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Article

A Theoretical Study to Improve the Efficiency of Solar Water Heater using PCM

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Annotation: This research contributes to improving the efficiency of a fully evacuated glass-tube solar water heater using phase change material. Paraffin wax utilized as the PCM. A theoretical investigation was performed to evaluate the thermal behavior of the system, which is integrated with a thermal energy storage system operating under solar thermal flux. Two separate cases were studied; without the PCM and with the PCM. The theoretical evaluation involved modeling the hourly change in tank water temperature from 6:00 AM to 12:00 PM. In both cases, system performance was analyzed using energy efficiency, quality of the consumed energy, and the hot water supply temperature. The results indicated that the maximum temperature reached to 71°C when using the PCM, compared to the case without the PCM, it was 60°C.

Furthermore, the overall energy efficiency improved from 57.1% for the system without PCM to 62%, for the system with PCM. This significantly improvement in energy storage and system's performance.

Keywords: solar water heater, PCM, Evacuated tube, solar collector, energy efficiency.

1. Introduction

This research highlights solar water heating (SWH) as a widely adopted, sustainable alternative to fossil fuels, yet core collector designs remain technologically stagnant. Structural improvements and increased thermal efficiency to overcome this constraint are a key to satisfy the world's sustainable energy needs. [1]. International authorities have created regulations and funding structures to speed up the adoption of renewable energy technologies to reduce environmental damage. [2].Government incentives and tax cuts are encouraging the use of solar water heaters, but high installation costs and poor winter peak performance remain barriers to year-round dependability. [3]. The kinds of renewable energy are shown in Figure(1)

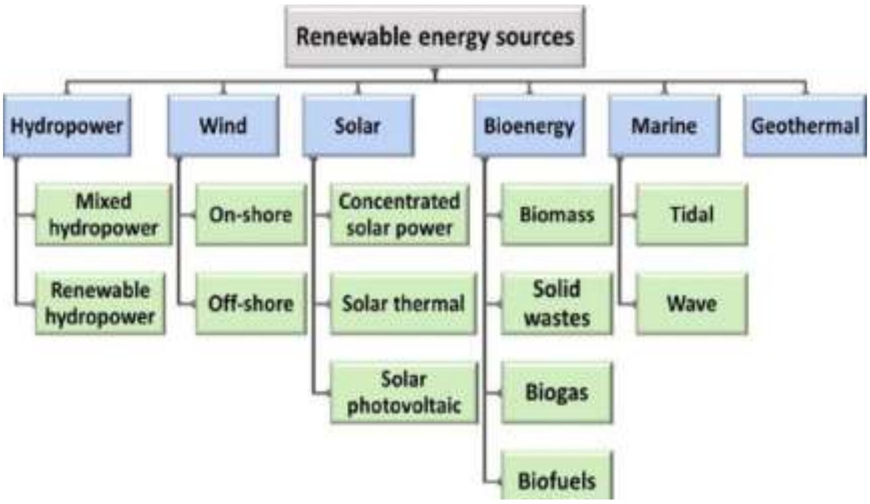

Figure 1 Renewable Power Classifications [1]

Sunday and Williams 2022 [4] they wre doing a study on thermosyphon solar water heater in Minna, Nigeria to assess the performance for commercial beauty salons. The system was tested on partially gloomy days and on sunny days with thermal efficiencies of 81.0% and 81.5% respectively. [5] studied the usage of (PCM) and nano-composite phase change materials (NCPCM) in a glass evacuated tube solar water heater. The findings revealed that the performance of PCM and NCPCM were improved, the temperature of water tank reached 53 and 56 °C and the efficiencies were 1.78%, 2.18% and 3.23% increased energy and exergy efficiencies.

The influence of phase shift features on solar energy collecting was quantitatively simulated by Malleoli et al. [6]. They observed that the phase-change characteristics need to be matched to the local solar conditions to maximise energy capture. [7] The comparative study has showed that the use of forced circulation in domestic solar water heaters has increased the thermal efficiency in the range of 35–80% as compared to the natural convection arrangement. [8] The thermal energy storage of the solar water heaters using paraffin wax based PCMs exhibited an increment of 64.5%. The testing cycles had a melting phase of 3 hours and the heat recovery duration was less than an hour. [9] In this study, the use of straight absorber tubes in solar water heaters is studied and it is demonstrated that the straight tube design is superior to the sinusoidal tubes in thermodynamic behaviour using computational fluid dynamic modelling. [10] Adding a solar water heater to recover the condensation in a passive single-basin double-slope distiller increased the daily thermal efficiency by 18-83 %, and the added water mass contributed 50 % further improvement.A solar collector combined with PCM (melting range 45–50°C) was designed by Kurklu et al. [11]. It was able to keep the storage at 30°C overnight and had thermal efficiencies ranging from 22% to 80%. Sharma et al. [12] reviewed the measurement techniques for latent heat and comparative storage performance, and explored the applications of PCM-based thermal storage systems in solar, building and aerospace systems. [13] fourth order Runge-Kutta method for solving a cylindrical solar water heater model with high agreement between numerical and experimental results. [14] Lagrangian derivations were used to forecast the temperature dynamics of a heat exchanger linked to a water-water preheater and countercurrent flow was simulated using Eulerian solutions and parametrised using Mathcad and were successful. [15] The ANSYS FLUENT simulation of a tube heater for solar-thermal powder coating at 240 °C revealed that the length of the heater is the key parameter in heat transfer and thermal efficiency. [16] A 3D design was built using a SolidWorks program to evaluate the numerical data of the compact high efficiency solar water heater. Ho et al.[17] experimentally and theoretically analyzed a recycling flat-plate solar collector with rectangular conduits, showing that thermal efficiency increases with higher conduit aspect ratios and recycle ratios. [18] Testing dual spiral-shaped flow tubes across three flow rates yielded an optimal thermal efficiency of 70.8% at 0.0117 kg/s, representing a 13.7% performance improvement over conventional collectors.

1-2 Solar energy

Solar energy is a renewable energy source that harnesses power from the sun. It is captured using technologies such as photovoltaic (PV) cells, which convert sunlight into electricity, or solar thermal systems, which use the sun's heat to produce energy see figure (2). While solar energy is abundant, harvesting it is more complex than fossil or nuclear options. However, active and passive solar water heaters offer a cost-effective, low-maintenance approach to reducing fossil fuel dependence, with performance driven by solar availability and inlet water temperatures.

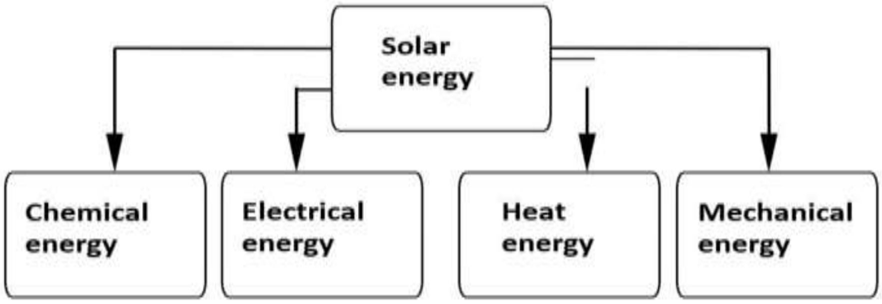

Figure 2 Conversion of solar radiation to other energy forms

Solar water heaters utilize solar energy across residential, commercial, and industrial sectors as a sustainable alternative to conventional gas or electrical systems, with global policies actively promoting their adoption to reduce environmental impacts.

Solar water heaters are categorized by their circulation mechanism into active systems—which use pumps via direct flow for warm regions or indirect heat exchangers for freezing climates, and passive systems, which rely on natural convection through thermosiphons or integrated collector-storage units ideal for mild conditions (Figure 3).

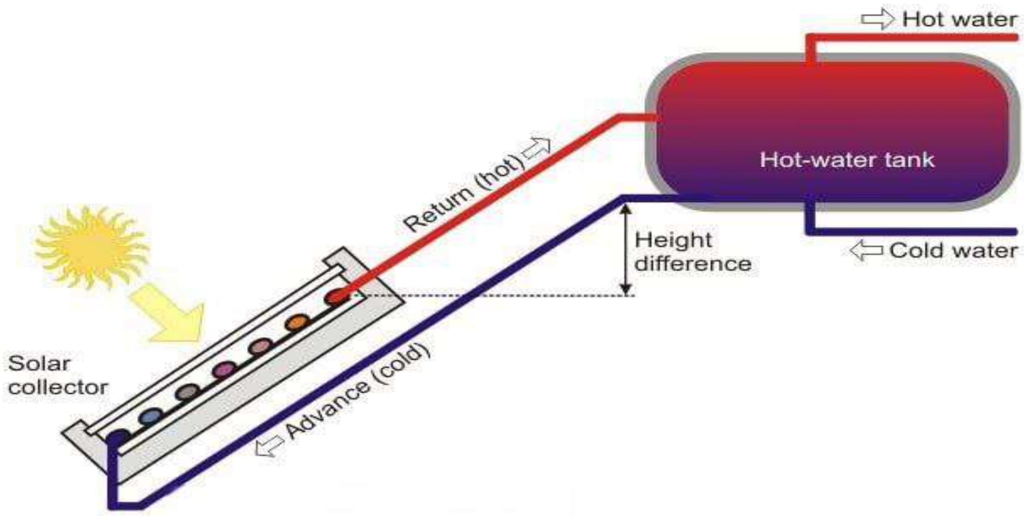

Figure 3 Solar water heater Passive System[6]

The objective of This study is theoretically enhance the thermal efficiency of solar water heaters (SWH) through the integration of phase change materials (PCM).

2. Methodology and Mathematical Model

2.1 Physical System Architecture and Operation

The proposed system consists of an evacuated tube solar collector integrated with paraffin wax as a phase change material (PCM) latent heat storage unit, connected to a 1000 L polyurethane-insulated storage tank is schematically illustrated in (Figure 4). The operation relies on a thermosiphon mechanism driven by buoyancy forces, establishing a natural circulation flow rate of 0.02–0.05 m/s without mechanical pumps. Incident solar radiation is absorbed by the evacuated tubes—reducing thermal losses by approximately 25% compared to conventional flat-plate collectors—and transferred to the circulating water. The integrated paraffin wax (melting point: 45–58°C, latent heat capacity: 145kJ/kg. absorbs excess energy during peak irradiance and discharges it during off-peak hours, extending thermal output by 3–5 hours post-sunset.

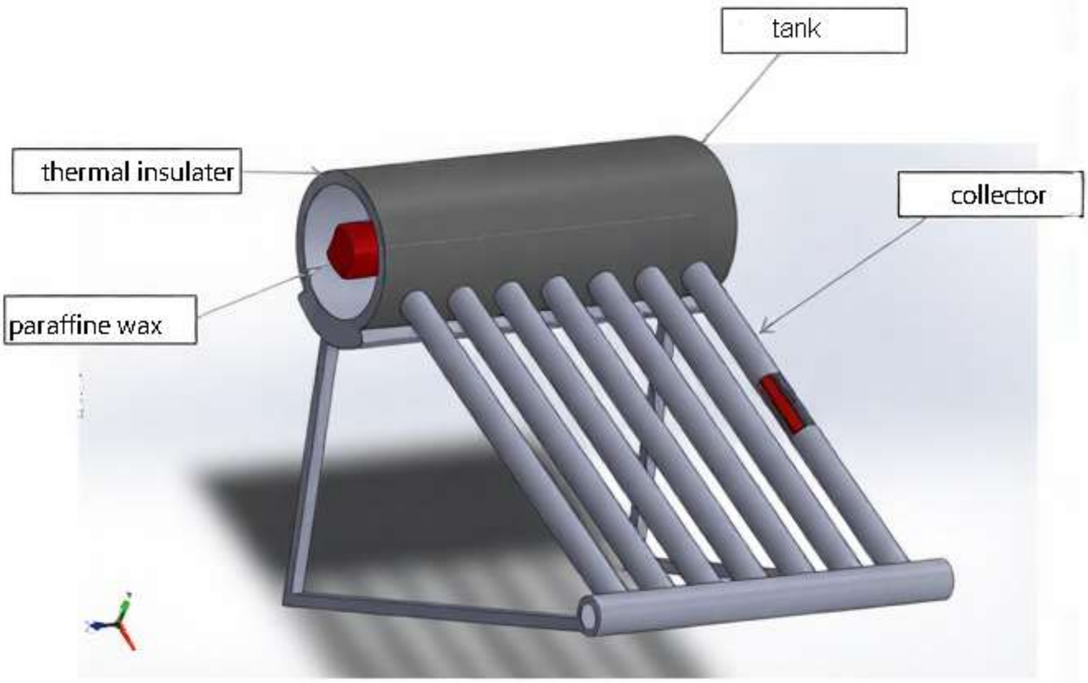

Figure 4 Schematic diagram of the evacuated tube solar water heater integrated with paraffin wax PCM thermal energy storage

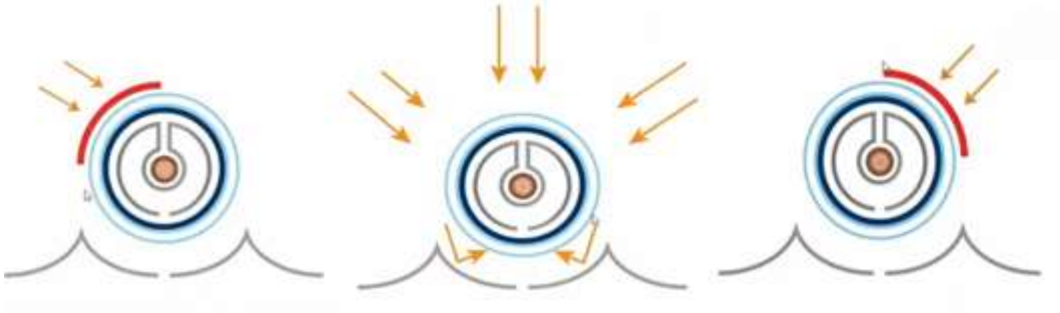

Figure 5 Evacuated Tube

2-2 System Specifications

Table 1. Design and geometrical parameters of the evacuated tube solar water heater system

Component	Value	Unit
Storage Tank Capacity	1000	L
Evacuated Tube Diameter	47	mm
Evacuated Tube Length	1800	mm
Insulation Thickness	1800	mm
Collector Inclination Angle	45	°

2-3 Mathematical Model

To evaluate the thermal dynamics and performance of the SWH-PCM framework, a governing mathematical formulation was established based on momentum and energy conservation principles. The numerical domain includes three important areas: the water, the HTF and the PCM unit. The governing structure is based on a number of basic simplifications:

1- Material thermophysical properties are constant [19], [20].

2- Thermal resistance via structural walls is neglected [21], [22].

3- The volume fluctuations in the PCM phase shift are overlooked [23], [24].

4- The fluid follows the Newtonian incompressible dynamics [25], [26].

5- The dimensional complexity is reduced to a 2D axisymmetric structure [27], [28].

2.4 Governing Conservation Equations

2.4.1 Conservation of Mass

$$\frac{\partial \rho}{\partial t} + div\left(\rho \vec{V}\right) = 0 \quad (1)$$

Here, *p* defines the density of the liquid, while V indicates its velocity.

2.4.2 Conservation of Momentum equation

$$\rho \frac{\partial \vec{V}}{\partial t} + \rho \vec{V}.\nabla\left(\vec{V}\right) = -\nabla p + \mu \nabla^2 \vec{V} + \rho \vec{g}\left(T - T_{ref}\right) \quad (2)$$

where p,μ ,g and $T_{ref,}$ refer to pressure, fluid dynamic viscosity, gravity vector, and reference temperature, respectively.

2.4.3 Energy conservation governing equations: Water phase

$$\rho C_P \frac{DT}{Dt} = k\nabla^2 T. \quad (3)$$

where Cp denotes specific heat, k denotes the thermal conductivity, and T denotes temperature.

2.5 Thermophysical Properties

The thermo-physical properties of the PCM material are shown in the table. (2)

Parameters	**Value**
Melting point	50 °C
Latent heat	145 KJ/kg
Viscosity	1.9 mm^2
Density	1412 kg/m^3
Specific heat	2.4 KJ/kg K
Thermal conductivity	0.2 W/m K

Table (2) The Paraffin waxes thermo-physical properties.[29],[30]

For the PCM Phase

The total enthalpy of the substance is determined through the energy transport equation by combining sensible enthalpy (h) with latent heat (L). The governing relationship is expressed as follows:

$$\frac{\partial(\rho h)}{\partial t} + \nabla.\left(\rho.\vec{V}.h\right) = \nabla.(k\nabla T) + S. \quad (4)$$

Where h, k, and S denote the enthalpy, the thermal conductivity and thes ourceterm, respectively. The following equation express the enthalpy, h:

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT + fL. \quad (5)$$

in which h_{ref} signifies the reference phase transition enthalpy at temperature T_{ref}, and L represents the latent heat capacity. The melt fraction f of the PCM domain is determined as follows:

$$f = \begin{cases} 0 & si \quad T\langle T_{solidus} \\ \frac{T-T_S}{T_S-T_l} & si \quad T_{solidus}\langle T \langle T_{liquidus} \\ 1 & si \quad T_{liquidus}\langle T \end{cases} \quad (6)$$

Calculating temperature requires an iterative procedure between energy equation (4) and liquid fraction equation (6).

The time-dependent HTF temperature profile was derived based on data from Salman ;

$$T_{HTF}(t) = a_0 + a_1 t + a_2 t^2 + \ldots\ldots\ldots + a_9 t^9. \quad (7)$$

- SWH-PCM System Heat Storage Efficiency

The heat storage efficiency assessing the thermal response of the SWH-PCM system is expressed as:

$$\eta_{SWH} = \frac{Q_{re}}{Q_{st}}. \quad (8)$$

in which Q_{re} denotes the released thermal energy and Q_{st} indicates the total stored heat. The stored thermal capacity of the system is given by:

$$Q_{st} = m\int_{T_0}^{T_m} C_{p,s}dT + mf\Delta H + m\int_{T_m}^{T_a} C_{p,l}dT. \quad (9)$$

The quantity of thermal energy discharged from the SWH-PCM setup is evaluated as follows:

$$Q_{re} = m\int_{T_0}^{T_m} C_{p,liq}dT + mf\Delta H + m\int_{T_m}^{T_a} C_{p,solid}dT \quad (10)$$

here, m, T_o, T_m, and T_a refer to the PCM mass, initial temperature, melting temperature, and final average temperature upon complete melting, respectively.

- The total incident radiation (I_{total}) accounts for direct beam (I_b) and diffuse (I_d) solar radiation components acting on the collector tilt angle β_c:

(11)

$$I_{total} = I_b \cos\theta + I_d\left(\frac{1+\cos\beta_c}{2}\right)$$

3- Results and Discussion

Figures 6, 7 and 8 show the full theoretical comparison of the output temperature (Tout) during the time period of 06:00 to 24:00 in configurations with and without phase change materials (PCM). Figure)6(illustrates that the non-PCM system starts at 22.5°C at 06:00 and slowly rising to the maximum temperature of 60°C at 16:00, and then drops to 39°C at midnight (24:00). Conversely, Figure (7) shows the simulated thermal response after the integration of the PCM, where the temperature starts at 23.5°C at 06:00, rapidly rises to a much higher peak of 71°C at 15:00, and then drops to 46°C at 24:00.Figure(8) presents the comparison study that shows the ability of PCM to provide better energy storage and transfer characteristics throughout the monitoring duration. The theoretical findings show that the PCM inclusion raises the peak outlet temperature by 11{\deg}C compared to the traditional configuration, and advances the peak occurrence by one hour (from 16:00 to 15:00). This performance improvement is due to the latent heat storing ability of the phase change material. The phase change material may store a large amount of thermal energy during its phase change in the time of peak radiation and then slowly release it throughout the nite when it solidifies. So at midnight the PCM-enhanced model has a temperature 7°C higher than the basic setup without PCM in Figure (8)

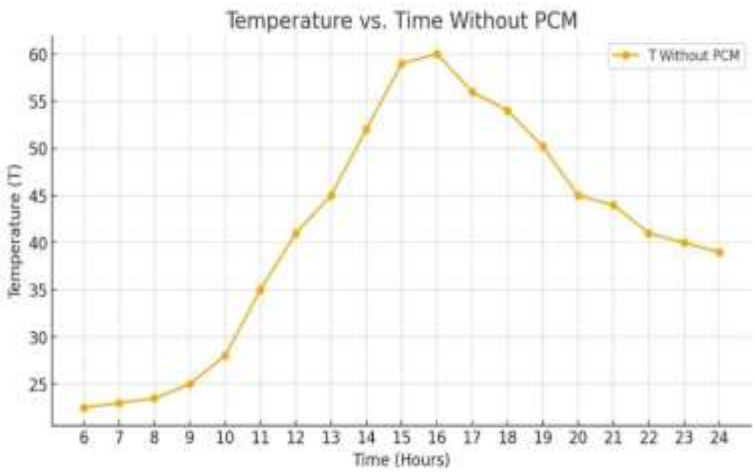

Figure 6 T_{out} Without PCM, Over Time

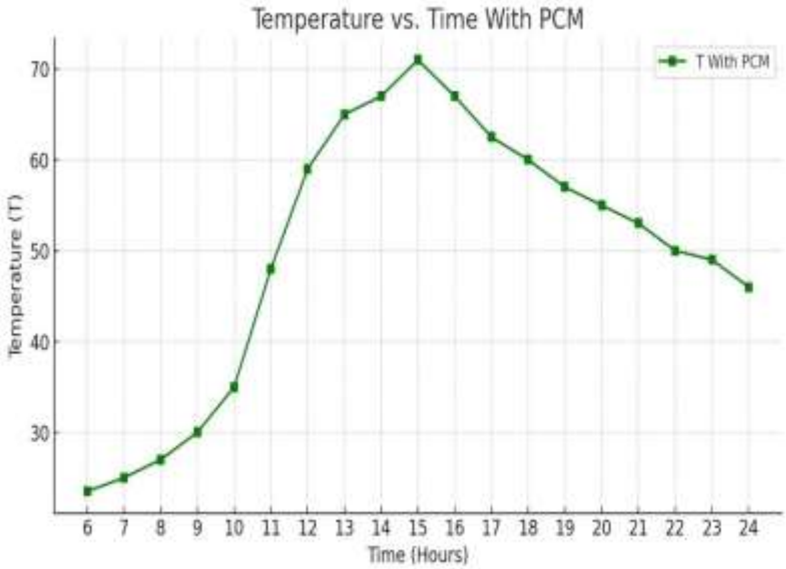

Figure 7 T_{out} With PCM, Over Time

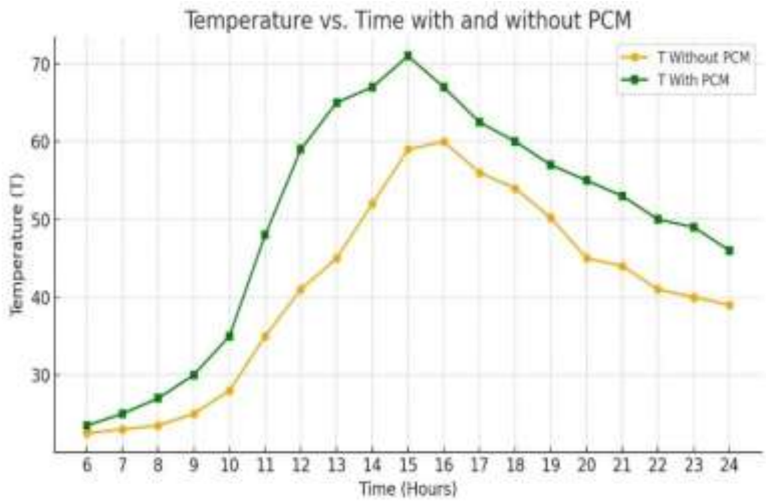

Figure 8 T_{out} With, Without PCM, Over Time

Figures 9 and 10 show the modelled diurnal patterns of the solar radiation and the dynamic outflow water temperatures in the 24-h period. To get a fair numerical assessment of the two collector designs, both were studied with the same profile of diurnal solar irradiation.The ambient temperature varies from 22 C at 06:00 to 38 C at 14:00 . The incident solar flux is maximum at 13:00 at 950 W/m2 .

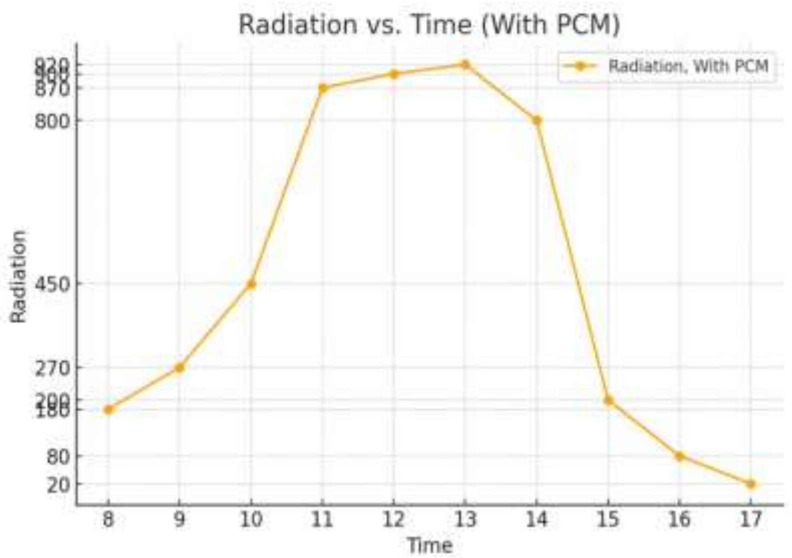

Figure 9 Radiation With PCM, Over Time

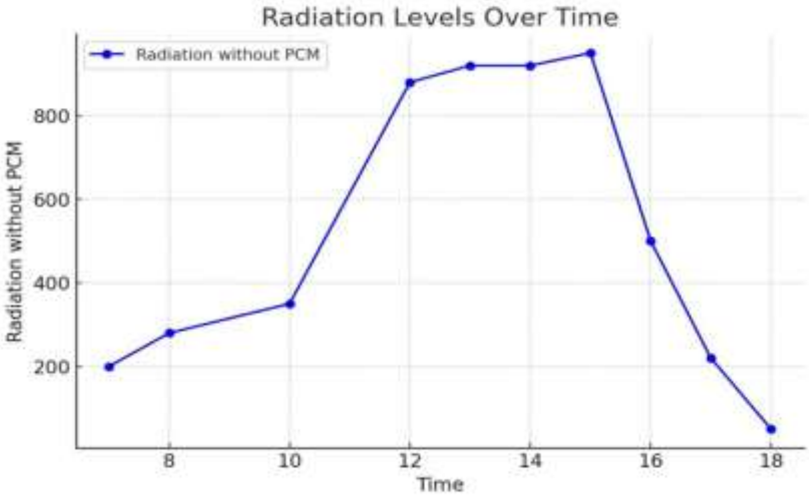

Figure 10 Radiation Without PCM, Over Time

Figure (11) shows the predicted thermal efficiency profiles for the systems running with and without phase change material (PCM) for the period from 06:00 to 24:00. The efficiency for the baseline setup without PCM (solid blue line) improves smoothly from 0% at 06:00 to an initial maximum of 62% at 15:00 then progressively drops with efficiencies above 35% from 24:00. But the efficiency of the PCM-integrated model (dashed red line) is lower in the beginning at the peak of daylight hours (08:00–15:00) with 51 % at 15:00. However, after the PCM is completely charged and transitions, the efficiency of the PCM system is above the baseline, with a peak maximum of 63% at 17:00 and steadily greater thermal efficiency during the evening and nite hours until 24:00. This is the theoretical behaviour that represents the traditional method of thermal energy storage by phase transition materials. Some of the incoming solar heat is absorbed by the PCM as latent heat during melting during high radiation times, resulting in a momentarily lower efficiency than the baseline. The PCM then solidifies during off-peak hours and again releases the stored energy to the fluid stream in the subsequent off-peak hours. This results in a longer period of greater efficiency levels for a longer period of time. This heat discharge phase successfully changes the efficiency peak by two hours (from 15:00 to 17:00) and increases the total energy extraction capacity during the late day operation.

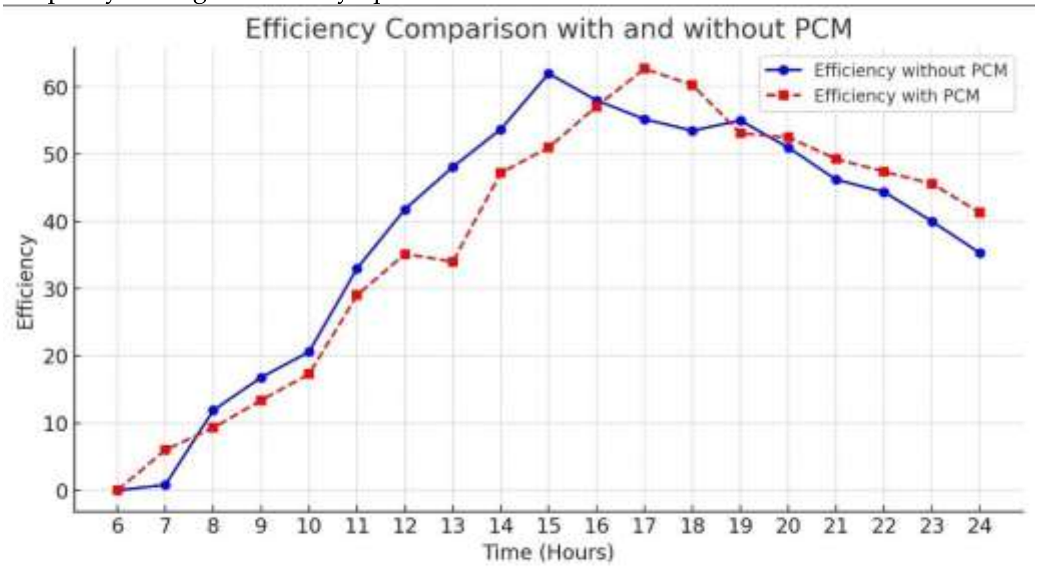

Figure 11 Efficiency With and With out PCM, Over Time

The theoretical comparison of energy stored (kJ) in the time (06:00 to 24:00) between the configurations functioning with and without phase change material (PCM) is presented in Figure 12. The sensible heat storage of the baseline model without PCM (solid blue line) steadily rises in the morning and attains the maximum storage capacity of 10,000 kJ at 14:00. The stored energy then steadily drops to 6300 kJ at 24:00 due to thermal losses to the surroundings, as the solar radiation declines. However, the system with PCM integration (dashed red line) accumulates sensible energy at a lower rate during the first charging period (08:00-14:00), with 8,350 KJ at 14:00, since a major part of the absorbed energy is required for the phase change (melting) of the paraffin wax. However, with the high latent heat thermal storage, the PCM system can maintain the maximum energy retention capacity of 10,000 kJ until 17:00, which is an effective two hours shift of the thermal peak storage period. The phase change solidification process during the nite period (17:00–24:00) releases the stored heat back to the fluid loop, so that the PCM system may maintain a higher energy status of 6,700 kJ at midnight.

The dynamic response shows the good thermal inertia that the addition of phase change materials provides. The PCM takes up energy via its endothermic phase transition (melting) during the peak hours of radiation, delaying the start of thermal saturation relative to the usual setup. The stored latent heat is released gradually with the reduction in ambient temperature and solar input during the exothermic solidification phase, which enables the system to keep a higher energy storage state in the nighttime hours than that of the system without PCM.

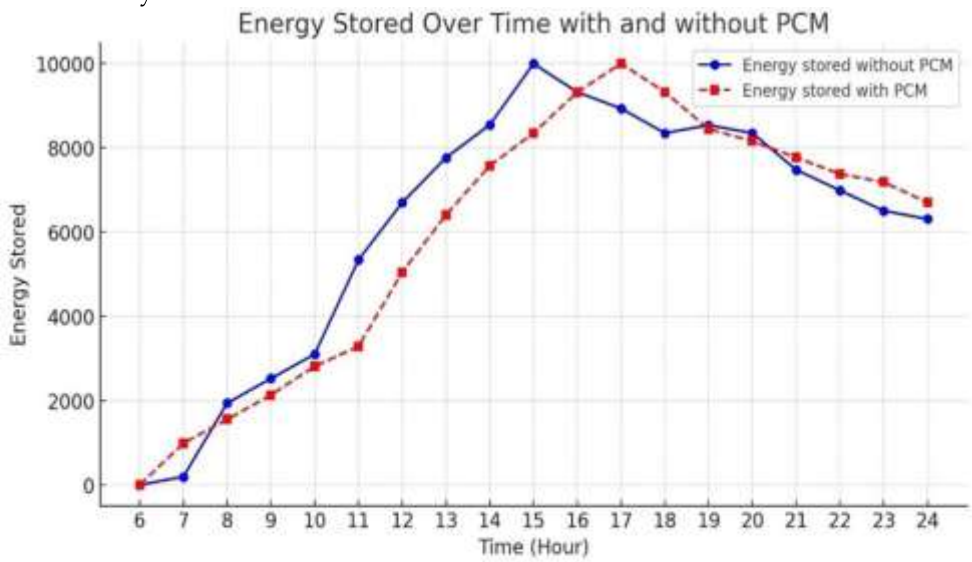

Figure 12 Energy Stored With and With out PCM, Over Time

4. Conclusion and Recommendations

The present study deals with the theoretical performance enhancement of an evacuated tube solar water heater utilising paraffin wax phase change material (PCM) in 24-h cycle (06:00–24:00). Main outcomes of a numerical simulation in comparison of the PCM and baseline configurations: The maximum output water temperature with PCM was 71 °C, which is 11 °C higher than the baseline (60 °C). The peak occurred one hour earlier (15:00 vs. 16:00). The highest thermal efficiency was improved to 63% with PCM as opposed to 62% for baseline. The peak time was delayed by two hours (17:00 instead of 15:00) and the performance during the overnight periods was enhanced (41% instead of 35% at midnight). Energy storage hit the maximum value of 10000 for the PCM system at 17:00 (instead of 15:00 for the baseline). This emphasises the fact that the latent heat absorption is an efficient way to prolong heat storage toward off-peak hours. Future work will include experimental validation with different PCMs, hybrid storage approaches and optimisation of design parameters to improve efficiency and reduce cost. Based on the theoretical results the following paths for additional investigation are recommended: Utilising phase change materials with thermal characteristics matched to local climatic conditions to optimise energy charge and discharge cycles. Testing PCM composite or binary mixes for constant thermal output under varying sun irradiation. Improving efficiency of collectors by improving surface shape and low-emissivity selective coatings to minimise heat losses.

4-list of symbols:

Symbol	Description	Unit
PCM	Phase Change Material	–
Ac	Collector area	m²
Cp,pcm	Specific heat of PCM	kJ/kg·K
Cp,w	Specific heat of water	kJ/kg·K
Qi	Energy received by the collector	Kj
Qs	Energy stored in the system	Kj
Qw	Energy stored in water	Kj

Qpcm	Energy stored in PCM	Kj
Ta	Ambient temperature	K
Tw,i	Initial water temperature	K
Tw,f	Final water temperature	K
Tpcm,i	Initial PCM temperature	K
Tpcm,f	Final PCM temperature	K
η (eta)	Thermal efficiency	%
L	Length of evacuated tube	M
D	Diameter of evacuated tube	M
Mw	Mass of water	Kg
Mpcm	Mass of PCM	Kg
Ht	Total daily solar radiation	kJ/m^2

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