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EXPERIMENTAL INVESTIGATION OF A SOLAR WATER DISTILLATION SYSTEM INTEGRATED WITH AN EVACUATED TUBE COLLECTOR AND A STEPPED EVAPORATION CHAMBER

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Abstract

This paper presents an experimental investigation to evaluate the performance of a solar-powered water distillation system integrated with evacuated tube collectors and a stepped evaporation chamber. The system was operated under outdoor conditions with a normalized evaporation surface area of 0.8m². Key parameters, including solar radiation, characteristic temperatures, and freshwater productivity, were recorded at 30-minute intervals.

The results indicate that the system achieved an average productivity of 3.30kg/m².day and an energy efficiency of approximately 39.5-41%. Regression analysis reveals a strong linear correlation between solar radiation and freshwater yield ($R^2 \approx 0.98$).

Comparative evaluation with previous studies demonstrates that the proposed system outperforms conventional solar stills and exhibits comparable performance to advanced stepped configurations. This study provides both scientific and experimental evidence supporting the application of solar distillation systems in maritime and coastal regions.

Keywords: *Solar water distillation, Evacuated tube collector, Stepped solar still, Freshwater productivity, Thermal efficiency.*

1. Introduction

Freshwater scarcity has emerged as one of the most critical global challenges of the 21st century, driven by rapid population growth, climate change, and increasing environmental pollution [1]. According to recent global assessments, more than two billion people are currently living in water-stressed regions, and this number is expected to increase significantly in the coming decades. This issue is particularly severe in coastal and island regions, where access to potable water is limited and conventional water supply methods such as transportation or desalination using fossil fuels are costly and energy-intensive. In maritime applications, the demand for freshwater onboard vessels and offshore platforms further exacerbates this challenge, highlighting the urgent need for sustainable and decentralized water production technologies [2].

Among various desalination technologies, solar-driven water distillation (solar still) has attracted considerable attention due to its simplicity, low cost, and ability to utilize renewable energy sources. However, conventional basin-type solar stills suffer from low productivity and limited thermal efficiency, typically in the range of 2-3 kg/m².day, primarily due to insufficient heat absorption and limited evaporation surface area [3], [4]. To overcome these limitations, numerous studies have proposed performance enhancement techniques, including the use of wick materials, nanofluids, phase change materials (PCM), and geometric modifications of the evaporation chamber. In particular, integrating solar collectors such as evacuated tube collectors has been shown to significantly increase water temperature and enhance evaporation rates [5], [6]. Additionally, stepped and thin-film configurations have been widely investigated for their ability to increase the effective evaporation area and improve heat and mass transfer characteristics[7].

Recent studies have also explored advanced designs such as textile-based solar stills and hybrid systems, demonstrating notable improvements in productivity and efficiency [8]. For instance, the use of capillary-driven wick materials has been reported to enhance evaporation rates due to increased surface area and reduced thermal inertia [9]. Despite these advancements, most existing studies focus on individual enhancement techniques rather than integrated system configurations.

Several research gaps remain, including the limited number of experimental studies on integrated solar distillation systems combining evacuated tube collectors with stepped evaporation chambers under real outdoor conditions, as well as insufficient analysis of the coupled relationships among solar radiation, thermal behavior, freshwater productivity, and energy efficiency. Furthermore, the lack of a standardized definition of effective evaporation area hinders consistent performance evaluation and comparison across different studies.

To address these research gaps, this study presents an experimental investigation of an active solar distillation system integrating an evacuated tube collector with a stepped evaporation-condensation chamber and a forced circulation loop powered by photovoltaic energy. The system is designed with a normalized effective evaporation area of 0.8m² to enable consistent performance evaluation. The main objectives of this work are: (i) to evaluate the thermal and productivity performance of the system under real outdoor conditions, (ii) to analyze the relationship between solar radiation, temperature distribution, and freshwater yield, and (iii) to compare the obtained results with those reported in previous studies to assess the effectiveness and practical applicability of the proposed configuration in maritime and coastal environments.

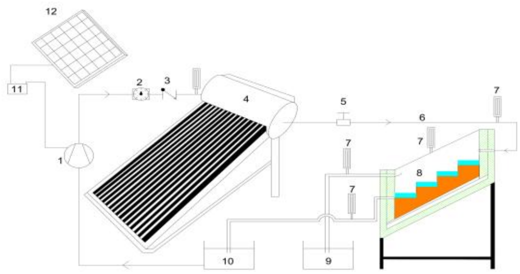
The novelty of this study lies in the integration of multiple performance enhancement mechanisms within a single experimental system, including evacuated tube preheating, stepped thin-film evaporation, and solar-powered circulation. Unlike conventional solar stills, the proposed system operates in an active mode, allowing better control of thermal input and improved heat and mass transfer. The findings of this research are expected to contribute to the development of efficient and practical solar desalination technologies for decentralized water supply applications.

2. Experimental setup

2.1. Experimental system configuration

The experimental system investigated in this study in Figure 1 is an active solar distillation system consisting of three main subsystems: (i) an evacuated tube solar collector, (ii) a stepped evaporation-condensation chamber, and (iii) a closed-loop water circulation system powered by a photovoltaic-driven pump.

The solar collector is used to preheat saline water before entering the evaporation chamber. The chamber is designed with a four-step configuration, allowing the heated water to flow as a thin film over inclined surfaces, thereby increasing the effective evaporation area and enhancing heat and mass transfer processes. Water vapor generated from the heated film rises and condenses on the inner surface of a transparent inclined glass cover, after which the condensed freshwater is collected through a channel system. The remaining brine is recirculated back to the storage tank. The system is designed with a normalized effective evaporation area of 0.8m², which is used for all performance evaluations in this study.



1- water pump, 2 - flow meter, 3- check valve, 4 - evacuated tube solar collector, 5 - shut-off valve, 6 - hot water piping, 7- thermometer, 8 - stepped evaporation - condensation chamber, 9 - distilled water tank, 10 - raw water tank, 11 - converter, 12 - solar panels.

Figure 1. A solar water distillation system integrated with an evacuated tube collector and a stepped evaporation chamber

2.2. Experimental setup and operating conditions

The experiments were conducted under outdoor conditions to ensure realistic operating performance. The system was operated continuously from 08:00 to 16:00, corresponding to the effective solar radiation period.

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The evaporation chamber has dimensions of 1000 × 400 × 25 mm, and the glass cover is installed at an inclination angle of approximately 25-30° to facilitate condensate flow. The solar collector has a storage capacity of 140L, a rotameter (variable area flow meter) was used to measure and regulate the flow rate of approximately 40L/h.

The measured parameters include: solar radiation intensity I (W/m²), ambient temperature T_{amb} (°C), collector outlet water temperature T_{col} (°C), evaporation chamber temperature T_{ev} (°C), glass surface temperature T_{glass} (°C), hourly freshwater yield. All measurements were recorded at 30-minute intervals, providing sufficient temporal resolution for dynamic analysis.

The experimental procedure was carried out according to the following steps: *Step 1* - Calibration and verification of all measuring instruments before each test; *Step 2* - Filling the system with saline water and ensuring proper circulation; *Step 3* - Activation of the photovoltaic-powered pump and solar collector system; *Step 4* - Continuous data acquisition at fixed time intervals throughout the test period; *Step 5* - Collection and measurement of distilled water output; *Step 6* - Shutdown and inspection of the system after each experimental run.

To ensure consistency, experiments were conducted under stable weather conditions, and any interruptions due to environmental disturbances were excluded from analysis.

2.3. Data acquisition and processing

All experimental data were first time-synchronized and organized into structured datasets. The data processing procedure included: Validation and filtering: Removal of erroneous or physically inconsistent measurements; Smoothing: Application of a moving average filter where necessary to reduce measurement noise; Normalization: Conversion of all variables into consistent SI units; Derived parameter calculation: Determination of temperature differences ($\Delta T = T_{ev} - T_{glass}$), hourly productivity, and cumulative yield.

Days with unstable environmental conditions or incomplete datasets were excluded to ensure data reliability. Measurement uncertainties are estimated based on the specifications of the instruments: solar radiation (±5%), temperature (±0.5°C), flow rate (±2%), and volume measurement (±1%). The overall uncertainty in derived parameters such as productivity and efficiency is evaluated using standard error propagation methods and is estimated to be within ±5-7%, which is acceptable for solar distillation experiments.

2.4. Performance evaluation methods

The freshwater productivity per unit area is calculated as:

$$m'' = \frac{M_d}{A} \qquad (1)$$

Where M_d is the total distillate mass (kg/day) and $A=0.8m^2$ is the effective evaporation area (represents the surface area of each wetted surface actively participating in the evaporation process, including stepped surfaces, inclined planes, and flowing thin-film regions).

The thermal efficiency of the system is defined as:

$$\eta = \frac{m_d \cdot h_{fg}}{I_{avg} \cdot A \cdot t} \qquad (2)$$

where h_{fg} is the latent heat of vaporization, I_{avg} is the average solar radiation, and t is the operating time.

The relationship between solar radiation (I is expressed in W/m²) and freshwater productivity (m is expressed in mL/h) is evaluated using linear regression analysis:

$$m = aI + b \qquad (3)$$

The coefficient of determination R^2 is used to assess the reliability and consistency of the experimental data.

3. Results and discussion

3.1. Variation of solar radiation and temperature profiles

Figure 2 illustrates the temporal variation of solar radiation and key temperature parameters during the experimental period. The solar radiation increased from approximately 420W/m² at 08:00 to a peak value of about 1020W/m² between 12:00 and 13:00, followed by a gradual decline toward the late afternoon.

This variation directly influenced the thermal behavior of the system. The collector outlet temperature reached a maximum of approximately 84°C, while the evaporation chamber temperature peaked at around 77°C. Meanwhile, the ambient temperature varied between 29°C and 36°C, resulting in a substantial temperature gradient between the heated water and the surrounding environment.

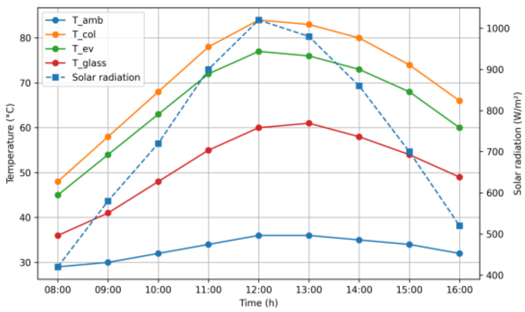

Figure 2. Variation of solar radiation and characteristic temperature profiles of the solar distillation system under outdoor conditions

The temperature difference between the evaporating water and the glass surface was maintained within the range of 8-12°C, which is sufficient to sustain continuous condensation. This thermal gradient plays a critical role in maintaining the vapor pressure difference required for efficient phase change processes.

The observed temperature trends demonstrate that the evacuated tube collector effectively enhances thermal energy absorption, leading to improved evaporation conditions compared to conventional passive systems.

A comparison with previously published studies further confirms the plausibility of the observed thermal behavior of the proposed system. The measured solar radiation range of 420-1020 W/m² is consistent with the values reported by Nguyen Huu Nghia *et al.* for a solar-driven freshwater production system, where the radiation varied from 300 to 1200W/m² during the daytime operation period, indicating that the present experiments were conducted under representative outdoor conditions [10]. Likewise, the collector outlet temperature reaching 84°C and the evaporation chamber temperature approaching 77°C are in good agreement with active solar still systems assisted by evacuated tube collectors. Hoang Van Viet *et al.* reported that a single-basin solar still integrated with evacuated glass tubes and an external condenser achieved 6kg/day under an average solar radiation of 517.54W/m², demonstrating the strong thermal enhancement effect of evacuated tube preheating[11]. In addition, studies on stepped solar stills have shown that stepped geometries improve internal heat and mass transfer and can increase productivity by about 19.7% compared with conventional configurations, mainly due to the reduction in heat and mass transfer distance between the evaporation and condensation surfaces [12]. A similar trend was also observed in hybrid PV/T-assisted solar distillation systems, where thermal coupling increased daily distillate production by 38.2% relative to the conventional single-basin still, confirming that external thermal support plays a critical role in raising water temperature and sustaining evaporation [13]. Therefore, the temperature profiles obtained in the present study are not only physically consistent with the measured radiation intensity, but also comparable with those reported for other advanced active and stepped solar distillation systems in the literature.

3.2. Freshwater productivity analysis

The hourly freshwater production exhibited a clear dependence on solar radiation intensity, as shown in Figure 3. The productivity increased steadily from 120mL/h in the early morning to a maximum of approximately 480mL/h around noon, before decreasing in the afternoon.

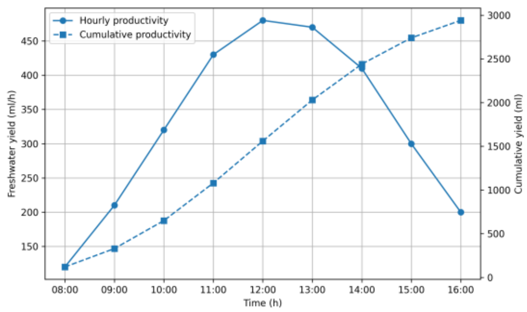

Figure 3. Hourly freshwater productivity and cumulative freshwater yield of the solar distillation system under outdoor conditions

The total daily freshwater yield was measured to be approximately 2.64L/day, corresponding to a normalized productivity of 3.30kg/m^2.day. This value is significantly higher than that reported for conventional basin-type solar stills, which typically achieve 2-2.5 kg/m²·day, confirming the effectiveness of the proposed design.

The enhanced productivity can be attributed to the combined effects of several key design features. First, preheating of the feedwater using the evacuated tube collector increases the initial thermal energy input, thereby elevating the water temperature and promoting evaporation. Second, the stepped evaporation configuration enlarges the effective evaporation surface area while reducing the water depth, which enhances heat transfer and facilitates faster phase change. Finally, the thin-film flow regime

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over the stepped surfaces improves convective heat transfer and reduces thermal resistance, leading to an accelerated evaporation process.

Furthermore, the productivity curve exhibits a slight time lag relative to the solar radiation peak, indicating the presence of thermal inertia within the system, particularly due to heat storage in water and structural components.

The obtained freshwater productivity of 3.30 kg/m².day is consistent with the performance range reported for enhanced solar still systems in the literature. Conventional basin-type solar stills typically yield 2-2.5 kg/m².day, as highlighted in several review studies, confirming that the present system achieves a significant improvement over passive configurations [7]. This enhancement is primarily attributed to the integration of an evacuated tube collector and the stepped evaporation design.

Compared with wick-based and textile-assisted solar stills, which generally produce 1-3 kg/m².day under similar climatic conditions, the present system demonstrates comparable or slightly higher productivity, indicating that increasing thermal input through collector-assisted heating can be as effective as capillary-driven evaporation enhancement [14]. Furthermore, stepped solar still configurations have been reported to improve productivity by approximately 15-25 % relative to conventional basin designs due to increased evaporation surface area and reduced water depth [15], which is in good agreement with the current findings.

However, the productivity remains lower than that of highly optimized collector-assisted systems. For instance, Hoang Van Viet et al. reported a daily yield equivalent to ~10 kg/m²·day for a solar still integrated with evacuated tube collectors and an external condenser, demonstrating the significant impact of enhanced condensation mechanisms [11]. Similarly, hybrid PV/T-assisted systems have achieved productivity levels exceeding 4-6 kg/m².day, mainly due to improved thermal coupling and heat recovery [13].

The relatively moderate productivity observed in this study can therefore be attributed to the absence of advanced features such as active cooling of the condensation surface, external condensers, or thermal energy storage. Nevertheless, the achieved performance confirms that the proposed system operates within the expected and reliable range for medium-complexity active solar stills, while maintaining a simpler and more practical design suitable for real-world applications.

3.3. Energy efficiency evaluation

The thermal efficiency of the system was calculated based on the ratio of useful energy utilized for evaporation to the total incident solar energy. The average daily efficiency was found to be in the range of 39.5-41 % (see the Figure 4).

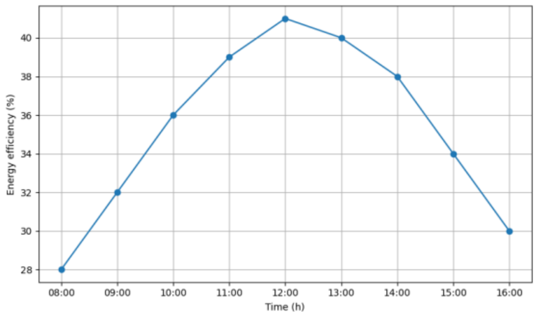

Figure 4. Variation of energy efficiency of the solar distillation system with time under outdoor operating conditions

This efficiency level is notably higher than that of passive solar stills, which generally operate at around 25-35%, yet lower than highly optimized active systems that incorporate advanced condensation techniques or thermal storage, where efficiencies may exceed 50%.

The moderate efficiency observed in this study can be explained by the balance between enhanced heat input and unavoidable energy losses. These losses primarily include convective and radiative heat transfer through the glass cover, conductive heat losses through the chamber walls, and the incomplete recovery of latent heat during the condensation process, all of which limit the overall energy utilization efficiency of the system.

Despite these losses, the efficiency achieved demonstrates that the integration of an evacuated tube collector and stepped chamber significantly improves energy utilization.

The obtained energy efficiency of approximately 39.5-41% is consistent with the performance range reported for active solar still systems assisted by external thermal sources. Conventional passive solar stills typically exhibit efficiencies in the range of 25-35%, primarily due to limited heat input and significant thermal losses [3]. The higher efficiency observed in the present study confirms the positive contribution of evacuated tube preheating and improved evaporation geometry.

A comparable trend was reported by Kabeel and

Abdelgaied [3], who demonstrated that enhancing heat input through advanced thermal techniques could significantly improve energy efficiency beyond that of conventional systems. In their study, efficiency improvements were achieved through modifications in heat transfer conditions, highlighting the importance of effective thermal utilization.

Furthermore, Huy et al. [13] investigated a hybrid PV/T-assisted solar distillation system and reported an increase in energy efficiency due to improved thermal coupling between photovoltaic and thermal subsystems. Their results showed that the integration of auxiliary heating mechanisms can enhance both evaporation rates and overall system efficiency, which is consistent with the findings of the present study.

However, the efficiency achieved here remains lower than that of highly optimized systems incorporating advanced condensation techniques or thermal storage. This difference can be attributed to residual heat losses through the glass cover and chamber walls, as well as the absence of active condensation enhancement. Nevertheless, the obtained efficiency falls within the expected and reliable range for medium-complexity active solar still systems, confirming the effectiveness of the proposed configuration while maintaining system simplicity.

3.4. Relationship between solar radiation and freshwater yield

A linear regression analysis was performed to quantify the relationship between solar radiation and hourly freshwater productivity. The resulting correlation is expressed as:

$$m = 0.44I - 19.78 \quad (4)$$

with a coefficient of determination: $R^2 \approx 0.98$.

The high R^2 value indicates a strong linear dependency, confirming that solar radiation is the dominant factor governing system performance.

The slight deviation from perfect linearity can be attributed to transient effects within the system, including thermal inertia, variations in ambient conditions, and nonlinear heat losses at elevated temperatures, all of which introduce minor fluctuations in the relationship between solar radiation and freshwater productivity.

Importantly, the strong correlation suggests that the system operates in a regime where evaporation is primarily energy-limited rather than mass-transfer-limited, which is consistent with theoretical models of solar distillation systems under natural convection conditions.

4. Conclusion

This study experimentally evaluated an active solar distillation system integrating an evacuated tube collector with a stepped evaporation chamber. With a normalized evaporation area of 0.8m², the system achieved a productivity of 3.30 kg/m².day and an energy efficiency of 39.5-41%, outperforming conventional passive solar stills.

The results confirm that evacuated tube preheating and stepped geometry effectively enhance heat and mass transfer, with a strong linear relationship observed between solar radiation and freshwater yield ($R^2 \approx 0.98$). The system performance falls within the medium-to-high range of active solar stills, offering a practical balance between efficiency and system simplicity.

Future improvements should focus on reducing heat losses and enhancing condensation through thermal storage and advanced cooling techniques to further increase system performance.

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