

Enhanced Thermal Performance of a Hybrid Solar Air Distiller through Porous Baffle Integration

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ABSTRACT

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In the context of growing global energy demand and increasing freshwater scarcity, the development of sustainable desalination technologies has become a major scientific and environmental challenge. Owing to its favorable geographical location, Algeria possesses considerable solar energy potential that remains largely underexploited. Among renewable energy applications, solar thermal distillation coupled with solar air heating systems represents an efficient and environmentally friendly solution for freshwater production, particularly in Saharan, arid, and semi-arid regions. This study presents the design and numerical modeling of a hybrid solar air distiller integrated with porous baffles to enhance thermo-hydraulic performance and heat transfer characteristics. The proposed system consists of a greenhouse-effect solar distiller combined with a flat-plate solar air collector. Porous baffles are incorporated within the airflow channel to improve turbulence intensity, increase air residence time, and promote convective heat exchange inside the distillation chamber. The operating principle is based on the greenhouse effect, where solar radiation is absorbed and converted into thermal energy. The heated air generated by the integrated solar collector is recovered and circulated through the distillation unit, leading to improved evaporation and condensation processes. The integration of porous baffles significantly enhances thermal energy utilization and contributes to higher system efficiency. The obtained results demonstrate that the proposed hybrid configuration improves heat transfer mechanisms and thermal performance compared with conventional solar distillation systems. Consequently, the developed system offers a promising renewable-energy-based solution for water desalination and solar heating applications in remote and water-scarce regions.

Keywords: Materials, Convection, Heat transfer, porous medium, collector solar, heat thermal, Solar Air Distiller, Horizontal channel

INTRODUCTION

Energy is a fundamental driver of socio-economic development and technological progress in modern societies. The continuous increase in global energy demand has intensified the need for sustainable energy strategies that ensure efficient utilization of conventional resources while promoting the development of renewable energy technologies. In this context, renewable energy systems have emerged as a key solution to address both energy security and environmental sustainability challenges.

Renewable energy sources, including solar, wind, biomass, and geothermal energy, are characterized by their abundance, wide geographical distribution, and minimal environmental impact. Their exploitation contributes significantly to reducing greenhouse gas emissions and mitigating climate change impacts. Among these resources, solar energy represents one of the most promising and widely accessible forms of renewable energy due to its high availability and scalability.

Solar energy can be harnessed through two primary conversion pathways: photovoltaic systems for electricity generation and solar thermal systems for heat production. The present study focuses on solar thermal applications, particularly their integration into water desalination systems for freshwater production.

The growing pressure on freshwater resources, driven by population growth, industrial development, climate change, and overexploitation of groundwater, has made access to potable water a critical global challenge. Consequently, desalination technologies have become essential for ensuring water supply in arid and semi-arid regions. Solar desalination, in particular, offers a sustainable and environmentally friendly alternative to conventional energy-intensive desalination methods.

Desalination technologies are generally classified into two main categories: thermal processes and membrane processes. Thermal desalination techniques, such as multi-stage flash (MSF) and multiple-effect distillation (MED), rely on phase-change mechanisms where saline water is evaporated and subsequently condensed to produce freshwater. These processes replicate the natural water cycle. Conversely, membrane-based processes, particularly reverse osmosis (RO), utilize semi-permeable membranes under high pressure to separate dissolved salts and impurities from water.

Despite their effectiveness, thermal desalination processes suffer from high energy consumption due to the latent heat of vaporization of water, approximately 2250 kJ/kg. This limitation significantly affects their economic feasibility and operational efficiency.

In regions such as Algeria, solar thermal desalination represents a highly promising solution due to abundant solar irradiation and the availability of brackish water resources, particularly in Saharan and semi-arid regions. These conditions make solar desalination a viable approach for addressing freshwater demands for domestic consumption and agricultural irrigation.

Recent studies have demonstrated that heat transfer enhancement techniques, such as the incorporation of porous baffles, can significantly improve thermo-fluid performance in solar thermal systems. Numerical investigations on turbulent forced convection in ducts equipped with porous corrugated baffles have shown substantial improvements in heat transfer and flow mixing characteristics, making such configurations highly relevant for solar energy applications (Fakiri and Rahmoun, 2017; Fakiri and Rahmoun, 2018).

Solar desalination systems are generally divided into solar thermal distillation and solar-driven reverse osmosis. Solar thermal distillation utilizes solar radiation to induce evaporation and condensation processes, whereas solar reverse osmosis employs photovoltaic-generated electricity to drive high-pressure membrane filtration systems. Both approaches have been widely investigated in recent literature for sustainable freshwater production (Zhao et al., 2023; Khan et al., 2022).

Although solar desalination offers significant environmental advantages, including reduced greenhouse gas emissions and reliance on renewable energy sources, several challenges remain. These include high initial investment costs, sensitivity to climatic variations, and the need for improved system efficiency. Therefore, ongoing research efforts focus on optimizing system design and enhancing heat transfer performance to improve economic viability and scalability (Smith et al., 2023; International Water Association, 2024).

In this context, the present study aims to develop and analyze a hybrid solar air distillation system incorporating porous baffles to enhance heat transfer, flow mixing, and overall thermo-hydraulic performance. The objective is to contribute to the development of efficient and sustainable desalination technologies suitable for arid and water-scarce regions.

SOLAR DESALINATION TECHNOLOGIES AND HYBRID SOLAR AIR DISTILLER CONCEPT

Solar desalination represents an emerging and sustainable technology that utilizes solar energy to convert saline or brackish water into freshwater, thereby offering a viable solution to the increasing global water scarcity. This approach is particularly relevant in arid and semi-arid regions where conventional water resources are limited. Solar desalination systems are generally based on two main technologies: solar distillation and solar-driven reverse osmosis. Solar distillation is a thermally driven process that replicates the natural hydrological cycle. In this system, saline water is heated using solar collectors, solar ponds, or other solar thermal devices. The absorbed solar energy increases the water temperature until evaporation occurs, leaving dissolved salts and impurities behind. The generated vapor is subsequently condensed on a cooled surface, producing freshwater that is collected in a storage tank. Various configurations of solar distillation systems exist, including simple solar stills, passive basin systems,

and advanced multi-effect distillation (MED) units. The latter enhances thermal efficiency by recovering latent heat from successive evaporation-condensation stages, thereby reducing energy losses and improving productivity (Zhao et al., 2023; Khan et al., 2022). In contrast, solar reverse osmosis (RO) systems rely on photovoltaic (PV) modules to convert solar radiation into electrical energy. This electricity is used to drive high-pressure pumps that force saline water through semi-permeable membranes. These membranes selectively allow water molecules to pass while rejecting dissolved salts and other impurities, resulting in the production of freshwater. Prior to membrane filtration, pretreatment processes are typically required to remove suspended particles and reduce fouling risks. Moreover, hybrid configurations combining photovoltaic systems with RO units have been widely investigated to improve energy efficiency and operational reliability (Smith et al., 2023; International Water Association, 2024; Gude, 2021; Kumar et al., 2022).

Solar desalination technologies offer significant environmental and economic advantages. The use of renewable solar energy substantially reduces greenhouse gas emissions compared to conventional fossil-fuel-driven desalination plants. Additionally, operational costs can be minimized due to the free and abundant nature of solar energy. These systems are particularly suitable for decentralized applications in coastal, desert, and isolated regions, providing autonomous freshwater production systems close to demand areas (Khan et al., 2022; Zhao et al., 2023). However, despite these advantages, challenges such as high initial capital investment, intermittent solar availability, and performance variability under different climatic conditions remain critical barriers to large-scale deployment (Smith et al., 2023; International Water Association, 2024). In this context, the present study focuses on the development of a hybrid solar air distiller/collector system enhanced with porous baffles to improve heat transfer and thermo-fluid performance. This system integrates solar energy collection with air heating and distillation processes in a unified configuration aimed at maximizing thermal efficiency. The incorporation of porous baffles within the air flow channel plays a key role in enhancing system performance. These baffles, characterized by controlled porosity, are strategically installed to induce flow disturbances, increase turbulence intensity, and improve air-surface interaction. As a result, the convective heat transfer between the absorber surface and the flowing air is significantly enhanced. Furthermore, the porous structure facilitates better flow distribution and reduces thermal stratification within the duct. The operating principle of the system is based on solar radiation absorption by the collector surface, which heats the circulating air. The heated air is then directed into the distillation chamber, where it promotes evaporation of saline water. The improved mixing and uniform temperature distribution induced by porous baffles contribute to higher evaporation rates and enhanced condensation efficiency. Numerical simulations and experimental investigations reported in the literature confirm that the integration of porous baffles leads to a substantial improvement in thermal performance compared to conventional configurations without internal obstacles. The increase in effective heat transfer area, combined with enhanced fluid mixing, results in improved system efficiency and higher freshwater production rates. In conclusion, the hybrid solar air distiller equipped with porous baffles represents a promising and efficient solution for solar-driven water purification. Its simplicity, sustainability, and adaptability make it particularly suitable for deployment in remote and water-scarce regions, contributing to the development of decentralized renewable desalination technologies.

ENERGY BALANCE AND MATHEMATICAL MODELING OF THE FLAT-PLATE SOLAR DISTILLER

Energy balance of the flat-plate solar distiller

A flat-plate solar distiller is a solar-driven device designed to convert saline water into freshwater through evaporation and condensation processes. Its performance strongly depends on the solar energy input, thermal losses, and phase-change mechanisms occurring within the system. A comprehensive energy balance is therefore essential to evaluate and optimize its thermo-energy behavior.

The solar collector constitutes the primary energy harvesting component. It absorbs incident solar radiation and converts it into useful thermal energy. The rate of solar energy collected can be expressed as:

$$Q_{solar} = I \times A \times \eta \quad (1)$$

Where I is the solar irradiation (W/m^2), A is the collector surface area (m^2), and η is the collector efficiency (dimensionless). The efficiency parameter depends on the optical properties of materials, absorber characteristics,

and thermal losses, and therefore plays a crucial role in determining the useful heat gain. The absorbed thermal energy is subsequently utilized for the evaporation of saline water inside the distillation chamber. The energy required for phase change is given by:

$$Q_{evap} = m \times L \times Q \quad (2)$$

Where m is the mass of evaporated water (kg) and L is the latent heat of vaporization of water (approximately 2.26×10^6 J/kg). This expression highlights that evaporation is the dominant energy-consuming mechanism in the distillation process. By equating the absorbed solar energy to the latent heat requirement, the mass of evaporated water can be estimated as:

$$m = \frac{Q_{solar}}{L} \quad (3)$$

This relationship clearly indicates that freshwater productivity is directly proportional to the available solar energy input and collector efficiency. The condensation process is responsible for converting water vapor into liquid freshwater. The heat transfer rate during condensation is expressed as:

$$Q_{cond} = h \times A_{cond} \times \Delta T \quad (4)$$

Where h is the convective heat transfer coefficient ($W/m^2 \cdot K$), A_{cond} is the condensation surface area (m^2), and ΔT is the temperature difference between vapor and condensing surface (K). Efficient condensation requires maintaining a sufficient temperature gradient to enhance vapor phase transformation.

Overall thermal efficiency

The overall performance of the solar distiller is evaluated using the thermal efficiency, which represents the ratio between useful energy output (evaporated water production) and incident solar energy input. This efficiency is strongly influenced by solar radiation intensity, ambient temperature, material properties, and thermal losses due to convection and radiation. Optimization of collector design, condenser geometry, and insulation quality is therefore essential to maximize system performance.

Mathematical modeling

The present study is based on the single-effect greenhouse solar distiller developed at the Renewable Energy Research Unit in Saharan Environment (URER/MS ADRAR, 2006). The energy performance of the system is evaluated using steady-state energy balance equations applied to each component of the distiller.

Numerical simulations are performed for a representative operating period of one hour of freshwater production, selected between 14:00 and 15:00, corresponding to the period of maximum solar irradiation. Under steady-state assumptions, the thermal behavior of the system can be described using coupled energy balance equations for the collector, evaporation chamber, and condensation surface.

These governing equations account for:

- Solar energy absorption in the collector,
- Convective heat transfer between air and water surfaces,
- Latent heat exchange during evaporation,
- Heat rejection during condensation,
- Thermal losses to the environment.

This mathematical framework allows prediction of system performance and provides a basis for optimizing design parameters to improve freshwater yield and thermal efficiency.

The thermal behavior of the hybrid flat-plate solar distiller is described using a coupled energy balance approach applied to the main components: solar collector, humid air zone, water basin, transparent cover, and thermal losses to the environment. The system is assumed to operate under quasi-steady conditions during a short time interval.

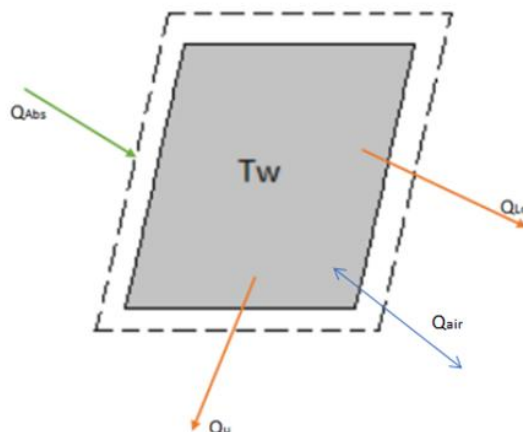


Figure 1. Thermal balance of the system.

THERMAL MODELING OF THE SOLAR DISTILLER SYSTEM

Mathematical modeling Thermal balance of the water mass

The thermal behavior of the water layer inside the distillation basin is governed by an energy balance that accounts for radiative, convective, evaporative, conductive heat exchanges, as well as the effect of feed water replenishment. The governing equation is expressed as:

$$q_{water} = q_{ri} + q_{ci} + q_e + m_d \times C_e \times (T_e - T_A) + q_b \tag{5}$$

Where q_{ri} , q_{ci} , and q_e represent radiative, convective, and evaporative heat fluxes inside the distiller, respectively. q_b denotes conductive heat transfer through the basin, while $m_d C_e (T_e - T_A)$ accounts for thermal losses associated with the incoming make-up water.

Thermal balance of the glass cover

The transparent glass cover plays a critical role in both energy transmission and condensation processes. The internal energy balance is given by:

$$q_{ri} + q_{ci} + q_e = \frac{\lambda_v}{e_v} (T_{vi} - T_{ve}) A_v \tag{6}$$

The external thermal balance is expressed as:

$$q_{ra} + q_{ca} = \frac{\lambda_v}{e_v} (T_{vi} - T_{ve}) A_v \tag{7}$$

Where q_{ra} and q_{ca} are radiative and convective heat fluxes between the glass and the external environment. T_{vi} and T_{ve} denote the internal and external glass temperatures, e_v is the glass thickness, and λ_v is its thermal conductivity.

Thermal balance of the absorber

The absorber plate receives solar radiation and transfers heat to both the water and insulation layers:

$$\tau \times A \times G = q_{eb} + q_{bis} \tag{8}$$

Where τ is the global transmittance of the glass-water system, G is the solar irradiation, and q_{eb} , q_{bis} represent heat transfer toward the water mass and the insulation layer, respectively.

Thermal balance of the insulation

To minimize heat losses through the bottom of the system, thermal insulation is employed. The conductive heat transfer through the insulation is expressed as:

$$q_{bis} = \frac{\lambda_{is}}{e_{is}}(T_{isi} - T_{ise}) \tag{9}$$

The external energy balance of the insulation is:

$$q_{ris} + q_{cis} = \frac{\lambda_{is}}{e_{is}}(T_{isi} - T_{ise}) \tag{10}$$

Where q_{ris} and q_{cis} represent radiative and convective losses to the surroundings.

Coupled temperature-based formulation

The governing equations of the system can be rewritten in terms of nodal temperatures to describe heat transfer between all components.

External side of the glass:

$$\left(h_{ca} - h_{ra} + \frac{\lambda_v}{e_v}\right) T_{ve} - \frac{\lambda_v}{e_v} T_{vi} = h_{ca} T_a + h_{ra} T_c + a_v G A \tag{11}$$

Internal side of the glass:

$$\frac{\lambda_v}{e_v} (T_{ve} - T_{vi}) - (h_{ci} + h_{ri} + h_e) T_{vi} - (h_{ci} + h_{ri} + h_r) T_E = 0 \tag{12}$$

Water mass balance:

$$-(h_{ci} + h_{ri} + h_e) T_{vi} + (h_{ci} + h_{ri} + h_e + h_{be}) T_e - h_{be} T_b = \alpha_t G A \tag{13}$$

Absorber plate balance :

$$-h_{be} T_e + \left(h_{be} + \frac{\lambda_b}{e_b}\right) T_b - \frac{\lambda_b}{e_b} T_{isi} = \tau G A_v \tag{14}$$

Internal insulation interface :

$$\frac{\lambda_b}{e_b} (T_b - T_{is}) - \left(\frac{\lambda_b}{e_b} + \frac{\lambda_{is}}{e_{is}}\right) T_{is} - \frac{\lambda_{is}}{e_{is}} T_{isi} = 0 \tag{15}$$

External insulation surface

$$\left(h_{ise}^e + h_{ise}^c + \frac{\lambda_{is}}{e_{is}}\right) T_{ise} - \frac{\lambda_{is}}{e_{is}} T_{isi} = h_{ise}^e T_{sol} + h_{ise}^c T_a \tag{16}$$

Physical description of the hybrid system

The studied system consists of a hybrid solar distiller integrated with a solar air collector equipped with porous baffles. This configuration enhances heat transfer by inducing turbulence and improving air–surface interaction within the collector. The solar collector absorbs incident radiation and converts it into thermal energy, which is transferred to the airflow. The presence of porous baffles increases turbulence intensity, improves mixing, and enhances convective heat transfer. Consequently, the air entering the distillation chamber is hotter and more uniformly distributed. Inside the distillation chamber, the heated air increases the water temperature, promoting evaporation. The porous structure ensures uniform thermal distribution, reduces stratification effects, and enhances overall system efficiency.

Objective and scientific contribution

The objective of this work is to improve the performance of the solar distiller originally proposed in 2006 (Fakiri Hicham & Fakiri Fethallah, 2006) by coupling it with an air solar collector and optimizing heat transfer mechanisms. The study investigates the coupled relationship between temperature, pressure, and system efficiency in order to identify optimal operating conditions. This understanding is essential for improving freshwater productivity and overall system performance. Future developments may focus on advanced materials, optimized

porous geometries, and hybrid CFD–experimental validation to further enhance system efficiency in real operating conditions.

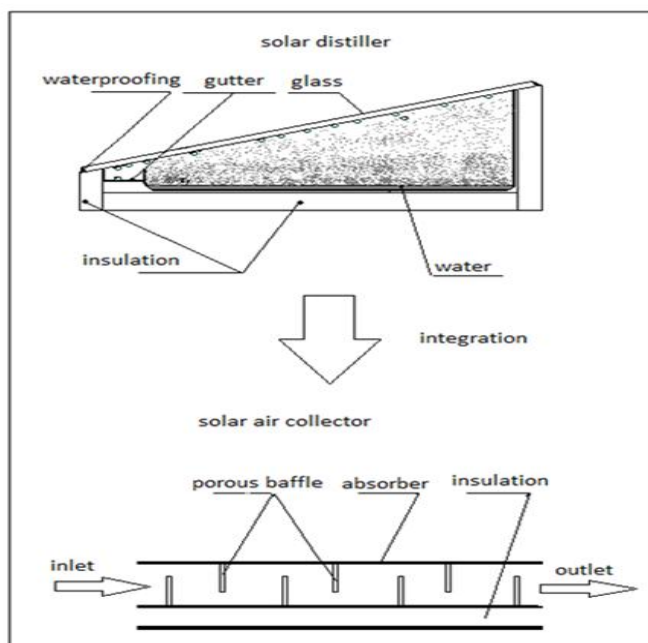


Figure 2. Integrated a solar distiller with a solar air collector equipped with porous baffles.

The sign added to the amount of heat recovered from the air by the solar air collector and water indicates that the direction is reversed in the energy balance of a simple distiller, with the integration of the solar air collector. This effect is observed between the amount of air entering the distiller and the quantity of salty water.

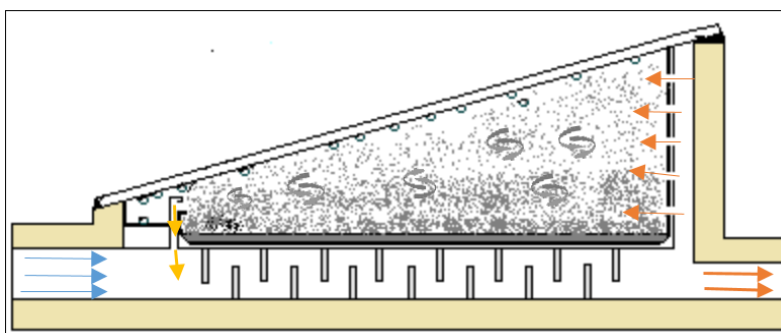


Figure 3. Model of a solar distiller - a solar air collector equipped with porous baffles.

The integration of a solar air collector into the conventional solar distillation system modifies the global thermal balance of the distiller. In the proposed hybrid configuration, part of the thermal energy recovered from the heated airflow is transferred to the saline water inside the distillation chamber. Consequently, the direction of heat exchange differs from that observed in a conventional passive solar distiller.

This additional thermal contribution enhances the evaporation process by increasing the temperature of both the humid air and the saline water. The interaction between the incoming heated air and the water mass plays a major role in improving the overall thermo-hydraulic performance of the system.

The convective heat exchange between the water surface and the surrounding medium is expressed as:

$$q_w = h_3(\theta_{X-0} - T_w) \tag{17}$$

Where q_w represents the heat flux exchanged with the saline water, h_3 is the convective heat transfer coefficient, θ_{X-0} is the reference temperature, and T_w is the saline water temperature.

Similarly, the thermal interaction between the heated air and the internal environment of the distiller is given by:

$$q_{air} = h_{air}(\theta_{Y-0} - T_{air}) \tag{18}$$

Where q_{air} is the heat transferred by the airflow and h_{air} is the corresponding convective coefficient.

To determine the thermodynamic constants governing the evaporation process, the pressure–temperature relationship proposed by Sodha et al. (1982) is employed. The equilibrium pressure is expressed as:

$$P_{eq} = R_{eq}T + R_2 \tag{19}$$

The equilibrium coefficient is defined as:

$$R_{eq} = R_1 + R_{air} \tag{20}$$

Consequently, the saturation pressure–temperature relation becomes:

$$P = 448.883T + 152.9 \times 10^3 \tag{21}$$

This relationship describes the variation of vapor saturation pressure with temperature and provides an essential basis for evaluating evaporation behavior within the distillation chamber.

The thermo-physical properties used in the present study are summarized as follows:

- Water density: $\rho=987.27 \text{ kg/m}^3$
- Specific heat capacity: $C_p=4.175 \text{ kJ/(kg}\ ^\circ\text{C)}$

The transient thermal behavior of the saline water is governed by the following energy equation:

$$M_w \frac{dT_w}{dt} = (1 - \rho_v)(1 - \alpha_v)\alpha_v G - q_{radbv} - q_{cov} + q_w + q_{air} \tag{22}$$

This equation accounts for:

- Absorbed solar radiation,
- Radiative heat losses,
- Convective heat exchanges,
- Thermal contribution of the heated airflow.

The temporal evolution of water temperature is determined experimentally and numerically by measuring:

- Saline water temperature inside the basin,
- Air temperature at the outlet of the solar air collector.

These measurements enable evaluation of temperature variation with time from the onset of solar exposure.

The thermal efficiency of the hybrid solar distiller is evaluated based on the useful heat utilized for water evaporation relative to the incident solar energy. The efficiency expression is written as:

$$\eta = \frac{q_{eq}}{AG} = \frac{m_w L}{AG} \tag{23}$$

Where:

- q_{eq} is the useful heat involved in evaporation and heat recovery from air,
- A is the exchange surface area,
- L is the latent heat of vaporization,
- m_w is the freshwater production rate,
- G is the incident solar radiation.

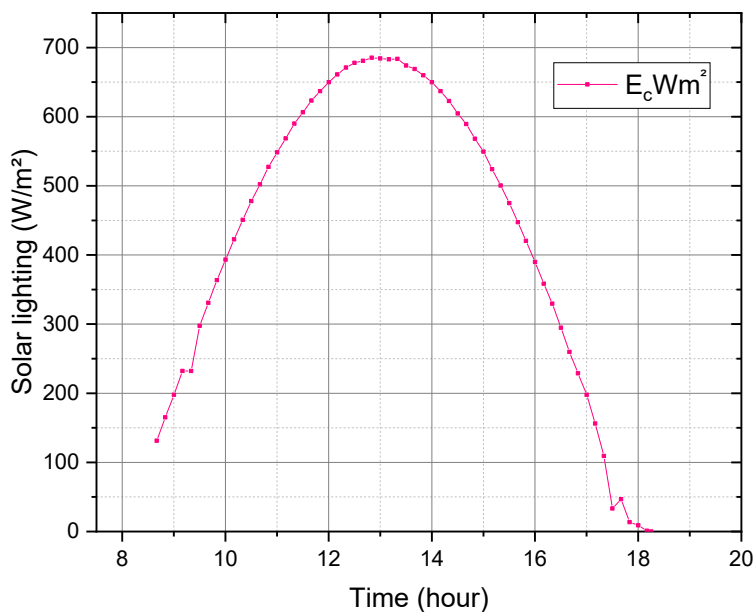


Figure 4. Solar Irradiation / Time (Hours) on the Horizontal Plane [14]

The experimental investigation conducted on the solar distillation system enabled the evaluation of the temporal evolution of solar irradiation and temperature under real climatic conditions. Two principal datasets were obtained during the experimental campaign: the variation of solar irradiation as a function of time and the evolution of system temperatures throughout the operating period. The experiments were carried out over two consecutive operating periods, from 31/12 to 01/01 and from 01/01 to 02/01, using the developed solar distiller prototype. The measurements were performed under outdoor conditions to assess the thermal behavior and energy performance of the system during typical winter solar exposure. Figures 4 illustrate the temporal variation of solar irradiation during the test days. The obtained results indicate favorable solar conditions characterized by relatively stable and sustained solar exposure throughout the daytime period. The measured irradiation corresponds to the combined contribution of direct, diffuse, and reflected solar radiation incident on the collector surface. The experimental data reveal that the maximum solar irradiation reached approximately: $G_{\max} \approx 650 \text{ W/m}^2$. [14].

This value confirms the availability of sufficient solar energy to drive the desalination process effectively during the considered experimental period. Furthermore, the results demonstrate that the effective solar exposure duration extended over nearly 10 hours per day, from approximately 08:00 until 18:00. Such an operating duration is highly favorable for solar desalination applications, as it ensures continuous thermal energy input for water evaporation and condensation processes. The extended solar exposure period contributes significantly to maintaining elevated water and air temperatures inside the distillation chamber, thereby improving evaporation intensity and freshwater productivity. These climatic conditions are particularly advantageous for desalination of brackish water in arid and semi-arid regions characterized by high solar potential. Overall, the experimental observations confirm that the studied site provides suitable meteorological conditions for solar-driven desalination systems and supports the feasibility of integrating solar air collectors with porous baffles to enhance thermal performance and operational efficiency.

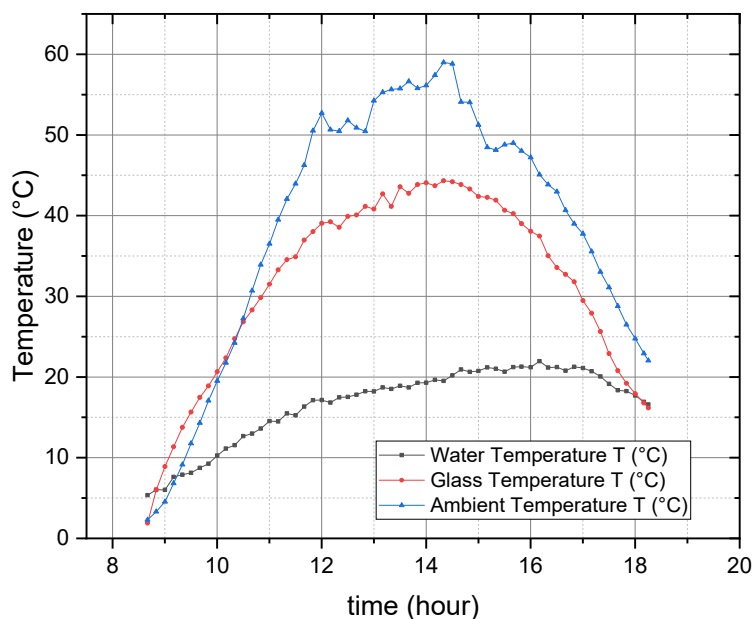


Figure 5. Temperature / Time (Hours) (Period from 01/01 to 02/01) [14].

The analysis of Figures 5. reveals the temporal evolution of the three main temperatures in the solar distillation system: ambient air temperature (T_A), glass cover temperature (T_G), and water temperature (T_W) as a function of time. The obtained results show that all temperature profiles follow a typical diurnal pattern governed by solar irradiation. During sunrise, the three temperatures increase progressively due to the continuous absorption of solar energy. They reach their maximum values around solar noon, corresponding to the peak of solar radiation. After this point, a gradual decrease is observed until sunset, when the solar input becomes negligible. It is also observed that the ambient air temperature (T_A) and saline water temperature (T_W) intersect at a specific point during the daily cycle. This intersection indicates a transient thermal equilibrium where heat exchange between the basin and the surrounding environment is momentarily balanced, leading to a reversal in the direction of certain heat transfer mechanisms within the system. During the following day, the same thermal cycle is repeated, confirming the periodic and stable behavior of the system under natural solar conditions. This cyclic thermal evolution continues until complete evaporation of the saline water, if no external replenishment is provided. The increase in saline water temperature relative to both the ambient air and glass temperatures facilitates the achievement of the latent heat of vaporization required for phase change from liquid to vapor. Once vapor is generated, it condenses on the inner surface of the glass cover through heat conduction and temperature gradient effects. The condensed droplets then flow downward under the action of gravity into the collection gutter, ensuring freshwater recovery. However, complete evaporation of saline water can be avoided by implementing a continuous feed system from an external reservoir with a controlled flow rate. This strategy ensures steady-state operation of the distiller, maintains optimal salinity levels, and enhances long-term system performance and sustainability.

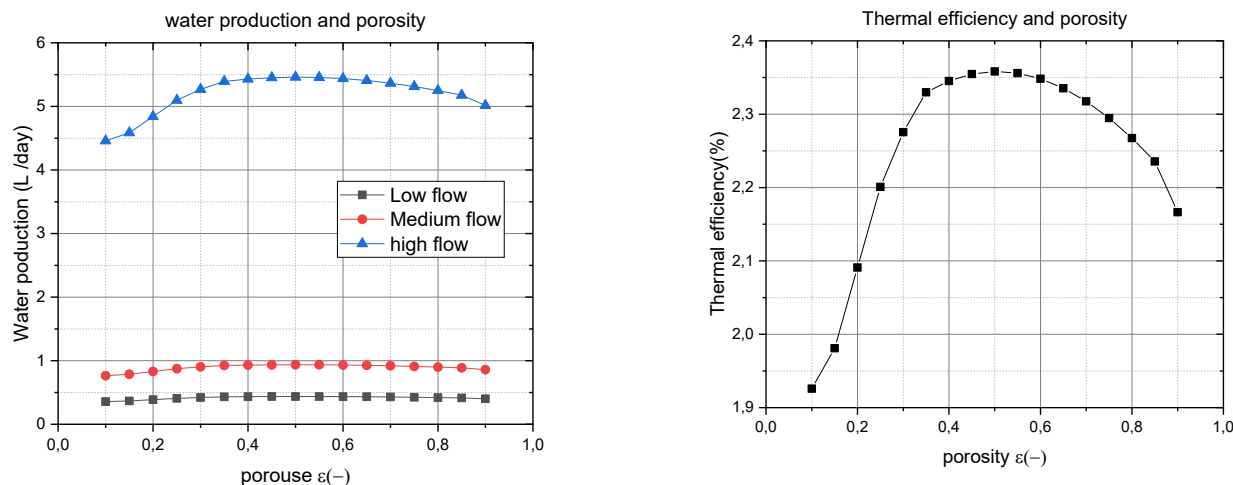


Figure 6. Effect of porosity on system performance.

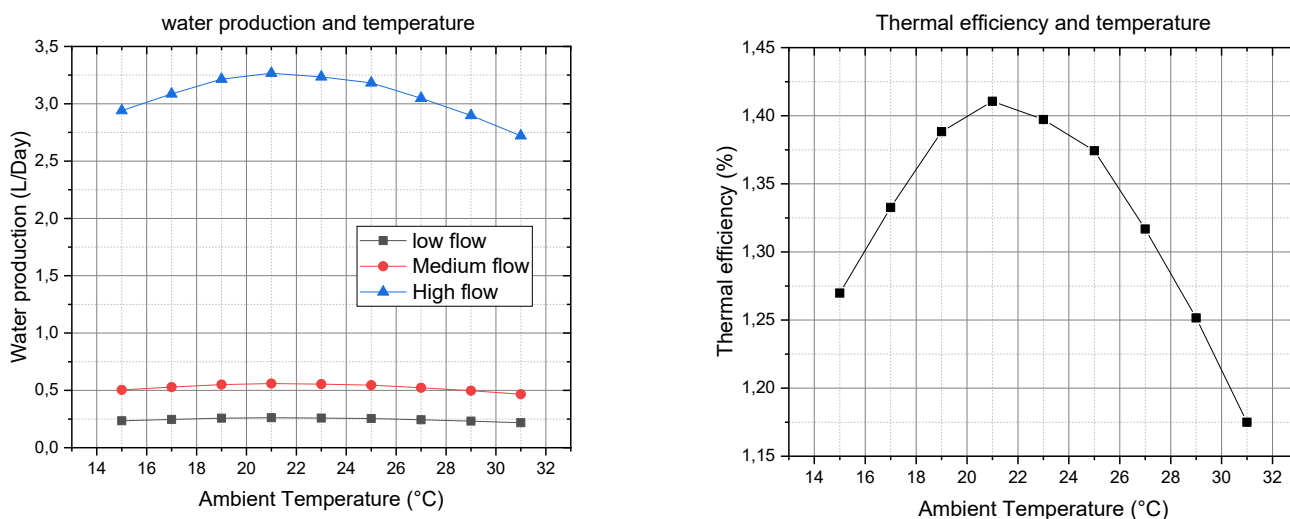


Figure 7. Effect of Ambient Temperature on system performance.

Figure 6 illustrates the variation of freshwater mass flow rate as a function of porosity. A clear positive correlation is observed between porosity and water production across all flow conditions. As porosity increases from 0 to 1.0, water output rises progressively, likely due to enhanced vapor transport and reduced resistance within the porous medium. The high-flow regime consistently yields the highest water production, indicating that convective flow synergizes with increased void space to maximize vapor extraction. Conversely, low-flow conditions limit this benefit, especially at low porosity values (<0.4), where water production remains near-zero.

In contrast, thermal efficiency exhibits a non-monotonic or even decreasing trend with increasing porosity, particularly under high and medium flow rates. While low porosity values (0–0.2) yield the highest thermal efficiency—attributed to reduced heat losses and better solid-liquid contact—efficiency declines beyond $\epsilon \approx 0.4$. This suggests a trade-off: higher porosity promotes water yield but at the expense of thermal performance, likely due to increased heat dissipation and reduced effective thermal conductivity. The low-flow regime maintains relatively stable efficiency across porosities, implying that flow rate modulates the sensitivity of thermal performance to structural changes. From a design perspective, optimal porosity is application-dependent:

- Maximizing water production favors $\varepsilon > 0.8$ with high flow rates.
- Maximizing thermal efficiency favors $\varepsilon < 0.3$, regardless of flow.

The crossing point between water yield and thermal efficiency occurs near $\varepsilon = 0.6$ for medium/high flows, representing a Pareto-optimal zone. These results highlight that porosity cannot be optimized independently; flow regime must be co-designed to balance productivity and energy effectiveness. Increasing porosity enhances water production but reduces thermal efficiency beyond a threshold of 0.4, revealing a critical trade-off that must be managed through flow regime selection.

Figure 7. Presents the influence of ambient temperature on freshwater productivity and thermal efficiency in a hybrid solar distillation system with porous baffles, under low, medium, and high airflow conditions. Water production increases with ambient temperature across all airflow regimes, reaching an optimum between 21–22 °C. Beyond this range, productivity declines progressively. This non-monotonic behavior results from two competing mechanisms: enhanced evaporation at moderate temperatures versus reduced condensation efficiency at higher temperatures due to a diminished vapor–glass temperature gradient. High airflow conditions yield the highest productivity, reaching approximately 3.25 L/day. This improvement is attributed to increased convective heat transfer and turbulence induced by the porous baffles, which enhance air mixing and thermal energy distribution. Conversely, low-flow configurations show significantly lower output due to weak convective transport, while medium-flow conditions yield intermediate values. The thermal efficiency follows a similar trend, increasing with ambient temperature up to ~21 °C (maximum ~1.41%), then decreasing. The initial rise reflects improved evaporation kinetics under higher thermal input. The subsequent decline is linked to reduced condensation effectiveness as the vapor–cover temperature difference shrinks. The integration of porous baffles stabilizes thermal behavior across a wide temperature range. Enhanced turbulence improves thermal uniformity within the collector and minimizes local temperature gradients.

CONCLUSION

The model of a solar air distiller/collector equipped with porous baffles demonstrates a significant enhancement in thermal efficiency and distillate production. By optimizing airflow and heat transfer through the incorporation of porous baffles, the system effectively utilizes ambient conditions to maximize the heating of saline water. Experimental data and polynomial approximations highlight the relationship between key variables, such as temperature differences and airflow rates, underscoring the impact of design modifications on performance.

The findings indicate that this innovative design can lead to improved energy recovery, particularly in regions with limited solar radiation or varying ambient temperatures. Overall, the integration of porous baffles in solar distillation systems represents a promising advancement in sustainable water treatment solutions, offering potential benefits for both efficiency and environmental impact. Future studies could focus on further optimizing baffle configurations and scaling the system for larger applications.

The energy balance of a flat-plate solar distiller provides essential insights for evaluating and optimizing the efficiency of the device. By quantifying the solar energy captured, the heat converted, and the energy used for water evaporation, it becomes possible to measure the system's performance in terms of freshwater production. The comparison between the energy captured and the energy recovered during condensation reveals the overall efficiency of the distiller, which serves as a key performance indicator. The main factors influencing this efficiency include the intensity of solar radiation, the quality of materials used, the design of the distiller with the presence of an integrated solar air collector equipped with porous baffles, as well as thermal losses due to conduction, convection, and radiation. Optimizing the management of these parameters allows for maximizing the conversion of solar energy into freshwater while minimizing losses.

Thus, a thorough understanding of the energy balance not only helps assess the current performance of a flat-plate solar distiller but also identifies opportunities for improvement to enhance its efficiency. By incorporating these elements into the design and operation of the system, it is possible to achieve a more sustainable and cost-effective desalination process, contributing to the efficient production of potable water from saline resources in an environmentally friendly manner. The fluid–structure interaction in porous-baffled hybrid solar stills establishes a

thermo-hydraulic trade-off where maximum water productivity is achieved only when airflow intensity, porosity, and operating temperature are co-optimized futur work [16]

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