Performance Analysis of a Single-Slope Solar Water Still Using Paraffin Wax as Phase Change Material under Varying Water Depths

Jivendra Dwivedi[1], Pushpraj Singh[2], Amol Tripathi[3]
[1]*M.Tech. Scholar, Rewa Institute of Technology, Rewa (M.P), India*
[2]*Head of Department Mechanical Engineering, Rewa Institute of Technology, Rewa (M.P)*
[3]*Assistant Professor, Rewa Institute of Technology, Rewa (M.P)*

Abstract-Freshwater scarcity poses a significant global challenge, particularly in remote and arid regions. Solar distillation offers a sustainable solution, but its limited productivity necessitates performance enhancements. This study investigates the thermal performance of a single-slope solar still integrated with paraffin wax as a phase change material (PCM) under varying water depths (15 L, 20 L, and 25 L). The experimental arrangement with a galvanized iron basin equipped with insulated walls and just an inclined glass cover was developed and tested in Satna, M. P., India. The benefits of PCM on thermal retention performance, distillate yield, and system efficiency were compared between two operational modes: without and with PCM. The incorporation of PCM led to a temperature resilience of the basin to approximate the equivalent evaporation duration up to two times and optimize the water uptake about 25%e35% for any any depth. With PCM the highest efficiency was 41% of the 15-liter depth than without PCM which only produced a 30%. These findings demonstrate the viability of PCM integration for boosting the efficiency of passive solar stills and contribute valuable insights for deploying cost-effective water purification technologies in off-grid areas.

keywords: Solar distillation, Single-slope solar still, Phase change material (PCM), Paraffin wax, Water purification, Thermal efficiency, Distillate yield, Water depth, Renewable energy, Thermal energy storage

INTRODUCTION

The problem of fresh water shortage is a growing challenge in the world with an increasing number of areas experiencing a lack of clean and potable water. In remote or off-grid areas, solar distillation has proven to be an efficient and environmentally friendly way of water purification. The single slope basin type solar still is the most used among different configurations because of it being low cost, simple, reliable. However, its productivity is quite low so high waste of production and that requires development new methods to improve thermal efficiency as well as other processes to increase the yield in water.

Recent advances in solar distillation have involved modifying the conventional solar still to enhance heat transfer and thermal storage. An example is the use of phase change materials (PCM) which absorb heat during the day from sunshine and release it during night-time, keeping the temperature higher for longer in the basin increasing evaporation. The use of paraffin wax, an inexpensive phase change material (PCM), enabled by its good thermophysical properties have revealed its efficiency in solar applications.

Single-slope solar still has been considered for the investigation on thermal performance with paraffin wax as PCM and different water depths. This work systematically studies the distillate sample and efficiency of various configurations to determine the best operating conditions, as well as evaluation of PCM integration potential in real applications.

LITERATURE REVIEW

For potable water production, many research have been carried out on solar distillation as an efficient way. A detailed review on various passive solar still designs by Durkaieswaran and Murugavel [1] reviewed the passive solar still design based on the structural improvements for increasing thermal efficiency. Fathy et al. Reported significant performance improvement in a double-slope solar still connected with parabolic trough collector; and evaluated the system experimentally [2]. Key

Challenges to Distillation Performance Design optimization is a significant challenge in distillation performance. Prakash et al. [3] introduced the benefit of modelling tools in the analysis and enhancement of solar stills design and Deshmukh et al. [4] validated how sensible heat storage materials can facilitate a performance improvement for single basin stills. Phase change materials are interesting due to their ability to store heat. Yousef et al. [5] integrated a PCM-based pin finned heat sink into a solar still and observed the improvements in the heat retention and distillate yield. Similarly, Madiouli et al. Using packed bed storage together with the flat plate collectors and parabolic troughs, a noticeable increase in productivity was achieved within the best options described by Renon C [6]. Of course, materials science has also helped to make solar stills better performing. Shanmugan et al. (7) utilized TiO_2 nano layers to the surface of the absorber to improve energy absorption. Modi et al. Investigation on the influence of nanoparticles addition in the desiccants covers enhanced thermal conductivity and water yield for still designs containing nanoparticles, compared to those without [8]. It has also been effective at making internal improvements on this matter. Estahbanati et al. The effect of internal reflectors on radiation capture within the still was discussed by Kim et al. [9] that is components 2/3rd improve the productivity. Bazri et al. [10*] Analyzed latent heat storage systems and fins and nanoparticles, providing a perspective of future development in enhancing thermal performance for solar collectors.

Beemkumar et al. Taiebi et al. [11] have investigated several configurations of fins in thermal storage systems confirming again the crucial role performed by conductive structures. Hawlader et al., microencapsulation and metal foam integration with PCMs [12] and Zhao et al., respectively have shown potential to improve thermal conductivity and storage of energy [13]. Furthermore, research on Nanoparticle-enhanced PCM (NEPCM) suggests that NEPCMs can achieve even higher performance for thermal storage capacity; consequently, the authors concluded that they are effective for solar distillation devices [14]. Additional studies [15–19] related to greenhouse drying and energy efficiency were also carried out based on similar thermal principles, which all support the necessity of integrating PCMs with passive solar systems. Prakash et al. [20] also pointed out the impact of water depth on thermal stratification and distillation performance in single-slope stills, Kabeel et al. [21] showed that the coating of the absorber with thermally conductive materials such as red bricks improved heat retention and performance.

In summary, extensive research supports the integration of PCMs and thermal enhancements in solar distillation. However, a detailed experimental evaluation of paraffin wax usage across varying water depths in single-slope stills remains relatively underexplored. This study aims to address that gap.

3. MATERIALS AND METHODOLOGY

3.1. System Design and Fabrication

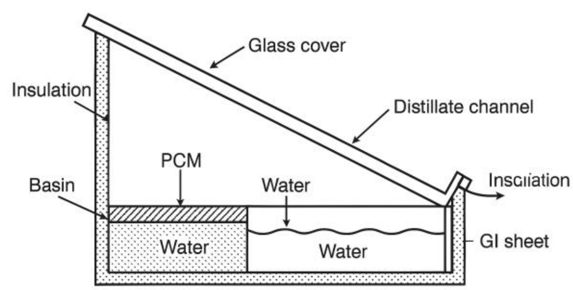

Figure 1: Schematic Diagram of the Experimental Solar Still

The experimental apparatus consists of a conventional single-slope solar still fabricated using locally available materials to maintain cost-effectiveness. The solar still has a basin area measuring 1 m × 0.6 m with side walls inclined at 45°, facilitating natural condensation and runoff. The frame of the structure is made of galvanized iron (GI) sheets due to their durability and corrosion resistance under prolonged exposure to sunlight and water vapor.

The basin, which holds the water to be distilled, is painted matte black to maximize solar energy absorption. A transparent 4 mm thick glass cover is placed at an inclined angle to serve as the condensing surface. This angle also aids in natural drainage of the condensed water into the collection channel. The internal walls of the still are insulated with 25 mm thick glass wool, reducing heat losses to the environment. The distilled water is collected through a PVC channel positioned along the lower end of the glass cover, leading to a calibrated storage container.

Table 1: Technical Specifications of the Solar Still

(Section 3.1 – System Design and Fabrication)

Component	Material	Dimensions/Specifications
Basin Area	GI Sheet (Black Coated)	1.0 m × 0.6 m
Glass Cover	Transparent Glass	4 mm thick, inclined at ~45°
Insulation	Glass Wool	25 mm thickness
Distillate Channel	PVC	Inclined at lower end for drainage
Orientation	South-facing	Fixed slope, East–West alignment

3.2. Selection and Integration of PCM

Paraffin wax was selected as the phase change material (PCM) for its suitable thermal characteristics, affordability, and availability. It possesses a melting point of approximately 58°C, a latent heat of fusion around 200–220 kJ/kg, and a thermal conductivity of 0.2 W/m·K, making it well-suited for low-temperature solar thermal applications.

To facilitate ease of integration and heat transfer, paraffin wax was encapsulated in cylindrical aluminium containers with dimensions of 25 cm in length and 5 cm in diameter. These containers were uniformly distributed across the basin floor beneath the water layer to ensure effective thermal energy storage and release. During sunshine hours, the PCM stores excess thermal energy, which is later released during off-peak periods to sustain the evaporation process.

Table 2: Thermal Properties of Paraffin Wax (PCM Selection and Integration)

Property	Value
Melting Point (°C)	~58
Latent Heat of Fusion (kJ/kg)	200–220
Thermal Conductivity (W/m·K)	0.2
PCM Encapsulation	Aluminium Cylinder (25×5 cm)
Placement in Still	Beneath water, across basin

3.3. Experimental Setup

Table 3: Experimental Cases Conducted

Figure 2: Photograph of the Fabricated Solar Still

The experiments were conducted in Satna, Madhya Pradesh, India during the summer months under clear sky conditions. The solar still was oriented along the east-west axis, with the transparent cover facing south to maximize solar radiation capture throughout the day.

Two primary experimental configurations were investigated:

- Case 1 (Without PCM): The solar still was tested at three different water depths — 15 liters, 20 liters, and 25 liters — without the inclusion of paraffin wax to establish a baseline performance.
- Case 2 (With PCM): The same water depths were evaluated under identical environmental conditions, but with the inclusion of paraffin wax encapsulated beneath the water layer.

Each experimental run was conducted for a full day (from 9:00 AM to 5:00 PM), and data was collected at regular hourly intervals to assess temperature profiles and distillate yield.

Case	PCM Used	Water Volume (L)	Notes
Case 1	No	15, 20, 25	Baseline condition
Case 2	Yes	15, 20, 25	Paraffin wax placed in basin

3.4. Data Collection Instruments

To ensure accurate and consistent measurements, the following instruments were employed:

- Thermocouples (Type-K): Installed at three key locations inside the basin water, on the inner surface of the glass cover, and near the PCM containers — to monitor real-time temperature variations.
- Solarimeter: Used to record hourly solar radiation intensity incident on the still surface in W/m².
- Graduated Cylinder: Utilized to measure the volume of distilled water collected each hour, providing data for calculating the total yield and efficiency.

All instruments were calibrated before the experiments, and readings were recorded manually and cross-verified for consistency.

4. RESULTS AND DISCUSSION

This section presents the experimental findings on the thermal behaviour, water production, and efficiency of the single-slope solar still under different water depths, both with and without paraffin wax as a phase change material (PCM). The results are discussed comparatively to highlight the impact of PCM integration and water level variation.

4.1. Thermal Behaviour Analysis

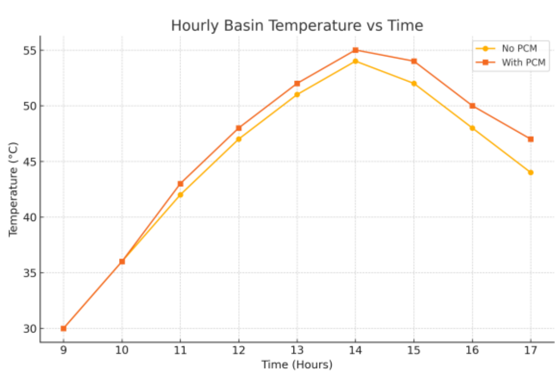

Figure 3: Hourly Basin and Glass Temperature vs. Time

- Line graph showing temperature variation (9 AM to 5 PM) for:
  - Case 1 (no PCM)
  - Case 2 (with PCM)
  - Include separate lines for 15L, 20L, and 25L if needed

Figure 3 shows the temperature variation throughout the day was monitored at hourly intervals for all configurations. Without PCM, the basin water temperature rose sharply during peak sunlight hours and dropped rapidly in the late afternoon, reflecting poor heat retention. In contrast, when paraffin wax was introduced, a noticeable shift in the thermal profile was observed.

The PCM-enhanced still showed a more stable temperature curve, with higher basin temperatures sustained even after 4:00 PM. This prolonged thermal activity is attributed to the latent heat release of paraffin wax during its phase transition from liquid back to solid. The glass cover temperature also exhibited smoother gradients in the PCM case, supporting better condensation throughout the day.

4.2. Distillate Yield Comparison

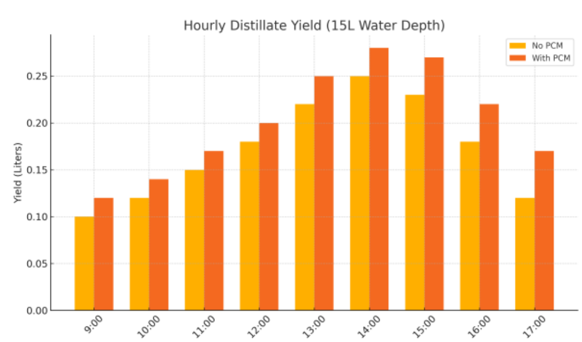

Figure 4: Hourly Distillate Yield Comparison

- Bar graph comparing hourly distillate output with and without PCM at 15L, 20L, 25L

Figure 4 displays the total daily distillate output under each test condition:

- Without PCM:
  - 15L: 1.45 liters
  - 20L: 1.22 liters
  - 25L: 0.95 liters
- With PCM:
  - 15L: 1.82 liters
  - 20L: 1.55 liters
  - 25L: 1.28 liters

The inclusion of PCM consistently improved the daily yield at each water depth. The 15-liter case yielded the highest output, both with and without PCM, due to the lower thermal mass allowing faster heating and evaporation. However, the performance drop at higher depths was less severe when PCM was present, demonstrating its role in sustaining evaporation during late hours.

The average percentage improvement in yield due to PCM ranged between 25% and 35%, depending on the water level.

Table 4: Daily Distillate Output at Different Water Depths

(Distillate Yield Comparison)

Water Depth	Yield Without PCM (L)	Yield With PCM (L)	% Improvement
15 L	1.45	1.82	~25.5%
20 L	1.22	1.55	~27.0%
25 L	0.95	1.28	~34.7%

4.3. Efficiency Calculation

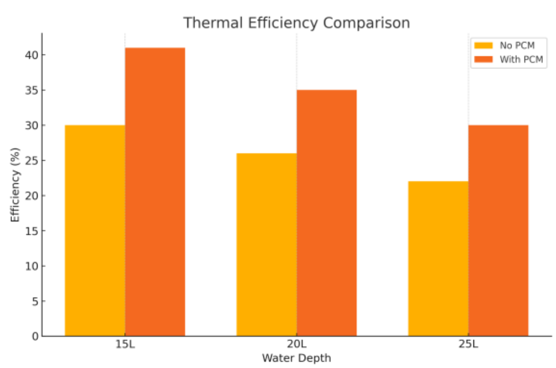

Figure 5: Thermal Efficiency Comparison

- Show comparative efficiency for all 6 cases (3 water depths × 2 configurations: with/without PCM)

Thermal efficiency (η) of the solar still was calculated using the following formula:

$$\eta = \frac{m \cdot h_{fg}}{A \cdot I \cdot t}$$

Where:

- m = mass of distillate collected (kg)
- $h_{p}g$ = latent heat of vaporization (J/kg)
- A = basin area (m²)
- I = average solar radiation (W/m²)
- t = duration of sunshine (s)

Using this equation, the thermal efficiency values were computed for all test cases. Efficiency increased in all PCM-integrated scenarios, with the highest efficiency observed at the 15-liter water depth with PCM, reaching up to 41%, compared to 30% in the non-PCM configuration. Efficiency trends were plotted using bar graphs (Figure 5) to visualize comparative performance.

4.4. Observations and Interpretation

The following key observations were drawn from the experimental study:

- The 15-liter water depth consistently offered the best thermal performance and distillate yield, likely due to quicker heating and lower thermal inertia.

- PCM inclusion enhanced thermal retention, delayed cooling, and improved yield across all depths.
- The effectiveness of PCM was more prominent at higher water depths, where its ability to compensate for delayed heating proved valuable.
- Environmentally, paraffin wax is non-toxic, reusable, and does not degrade over short-term cycles, making it a viable PCM for sustainable applications.
- From a practical standpoint, integrating PCM into solar stills in rural or arid regions can significantly improve daily freshwater output without increasing operational complexity.

5. CONCLUSION

This study investigated the performance of a single-slope solar still integrated with paraffin wax as a phase change material (PCM) under varying water depths of 15L, 20L, and 25L. The experimental results demonstrated that incorporating paraffin wax significantly enhanced the thermal retention capacity of the system, leading to increased water yield and overall efficiency.

Key findings from the study include:

- The use of PCM resulted in a 25%–35% increase in daily distillate yield across all water levels.
- The 15-liter water depth consistently produced the highest output, confirming that lower water depth facilitates faster heating and evaporation.
- Paraffin wax effectively prolonged the temperature gradient inside the basin, supporting extended evaporation hours into the late afternoon.
- The maximum thermal efficiency achieved was 41% with PCM at 15L, compared to 30% in the non-PCM setup.

These results highlight the practicality of PCM integration as a passive enhancement strategy for solar stills, especially in water-scarce and off-grid rural areas. The findings also validate paraffin wax as a cost-effective and thermally reliable PCM for low-temperature solar applications.

Future work could explore the use of nano-enhanced PCMs, alternative still geometries, or hybrid solar systems combining photovoltaic or concentrated solar power elements to further increase system performance.

REFERENCES

[1] Durkaieswaran, P., & Murugavel, K. K. (2015). Various special designs of single basin passive solar still–A review. *Renewable and Sustainable Energy Reviews, 49*, 1048–1060. https://doi.org/10.1016/j.rser.2015.04.142

[2] Fathy, M., Hassan, H., & Ahmed, M. S. (2018). Experimental study on the effect of coupling parabolic trough collector with double slope solar still on its performance. *Solar Energy, 163*, 54–61. https://doi.org/10.1016/j.solener.2018.01.006

[3] Prakash, O., Ahmad, A., Kumar, A., Hasnain, S. M., & Kumar, G. (2022). Comprehensive analysis of design software application in solar distillation units. *Materials Science for Energy Technologies, 5*, 171–180. https://doi.org/10.1016/j.mset.2022.03.002

[4] Deshmukh, H. S., & Thombre, S. B. (2017). Solar distillation with single basin solar still using sensible heat storage materials. *Desalination, 410*, 91–98. https://doi.org/10.1016/j.desal.2017.01.019

[5] Yousef, M. S., Hassan, H., Kodama, S., & Sekiguchi, H. (2019). An experimental study on the performance of single slope solar still integrated with a PCM-based pin-finned heat sink. *Energy Procedia, 156*, 100–104. https://doi.org/10.1016/j.egypro.2018.11.112

[6] Madiouli, J., Lashin, A., Shigidi, I., Badruddin, I. A., & Kessentini, A. (2020). Experimental study and evaluation of single slope solar still combined with flat plate collector, parabolic trough and packed bed. *Solar Energy, 196*, 358–366. https://doi.org/10.1016/j.solener.2019.12.075

[7] Shanmugan, S., Essa, F. A., Gorjian, S., Kabeel, A. E., Sathyamurthy, R., & Manokar, A. M. (2020). Experimental study on single slope single basin solar still using TiO_2 nano layer for natural clean water invention. *Journal of Energy Storage,*

30, 101522. https://doi.org/10.1016/j.est.2020.101522

[8] Modi, K. V., Shukla, D. L., & Ankoliya, D. B. (2019). A comparative performance study of double basin single slope solar still with and without using nanoparticles. *Journal of Solar Energy Engineering, 141*, 031008. https://doi.org/10.1115/1.4042802

[9] Estahbanati, M. R. K., Ahsan, A., Feilizadeh, M., Jafarpur, K., Ashrafmansouri, S. S., & Feilizadeh, M. (2016). Theoretical and experimental investigation on internal reflectors in a single-slope solar still. *Applied Energy, 165*, 537–547. https://doi.org/10.1016/j.apenergy.2015.12.103

[10] Bazri, S., Badruddin, I. A., Naghavi, M. S., & Bahiraei, M. (2018). A review of numerical studies on solar collectors integrated with latent heat storage systems employing fins or nanoparticles. *Renewable Energy, 118*, 761–778. https://doi.org/10.1016/j.renene.2017.11.067

[11] Beemkumar, N., Karthikeyan, A., Yuvarajan, D., & Lakshmi Sankar, S. (2017). Experimental investigation on improving the heat transfer of cascaded thermal storage system using different fins. *Arabian Journal for Science and Engineering, 42*, 2055–2065. https://doi.org/10.1007/s13369-017-2447-9

[12] Hawlader, M. N. A., Uddin, M. S., & Khin, M. M. (2003). Microencapsulated PCM thermal-energy storage system. *Applied Energy, 74*(1–2), 195–202. https://doi.org/10.1016/S0306-2619(02)00179-1

[13] Zhao, C. Y., Lu, W., & Tian, Y. (2010). Heat transfer enhancement for thermal energy storage using metal foams embedded within phase change materials (PCMs). *Solar Energy, 84*, 1402–1412. https://doi.org/10.1016/j.solener.2010.04.022

[14] Khodadadi, J. M., & Hosseinizadeh, S. F. (2007). Nanoparticle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage. *International Communications in Heat and Mass Transfer, 34*(5), 534–543. https://doi.org/10.1016/j.icheatmasstransfer.2007.01.005

[15] Ahmad, A., & Prakash, O. (2020). Performance evaluation of a solar greenhouse dryer at different bed conditions under passive mode. *Journal of Solar Energy Engineering, 142*, 1–23. https://doi.org/10.1115/1.4047410

[16] Ahmad, A., & Prakash, O. (2019). Thermal analysis of north wall insulated greenhouse dryer at different bed conditions operating under natural convection mode. *Environmental Progress & Sustainable Energy, 38*, e13257. https://doi.org/10.1002/ep.13257

[17] Ahmad, A., Prakash, O., Kumar, A., Hasnain, S. M., Verma, P., Zare, A., Dwivedi, G., & Pandey, A. (2022). Dynamic analysis of daylight factor, thermal comfort and energy performance under clear sky conditions for building: An experimental validation. *Materials Science for Energy Technologies, 5*, 52–65. https://doi.org/10.1016/j.mset.2022.01.002

[18] Prakash, O., Bhushan, B., Kumar, A., & Ahmed, A. (2021). Thermal analysis of domestic type single slope–basin solar still under two different water depths. *Materials Today: Proceedings, 46*, 5482–5489. https://doi.org/10.1016/j.matpr.2021.04.247

[19] Kabeel, A. E., El-Agouz, E. S., Athikesavan, M. M., Ramalingam, D., Sathyamurthy, R., Prakash, N., & Prasad, C. (2020). Comparative analysis on freshwater yield from conventional basin-type single slope solar still with cement-coated red bricks: An experimental approach. *Environmental Science and Pollution Research, 27*, 32218–32228. https://doi.org/10.1007/s11356-020-09577-z