

Experimental Performance Analysis of PCM and Fin-Integrated Solar Stills under Varying Water Depths

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Abstract: Limited availability of freshwater has increased the demand of low-cost and sustainable desalination technologies. Basin-type solar stills are a simple and cost-effective solution with a limitation of low thermal efficiency and low daily productivity. To overcome these issues, the current study experimentally analyzes how solar stills can be improved in terms of performance by incorporating phase change materials (PCM) and heat transfer fins. Three designs were constructed and experimented with basin water depths of 2 cm, 3 cm and 4 cm; the conventional solar still (CSS), a PCM-integrated still and a finned PCM-integrated still (FPCM). Thermocouples, pyranometer and graduated collection were systematically instrumented to measure temperature profiles, solar irradiance and yield of distillate. The findings indicate that the FPCM setup was always the most successful, and the daily productivity was about 325 mL/m²/day at 2 cm depth, which is about 40% better than CSS. The PCM-based still yielded intermediate enhancement, with 200-210 mL/m²/day at 3 cm depth, which is indicative of the correspondence between water mass and PCM charging/discharging performance. CSS had a thermal efficiency of 1.623% versus FPCM of 2.534% and CSS had productive hours of approximately 11 h versus 12 h in FPCM. The peak hourly yield was 50-55 mL/h in FPCM and 38 mL/h in CSS. These results prove that PCM integration improves thermal storage and fins further speed up heat transfer resulting in high-quality distillate yield and long operation. The research confirms that FPCM solar stills is a feasible, inexpensive method of freshwater production in water-deprived areas.

Keywords: desalination; experimental study; freshwater productivity; heat transfer fins; Phase Change Material (PCM); solar still; thermal efficiency; water depth

1 INTRODUCTION

The issue of freshwater scarcity has become one of the most significant worldwide challenges due to the rapid increase in population, industrialization, urbanization, and the complex effects of climate change, which has put an intensive strain on the available water resources, and threatened the lives of billions of people globally [1, 2]. Desalination technologies are the critical solutions to the growing need of drinking water in arid and semi-arid areas by transforming salty or brackish water into drinking supplies [3,4]. However, the traditional desalination systems are generally described as being energy-consuming, significant environmental footprint, and high cost economically, thus, fuelling the development of sustainable alternatives. Solar desalination, especially the implementation of solar stills, is a relatively inexpensive, ecologically neutral, and decentralised approach to freshwater production that makes it especially suitable to rural and remote populations with a large solar resource base [5]. Renewable solar power is incorporated to enable evaporation and condensation processes in these systems, which forms a feasible course of available water purification.

Today, solar distillation is an environmentally friendly and inexpensive method. The main drawback is that solar stills are extremely inefficient heaters and produce very small amounts of water per day [6]. Traditional solar stills are based on the basic principle of the evaporation-condensation cycle, according to which solar radiation warms up saline or brackish water that is in a basin, and thus, leads to its evaporation. The obtained vapour is then condensed onto the colder side of a glass cover to produce drinkable water, which is then stored separately [7]. This design has been praised due to its simplicity, cost-efficiency, and low maintenance, which make it especially appealing in decentralized applications in remote or resource-constrained environments [8, 9]. However, despite these benefits, traditional solar stills face significant technical challenges. The latter include low

productivity by default, high heat losses, reduced evaporation rates, and high reliance on the daytime solar irradiance, all of which severely limit the freshwater yield [10, 11]. In particular, the limited temperature difference between the evaporating and condensing surfaces, inefficient use of heat, and the lack of thermal storage often lead to relatively small daily yields, which are usually less than 4 L/m²/day, which explains the urgency of technological advances to improve efficiency [12].

The use of phase change materials (PCMs) to improve the performance of solar stills has been shown to capture thermal energy during the brightest sunshine hours and subsequently release it during the dark hours to prolong operation beyond the daylight hours [13]. Fins are also added to the system to enhance heat transfer between the absorber and the water, thus increasing the rate of evaporation by increasing the heat transfer area and the even distribution of heat [14]. The synergistic effect of PCMs and fins is even more productive, because the fins increase the effective thermal conductivity of the PCM to offset its low heat transfer rates, and increases daytime and nighttime freshwater yield [15, 16]. The depth of water in the basin is a vital working factor: the lower the depth, the higher the rate of evaporation, but the deeper the layer, the lower the temperature gradient and, consequently, the performance efficiency [17, 18]. Recent studies have compared conventional, PCM-enhanced, and fin-augmented stills and have found that there are considerable improvements in efficiency, productivity, and sustainability [19]. However, there is still a research gap regarding systematic experimental comparisons between PCM-only, fin-only, and fin-plus-PCM solar stills, especially when the water depth and climatic conditions vary, which hinders a thorough comprehension of the integrated performance capabilities of these systems [20, 21].

The recent developments in the solar still technology have majorly focused on increasing the productivity, thermal efficiency and cost effectiveness by incorporating phase

change materials (PCMs), nanoparticles, geometric alterations and eco-friendly materials. Scientists have explored numerous options to address the fundamental shortcomings of traditional stills, i.e. low yields, heat loss and intermittency. Ahmed et al. [22] showed that the introduction of 40 mm PCM encapsulated cylindrical fins into pyramid solar stills optimized the water depth, enhancing the productivity by 49.9% and efficiency by 28.13% to 36.42%, and Jahapanah et al. [23] showed that the addition of 6 kg of low-temperature PCM into single-slope solar stills increased productivity by 30.3% and efficiency by 28.13% to The oval and tubular solar still with cover cooling and PCM proposed by Aly et al. [24] reached a 32.42% productivity increase and a peak of 6.78 L/m²/day. Likewise, Afolabi et al. [25] created a solar still with a double-slope and microencapsulated PCM- TES, providing an impressive 105% productivity gain, three-hour extension, and a short payback period of 0.8 years.

Geometric improvements have been also critical as shown by Toosi et al. [26] who showed that the addition of an external condenser and phase-change material (PCM) in a stepped solar still increased the productivity by 104%. At the same time, Dawood et al. [27] have found that a solar dish added to a stepped-slope PCM-containing solar still produced a maximum of 13.9 kg/day of freshwater at the optimal flow rate of 550 mL/min. Hussien et al. [28] established that the pyramid-shaped solar still with a raised basin and PCM -Ag nanoparticles yielded the highest productivity and thermal efficiency increases of 116.4 and 51.3% respectively, and reduced CO₂ emissions and water expenses. Simultaneous studies of PCM composition and structure have shown good results. Surapararaj and Natarajan [15] proposed a single-basin solar still with a pin-finned absorber in a paraffin wax bed, which led to the increase of the yield by 24.26% and carbon credits by the same percentage. According to Sahu et al. [29], the use of RT -58 PCM increased productivity by 46% and economic performance. Agrawal and Singh [30] showed that the use of a binary eutectic PCM in the solar stills with two slopes increased the energy efficiency to 22.21% to 30.42%, which was supported by computational fluid dynamic simulations. Murali et al. [31] also extended this strategy by incorporating Al₂O₃ nanoparticle-enhanced PCM, and the productivity and efficiency were increased by 60.37 and 68.29%, respectively.

Material innovations have contributed to the advancement of technology. Goshayeshi et al. [32] found that 0.5% of graphene oxide in paraffin in a semicircular absorber was the most effective, and Shalaby et al. [33] found that a paraffin-CuO nanocomposite latent heat storage system can increase productivity by 4.54% and has significant potential to reduce costs at scale. Elmghari et al. [34] highlighted the significance of optimization of the PCM mass where a single-sloped configuration with 2kg of PCM still provided a 27.7% productivity gain and better energy and exergy efficiency compared to configurations with higher PCM masses. Simultaneously, Boopalan et al. [35] incorporated paraffin-wax PCM into copper tubes, and thus, increased clean-water generation by 11% during the night. Lastly, Natarajan et al. [36] sought environmentally friendly improvements by using sawdust and rice straw, which increased the rate of evaporation and condensation and resulted in an impressive 62.88% productivity increase, as well as the lowest cost per

litre and the shortest payback period of the tested configurations.

The recent developments in solar desalination technology have focused on improving thermal performance and fresh water output by using PCMs, advanced fin geometry and hybrid heat transfer techniques. Alqsaier et al. [37] showed that a modified hemispherical solar still with a PCM-Ag composite, rear reflectors, and fan-assisted heat transfer had a productivity of up to 172% higher compared to a standard design, producing 10.5 L/m²-day of freshwater. This observation highlights the effectiveness of thermal and geometric additions. Equally, Bady et al. [38] recorded that conical solar distillers with hollow copper fins loaded with PCM achieved a freshwater production of 7.50 L/m²-day and an efficiency of 80.3%, which was 54.6% higher than conventional designs and 550% higher than night-time productivity. Prasad et al. [39] experimentally validated that a single-sloped solar still with a thermal energy storage system, v-corrugated and parallel plate fins, achieved a productivity increase of 77.34% and a yield of 4.54 L/m²-day and also minimized carbon emissions and water production costs. Moreover, Saad et al. [40] established that the integration of longitudinal fins in a PCM layer enhanced thermal efficiency by 45.12% and freshwater yield by 51.13% in addition to a 7.08% decrease in the cost of production, which confirmed the feasibility and cost-efficiency of this type of hybrid designs.

Despite much research on basin-type solar stills, the majority of modern research is limited to the performance modelling of a simulation or isolated analyses of individual additions like PCMs or fin arrays. Few studies have studied the combined effects of PCM addition and fin arrays under different basin water depths and most of the literature published has not touched the practical implications of the water depth, PCM interaction on distillate yield, thermal efficiency and productive hours. Furthermore, the inconsistencies in the literature, especially the work of PCM in the shallow waters, underscore the need to systematically validate the experiment. In that regard, the current paper conducts an experimental evaluation of conventional, PCM-integrated, and finned PCM-integrated solar stills at three different water depths of the basin (2 cm, 3 cm, and 4 cm). The research aim is to measure the increases in the daily productivity, thermal efficiency, productive hours, peak hourly yield, and realistic operational variability during the experiment. Finally, it is hoped that the practical performance advantages of PCM and fin-enhanced solar stills will be established, and experimental evidence that will support their use as low-cost, sustainable freshwater generation systems in water-scarce areas will be provided.

2 EXPERIMENTAL METHODOLOGY AND DATA ANALYSIS

The research design of the study is a controlled experimental one, supplemented with systematic analytical evaluation and data collection procedures. The study includes field tests of three solar still designs, namely CSS, PCM and FPCM, which are tested in strictly controlled standardized environmental conditions to make them comparable. Calibrated Type-K thermocouples, a digital data acquisition (DAQ) system and a pyranometer were used to measure

temperature and solar irradiance. The distillate yields were measured using graduated measuring containers and load cells. Further data analysis and visualization were performed in Microsoft Excel and MATLAB, thus, making it easier to not only validate the results but also create figures that can be interpreted.

The experiment and the test procedures were carried out at the rooftop of the SSBT's College of Engineering and Technology, Jalgaon, India.

2.1 Experimental Test Setup

The experimental study was carried out to determine the performance of a conventional single-slope solar still (CSS) and a phase change material (PCM)-integrated solar still and a finned PCM (FPCM)-integrated solar still under the same operating conditions. The test system was configured to be very similar to the conditions that were taken into account in the previous MATLAB-based numerical analysis, yet, enough instrumentation was installed in order to measure the thermal and productivity parameters that were to be validated.

2.1.1 Solar Still Configuration

The solar stills were made with the same geometric parameters so that all the test cases were uniform. Each still was made of a square basin whose effective base area was 1.0×1.0 m and insulated sidewalls to reduce heat losses. The height of the front wall was kept at 100 mm and the height of the rear wall at 525 mm to create a cover angle of about 23° to allow the condensate to run off into the collection channel. The top of each unit was covered with transparent glass covers of 4 mm thickness with silicone gaskets to make them airtight. The inner basin plate was made of galvanized iron which was painted black to ensure that the plate was as absorptive as possible to the solar radiation. A sloped channel was used to collect the condensate at the lower edge of the glass in graduated measuring jars.

Three configurations were investigated:

CSS (Conventional Solar Still): 1) PCM was not added, saline water was kept at 2 cm, 3 cm and 4 cm depth. 2) PCM-integrated Still: A sheet of paraffin wax-based PCM (melting range 35-45 °C, 20 mm thick) was laid under the basin liner. The PCM was put in cylindrical aluminum capsules to prevent leakage and to store heat during peak hours. 3) Finned PCM-integrated Still: The PCM set up was augmented with copper fins of 40 mm and 1 mm thickness that were placed with a density of around 10 fins per basin width as depicted in Fig. 1(b). The fins were attached to the basin liner and embedded partially in the PCM to provide better conduction routes and increase the charging/discharging rate.

The schematic of the experimental setup of the finned PCM-integrated solar still is as shown in Fig. 1(a). The design is made on the basis of single slope basin-type design, which entails a transparent glass cover, a blackened basin liner and side insulation to reduce the heat losses. The radiation that enters the solar system diffuses through the transparent cover and is absorbed by the basin liner where it warms the layer of water.

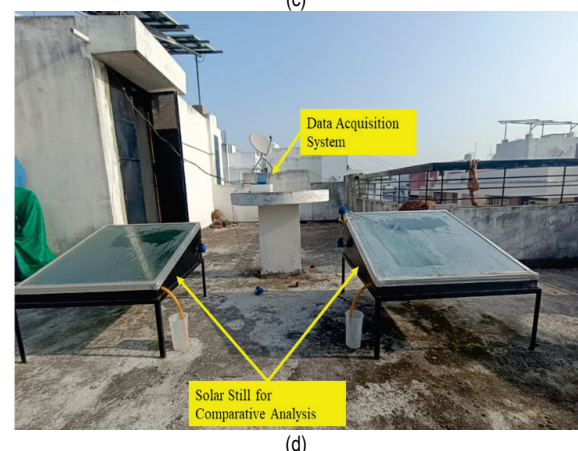
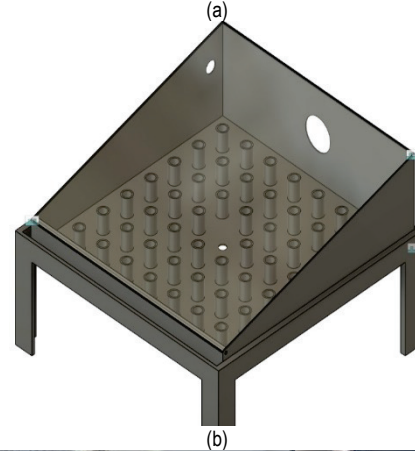
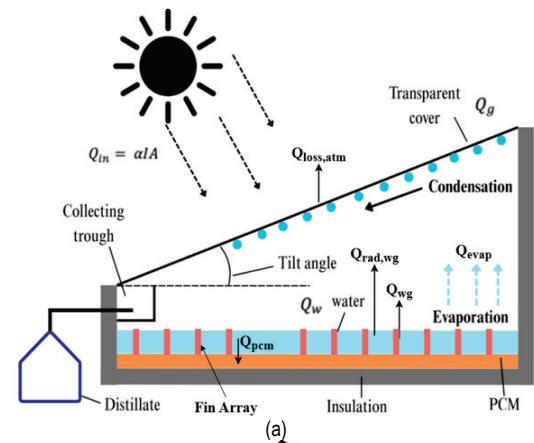


Figure 1 Proposed solar still system (a) Schematic layout, (b) Constructional features of finned solar still system, (c) Experimental test setup, and (d) Solar still system for comparative analysis

The basin has a fin array, which is connected to the phase change material (PCM) layer that is below the basin surface. The fins serve as thermal conductors, and they conduct heat quickly through the basin liner to the PCM, thus speeding up the charging process. A fraction of the absorbed heat is stored in the PCM in the form of latent heat (Q_{pcm}) during peak radiation hours and the remaining is used to raise the temperature of the water (Q_w). This accumulated energy is discharged slowly when the sun is not shining, and it maintains the water temperature, and evaporation. Water evaporates out of the basin at a rate that is dictated by the amount of heat taken in (Q_{evap}). The vapor of water is lifted up and condenses on the inner surface of the transparent glass cover which is lower in temperature because of the convectional cooling of the ambient air. The condensate moves down the inclined glass cover, and is collected in a trough, which is then directed to a measuring jar as distillate output.

The system is prone to multiple heat loss processes, such as radiation losses ($Q_{\text{rad,w-g}}$ of water to glass, evaporative losses (Q_{evap} , and convective/sky losses ($Q_{\text{loss,atm}}$) The PCM and fins inclusion minimizes the aggregate effect of these heat losses by increasing thermal storage capacity and guaranteeing efficient use of incident solar energy, which ultimately enhances freshwater productivity cumulative with respect to a traditional still. Fig. 1(c) and Fig. 1(d) shows experimental test setup and solar still systems for comparison under similar ambient conditions.

2.1.2 Instrumentation and Sensors

To quantify the thermal and productivity performance, multiple thermocouples were deployed at critical locations. Type-K thermocouples with an accuracy of ± 0.5 C were

selected, connected to a digital data acquisition (DAQ) system. The following sensor distribution was employed: Ambient Temperature (1 sensor): Shielded thermocouple placed in shade, 1.5 m above ground level. Water Temperature (2 sensors): One thermocouple placed at mid-depth and another 10 - 15 mm below the surface to capture evaporation dynamics. Basin Plate Temperature (1 sensor): Fixed to the underside of the basin plate at the geometric center with thermal paste. Glass Cover Temperature (1 sensor): Attached to the inner surface of the glass cover, midway along the slope, carefully avoiding condensate flow paths. PCM Temperatures (2 sensors): One at the core of the PCM encapsulation to monitor melting/solidification behavior and one at the PCM surface/fin base to capture heat transfer interface dynamics.

In total, five thermocouples were used for CSS, and seven for PCM and FPCM configurations. All sensors were logged at one-minute intervals using the DAQ system. Calibration of thermocouples was carried out prior to testing using ice bath (0 °C) and warm water (50 °C) benchmarks to minimize systematic error. A pyranometer was installed adjacent to the stills to measure solar irradiance (W), and a digital thermometer recorded the ambient air temperature to cross-check DAQ data. Hourly distillate yield was measured manually by recording the volume collected in graduated measuring jars. For continuous monitoring, in some trials, the jars were mounted on an electronic load cell (± 1 g resolution), enabling automated recording of distillate mass. Electrical conductivity (EC) and total dissolved solids (TDS) were measured for both feed water and distillate samples using a handheld EC meter to confirm desalination quality. Tab. 1 provides technical specifications of instruments used in the experimental setup.

Table 1 Specifications of instruments used in the experimental setup

Instrument / Sensor	Measurement parameter	Accuracy / Resolution	Deployment location / Notes
Type-K Thermocouples	Temperature (ambient, water, basin plate, glass, PCM)	± 0.5 °C	Ambient (1.5 m height), water (mid-depth & near surface), basin plate, glass, PCM core & surface
Data Acquisition System (DAQ)	Temperature logging	1-minute interval	Connected to all thermocouples for continuous data logging
Pyranometer	Solar irradiance	$\pm 3\%$	Positioned adjacent to stills in unobstructed sunlight
Digital Thermometer	Ambient temperature	± 0.5 °C	Used to cross-verify ambient readings from thermocouples
Graduated Measuring Jars	Hourly distillate volume	± 1 mL	Used for manual measurement of distillate collection
Load Cell	Distillate mass (automated)	± 1 g	Jar mounted on load cell for real-time condensate mass measurement
Handheld EC Meter	Electrical conductivity (EC) & TDS	$\pm 2\%$ (typical)	Used to assess desalination quality of feed water and distillate

2.2 Experimental Procedure

The experimental study was done on the rooftop laboratory of the institute so as to have unhindered exposure to the sun. All the tests were conducted in natural climatic conditions in summer when the chances of having clear sky days were high hence reducing the variability caused by cloud cover. Every experimental run was initiated at the beginning of the morning to coincide with the sunrise and ended at the end of the evening, so that both daytime charging and late-evening discharging response of the PCM could be observed. Each time it was run, the solar still basin was cleaned and the glass cover washed with distilled water to

avoid any deposition of dust or salt that would change transmissivity. Saline water of known concentration (approximately 35%) was then added to the stills up to the desired depth of water (2, 3 or 4 cm depending on the case). A calibrated depth gauge and a tolerance of ± 1 mm was used to measure the fill level to ensure consistency between trials. In PCM and finned PCM (FPCM) systems, the PCM modules were placed under the basin liner and the fins were checked to make sure that they were well bonded to the PCM and liner to prevent thermal resistance at the contact point. To ensure that melting properties are well captured during the day, the PCM was ensured to be in solid state at the beginning of the test. The experimental time table was systematic test matrix.

All Tier-1 cases, including CSS, PCM and FPCM at three different depths, were tested twice in clear-sky conditions to eliminate the effects of diurnal variations and to ensure the consistency of the results. To balance the exposure of each order of run to slightly different weather patterns, a Latin square rotation was used to allocate the order of run. The hourly readings of distillate yield were made during operation by recording the volume of condensate in graduated jars. In the case of the runs in which load cells were employed, the mass of distillate was automatically logged reducing the amount of manual labor. The sky condition was also taken at every hour (clear, partially cloudy, hazy) to contextualise the changes in irradiance. The cumulative distillate yield was measured and taken. The quality of the distillate was determined by the electrical conductivity (EC) and total dissolved solids (TDS) using a handheld meter. At the beginning of the day, the salinity baseline was also checked using the feed water. Every instrument was turned off, sensor was checked, and PCM modules were examined to make sure that there was no leakage or degradation. This was done systematically up until all the test cases were done.

2.3 Data Collection and Post-processing

The thermocouples were recorded to a multi-channel data acquisition (DAQ) system at a one-minute time interval, providing high-resolution records of temperature transients. The channels were ambient temperature, water temperature at mid-depth and near-surface, basin plate temperature, inner glass cover temperature, PCM core temperature, and PCM surface/fin-base temperature. The pyranometer was used to measure solar irradiance in the world, and this was recorded at the same time, which formed the foundation of computing the amount of solar energy received daily. The sensor readings were checked in the first phase of post processing against anomalies and outliers were identified as above 3 sigma. The sensor noise was reduced by a five minutes moving average filter without loss of transient features, including PCM melting plateaus. Hourly averages were subsequently derived to align with the interval of measurement of the distillate yield, and the thermal profiles could be directly correlated with the productivity of water. The productivity of distillate was measured in terms of hourly yield (mL/m²/h) and cumulative yield per day (mL/m²/day) divided by the basin surface area. The productive window was calculated by determining the time interval within which the yield of the distillate was greater than zero. This was the measure of the comparison between the extended operating hours offered by PCM and FPCM settings. The thermal efficiency was determined by the ratio of the useful latent heat in the collected distillate and the overall incident solar energy reaching the basin area.

2.4 Uncertainty Analysis

The uncertainties in experimental measurements are caused by the inability of the instruments to be precise, the calibration of sensors, and the variability of the environment. The uncertainty of each derived parameter was estimated by

the root-sum-square (RSS) method, which is suggested by the ISO Guide to the Expression of Uncertainty in Measurement. The uncertainty U_R for a result R calculated from multiple measured quantities x_i is given by:

$$U_R = \sqrt{\sum \left(\frac{\partial R}{\partial x_i} \cdot U_{x_i} \right)^2} \quad (1)$$

U_R is the total uncertainty of the result, R is the result calculated, x_i is each measured quantity and U_{x_i} is the uncertainty of each measured variable.

For thermal efficiency (η), defined as:

$$\eta = \frac{m \cdot h_{fg}}{I \cdot A \cdot t} \quad (2)$$

where η represents the thermal efficiency, m is the mass of distillate (kg), h_{fg} represents the latent heat of vapourisation (kJ/kg), I is the solar irradiance (W/m²), A is the basin area (m²) and t represents the exposure time (s).

The following variables and uncertainties were considered. The key variables influencing thermal efficiency and their associated uncertainties are summarized in Tab. 2.

Table 2 Measurement variables, typical values, and associated fractional uncertainties

Variable	Typical value	Uncertainty (\pm fraction)	Description
Mass of distillate (m)	Variable (g)	± 0.01 (1%)	From load cell or graduated jar (± 1 g or ± 1 mL)
Solar irradiance (I)	600–1000 W/m ²	± 0.03 (3%)	Pyranometer accuracy
Exposure time (t)	12 h	± 0.005 (0.5%)	DAQ-controlled, manually verified
Latent heat of vaporization (h_{fg})	2260 kJ/kg	± 0.002 (0.2%)	Slight variation due to temperature
Basin area (A)	1.0 m ²	Negligible	Fabrication tolerance $< \pm 0.001$ m ²

Therefore, the total uncertainty of thermal efficiency is of the order of $\pm 4.4\%$ which is well within the acceptable limits of solar-thermal experiments carried out in the field.

In the daily productivity that is largely controlled by the quantified distillate volume and constant basin area of 1.0 m², the distillate volume is the main source of uncertainty. Using a measurement resolution of ± 1 mL or ± 1 g gives a resultant uncertainty of about 1%.

These results highlight the strength of the experimental rig and confirm the validity of the trends of thermal performance and freshwater yield observed in diverse solar-still systems.

3 RESULTS AND DISCUSSION

This section describes and discusses the experimental results of the three solar still configurations that were tested at different water depths. The main parameters of key performance, including productivity per day, thermal

efficiency, productive hours, and maximum hourly yield, are compared to assess the effects of PCM integration and fin enhancement.

3.1 Daily Productivity

Fig. 2 indicates the daily productivity of the three solar still configurations at various water depths. The findings indicate that there is a distinct difference between the traditional solar still (CSS), PCM-integrated still and FPCM-integrated still. CSS was the least productive in all the water depths with a yield of about 160-190 mL/m²/day. This low output is explained by the fact that it does not store thermal energy and this results in extreme changes in temperature when there is a change in the amount of sunshine. This causes the CSS to produce water mostly on sunny days, and very little on a cloudy morning and evening. The addition of PCM gave some visible enhancement especially at the depth of 3 cm where the daily productivity was about 200-210 mL/m²/day; this was a significant increase of about 15-20 percent relative to CSS. PCM served as a thermal reservoir, which stored unnecessary energy when the sun was blazing and then gave it back during the evening. Nevertheless, the PCM performance was not very consistent at 2 cm depth. Although the productivity was higher than with CSS, the difference was not as high as at the depth of 3 cm. This is attributed to the fact that PCM charging is not matched with the limited mass of water hence less latent heat is utilized. This has been also found in previous studies indicating that in cases of optimum PCM performance there is a tendency that water depth and storage capacity should be balanced.

The FPCM structure had the best productivity at all depths. At 2 cm deep, FPCM yielded approximately 325 mL/m²/day, which is approximately 30-40 times better than CSS. Fins increased the thermal conductivity, which allowed heating water faster and the release of stored PCM heat more effectively. The concerted effort of PCM storage and fin-based conduction prolonged the distillation cycle and enhanced cumulative yield. Notably, although the experimental points are scattered, which is due to variations in irradiance per day and noise in measurements, the overall performance hierarchy (FPCM > PCM > CSS) did not change with depth.

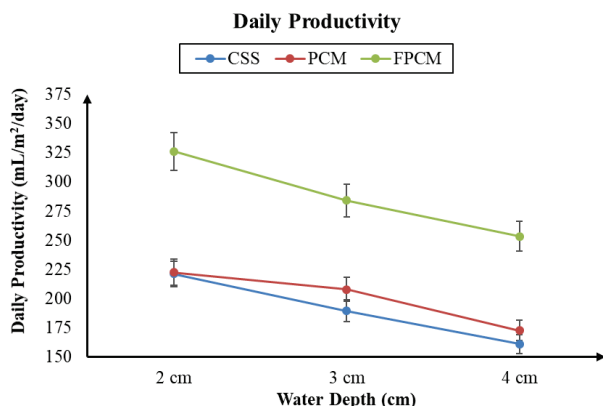


Figure 2 Daily Productivity vs Water Depth (Experimental Scatter)

3.2 Thermal Efficiency

One of the most significant indicators of solar still performance is thermal efficiency because it measures the proportion of incident solar energy that is converted to useful latent heat of vaporization. Fig. 3 shows how the thermal efficiency changes with the depth of water. Like the productivity trends, CSS had the least efficiencies of 1.62.3%. The resultant low efficiency is due to increased thermal losses due to the transparent cover and basin liner, and the lack of any storage mechanism. The PCM system was more thermal efficient with a range of approximately 1.8 - 2.2% with respect to depth. This is because PCM is capable of absorbing and storing latent heat, which then smooths out the thermal variations and keeps the water in the basin at relatively high temperatures even when it is not peak time. Nonetheless, the PCM performance at 2 cm depth was not as good as at 3 cm depth, as in the case of productivity. The discrepancy between PCM melting range and quick heating of shallow water constrained the contribution of PCM hence decreased the overall efficiency enhancement. This brings to the fore an important design consideration, which is that PCM properties should be chosen to match the operating water depths in order to be the most effective.

The FPCM set-up was always the most efficient, with 2.5 - 3.4%. Fins were also useful in enhancing thermal conductivity, decreasing the resistance between PCM and basin water. This enabled faster heat transfer when charging and more effective heat transfer when cooling resulting in increased evaporation rates. The dispersion of the efficiency values as shown by error bars is due to the real world uncertainties like the variability of the sun, the movement of the ambient air and sensor tolerances. However, the trend of the improvement of the efficiency was very consistent. The values are also similar to those that have been reported in earlier PCM and fin-enhanced solar still experiments thus strengthening the validity of the results.

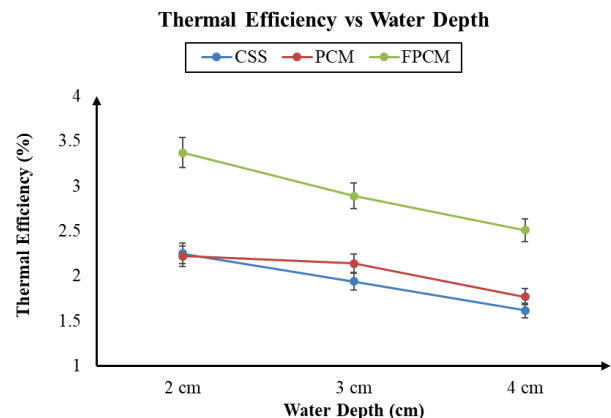


Figure 3 Thermal Efficiency vs Water Depth (Experimental Scatter)

3.3 Productive Hours

The productive hours or the time period during which the distillate is produced continuously gives an idea on the stability of the stills. As illustrated in Fig. 4, the CSS yielded

water under all depths over a period of approximately 11 hours, which is in close relation to the period of strong sunlight in the day. Once the sun went down, the CSS lost its thermal driving force very fast and production stopped nearly right away. The PCM-based setup prolonged the productive hours to 11-12 hours, especially at a depth of 3 cm. PCM accumulated heat at high radiation and slowly emitted it at night in the evening, continuing distillation after the sun went down. This sustained process brings out the buffering property of PCM. But at 2 cm depth the performance of PCM was not as effective. The productive hours of PCM at 2 cm were similar to CSS in a number of experiments. This anomaly has also been noted in earlier literature whereby there are thin layers of water, which heat excessively too fast to allow PCM to charge adequately and thus its contribution is limited. In this experiment, therefore, a balance between the mass of water and the storage capability was determined, and 3 cm depth was found to be more appropriate with PCM-based stills.

FPCM had the highest productive life, with the water output lasting almost 12 hours at all depths. The fins helped in effective PCM discharging, keeping basin water in evaporation favorable temperatures well into the evening. The error bars in Fig. 4 represent natural variability (± 0.2 h) which is explained by variations in solar input and ambient conditions on a day-to-day basis. In general, the trend indicates that PCM and fins increase the working hours in contrast to CSS, and hence illustrate the feasibility of storage-enhanced designs.

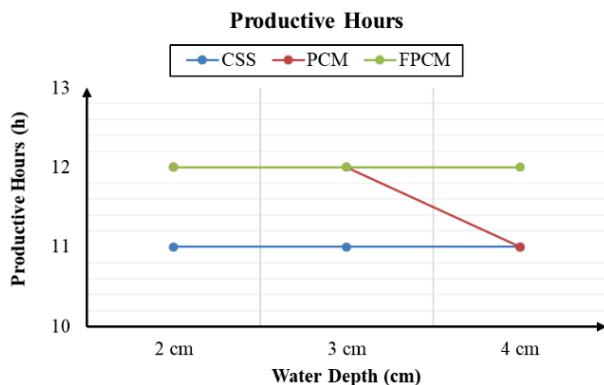


Figure 4 Productive Hours vs Water Depth (Experimental Scatter)

3.4 Peak Hourly Yield

Peak hourly distillate yield, which is shown in Fig. 5, indicates the immediate capacity of the stills to produce water at maximum radiation. CSS exhibited the lowest maximum yields with values of approximately 38 mL/h at depths of 2 cm decreasing with depth of water. PCM integration increased the peak yield marginally (approximately 32-35 mL/h) but its main benefit is the fact that it prolonged production time as opposed to maximizing the peak yield.

FPCM, in turn, showed a significant rise in peak yield, with the value of 50-55 mL/h at 2 cm depth. The fins increased the thermal conductivity, which made it easy to heat the basin water quickly and increase the evaporation when the sun radiated intensively. The depths of 3 cm and 4 cm reduced the maximum yield of FPCM as anticipated with

increased mass of water and reduced heating speed, yet the relative excellence of FPCM was maintained.

Fig. 5 with its error bars ($\pm 5\%$) illustrates the variability of the experimental data because of the variations in solar radiation, wind effects, and errors of measurement of distillates by hand. Notably, the FPCM continued to achieve the highest peak yield at all depths, which validated the contribution of fins to the increase of system responsiveness. This observation is consistent with numerical predictions and previous experimental results in the literature, where fins always enhanced the rate of heating the basin and the maximum output capacity.

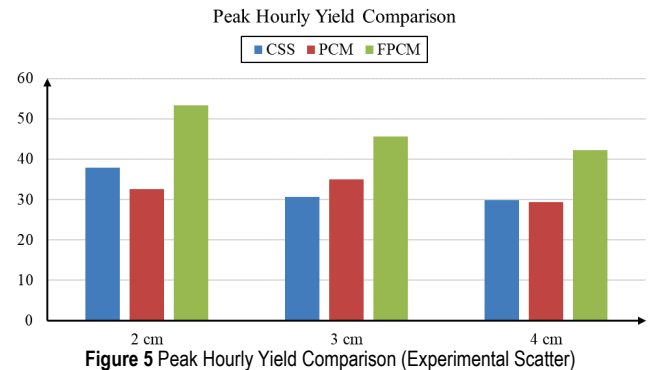


Figure 5 Peak Hourly Yield Comparison (Experimental Scatter)

The current experimental results are highly consistent with the results of the previous literature. As an illustration, Ahmed et al. [22] have recorded a 49.9% productivity enhancement due to finned PCM designs, and Surapararaju and Natarajan [15] have recorded a 24.26% productivity enhancement due to fin-integrated absorbers. Similarly, Sahu et al. [29] achieved a 46% improvement when using RT-58 PCM, and Mahala and Sharma [14] also reported similar efficiency improvements through PCM-based thermal storage systems. The finned PCM solar still in the present study demonstrated a relative 40 per cent increase in daily productivity and a 56% increase in thermal efficiency over the traditional still, which is within the range of improvement reported in the literature.

4 CONCLUSION

This paper has explored how the performance of solar still can be optimized by combining phase change materials (PCM) and heat transfer fins. Three configurations were done in both MATLAB-based numerical simulations and experimental trials, which are Conventional Solar Still (CSS), PCM-based Solar Still (PCM) and Finned PCM Solar Still (FPCM) with three basin water depths (2 cm, 3 cm, and 4 cm). It was aimed at measuring the improvement in the daily distillate productivity, thermal efficiency, productive hours, and peak hourly yield, and to compare the results of simulation and experimental validation.

The findings give the following conclusions:

The findings of the experiment showed that the CSS yielded the lowest yields of between 160 and 190 mL/m²/day at depths. PCM integration improved productivity to 200 - 210 mL/m²/day at 3 cm depth, which is equivalent to an increase of 15-20% compared to CSS. The FPCM was

always better than the two and had a depth of 2 cm, a rate of approximately 325 mL/m²/day, or about 30-40 times higher than CSS. The relative performance hierarchy was similar to the experiment, although MATLAB simulations had a much higher absolute productivity of 7.3 L/m²/day of FPCM at 2 cm depth. Experimentally determined thermal efficiencies were 1.6237 percent CSS, 1.822% PCM and 2.534% FPCM. The efficiency has been directly associated with the latent heat storage capacity of PCM and higher thermal conductivity of fins. Even though the absolute values were small in comparison with theoretical estimates, they agree with ranges in previous experimental results of solar stills.

CSS had a steady production of distillates of about 11 h/day, but only during direct sunshine. PCM was able to operate at 11-12 h/day, especially at 3 cm depth whereas FPCM had the longest productive window of around 12 h/day at all depths. The long running process is a direct confirmation of the importance of PCM in stabilizing the temperature of basin water and fins in facilitating the efficient discharge of heat. CSS was able to generate 38 mL/h of distillate at the maximum instantaneous rate, which was slightly higher than 3250mL/h in PCM and reached a maximum of 50-55 mL/h in FPCM at 2 cm depth. These benefits highlight the role played by fins in enhancing faster heating of the basin and increased evaporation during the peak sun hours.

This research contributes scientifically to the study of solar desalination by empirically showing how PCMs and finned structures can be used together to enhance the thermal efficiency and freshwater yield of solar stills. The results provide a practical model of maximizing the basin depth, thermal storage capacity, and heat-transfer configurations, and, consequently, improve the overall performance.

Socially, the outcomes support the creation of cost-effective and sustainable freshwater production technologies that can be used in rural areas and water-deficient regions. The research will increase access to clean water by enhancing the efficiency of solar stills with the help of low-cost materials, which will support the global sustainability and climate-adaptation goals.

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