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Analysis of thermal performance and collector efficiency of solar distillation system with modified absorber surface shape

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ABSTRACT

Solar distillation is an environmentally friendly technology that is effective for addressing the clean water crisis; however, its performance is often limited by the low heat transfer rate on the absorber plate. This study aims to analyze the effect of variations in absorber geometry (flat plate, and U-corrugated) on the water temperature profile, cumulative freshwater productivity, and collector efficiency in a solar distillation system. Experimental testing was conducted from 10:00 to 14:00. The results indicate that modifying the absorber geometry significantly enhances thermal performance. The U-corrugated absorber recorded the highest water temperature of 59.9 °C at 12:00, coinciding with the peak solar radiation intensity. Furthermore, the U-corrugated absorber produced the highest cumulative freshwater yield, reaching 895 mL at the end of the testing period (14:00), and the flat plate (705 mL). In terms of thermal collector efficiency, the U-corrugated type achieved the highest efficiency of 33.6% at 13:00. The enlarged surface area of the absorber and the enhanced fluid turbulence induced by the U-corrugated geometry were proven to accelerate the evaporation rate. Overall, the utilization of a U-corrugated absorber represents geometric strategy for enhancing heat energy transfer and maximizing the productivity of solar water distillation systems.

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1. INTRODUCTION

The availability of clean water has become one of the most crucial challenges facing modern civilization in the twenty-first century. The Earth's water availability is overwhelmingly dominated by marine and oceanic domains, which account for approximately 97.5% of the total global water volume. Conversely, the fraction of freshwater comprises a highly limited proportion, standing at merely 2.5%. Of this limited freshwater volume, the vast majority is trapped in the form of polar ice caps and glaciers or stored within deep groundwater aquifers. Consequently, the fraction of accessible surface freshwater that can be directly utilized to sustain human life and socio-economic activities is recorded at less than 1% (Mishra, 2023). This spatial disparity in water resource distribution is further exacerbated by rapid global population growth, escalating industrialization, land-use

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change, and global climate change dynamics that induce shifts in regional precipitation patterns. Across various regions worldwide, particularly in coastal areas and remote archipelagos, the freshwater crisis threatens food security, public health, and economic stability. Within this context, the exploration of non-conventional water resources has become a technological imperative. Desalination technology serves as a strategic instrument to bridge the gap between high demand for clean water and the constraints of natural freshwater supply. Desalination refers to a series of physical and chemical engineering processes designed to remove total dissolved solids (TDS) and other hazardous minerals from seawater or brackish water to produce high-efficiency water that meets the qualifications and standards for human consumption and industrial applications. Conventionally, various desalination engineering techniques have been developed and deployed on a massive scale. Prominent methods dominating the global market include membrane-based reverse osmosis (RO), electrodialysis (ED), and thermal distillation techniques such as multi-stage flash (MSF) and multiple-effect distillation (MED) (Kadhim et al., 2023). These technologies have long proven reliable in overcoming freshwater scarcity across isolated regions and urban coastal areas. However, the operationalization of such industrial-scale desalination systems diverges from energy sustainability principles due to their heavy reliance on high fossil fuel consumption. Statistical estimates indicate that to produce a specific volume of freshwater per day, a conventional thermal-based desalination plant consumes up to 10,000 tons of fossil fuels annually. This overreliance on fossil fuels not only drives high operational expenditures, but also contributes significantly to greenhouse gas (GHG) emissions and the global carbon footprint. Therefore, a paradigm shift toward the deployment of renewable energy-based desalination technologies is imperative to achieve environmentally sustainable water resource management.

Among various renewable energy options, solar energy offers the most abundant potential, evenly distributed across both tropical and subtropical regions. Solar radiation can be captured and converted directly into thermal energy via absorber media. This extracted thermal energy then serves as the primary driving force in seawater or brackish water distillation systems, an engineering process known as solar distillation. The working principle of solar distillation mimics the natural hydrological cycle on an integrated micro-scale. Solar radiation penetrates a transparent cover (such as glass or plastic) and is absorbed by the basin absorber plate containing the raw feedwater. The absorption of thermal energy elevates the fluid temperature and triggers an accelerated evaporation rate. The resulting pure water vapor ascends, leaving behind dissolved solids, contaminants, pathogens, and salt molecules at the basin bottom. As the water vapor comes into contact with the inner surface of the transparent cover—which remains at a lower temperature—latent heat transfer occurs, inducing condensation. The condensed clean water droplets (distillate) subsequently flow under gravitational force into collection channels for utilization (Arunkumar et al., 2022). Solar distillation possesses substantive advantages over conventional membrane-based desalination technologies. This method is capable of producing high-quantity and high-quality pure water without requiring the addition of reactive chemicals, thereby minimizing the potential for secondary pollution in ecosystems (Zhang et al., 2021). The distilled water not only complies with drinking water quality standards but is also highly applicable to high-precision demands, such as pharmaceutical manufacturing, electronic fabrication, and hydroponic irrigation systems in modern agriculture (Chiavazzo et al., 2018). Furthermore, processing by-products such as concentrated brine and dissolved salt residues can be repurposed for the mineral salt industry or safely discharged without compromising the structure of local coastal habitats if managed systematically. The relatively low initial investment and maintenance costs—combined with zero fossil fuel requirements during the operational phase—render solar distillation the most ideal sustainable solution for mitigating long-term ecological impacts (Goh et al., 2021).

The development of decentralized solar distillation systems plays a crucial role in enhancing socio-economic welfare in small-scale communities, remote regions, outer islands, and disaster-affected zones with minimal or no access to conventional water supply infrastructure networks. The reliable supply of pure water provided by this self-sustaining technology directly supports improvements in public health and hygiene, reinforces local food security, and stimulates regional economic activities. Furthermore, the effective integration of solar distillation substantially reduces unsustainable groundwater overexploitation, thereby preserving the ecological stability of freshwater aquifers for future generations. Despite offering numerous functional and environmental advantages, the widespread deployment of solar distillation systems remains constrained by fundamental technical limitations, namely a relatively low water productivity rate and low thermal efficiency. The performance characteristics of a solar still are highly dependent on the dynamics of convective, radiative, and evaporative heat transfer within the distiller chamber. To overcome these limitations, various geometric design innovations continue to be developed by researchers. Among these is the implementation of the hemispherical solar still (Younis et al., 2022), which has been technically proven to provide a more optimal radiation absorption area and superior thermal performance compared to conventional single-slope or double-slope designs.

The thermodynamic performance and distillate yield are influenced by a complex array of operational and environmental parameters. These parameters include the shape and geometry of the transparent cover, cover material thickness, thermophysical properties of the basin insulation, fluid depth within the basin, solar radiation

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intensity, ambient wind speed, and the salinity level of the raw feedwater. Regarding fluid properties, an increase in feedwater salinity concentration has been statistically proven to decrease the evaporation rate due to a reduction in saturated vapor pressure at the water surface, which ultimately suppresses the rate of pure vapor generation (Yan et al., 2021). In addition to fluid properties and environmental variables, the glass cover plays a vital, multifunctional role in determining distillation efficiency. The glass acts simultaneously as: a transmitting medium (transmitter) and an insulator preventing back-loss through long-wave radiation emission from inside the distiller chamber to the external environment. In this mechanism, the inclination angle and thickness of the glass cover material serve as two geometric and physical factors that heavily dictate system efficiency (Rubio et al., 2020). If the inclination angle of the glass is overly shallow, condensate droplets fail to flow smoothly into the collection channel, instead accumulating on the inner surface of the glass. This accumulation of a thin water layer (film condensation) acts as a new thermal resistance that reduces the temperature gradient between the water vapor and the glass, while simultaneously reflecting a portion of the incoming solar radiation, thereby causing a sharp drop in system productivity. Conversely, selecting a precise inclination angle combined with the appropriate physical material characteristics of the cover maximizes radiation transmittance and accelerates gravity-driven condensate sliding toward the collection outlet (Rubio et al., 2020). Although studies on solar energy-based water distillation engineering have advanced rapidly in recent decades, investigations focusing on the simultaneous quantitative effects of absorber geometry variations on overall thermal efficiency remain scarce. The majority of prior research has predominantly focused on water depth or volume within the basin, the incorporation of latent energy storage materials (phase change materials/PCMs), or the isolated analysis of cover inclination angles under the assumption of a constant (static) glass thickness. To bridge this research gap, this experimental study was systematically designed to analyze the effects of absorber geometry variations on heat transfer dynamics, overall thermal efficiency, and pure water yield in a solar distillation system. It is anticipated that the outcomes of this study will not only provide practical contributions to designing highly efficient and cost-effective solar distillation equipment, but also offer adaptive solutions for self-sustaining and sustainable implementation in water-scarce regions.

2. RESEARCH METHODS

The working principle of the solar distillation system is schematically illustrated in Figure 1. The system's operation is fundamentally driven by heat transfer mechanisms classified into internal and external heat transfer. Short-wave solar radiation penetrates the glass cover and is optimally absorbed by the absorber surface. Conversely, long-wave (infrared) radiation emitted by the water surface is re-absorbed by the water and the glass within the distillation chamber. This greenhouse effect phenomenon effectively intensifies thermal energy accumulation, raising the seawater temperature above ambient levels to trigger evaporation. A significant temperature gradient between the water surface and the glass cover stimulates water vapor condensation on the inner surface of the glass, where the resulting condensate flows down and is collected in a distillate container.

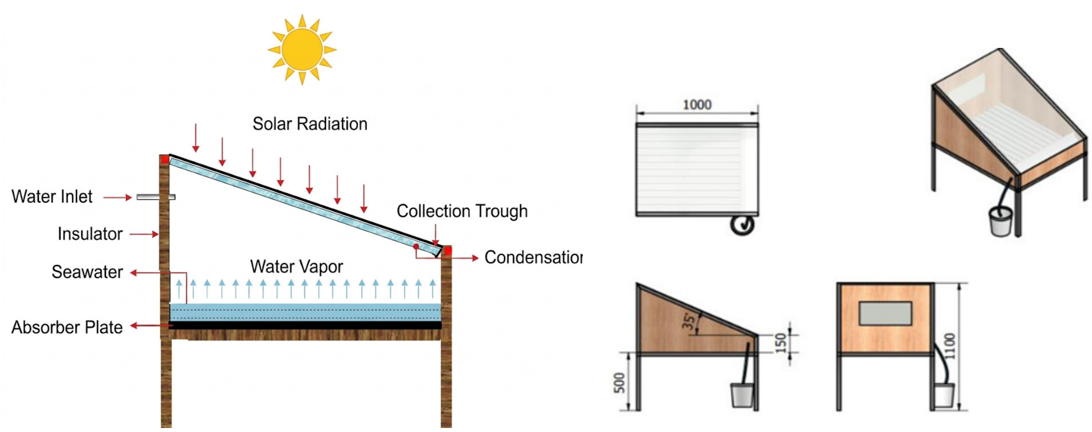

Figure 1. Solar distillation design

The distillation cover is made of 5 mm thick glass and set at an inclination angle of 35° (Alit et al., 2026). The volume of seawater in the distillation basin influences the volume of fresh water produced. Testing of this distillation unit was conducted using an initial seawater volume of 25 liters. The absorber utilizes black-painted plates in various configurations: flat, and U-corrugated. Testing was conducted simultaneously from 10 a.m. to 2 p.m. on three different days. Cover temperature, water temperature, distillate volume, and solar intensity were measured using thermocouples, measuring cylinders, and a solar power meter.

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Table 1. Specifications of the distillation apparatus

Specification	Dimensions
Length	1 m
Width	0,8 m
Seawater volume	25 liters
Glass thickness	5mm
Cover slope	35^O
Insulator thickness	5 mm

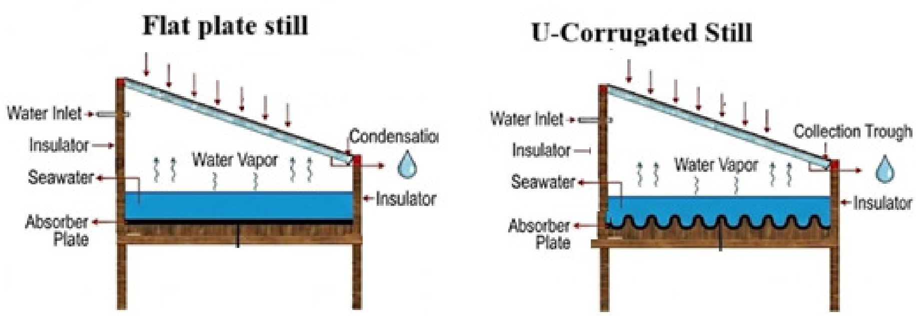

Figure 2. absorber shape variations

To calculate the thermal energy received by the collector (Q_{in}), the required data includes the solar radiation intensity (IT) and the collector's surface area

$$Q_{in} = I\ A\ \tau\ \alpha\ (watt) \quad (1)$$

Notation: I = solar radiation intensity, A = solar collector area, τ = glass transmissivity, σ = material absorptivity. The energy utilized by the collector (Q_{use}) is obtained using the equation

$$Q_{use} = \frac{m\,h_{fg}}{t}\ (watt) \quad (2)$$

Notation: m = mass of fresh water produced, h_{fg} = latent heat of vaporization of water, t = duration of the test. The efficiency of the distillation device is calculated using the equation:

$$\eta - \frac{Q_{use}}{Q_{in}}\ 100 \quad (\%) \quad (3)$$

3. RESULTS AND DISCUSSION

Figure 3. illustrates the linear relationship between solar radiation intensity and the rise in water temperature across two absorber variations: flat plate, and U-corrugated. Experimental data show that solar radiation intensity increased gradually from 10:00 (830 W/m²) to a peak at 12:00 (975 W/m²), before slowly declining until 14:00 (895 W/m²). This increase in solar radiation flux was directly proportional to the rise in water temperature for all absorber variations (Alwan et al., 2024). Maximum water temperatures for all variations were recorded at the peak of radiation (12:00); the U-corrugated absorber reached the highest temperature at 59.9°C, and the flat plate absorber 55.4°C. The nature of this physical phenomenon can be explained through the mechanisms of convection and thermal radiation absorption.

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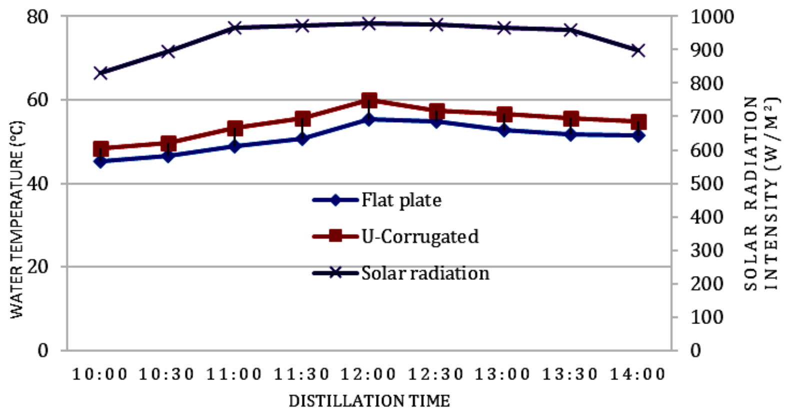

Figure 3. The relationship between distillation time and water temperature

U-corrugated geometries yield a higher surface-area-to-volume ratio compared to conventional flat plates. This increased surface area accelerates the rate of solar photon energy absorption and its conversion into thermal energy. Furthermore, the U-corrugated design creates a heat-trapping effect and reduce reflection losses, thereby optimizing heat absorption efficiency (Sanserwal et al., 2020). Significant temperature differences confirm that the engineering of the absorber's shape directly influences the increase in the water's energy content. In the period following peak intensity (after 12:00 PM), even as solar radiation began to decline, the water temperature in the U-corrugated absorber remained higher (54.8°C at 2:00 PM) than in the flat plate (51.4°C). This demonstrates superior thermal storage stability in the textured construction (Kabeel et al., 2021).

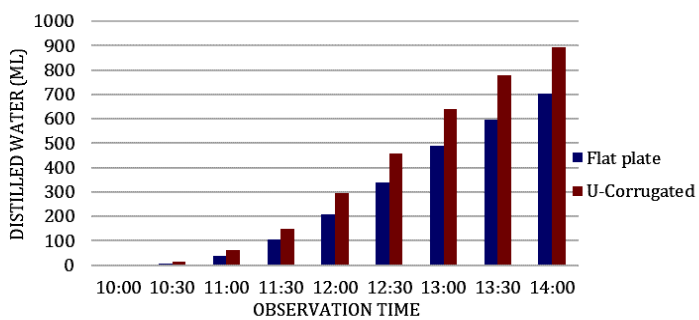

Figure 4. Distilled water with varying absorber shapes

Figure 4 demonstrates that the absorber geometry significantly influences the volume of distilled water produced during the testing process. Water yield begins to rise noticeably after 11:00 AM and continues to increase until 2:00 PM. This phenomenon occurs because, during the initial phase of operation, most of the solar energy is consumed to raise the temperature of the water and the solar still components. Once the operating temperature is achieved, the evaporation rate accelerates, leading to greater water vapor formation and a higher accumulation of condensate (Alwan et al., 2024). The superior productivity of the U-corrugated geometry is attributed to the fact that the rate of water molecule evaporation is directly proportional to the vapor pressure differential between the water surface and the glass cover, driven by higher water temperatures. Because the U-corrugated absorber maintains the highest water temperature (as illustrated in figure 3), the phase change rate from liquid to vapor becomes substantially more pronounced (Abu-Zeid et al., 2024). Beyond the temperature factor, the corrugated design splits the water pool into thin-film layers along its grooves. Conditioning water for thin-film evaporation significantly reduces the effective heat capacity of the water mass required to be heated at any given moment, enabling the latent heat of vaporization to be surpassed more rapidly (Flayh et al., 2025). Conversely, in a flat-plate absorber, the water remains at a uniform depth, requiring a longer thermal induction period to evaporate. This is evidenced at 10:30, when the flat plate produced only a minimal distillate yield 8mL, whereas the U-corrugated absorber had already produced 14 mL.

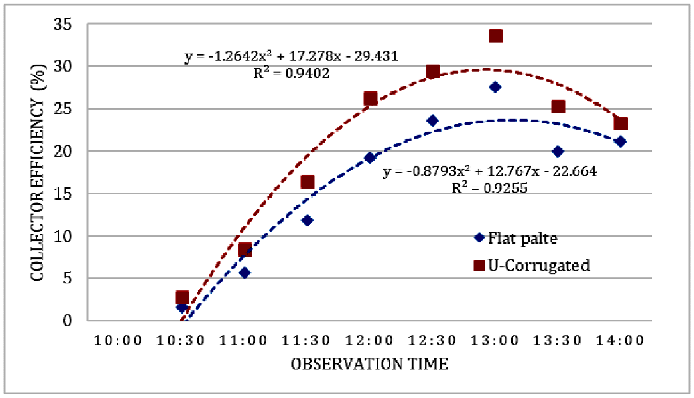

Figure 5. Relationship between observation time and collector efficiency.

Figure 5 illustrates the dynamics of solar still collector energy availability efficiency as a function of time. Collector efficiency (η) is defined as the ratio of the energy utilized for water evaporation to the total incident solar radiation energy received. Observational results indicate that the efficiency of all systems gradually increased from its lowest point at 10:30 and reached its peak during midday, before eventually declining in the late afternoon. The highest peak efficiency was achieved by the U-corrugated absorber at 13:00 at 33.6%. In comparison, the flat-plate absorber reached a maximum efficiency of only 27.6 at 13:00.

The shift in the peak efficiency of the U-corrugated absorber to 13:00—occurring faster than that of the flat-plate absorber—demonstrates significantly higher thermal responsiveness. This is attributed to an enhanced natural convection heat transfer coefficient on the corrugated surface. The wave geometry induces local turbulence in the rising water vapor, thereby minimizing boundary layer resistance (Prasad et al., 2022). However, after 13:00, a relatively sharp decline in efficiency was observed in both the U-corrugated and flat-plate absorbers until the final measurement. This reduction was driven by high convective and radiative heat losses to the ambient environment when the system temperature remained very high while solar radiation began to drop drastically. Overall, these efficiency curves prove that the corrugated geometry is thermodynamically far more effective in converting radiative energy into useful energy for the desalination process (Flayh et al., 2025).

4. CONCLUSION

Based on the research findings, it can be concluded that absorber geometry influences the performance of solar distillation systems. Varying the absorber shape results in differences in distilled water yield and collector efficiency. The enhanced performance observed with the U-corrugated absorber is attributed to its larger surface area for solar radiation absorption and more uniform heat distribution. These conditions raise the seawater temperature within the basin, accelerate the evaporation process, and generate a greater volume of condensate.

Overall, this study demonstrates that modifying the absorber shape is an effective approach to improving solar distillation system performance. Consequently, the U-corrugated absorber is recommended as a viable design for solar distillation technology, as it achieves higher basin seawater temperatures, greater distilled water productivity, and superior collector efficiency compared to flat-plate absorber geometries. These findings are expected to serve as a reference for developing more efficient, economical, and sustainable solar distillation technologies to meet clean water needs, particularly in regions with high solar radiation potential.

NOMENCLATURE

A : Solar collector area (m^2)
h_{fg} : latent heat of vaporization (kJ/kg)
I : Solar radiation intensity (W/m^2)
m : Mass of fresh water produced (kg)
t : Time (s)
Q_{in} : Thermal energy received (watt)
Q_{use} : Energy utilized by the collector (watt)
τ : Glass transmissivity (%)
σ : Material absorptivity (%)
η : Collector efficiency (%)

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