



RESEARCH ARTICLE

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EXPERIMENTAL AND THEORETICAL INVESTIGATION OF A MODIFIED SOLAR STILL INCORPORATING PCM, CuO NANO-COATED ABSORBER, AND A COPPER SPIRAL TUBE

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ABSTRACT

Access to safe freshwater remains a global challenge, motivating the development of efficient passive solar desalination systems. Conventional Solar Stills (CSS) suffer from low productivity due to limited heat absorption and the absence of thermal storage. In this study, a Modified Pyramid Solar Still (MPSS) integrating paraffin wax Phase Change Material (PCM), CuO nanoparticle-enhanced matt black coating, and a copper spiral absorber is experimentally and theoretically investigated. Performance comparisons were conducted at water depths ranging from 10–50 mm. The MPSS consistently outperformed the CSS at all depths, with maximum productivity achieved at 10 mm, yielding 2.311 L/day—representing a 162.5% enhancement over the CSS. The PCM effectively sustained evaporation during post-sunset hours, while CuO nanoparticles and the copper spiral improved solar absorption and internal heat transfer. A comprehensive thermal model incorporating PCM charging–discharging and enhanced heat transfer mechanisms showed good agreement with experimental data, with deviations within $\pm 10\%$, confirming the reliability of the proposed approach.



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I. INTRODUCTION

Currently, the availability of safe, potable freshwater is critical for human civilization, public health, and industrial expansion [1-3]. Despite water covering approximately 75% of the planet's surface, less than 0.5% [4],[5] is available as freshwater resources readily accessible to humanity, leading to growing concerns about future scarcity [3]. Many nations worldwide, particularly developing countries and those in the Middle East, are suffering from a shortage of fresh water. Compounding this challenge, the United Nations (UN) estimates that one-third of the global population lives in regions where freshwater supplies are insufficient to support the population. In response to this exacerbating crisis, solar desalination systems represent a viable, eco-friendly solution for converting abundant saline or brackish water into potable water [4, 6]. Among the various desalination technologies, the solar still is favored, particularly for remote and rural areas, due to its low cost, uncomplicated construction, minimal maintenance requirements, and reliance solely on free solar energy [3],[6].

The most fundamental solar distillation device, the Single Slope Solar Still, suffers from inherently low productivity, often attributed to heat losses to the surroundings and the significant energy required to heat the basin water [4],[7]. Consequently, significant research has focused on developing modified designs, leading to the evolution of the Pyramid Solar Still (PSS), which often offers improved performance over the conventional single-slope design. The pyramid configuration offers less shading on the water surface and a larger condensing area compared to single-slope stills [2]. Early experimental work established the PSS as a promising design, exemplified by the study performed by Taamneh and Taamneh (2012) in Jordan, which showed that forced convection could increase the daily productivity of a PSS by up to 25% compared to a free convection still [4],[8]. To further augment the thermal performance and combat the limitation of low nighttime production, researchers began integrating PCM, which function as thermal energy storage to extend the distillation period after sunset [3],[9].

For example, Sathyamurthy et al. (2014) demonstrated that incorporating paraffin wax (a type of PCM) into a triangular PSS increased the distillate output by 20% compared to a still without PCM, achieving this by storing heat during sunlit hours and releasing it subsequently [2],[3],[10]. In more recent studies, the combined approach of using fins and PCM in PSS successfully delivered a substantial enhancement of 101.5% in daily productivity over a conventional PSS [9]. Beyond thermal storage, improvements in solar energy absorption and heat transfer characteristics within the basin proved crucial. This led to the application of nanofluids and advanced absorber designs. Nanofluids, which are working fluids enhanced with minute particles, exhibit remarkable thermal-physical properties, including improved thermal conductivity and greater solar absorptivity [1].

Studies showed that coating the absorber plate with black paint mixed with nanocomposites, such as CuO nanoparticles, is highly effective [11],[12]. Experimentally, the addition of CuO nanofluids to a PSS achieved a total freshwater improvement of 27.85% over the conventional PSS [4]. Furthermore, the geometric modification of the absorber surface, such as the use of fins, corrugated shapes [1], or specialized heating coils, significantly increases the surface area for evaporation and heat exchange, consequently boosting heat absorption [5]. For example, integrating a complex absorber structure, such as a stepped PSS coupled with a solar parabolic dish featuring a spiral coil, resulted in an exceptional increase in daily yield of 131% over a conventional PSS [13]. Drawing upon these proven enhancement strategies, the efficacy of integrating multiple, complementary techniques simultaneously holds substantial research interest.

These techniques include the utilization of PCM for thermal regulation, the enhancement of solar absorption using CuO nanoparticles applied via black paint coating, and the optimization of heat transfer mechanisms through the geometric augmentation of the absorber surface using a copper spiral coil. Although previous studies have examined these components individually or in partial combinations—such as the PSS with PCM [2], or the PSS with nanofluids and corrugated absorbers [1], or PSS with fins/coils [5], a comprehensive experimental evaluation of a PSS integrating paraffin wax as PCM, CuO nanoparticles applied with matt black paint, and a copper spiral absorber is necessary to quantify their synergistic effect. This study addresses this gap by comparing the performance of a CSS with a MPSS incorporating these three enhancements, thereby seeking to quantify the maximum potential yield augmentation under real-world conditions.

II. MATERIALS AND SYSTEM DESIGN

The experimental methodology was structured to ensure a fair and reliable comparison between the CSS and MPSS by maintaining identical geometric dimensions, materials, and operating conditions wherever possible. All modifications introduced in the MPSS were selected based on their proven potential to enhance heat absorption, thermal storage, and internal heat transfer without increasing system complexity or compromising passive operation. This systematic approach allows the observed performance differences to be attributed solely to the integrated enhancements, thereby strengthening the validity of the experimental findings and subsequent analysis.

II.1 SYSTEM DESIGN

This experimental investigation, conducted in Surendranagar, Gujarat, India (22.7287°N, 71.6191°E), compared a CSS with a MPSS built on identical 0.25 m² basin units with a 2 mm thick acrylic glass cover at inclination 23° and 20 mm thick polystyrene insulation. The MPSS incorporated three performance-enhancing features: a layer of paraffin wax beneath the basin for thermal energy storage, a coating of matt black paint mixed with CuO nanoparticles on the basin surface to increase solar absorption, and a copper spiral absorber tube installed in the water to enhance internal heat transfer. To enable precise thermal monitoring, each airtight unit was equipped with three K-type thermocouples positioned to measure the basin surface, water, and inner glass cover temperatures. Table 1 shows the specifications of the materials used.

Table 1: Specifications of the materials.

Component	Material/Type	Specifications/Role
Basin	Sheet Metal	Square dimensions of 500 mm×500 mm (0.25 m ²). 1.5 mm thick.
Cover	Acrylic Glass (Plexiglass)	Pyramid shape, 2 mm thickness. Inclination 23°.
Insulation	Polystyrene	20 mm thickness. Used beneath the basin and on the sides to minimize heat loss to the surroundings.
Absorber Plate Coating (CSS)	Matt Black Paint	Applied to the basin to maximize solar radiation absorption.
Absorber Plate/Spiral Coating (MPSS)	Matt Black Paint mixed with CuO Nanoparticles	Applied to the MPSS basin surface and copper spiral absorber to enhance absorptivity and thermal conductivity.
Phase Change Material (MPSS)	Paraffin Wax	Utilized beneath the absorber basin for thermal energy storage, extending the distillation period into evening hours. 40 mm thick.
Heat Absorption Enhancement (MPSS)	Copper Spiral Absorber	Fabricated from copper tubing (3/8" tube diameter) and coiled with a minor diameter of 50 mm, a major diameter of 405 mm, and a pitch of 1".

Source: Authors, (2026).

II.2 MATERIAL SPECIFICATIONS

To ensure reproducibility and precise theoretical modelling, standard commercial-grade materials were selected. The thermophysical properties of the PCM and the nanoparticles used in the coating are shown in Table 2 and Table 3 respectively.

Table 2: Specifications of Paraffin Wax.

Property	Value	Unit
Colour	White	-
Melting Temperature	52	°C
Thermal Conductivity	0.288	W/ (m.K)
Latent heat of fusion	227	kJ/kg
Specific Heat Capacity (Liquid)	2.51	kJ/(kg.K)
Specific Heat Capacity (Solid)	2.95	kJ/(kg.K)
Density (Liquid)	760	kg/m ³
Density (Solid)	818	kg/m ³

Source: Authors, (2026).

Table 3: Specifications of CuO Nanoparticles.

Property	Value	Unit
Purity	99.9%	%
Average particle size	30-70 nm	nm
Specific surface area	60-80	m ² /g
Molecular weight	79.545	g/mol
Melting point	1326	°C
Bulk Density	0.66	g/cm ³
Morphology	Spherical	-
Color	Brownish Black	-

Source: Authors, (2026).

II.2.1 Preparation of CuO Nano-Coated Absorber Surface

To enhance the solar absorptivity and thermal conductivity of the absorber surface in the MPSS, a nano-enhanced coating was prepared using CuO nanoparticles. Commercially available CuO nanoparticles were mixed with matt black paint at a concentration of 25% by weight to ensure a high nanoparticle loading while maintaining coating uniformity and adhesion. The mixture was mechanically stirred for sufficient duration to achieve a homogeneous dispersion of nanoparticles within the paint matrix and to minimize particle agglomeration. Prior to coating, the basin surface and copper spiral tube were thoroughly cleaned and dried to remove dust, grease, or oxidation layers. The prepared CuO–paint mixture was then uniformly applied to the absorber basin surface and the copper spiral tube using a brush-coating technique, ensuring complete surface coverage and consistent coating thickness. After application, the coated components were allowed to dry under ambient conditions before assembly of the solar still.

II.3 SCHEMATIC DIAGRAM AND ACTUAL SETUP PHOTO

A detailed schematic diagram (Figure 1 and 2) showing the cross-sectional view of the CSS and MPSS is provided. The schematic illustrates the arrangement of the acrylic glass cover, sheet metal basin, polystyrene insulation, PCM layer (in MPSS), the application of the CuO nanoparticle coating, and the integration of the copper spiral absorber (in MPSS).

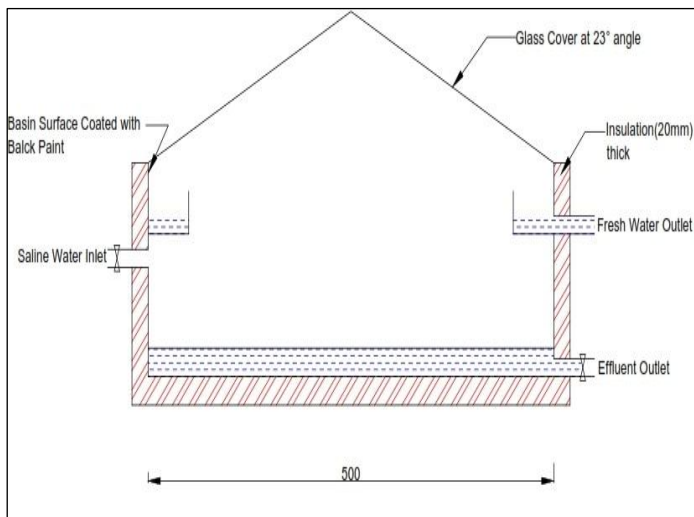


Figure 1: Diagram of CSS.
Source: Authors, (2026).

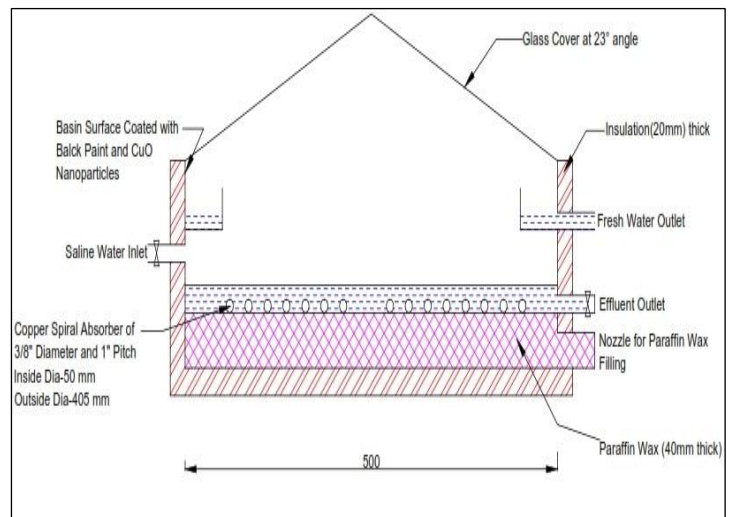


Figure 2: Diagram of MPSS.
Source: Authors, (2026).

A photographic view (Figure 3) displays the actual outdoor experimental setup, showing the two fabricated square pyramid solar stills (CSS and MPSS) operating side-by-side under local climatic conditions, along with the associated measuring equipment.

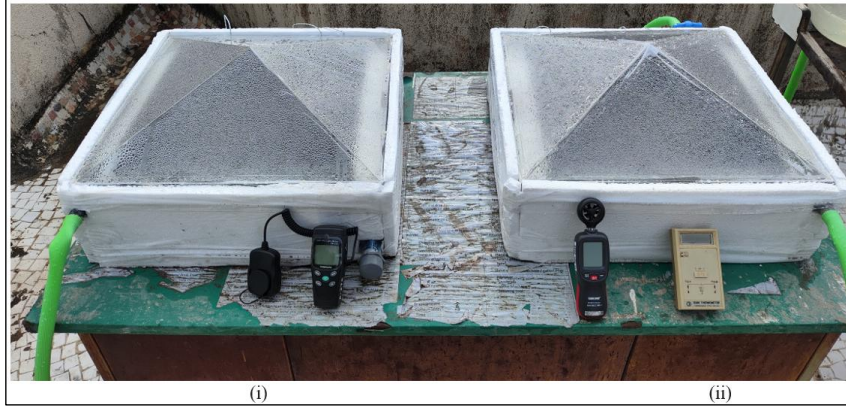


Figure 3: (i) MPSS (ii).
Source: Authors, (2026).

III. THEORETICAL ANALYSIS

This section outlines the mathematical model used to simulate the performance of the Solar Still. The model compares theoretical predictions with experimental findings by analysing the thermal behaviour of the basin, water mass, and glass cover.

III.1 ASSUMPTIONS

To simplify the thermal analysis, the following assumptions were made:
The system operates under a quasi-steady-state regime during daylight hours.
Water vapor behaves as an ideal gas, and the still is completely sealed to prevent vapor leakage.
No thermal stratification occurs in the water mass; temperature is assumed uniform throughout the depth.
Film wise condensation occurs on the inner surface of the glass cover.

III.2 GOVERNING EQUATIONS

The thermal performance is governed by energy balance equations for the basin, water, and glass cover. These equations account for solar radiation inputs and heat transfer via conduction, convection, radiation, and evaporation.

III.2.1 Basin Energy Balance:

The temperature change of the basin T_b is determined by the absorbed solar radiation minus the convective heat transfer to the water $Q_{cv,b-w}$ and heat losses to the ambient environment Q_l [14].

$$\frac{dT_b}{dt} = \frac{I(t)A_b\alpha'_b - Q_{cv,b-w} - Q_l}{m_b C_b} \quad (1)$$

Where the heat transfer components and coefficients are calculated as follows: [15]:

$$Q_{cv,b-w} = h_{cv,b-w}A_b(T_b - T_w) \quad (2)$$

$$Q_l = U_b A_b (T_b - T_s) \quad (3)$$

$$U_b = \frac{1}{\left(\frac{x_{ins}}{k_{ins}} + \frac{1}{h_{t,b-s}}\right)} \quad (4)$$

$$h_{t,b-s} = 5.7 + 3.8V \quad (5)$$

III.2.2 Water Energy Balance:

The water temperature T_w is governed by the energy gain from the basin and solar radiation, balanced against heat losses to the glass cover $Q_{t,w-g}$ [14].

$$\frac{dT_w}{dt} = \frac{I(t)A_w\alpha'_w + Q_{cv,b-w} - Q_{t,w-g}}{m_w C_w} \quad (6)$$

The total heat transfer to the cover $Q_{t,w-g}$ includes convective h_{cv} , radiative h_r , and evaporative h_e components, derived using Dunkle's model: [16]

$$Q_{t,w-g} = (h_{cv,w-g} + h_{r,w-g} + h_{e,w-g})A_w(T_w - T_g) \quad (7)$$

$$h_{cv,w-g} = 0.884 * \left[(T_w - T_g) + \frac{(p_w - p_g)T_w}{268900 - p_w} \right]^{\frac{1}{3}} \quad (8)$$

$$h_{r,w-g} = \varepsilon_{eff} \sigma (T_w + T_g)(T_w^2 + T_g^2) \quad (9)$$

$$h_{e,w-g} = 16.273 \times 10^{-3} * h_{cv,w-g} \left(\frac{p_w - p_g}{T_w - T_g} \right) \quad (10)$$

The saturation vapor pressure P at a specific temperature is calculated as: [17].

$$P = e^{\left(25.317 - \frac{5144}{T}\right)} \quad (11)$$

III.2.3 Glass Cover Energy Balance:

The glass cover temperature T_g is derived by balancing the heat gained from the water against losses to the ambient air and sky via convection $Q_{cv,g-s}$ and radiation $Q_{r,g-sky}$ [14].

$$\frac{dT_g}{dt} = \frac{I(t)A_g\alpha'_g + Q_{t,w-g} - Q_{t,g-s}}{m_g c_g} \quad (12)$$

The associated heat transfer equations are: [15].

$$Q_{cv,g-s} = h_{cv,g-s} A_g (T_g - T_s) \quad (13)$$

$$h_{cv,g-s} = 2.8 + 3V \quad (14)$$

$$Q_{r,g-sky} = h_{r,g-sky} A_g (T_g - T_{sky}) \quad (15)$$

$$h_{r,g-sky} = \varepsilon_g \sigma (T_g + T_{sky})(T_g^2 + T_{sky}^2) \quad (16)$$

III.2.4 Optical Parameters and Performance Metrics

The effective absorptivity for the glass cover α_g , water α_w , and basin α_b are adjusted for reflections and absorption [18]:

$$\alpha'_g = (1 - R_g) \alpha_g \quad (17)$$

$$\alpha'_w = \alpha_w (1 - \alpha_g) (1 - R_g) (1 - R_w) \quad (18)$$

$$\alpha'_b = \alpha_b (1 - \alpha_g) (1 - R_g) (1 - R_w) (1 - \alpha_w) (1 - R_b) \quad (19)$$

The hourly freshwater productivity P_h and thermal efficiency η_h are calculated based on the evaporative heat transfer coefficient and latent heat of vaporization L_w :

$$P_h = \frac{3600 * h_{e,w-g} (T_w - T_g)}{L_w} \quad (20)$$

$$\eta_h = \frac{P_h L_w}{3600 * I(t) A_b} * 100 \quad (21)$$

III.3 MODIFIED BASIN MODEL WITH PCM, CUO NANO-COATING AND SPIRAL COPPER TUBE

This subsection extends the conventional thermal model to account for the integrated effects of CuO nanoparticle-enhanced absorptivity, paraffin wax PCM, and a copper spiral tube used in the MPSS.

The governing equations preserve energy conservation while introducing additional heat storage and transfer mechanisms responsible for the experimentally observed enhancement and extended night-time productivity.

III.3.1 Modified Basin Energy Balance

For the MPSS, the basin liner is coated with matt black paint mixed with CuO nanoparticles, which enhances solar absorptivity and thermal conductivity. In addition, thermal energy is transferred simultaneously to the basin water and to the PCM layer located beneath the basin. Accordingly, the transient energy balance of the modified basin is expressed as:

$$m_b c_b \frac{dT_b}{dt} = I(t) A_b \alpha_{b,eff} \tau_g - Q_{b-w} - Q_{b-PCM} - Q_{b-loss} \quad (22)$$

Where the effective absorptivity of the CuO-coated basin surface is given by:

$$\alpha_{b,eff} = \alpha_{paint} + \phi_{CuO} (\alpha_{CuO} - \alpha_{paint}) \quad (23)$$

$$Q_{b-w} = h_{b-w} A_b (T_b - T_w) \quad (24)$$

The heat transfer terms are defined as:

$$Q_{b-PCM} = h_{b-PCM} A_b (T_b - T_{PCM}) \quad (25)$$

$$Q_{b-loss} = h_{b-a} A_b (T_b - T_a) \quad (26)$$

The CuO nanoparticles improve the basin's ability to absorb and conduct heat, thereby accelerating heat transfer to both the basin water and the PCM layer.

III.3.2 Copper Spiral Tube Heat Transfer Model

A spiral copper tube immersed in the basin water acts as an additional heat absorption and redistribution element. The spiral tube receives solar energy through the CuO-coated surface and transfers it to the basin water by convection. The transient energy balance of the copper spiral is written as:

$$m_{coil}c_{Cu} \frac{dT_{coil}}{dt} = I(t)A_{coil}\alpha_{CuO} - Q_{coil-w} \quad (27)$$

Where the heat transfer from the spiral tube to the basin water is:

$$Q_{coil-w} = h_{coil}A_{coil}(T_{coil} - T_w) \quad (28)$$

The presence of the spiral tube increases the effective heat transfer area inside the basin, enhances temperature uniformity, and promotes faster charging of the PCM during peak solar hours.

III.3.3 Modified Water Energy Balance

Considering the additional heat supplied by the copper spiral tube, the basin water energy balance becomes:

$$m_w c_w \frac{dT_w}{dt} = Q_{b-w} + Q_{coil-w} - Q_{w-g} \quad (29)$$

The heat transfer from water to glass cover, Q_{w-g} , is calculated using Dunkle's correlations for convective, radiative, and evaporative heat transfer, as defined in Section III.2.

III.3.4 PCM Charging and Discharging

The paraffin wax PCM undergoes sensible heating, phase change, and sensible cooling depending on its temperature relative to the melting temperature T_m . The PCM energy balance is therefore modelled using a piecewise formulation.

(a) Daytime Charging Mode ($I(t)>0$)

Solid PCM ($T_{PCM} < T_m$)

$$m_{PCM}c_{PCM,s} \frac{dT_{PCM}}{dt} = Q_{b-PCM} - Q_{PCM-loss} \quad (30)$$

Phase Change Region ($T_{PCM} = T_m$)

$$m_{PCM}L_{PCM} \frac{df}{dt} = Q_{b-PCM} \quad (31)$$

Liquid PCM ($T_{PCM} > T_m$)

$$m_{PCM}c_{PCM,l} \frac{dT_{PCM}}{dt} = Q_{b-PCM} - Q_{PCM-loss} \quad (32)$$

Where f represents the liquid fraction of the PCM.

(b) Night-Time Discharging Mode ($I(t)=0$)

After sunset, the PCM releases stored thermal energy back to the basin and water, sustaining evaporation even in the absence of solar radiation. The basin energy balance during night-time becomes:

$$m_b c_b \frac{dT_b}{dt} = Q_{PCM-b} - Q_{b-w} - Q_{b-loss} \quad (33)$$

Where the heat released from PCM to basin is:

$$Q_{PCM-b} = h_{b-PCM}A_b(T_{PCM} - T_b) \quad (34)$$

During discharging, the PCM equations are written as:

Liquid PCM Cooling

$$m_{PCM}c_{PCM,l} \frac{dT_{PCM}}{dt} = -Q_{PCM-b} - Q_{PCM-loss} \quad (35)$$

Solidification Phase ($T_{PCM} = T_m$)

$$m_{PCM}L_{PCM} \frac{df}{dt} = -Q_{PCM-b} \quad (36)$$

This controlled release of latent heat maintains higher basin and water temperatures during evening and night hours, thereby extending the distillation period and explaining the experimentally observed enhancement in night-time productivity.

III.3.5 Contribution of the Modified Basin Model

The proposed modified basin model effectively captures the combined influence of CuO nanoparticle-enhanced absorptivity, improved internal heat transfer due to the copper spiral tube, and latent heat storage and release by the PCM. These coupled mechanisms explain the elevated basin and water temperatures, delayed thermal decay after sunset, and sustained evaporation rates observed in the MPSS. The model thus provides a physically consistent framework for predicting the enhanced thermal and productivity performance of the modified solar still.]

III.4 UNCERTAINTY ANALYSIS

An uncertainty analysis was performed to quantify the reliability of the measured data and the calculated results, typically following the methodology established by Holman. The overall uncertainty of a result (W_R), which is a function of independent measured variables ($X_1, X_2, \dots, X_n$), is computed using the general formula for the propagation of uncertainties:

$$W_R = \sqrt{\left(\frac{\delta R}{\delta X_1} W_1\right)^2 + \left(\frac{\delta R}{\delta X_2} W_2\right)^2 + \dots + \left(\frac{\delta R}{\delta X_n} W_n\right)^2} \quad (37)$$

Where $W_1, W_2, \dots, W_n$ are the uncertainties associated with the independent measured parameters listed in the instrumentation Table 4. The errors in calculated parameters, such as the total freshwater distillate is typically found to be in the range of $\pm 1.4\%$ for productivity ensuring the credibility of the experimental findings.

IV. EXPERIMENTAL INVESTIGATION

This section describes the experimental methodology adopted to evaluate and compare the performance of the CSS and the MPSS. The experimental work was designed to ensure identical operating and environmental conditions for both systems so that the observed performance differences could be attributed solely to the proposed modifications. Details of the measuring instruments, test procedure, operating parameters, and data acquisition methodology are presented to ensure transparency, repeatability, and reliability of the experimental results.

IV.1 INSTRUMENTATION

Accurate measurement of thermal, meteorological, and productivity parameters is essential for reliable performance evaluation of solar stills. Therefore, calibrated measuring instruments with appropriate accuracy and resolution were employed to monitor the operating conditions of both the CSS and MPSS throughout the experimental duration. The measured parameters included basin temperature, water temperature, inner glass cover temperature, ambient temperature, solar radiation intensity, wind velocity, and freshwater yield. The instruments used, along with their specifications, are detailed below in Table 4.

Table 4: Specifications of the measuring instruments.

Instrument Name	Measured Parameter	Resolution	Range	Accuracy/Error
K-type Thermocouple with Digital Thermometer	Basin Surface Temperature (T_b), Water Temperature (T_w), Inner Cover Temperature (T_g), Ambient Temperature (T_a)	0.1°C	-50°C to 200°C	$\pm 1^\circ\text{C}$ ($\pm 1\%$)
Solar Power Meter (Solarimeter)	Solar Radiation Intensity ($I(t)$)	1W/m ² or 1 BTU / (ft ² *h)	0-1999W/m ² or 0-634 BTU / (ft ² *h)	$\pm 10\text{W/m}^2$ [$\pm 3\text{ BTU} / (\text{ft}^2*\text{h})$] or $\pm 5\%$, whichever is higher
Digital Vane Anemometer	Wind Velocity (V)	0.1 m/s	0-30 m/s	$\pm 5\%$ or $\pm 0.1\text{ m/s}$ whichever is higher
Calibrated Measuring Jar/Scaled Vessel	Hourly Distillate Productivity (m)	5 mL	0–1500 mL	$\pm 5\text{ mL}$ ($\pm 1\%$)

Source: Authors, (2026).

The experimental design investigated the influence of water depth on productivity by testing five distinct levels: 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm over a 15-day period, with three days allocated to each depth to ensure data reliability. From July 3 to July 17, 2025, system performance was monitored hourly between 9:00 a.m. and 9:00 p.m.

During these intervals, internal and ambient temperatures (T_w, T_b, T_g, T_a) were recorded simultaneously, meteorological parameters including solar radiation intensity $I(t)$ and wind velocity V , and the volume of freshwater distillate using calibrated vessels to determine the cumulative daily yield.

IV.2 EXPERIMENTAL PROCEDURE

The experimental procedure was systematically planned to investigate the influence of basin water depth on the thermal and productivity performance of the solar stills under real outdoor climatic conditions. Both the CSS and MPSS were tested simultaneously to eliminate the effect of day-to-day weather variations. The procedure followed during experimentation is described below. Prior to the commencement of experiments, both solar stills were thoroughly inspected to ensure airtight sealing, proper alignment of the glass covers, and correct placement of thermocouples. The basin surfaces, copper spiral tube (in MPSS), and glass covers were cleaned to remove dust and impurities that could affect heat transfer and condensation. The systems were then filled with saline water to the desired depth and positioned side-by-side in an open outdoor location to receive identical solar radiation and wind exposure. The experiments were conducted at five different basin water depths, namely 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm, to assess their influence on still performance.

For each water depth, experiments were carried out over three consecutive days, and the average values were used for analysis to minimize the effect of transient environmental fluctuations. After completing tests for a given depth, the basin water was drained, and the next depth was set for subsequent experimentation. Each experimental run was conducted from 9:00 a.m. to 9:00 p.m., covering both peak solar hours and post-sunset periods to capture the thermal storage and discharge behaviour of the PCM in the MPSS. Hourly measurements of basin temperature (T_b), water temperature (T_w), inner glass cover temperature (T_g), and ambient temperature (T_a) were recorded using calibrated K-type thermocouples. Simultaneously, solar radiation intensity $I(t)$ was measured using a solar power meter, and wind velocity was recorded using a digital vane anemometer. The freshwater distillate produced by each still was collected hourly in calibrated measuring jars placed at the outlet channels.

The collected distillate was measured and recorded to determine hourly productivity and cumulative daily yield. At the end of each day, the total distillate output was noted, and the measuring jars were emptied and reset for the next experimental run. The recorded experimental data were subsequently used for comparison with theoretical predictions and for evaluating the effects of water depth, PCM integration, CuO nanoparticle coating, and copper spiral absorber on the thermal and productivity performance of the solar stills.

V. RESULTS AND DISCUSSION

Before examining individual performance metrics, the experimental results are first interpreted in relation to the prevailing environmental conditions and the resulting thermal response of the solar stills. Since solar radiation and ambient temperature directly influence evaporation and condensation processes, analysing the hourly variation of basin, water, and glass temperatures provides a fundamental basis for understanding the observed productivity trends discussed in the following subsection.

V.1 HOURLY VARIATION OF ENVIRONMENTAL CONDITIONS AND STILL TEMPERATURES

The hourly variation of solar radiation, ambient temperature, and internal still temperatures were analysed to understand the thermal behaviour of both the stills. Solar radiation increased steadily during the morning hours, reaching a maximum around midday, which resulted in a corresponding rise in basin, water, and glass cover temperatures for both stills. Throughout the daytime operation, the MPSS consistently exhibited higher basin and water temperatures compared to the CSS. This enhancement is primarily attributed to the CuO nanoparticle-coated absorber surface, which increased effective solar absorptivity and accelerated heat transfer to the basin water. Moreover, the copper spiral tube promoted uniform heat distribution within the basin, reducing thermal resistance and enhancing evaporation.

As solar radiation declined during the late afternoon and evening hours, the CSS experienced a rapid temperature drop, whereas the MPSS maintained elevated temperatures due to the latent heat released from the paraffin wax PCM layer. This sustained thermal effect preserved a favourable temperature difference between water and glass cover, enabling continued evaporation beyond sunset. Theoretical temperature predictions obtained from the modified basin energy balance closely followed the experimental trends. Minor deviations observed during peak solar hours are attributed to transient environmental effects and unavoidable experimental heat losses, while overall agreement confirms the robustness of the proposed theoretical model. Figure 4 illustrates the hourly variation of solar radiation and the corresponding temperatures of the CSS and MPSS for experimental data.

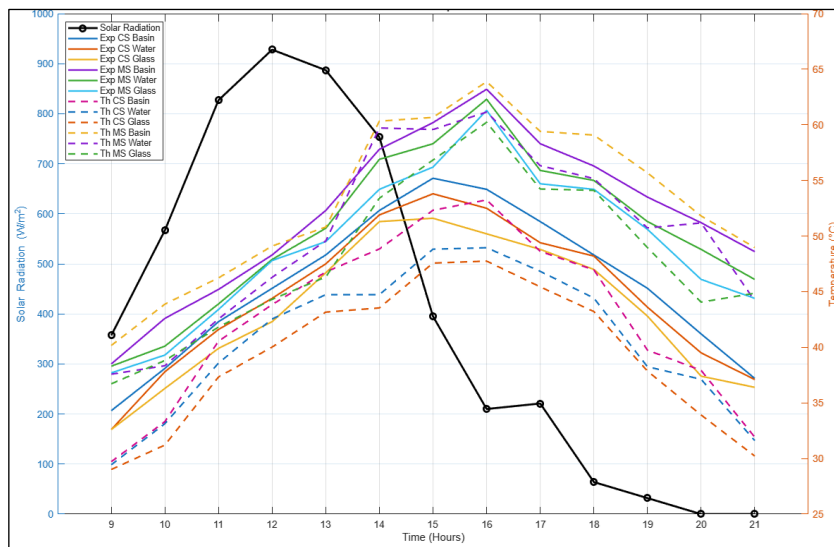


Figure 1: Graph of solar radiation vs temperature profile.

Source: Authors, (2026).

V.1.1 Validation of Theoretical Model with Experimental Data

The validity of the developed theoretical model was assessed by comparing the predicted basin, water, and glass cover temperatures with the corresponding experimental measurements for the MPSS. The theoretical results closely follow the experimental trends throughout the day, including peak solar hours and post-sunset conditions. The maximum deviation between theoretical and experimental temperatures was found to be within $\pm 10\%$, which is acceptable for solar still thermal modelling considering environmental fluctuations and experimental uncertainties. The close agreement confirms that the modified basin energy balance, incorporating the effects of CuO nanoparticle-enhanced absorptivity, copper spiral tube heat transfer, and PCM charging–discharging behaviour, accurately represents the real thermal behaviour of the MPSS. This validation demonstrates that the proposed model can be reliably used for performance prediction and future parametric optimisation without extensive experimental trials.

V.2 COMPARATIVE PRODUCTIVITY AND EFFICIENCY ANALYSIS WITH VARYING WATER DEPTHS

The core objective of the experiment was to compare the freshwater productivity of the two solar stills across different water depths. The results, summarized in Figure 5, clearly demonstrate the significant benefits of the proposed modifications and underscore the critical role of water depth in system performance.

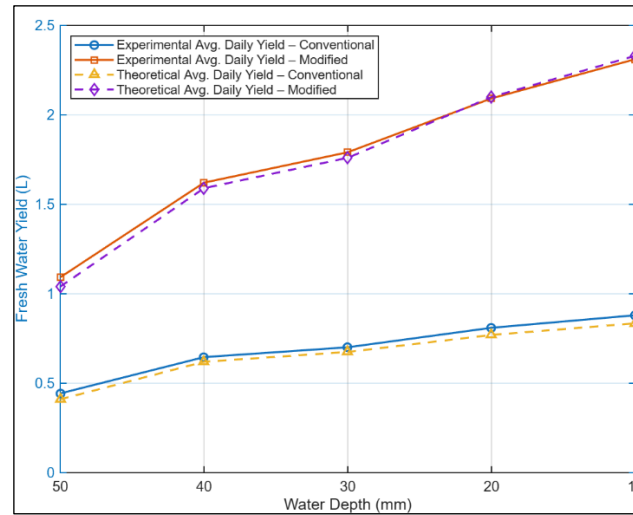


Figure 2: Summary of Daily Performance Metrics by Water Depth (Average of 3 Days).
Source: Authors, (2026).

The data reveals a clear and consistent trend: as the water depth decreases, the average daily yield of both the conventional and modified solar stills increases. The highest productivity for both stills was recorded at a water depth of 10 mm. This is a well-documented phenomenon in solar distillation, as a shallower water layer has less thermal mass, allowing it to heat up faster and reach a higher peak temperature during the day. The results show that the MPSS consistently outperformed the CSS at every water depth, with productivity enhancements ranging from an impressive 146.1% to 162.5%.

V.3 DISCUSSION OF FINDINGS AND UNDERLYING MECHANISMS

The experimental results clearly demonstrate that integrating PCM, CuO nanoparticle coating, and a copper spiral absorber significantly enhances the thermal and productivity performance of a pyramid solar still. Compared to previously reported studies employing individual modifications, the present system achieved a maximum productivity enhancement of 162.5%, indicating a strong synergistic effect among the combined techniques. The improved performance is attributed to enhanced solar absorption by the CuO-coated basin, accelerated internal heat transfer due to the copper spiral tube, and effective thermal energy storage and release by the PCM. These mechanisms collectively increase water temperature, maintain a favourable water–glass temperature difference, and sustain evaporation during post-sunset hours. The results confirm that reducing basin water depth further amplifies these benefits by lowering thermal inertia. Overall, the findings highlight the importance of integrated system design for achieving substantial and practically relevant performance improvements in passive solar desalination systems.

VI. CONCLUSIONS

The experimental results demonstrate that the MPSS, integrating paraffin wax PCM, CuO nanoparticle-enhanced absorber coating, and a copper spiral tube, consistently outperformed the CSS under all tested operating conditions. The maximum freshwater productivity was achieved at a water depth of 10 mm, where the MPSS produced 2.311 L/day, corresponding to a 162.5% enhancement compared to the CSS, confirming the strong influence of reduced thermal mass on evaporation performance. The incorporation of paraffin wax PCM effectively extended the distillation process into post-sunset hours by storing latent heat during peak solar periods and releasing it gradually, resulting in sustained basin and water temperatures. The CuO nanoparticle-coated absorber and copper spiral tube significantly improved solar energy absorption and internal heat transfer, leading to higher water temperatures, improved temperature uniformity, and increased evaporation rates throughout the day. The developed theoretical model, incorporating PCM charging–discharging behaviour and enhanced heat transfer mechanisms, showed good agreement with experimental data with deviations within $\pm 10\%$, confirming its suitability for performance prediction and future system optimization.

This multi-faceted approach provides a viable and highly effective method for improving the performance of passive solar stills, presenting a more robust solution for water-stressed regions. Further investigation is recommended to optimize the system's design parameters, including the precise concentration of nanoparticles and the dimensions of the PCM layer and spiral tube. Future work could also involve a detailed thermodynamic analysis or computational fluid dynamics simulation to precisely model the internal heat and mass transfer phenomena and further refine the system's design for even greater efficiency.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Bhavin G Chavda, Virang H Oza and Vipul M Patel.

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