability remains limited [23]. Solar distillers (solar stills), on the other hand, provide an environmentally friendly solution, leveraging natural solar energy to purify saline water and representing a promising technology for potable water production [24]. These systems operate by heating saline water in a basin using solar radiation, while the generated vapor condenses on a relatively cooler transparent surface (glass), yielding distilled water [25]. Despite the simplicity of their design and low operational costs, the daily productivity of solar distillers remains relatively low, necessitating extensive research on design improvements and optimization through computational modeling [26, 27, 28]. Enhancing system efficiency is generally achieved by redesigning the unit, substituting materials, or integrating additional heating sources. While these approaches can improve performance to some extent, they are often economically expensive and challenging to implement on a large scale [29,30]. Nevertheless, solar-based desalination units are recognized as an effective solution for purifying contaminated or saline water, especially in remote areas lacking a centralized water supply. The water purification process inherently requires significant energy input, and recent increases in conventional fuel costs have further underscored the need to utilize renewable energy sources [31]. The productivity of solar distillers is primarily linked to the intensification of evaporation and condensation

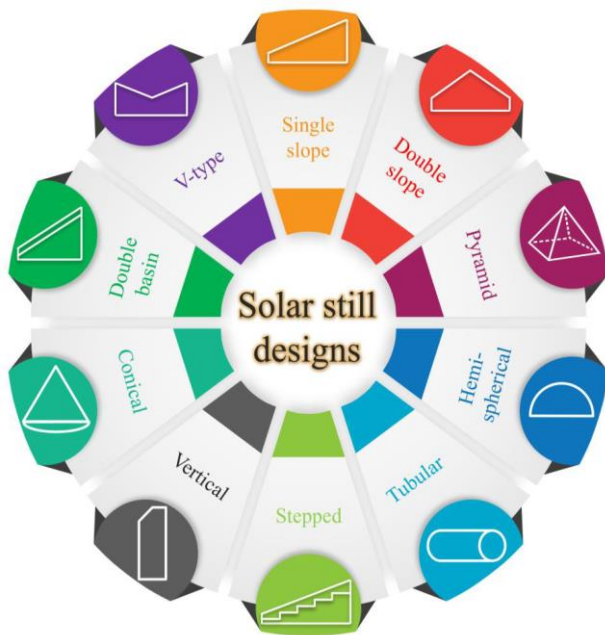


Fig. 1. Various structural designs of solar water desalination systems [3]

processes within the system. Overall efficiency depends on several critical design and thermal factors, including the depth of the evaporation basin, the solar radiation absorption capacity, heat transfer characteristics, and thermal losses through the bottom and side walls [32]. These constraints have driven extensive scientific research aimed at enhancing the performance of solar distillers. Notably, advanced technical solutions such as thermal energy storage systems [33], reflectors, integration of solar collectors, and external cooling systems [34] have been proposed. The objective of the present study is to develop a novel type of desalination unit in which a solar cell array is used as the absorber material in combination with reflective surfaces. This configuration aims to achieve higher efficiency compared to conventional solar stills by optimizing the capture and utilization of solar energy.

2. Materials and methods

2.1 Structural design of the system

Within the scope of this study, a solar water desalination unit was developed as a high-efficiency portable system designed to convert saline and mineralized water into

environmentally safe drinking water. The primary component of the system is a heat collector (HC). The heat collector was fabricated in the form of a rectangular box using AISI 316 stainless steel sheets with a thickness of 1 mm. The high corrosion resistance of this material, as well as its stability in saline environments, ensures long-term and reliable operation of the system.

The heat collector basin has a rectangular geometric shape with internal dimensions of 700×500×8 mm. This design allows for a relatively shallow water layer, promoting rapid and uniform water heating and intensifying the evaporation process. The total active heat-absorbing surface area of the system is 3300 mm². The device is equipped with high-reflectivity reflectors made of aluminum composite material, installed on the upper part and both lateral sides. These reflectors concentrate solar radiation onto the collector from three directions with an approximate optical incidence angle of 120°, achieving an optical concentration coefficient of $C \approx 1.9\text{--}2.1$. As a result, the overall solar radiation intensity incident on the collector surface was nearly doubled.

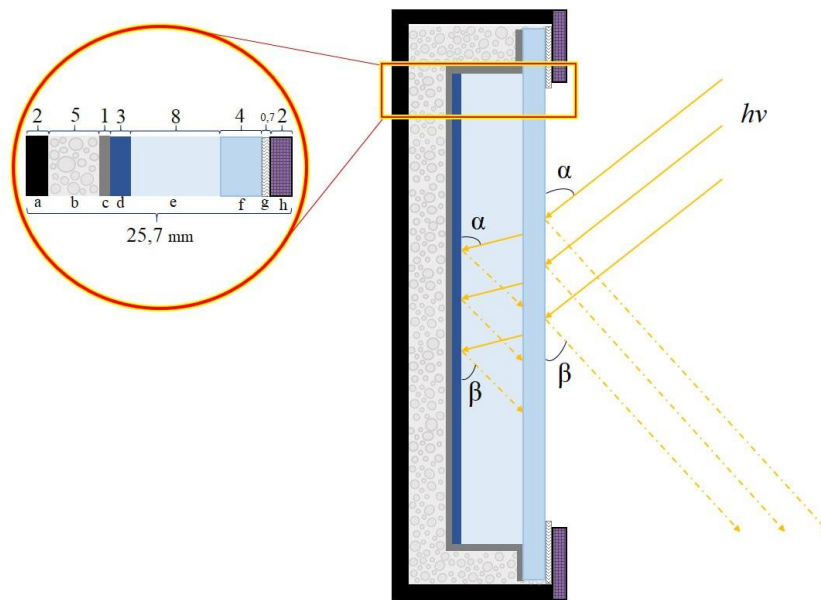


Fig. 2. Cross-sectional view of the reusable liquid section of the saline water desalination system

The system consists of several functional layers and components, each contributing to the overall thermal efficiency and the production of clean drinking water. The layers and their technical specifications are as follows (Fig. 2):

- **a** – Aluminum composite (Alucobond)-based steel frame (2 mm),
- **b** – Thermal insulation layer made of sintofon material (5 mm),
- **c** – Nickel-based heat collector (1 mm),
- **d** – Heat-absorbing solar cells (3 mm),
- **e** – Reusable water basin (8 mm),
- **f** – Transparent tempered glass (4 mm),
- **g** – Rubber sealing strip (0.7 mm),
- **h** – Steel frame fastener (2 mm).

Incident solar radiation ($h\nu$) passes through the transparent tempered glass and is absorbed by the solar cells positioned inside the heat collector. The angle of incidence (α) and the reflection angle (β) are shown in the schematic, illustrating the trajectory of solar radiation within the distiller. This configuration ensures optimal heat collection and retention, thereby accelerating the evaporation rate and significantly enhancing the overall freshwater production efficiency.

The internal section of the thermal collector (TC) is equipped with a crystalline silicon-based photovoltaic module with a nominal power of 60 W. The module consists of a front transparent protective glass layer with a thickness of 1.2–1.5 mm, a central layer comprising 108 interconnected solar cells, and a rear polymer-based laminating layer. The photovoltaic structure absorbs incident solar radiation and converts it into thermal energy, thereby ensuring effective utilization of the total thermal energy within the system.

2.2 Condensation system and cooling mechanism

To achieve rapid and efficient condensation of the generated water vapor, a cooling system constructed from high thermal conductivity copper material was employed. The cooling system accelerates the condensation process by rapidly reducing the vapor temperature, causing the resulting water droplets to flow under gravity into the lower

water collection container. Consequently, high-quality purified drinking water is obtained.

2.3 Experimental conditions

The experiments were conducted in 2025 under sunny weather conditions at the Heliopfield of the Institute of Physics and Technology in Tashkent. Each experimental run was carried out between 10:00 and 17:00. During the experiments, the initial salinity of the saline water was maintained at 30–35 g/L, and the initial water temperature was $t_0 = 12\text{--}15^\circ\text{C}$. Each experiment was repeated at least three times, and the average values were considered for analysis. The heat collector was positioned at an inclination angle of 26° relative to the horizontal. This angle was selected to optimize the perpendicular incidence of solar radiation based on the geographical latitude of Tashkent.

2.4 Measurement methodology and instruments

During the experiments, water temperature in the heat collector basin, ambient temperature, and solar radiation intensity were measured at 30-minute intervals. Temperature readings were obtained using a TA-278 culinary thermometer, while solar radiation intensity was measured using a Di-LOG SL101 pyranometer. The amount of produced freshwater was determined using a calibrated graduated cylinder (**Table 1**).

Table 1. Measuring instruments used during the experimental process

Instrument	Parameter	Resolution	Error	Measurement range
Di-LOG SL101 pyranometer	Solar radiation flux density	0,1 W/m ²	±5 W/m ²	0-2000 W/m ²
TA-278 thermometer	Temperature	0,1°C	± 1°C	-50 ...+300°C
Calibrated graduated cylinder	Freshwater productivity	1 ml	± 1 ml	0-500 ml

3. Results and Discussion

In this study, the performance of the newly designed solar-powered water desalination system was evaluated based on the temporal variation of solar radiation flux density incident on the heat collector (HC). The effective volume of the heat collector, which constitutes the main component of the system, was 8.7 liters, and it required an average of 3 minutes to fill completely [35]. Under solar irradiation, the heating of saline water initiated the evaporation process, which on average began after approximately 35 minutes [36]. The generated water vapor was condensed within a dedicated cooling system, and over an average duration of 47 minutes, the resulting droplets accumulated and were collected as purified water in a designated container.

The components shown in Fig. 3 are as follows: 1 – reflectors positioned on the upper part and both lateral sides of the device, 2 – active evaporation process, 3 – freshwater storage container. This study presents experimental data corresponding to the improved configuration of a portable

solar-powered water desalination system.

The temporal variation of the total solar energy incident on the surface of the heat collector (HC) can be determined using the following integral expression:

$$Q_{in} = A_c \int_0^t G(t) dt \tag{1}$$

where Q_{in} is the total solar energy incident on the collector surface during the given time interval (J), A_c is the active surface area of the heat collector (m²), $G(t)$ is the time-dependent solar radiation flux density (W/m²), and t is the duration of the experiment (s).

This expression allows for the calculation of the total solar energy received by the collector and serves as a key energetic parameter for evaluating the thermal efficiency of the system. The integral expression accounts for the temporal variation of measured solar radiation intensity under real operating conditions, providing an accurate assessment of energy input during the experiment.

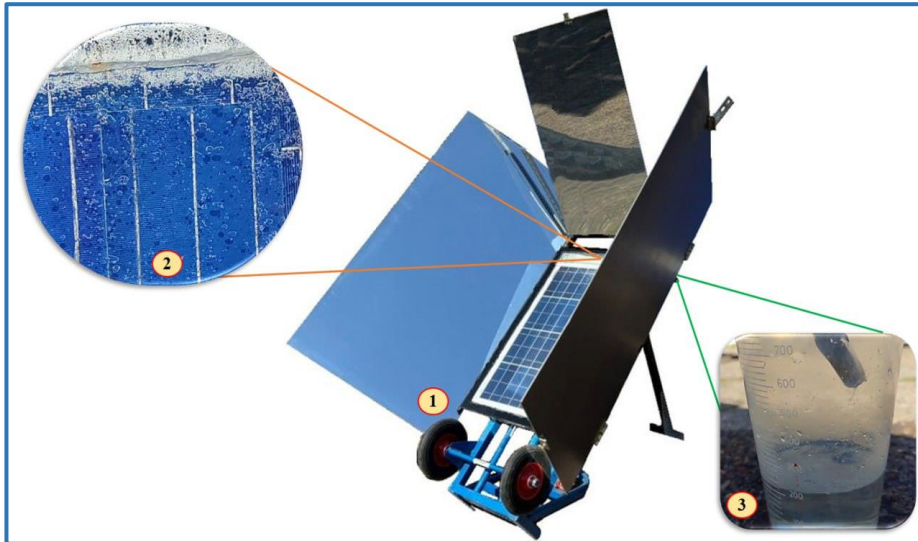


Fig. 3. View of the portable solar-powered water desalination system [37]

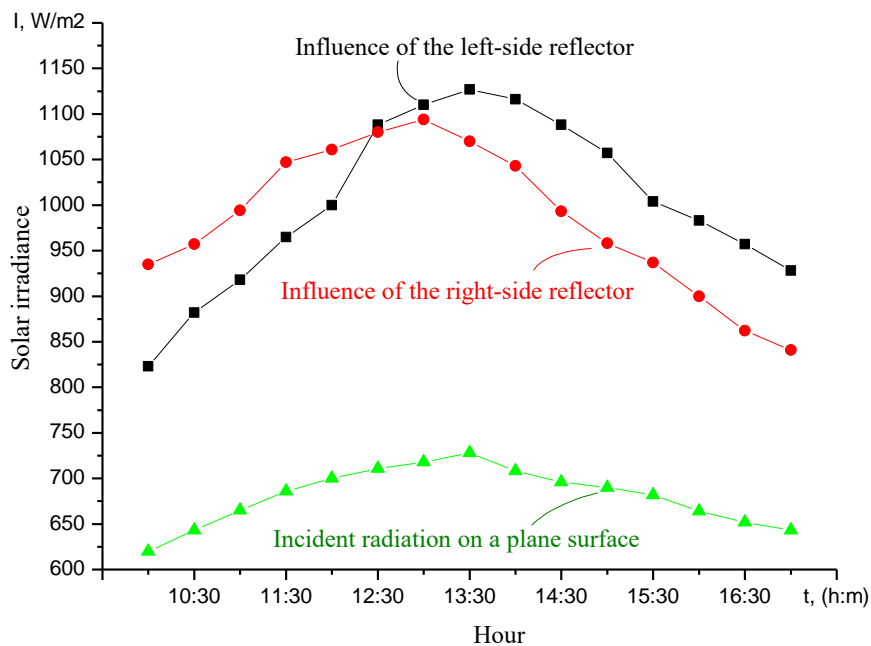


Fig. 4. Temporal variation of solar radiation incident on the front surface of the water desalination unit

The graph presented in Fig. 4 shows the temporal variation of the maximum and minimum solar radiation observed on March 17, 2025. Solar radiation is influenced by several primary factors, including atmospheric effects, geographic location, temporal factors, and solar activity [38, 39]. In order to enhance the efficiency of solar energy utilization, increasing the solar radiation flux directed onto the heat collector (HC) is a key technological objective. One of the optimal solutions for this purpose is the use of a reflector system, which increases solar energy input and maintains its stability throughout the day, making it a recognized scientific and practical approach.

Increasing the solar radiation flux accelerates the generation of thermal energy within the solar cell array located inside the collector. In this study, the solar radiation flux directed onto the collector surface was measured under different reflector configurations, and its temporal variation

was analyzed. According to the graph, under open-surface conditions, the maximum solar radiation flux was approximately 720–730 W/m² around midday.

When a left-side reflector was applied, the radiation flux increased significantly between 10:20 and 13:20, reaching a maximum of 1110–1130 W/m². For the right-side reflector configuration, the radiation flux was mostly observed in the range of 1080–1100 W/m². These results indicate that the additional radiation directed onto the collector surface by the reflectors significantly increases the incident solar radiation intensity compared to the open-surface case.

Furthermore, the graph shows that in the left-reflector configuration, the radiation intensity remained relatively stable throughout the day, with peak values recorded near midday. This behavior can be explained by the alignment of the reflector angle with the sun's diurnal movement.

Table 2. Quantitative comparison of experimental results on March 17, 2025

Condition	Maximum solar radiation W/m ²	Average solar radiation W/m ²	Relative Increase%
Open surface	725 ± 15	610 ± 20	–
Left-side reflector	1120 ± 20	945 ± 25	54.9
Right-side reflector	1090 ± 20	920 ± 30	50.8

Overall, the experimental results presented in Table 2 confirm that the use of reflectors for concentrating solar energy accelerates heat generation within the heat collector

and represents an important technical solution for enhancing the efficiency of solar-based water desalination systems.

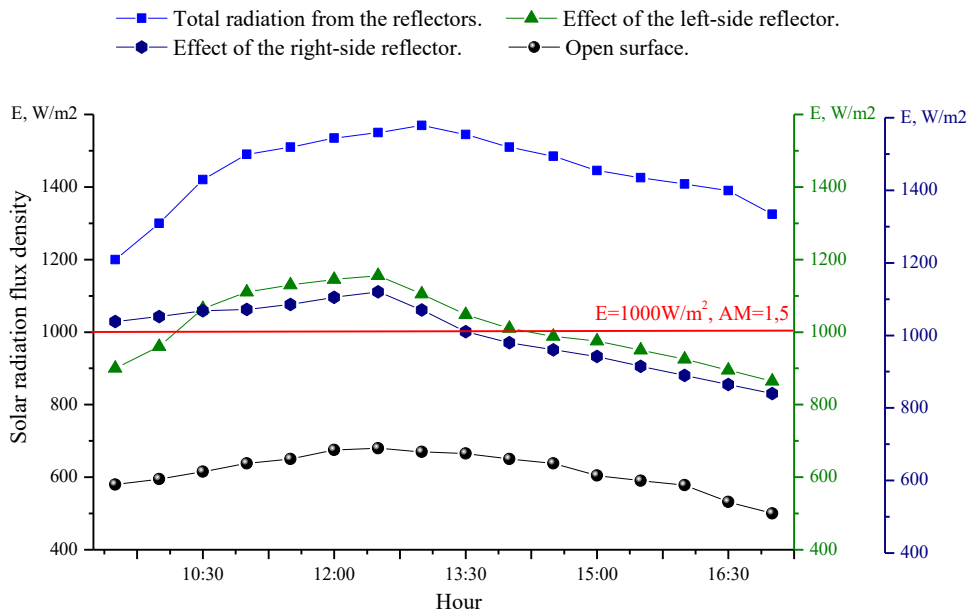


Fig. 5. Temporal variation of solar radiation measured on the front surface of the water desalination unit

The data presented in Fig. 5 were obtained on July 14, 2025, for the fully equipped reflector configuration (i.e., combined radiation from all reflectors). The solar radiation flux density incident on the heat collector reached a maximum of 1530–1550 W/m². This result indicates an increase of over 50% compared to the standard solar radiation intensity of 1000 W/m² under AM 1.5 spectral conditions [40]. Under the

influence of the left-side reflector, the solar radiation flux density varied between 1100 and 1170 W/m² during the time interval from 10:10 to 13:10. For the right-side reflector, the measured flux density ranged from 1050 to 1150 W/m². These results demonstrate that the use of reflectors can increase the solar radiation incident on the collector surface by 40–60% through additional directed radiation.

Table 3. Maximum and average solar radiation values under reflector influence

Condition	Maximum solar radiation W/m ²	Average solar radiation W/m ²	Relative Increase%
Open surface	980 ± 20	840 ± 25	–
Left-side reflector	1160 ± 25	1010 ± 30	20.2
Right-side reflector	1120 ± 25	980 ± 30	16.7
Full reflector system	1540 ± 30	1310 ± 35	55.9

The enhancement of solar radiation flux by the reflectors (Table 3) can be explained through geometric concentration. Solar rays reflected from the reflector surfaces are directed onto the collector surface, thereby increasing the

overall radiation balance. As a result, the rate of heat generation on the collector surface is accelerated, leading to an increased water heating rate and higher evaporation intensity.

The higher performance observed in the left-reflector configuration can be attributed to the optimal alignment of the reflector angle, the diurnal motion of the sun, and the reflectivity coefficient. In particular, the attainment of peak radiation flux near midday confirms that the reflector positioning ensures a near-perpendicular incidence of solar radiation on the collector surface.

The data presented in Fig. 6 were obtained on July 14, 2025, and show the temporal variation in water temperature within the HC basin and in ambient air temperature over the period from 10:00 to 17:00. The results indicate that, with increasing solar radiation intensity, the water temperature in the HC basin rose rapidly. At the initial stage of the experiment, the water temperature was approximately 25 °C, reaching its maximum value of 90–95 °C near midday (between 12:30 and 13:00). This behavior can be attributed to the efficient absorption of solar energy by the heat collector and the accumulation of thermal energy within the water.

During the afternoon, as solar radiation decreased, a gradual decline in the water temperature was observed.

Nevertheless, the water temperature remained elevated for an extended period, indicating that the collector material possesses a high heat capacity and experiences relatively low heat losses. This characteristic is critical for maintaining stable evaporation rates throughout the day.

The ambient air temperature remained significantly lower than the water temperature and exhibited relatively minor fluctuations over the course of the day. The maximum ambient temperature reached approximately 27–28 °C, followed by a decreasing trend. The considerable temperature difference between the water and the surrounding air establishes a high thermal gradient in the collector, thereby enhancing the evaporation rate and improving the overall thermal efficiency of the desalination system.

Overall, the experimental results confirm that the developed solar-based water desalination unit effectively utilizes solar thermal energy and maintains a high-temperature operational regime within the HC basin, demonstrating its potential for efficient performance under real-world conditions.

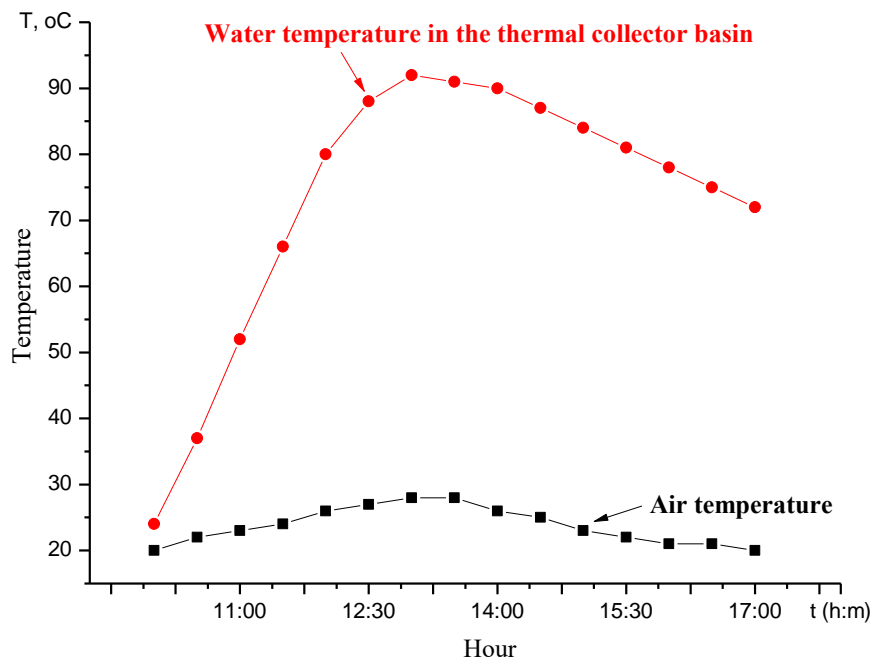


Fig. 6. Temporal variation of water temperature in the heat collector (HC) basin and ambient air temperature of the solar cell-based desalination unit equipped with reflectors

The data presented in Fig. 7 were obtained on March 17, 2025. At the beginning of the experiment, at 10:00 AM, the hourly freshwater productivity was approximately 50–70 ml/m²·h. With the increasing solar radiation intensity, this value rose rapidly, reaching a maximum of 410–430 ml/m²·h between 12:30 and 13:30. This represents an approximately 6–7-fold increase (~500–600%) relative to the initial value. After midday, as solar radiation decreased, the hourly productivity gradually declined, reaching around 150–170 ml/m²·h by 16:30, corresponding to a reduction of approximately 60–65% from the peak value.

This decline is attributed to the slowdown in the evaporation process and the decrease in the heat collector temperature.

The cumulative daily freshwater productivity, represented by the C curve, increased continuously throughout the day, reaching 3200–3400 ml/m² by the end of the experiment. At the beginning of the day, this value was nearly zero; by the early afternoon, it reached 1600–1800 ml/m², accounting for approximately 50–55% of the final cumulative productivity. This indicates that the main part of the distillation process occurs during the period of peak solar radiation.

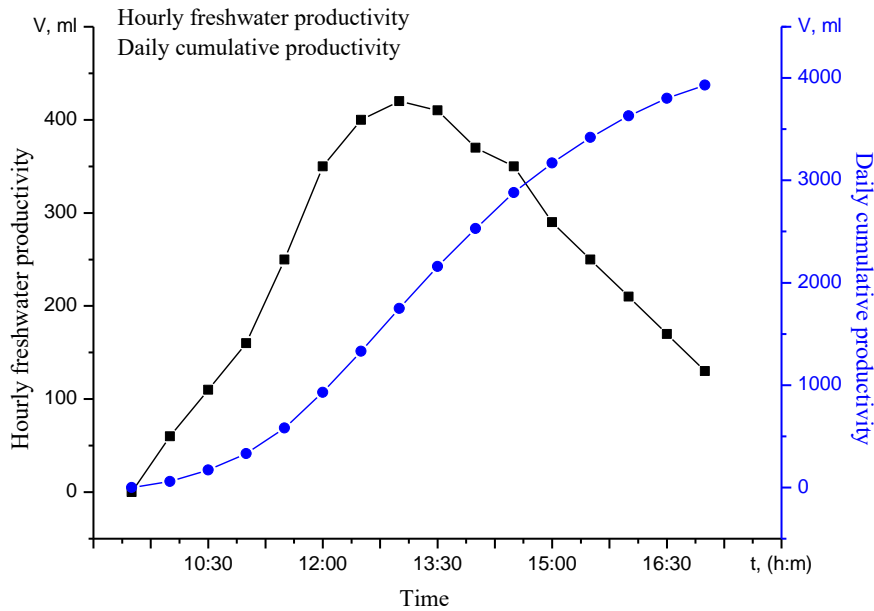


Fig. 7. Temporal variation of hourly and daily freshwater productivity

The experimental results confirm that the solar cell-based desalination unit, enhanced with reflectors, can effectively utilize solar energy. Specifically, the high peak hourly productivity and the cumulative daily yield of 3.2–3.4 L/m² indicate that the processes of heat collection, evaporation, and condensation occur efficiently. These findings demonstrate that the solar cell-based desalination unit achieves high performance in solar thermal energy collection, water evaporation, and vapor condensation, leading to effective freshwater production.

In this study, the term “solar cell” refers not only to a semiconductor device that converts solar radiation into electrical energy, but also to an active surface that absorbs a portion of solar energy as heat. A solar cell is typically based on a silicon p–n junction structure, where incident photons generate electron–hole pairs that are separated by the internal electric field, producing an electric current. However,

a significant fraction of the incident solar radiation is not converted into electricity and is instead absorbed as thermal energy, leading to an increase in the cell temperature.

This heat absorption process becomes particularly important under high solar irradiance conditions, as it significantly affects the overall system performance. In the proposed system, the solar cell operates simultaneously as an electrical energy generator and as a thermal absorber. With the use of reflectors, the incident radiation flux is increased, enhancing heat accumulation on the cell surface, which in turn contributes to the intensification of the water evaporation process. Structurally, the solar cell consists of a protective front glass, an anti-reflective coating, semiconductor layers (p-type and n-type), metallic contacts, and a back support layer. Its surface thus plays a dual role, enabling both photovoltaic conversion and effective absorption and transfer of thermal energy.

Table 4. Comparative analysis of freshwater productivity

Parameter	Conventional Solar Distiller	Proposed Unit	Difference / Gain
Maximum solar radiation	900–1000 W/m ²	1500–1550 W/m ²	+50–60%
Maximum water temperature	65–75°C	90–95°C	+25–30%
Thermal efficiency	30–35%	55–65%	+80–90%
Hourly freshwater productivity	150–180 ml/m ² ·h	240–280 ml/m ² ·h	+45–50 %
Daily cumulative productivity	2400–2600 ml/m ²	3200–3400 ml/m ²	35–40 %

Conclusion

In this study, a novel portable solar-powered water desalination system was developed and experimentally investigated. The system is based on photovoltaic (PV) elements

used as photothermal absorbers and enhanced with side and bottom reflectors. Unlike conventional solar distillers, where a simple black surface is typically used as a heat absorber, this design employs an array of crystalline silicon

solar cells, which significantly improves the absorption of solar radiation and its conversion into thermal energy. This constructive solution represents one of the key distinctions from previously proposed systems and contributes to enhancing the overall thermal performance of the device.

In addition, the integration of multi-directional reflectors constitutes an important technical advantage. While conventional systems utilize only direct solar radiation, the proposed device increases the radiation flux incident on the collector surface by 40–60% through optical concentration. As a result, the total solar radiation intensity reaches up to 1500–1550 W/m², which is substantially higher than the typical range of 900–1000 W/m². Experimental results (Table 4) demonstrate that the combined effect of enhanced photothermal conversion and radiation concentration via reflectors leads to an increase in the working water temperature up to 90–95 °C. This elevated temperature regime intensifies evaporation and condensation processes, thereby improving freshwater production efficiency.

Consequently, the overall thermal efficiency of the system reaches 55–65%, which is approximately 80–90% higher than that of conventional solar distillation systems. Moreover, the hourly freshwater production increases by 45–50%, while the cumulative daily yield reaches 3.2–3.4 L/m², representing a 35–40% improvement compared to traditional systems. Importantly, the proposed device operates entirely without conventional energy sources such as electricity or fuel. This makes it particularly suitable as an environmentally friendly and sustainable solution for remote and arid regions lacking centralized water and energy supply infrastructure. In conclusion, the integration of photovoltaic-based photothermal absorption with reflector-assisted solar radiation concentration effectively overcomes the low-efficiency limitations of conventional solar distillers. The developed system offers significant advantages, including high efficiency, low operational costs, structural simplicity, portability, and independence from external energy sources, making it a promising and practical solution for freshwater production under real climatic conditions.

This work constitutes a part of an ongoing comprehensive research project, and the results obtained represent an important stage within the broader scope of investigations. The findings provide both theoretical and practical foundations for future studies and create a basis for further in-depth research in this field.

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