

# Experimental evaluation of solar water heater with and without beeswax phase change material utilizing a hybrid-coated absorber plate

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## Abstract:

The present study investigates the performance enhancement of a solar water heater integrated with Beeswax-Based Phase Change Material (PCM) at a tilt angle of 45°. Experiments were conducted at three different flow rates 60 kg/hr, 90 kg/hr, and 120 kg/hr to evaluate the hourly and overall thermal efficiency. The system with PCM (WPCM) exhibited superior efficiency compared to the system without PCM (WOPCM) under all tested conditions. The maximum efficiencies obtained for WPCM were approximately 31%, 36%, and 38% at flow rates of 60 kg/hr, 90 kg/hr, and 120 kg/hr, respectively, whereas the corresponding efficiencies for WOPCM were around 24%, 27%, and 29%. The enhancement in efficiency is attributed to the PCM's ability to absorb excess heat during peak sunshine hours and release it gradually during the evening, ensuring stable thermal performance. The results confirm that incorporating beeswax-based PCM improves the overall energy utilization and extends the effective operating period of the solar water heater.

**Key words:** Solar water heater, WBPCM, WOBPCM, Bees wax, Copper tubes, Absorber plate, Thermocouples.

## 1. Introduction

Solar energy serves as a viable power source for both industrial and domestic use. A key component in enhancing its efficiency is the application of phase change materials substances that absorb and release large amounts of thermal energy as they melt and solidify at specific temperatures. By storing heat during peak sunlight and releasing it when needed, PCMs improve energy management, making solar power more reliable and effective for various applications. The thermal performance and efficiency of a solar water heater depend on several factors, including design parameters (such as thickness and absorber plate configuration), Design parameters (such as thickness and absorber plate configuration), Insulation type and quantity, Number and type of glass cover, Spacing between the absorber plate and inner glass. Additionally, climatic conditions (such as solar intensity and ambient temperature) and operational parameters (like flow rate and water temperature) significantly influence system performance. Most solar water heaters rely on natural convection for water circulation, driven by density differences between hot and cold water. As water heats up in the collector, it rises into the storage tank, while cooler water flows down to be reheated creating a continuous thermosiphon cycle. A typical solar water heating system consists of collector panels, which absorb solar radiation and transfer heat to the water. When combined with a well-insulated storage tank, this system significantly reduces the need for conventional fuel-based water heating, making it an energy-efficient solution for household hot water supply.

Solar thermal systems offer an efficient solution for both space heating and domestic/institutional hot water supply. These systems operate by circulating water through tubes connected to a black metal absorber plate, which maximizes heat absorption from sunlight. The absorber assembly is housed in an insulated box with a transparent glass cover, allowing optimal sunlight penetration while minimizing heat loss. As water heats up

in the absorber plate, it is pumped or naturally circulated to an insulated storage tank. This stored hot water can then be distributed for various residential, commercial, or industrial applications. By harnessing solar energy for thermal needs, these systems reduce reliance on conventional energy sources, offering an eco-friendly and cost-effective alternative. studied the transient thermal performance of a phase change material (PCM)-based thermal energy storage unit utilizing spherical capsules. Both theoretical modeling and experimental validation were performed to assess the system's dynamic heat transfer characteristics during charging (energy storage) and discharging (energy release) phases [1]. developed to predict the transient thermal behavior of a latent heat storage module. The model incorporated a finite overall heat transfer coefficient between the phase change material (PCM) and the heat transfer fluid (HTF). Experimental validation was performed using paraffin waxes with varying melting points as the PCM and water as the HTF. implementing a "three-type" PCM configuration incorporating multiple paraffin waxes with distinct phase transition temperatures enhanced both charging (heat storage) and discharging (heat release) rates compared to single-PCM systems [2]. examined the phase transition characteristics of paraffin-based phase change materials within spherical capsules, focusing on both freezing and melting processes. Experimental investigations were conducted using Pure n-tetradecane, A binary mixture of n-tetradecane (40%) and n-hexadecane (60%), Water as the heat transfer fluid. The parameters were Reynolds number, and the inlet temperature during the freezing and melting process of the PCM- thermal energy storage system [3]. The incidence radiation value was variable, with the best value being about eleven hundred watt per meter square. The SC (Solar collector) suffers from poor and fluctuating radiation. For a flat plate arrangement, the appropriate temperature was achieved [4]. Hot water was employed in both home and industrial uses. The heat came from the conversion of solar energy, and the system used several traditional collectors with an opaque cover and a metallic absorption surface [5]. The greatest drawback was that the temperature of hot water dropped drastically throughout the entire night [6]. The impact of installing PCM modules in a tiered solar home hot water system has been investigated. Three kg of paraffin mixed with various fatty acids (stearic acid, palmitic acid, myristic acid) at an Eighty:Twenty weight percent ratio were utilized as phase transition material[7]. Placing a PCM module to the topmost layer of a water reservoir results in increased energy retention density[8]. Encapsulated phase change materials significantly improved the thermal performance of a household hot water cylinder[9]. The thermal features of a packed bed with spherical capsules in a latent heat storage system with a solar heating collector were investigated. Myristic acid is chosen as the phase change material (PCM), whereas water is employed as the heat transfer fluid (HTF)[10].examined the thermal behaviour and practicality of a cylindrically enclosed PCM. A storage tank holding latent heat storage material is used to evaluate the performance of a latent heat thermal energy storage system. Experiments were conducted at a constant flow rate of heat transfer fluid to determine the thermal properties of the LHTES system and its efficiency. It is concluded that LHTES systems are a commercially viable solution for storing solar thermal energy [11].Water-PCM storage's performance was empirically studied for usage with traditional solar water heating systems. The PCM is made of paraffin wax and stored in compact cylindrical aluminium canisters. The storage performance was tested when linked to flat plate collectors with conventional natural circulation. The use of paraffin wax as PCM is a simple and inexpensive thermal energy storage solution. The melting temperature of paraffin wax is suitable for storing extra energy accessible during daytime hours as latent heat and then releasing this stored heat to maintain the water temperature in an appropriate range for most home uses [12]. offered a study of solar water heating systems for both residential and industrial applications. They are divided into two categories: passive and active solar water heating systems. Active systems are generally more efficient than passive systems. The best efficiencies of passive solar hot water systems (PHWS) are between 30 and 50%. The integrated column storages (ICS) are on the order of 30%, while those with thermosiphon systems are around 50%. Solar hot water systems (SHWS) have a strong potential for considerably contributing to hot water demand [13].

## 2. Role of PCM in Solar water heaters

The energy from the sun's source varies with the altitude of the sun. In the after midday, we can obtain optimum and nil at night. To counteract the nil supply at night, a significant amount of energy from the sun must be absorbed throughout the day. As a result, preserving energy is vital for any system that relies heavily on solar power. The radiation from the sun cannot be stored as is, hence an energy conversion must first occur, followed by the creation of a storage device based on this conversion. The key requirement is a material that

can store thermal energy and discharge it when required. The setup comprises a solar energy collector and an integrated storage module to ensure efficient energy harvesting and delayed utilization. The solar collector harnesses incident radiation, and the integrated storage unit mitigates variability in solar availability by retaining thermal energy during low-irradiance or non-sunlight periods. The method of storing thermal energy through phase change material fusion provides advantages including increased energy storage capacity per unit volume and temperature stabilization during energy absorption/release phases. The utilization of phase change materials for latent heat storage provides an effective thermal energy storage method, with the benefits of compact storage capacity and temperature maintenance at the phase change point. Phase change materials (PCMs) represent a class of latent heat storage media that utilize enthalpy of fusion during solid-liquid phase transitions.

### 3. Bees wax Phase change material

Bees construct combs from wax to store honey, pollen, and to nurture their young. Worker bees secrete beeswax from wax glands located on the underside of their abdomen, specifically on the front part of the sternum from segments IV to VII. This wax is released as small scales. To produce a single part of wax, bees must consume approximately 10 to 15 parts of honey. Once secreted, the wax scales are scraped off and chewed by the bees, mixed with saliva and various enzymes to make them pliable. Through repeated chewing and manipulation, the softened wax is shaped and attached to the comb. Over time, these tiny pieces fuse to form a remarkable structure just 20 grams of wax can create a hexagonal-cell comb capable of holding up to 1,000 grams of honey. Once the honey is ripened, bees often seal the cells with a wax cap for preservation.

### 4. Experimental setup

The experimental setup, shown in Fig. 1, consists of a 100-liter water tank mounted on a table and connected to a pump and rotameter. The system includes a frame adjustable to angles of 15°, 30°, and 45°. The rotameter regulates the water flow rate, which is directed through a pipe to a flat plate collector at three specific flow rates: 60, 90, and 120 kg/hr. The setup uses copper tubes with a circular cross-section and an outer diameter of 10 mm. Each tube is 2 meters long and fitted with 1 mm thick, corrugated black-painted fins that are 75 mm wide. The top and bottom headers are also made of copper tubing, with an outer diameter of 25 mm. As water flows through the copper tubes, it is heated by the absorber plate. Temperature readings are recorded using twelve K-type thermocouples positioned at various points: for water inlet and outlet, nano-embedded beeswax phase change material (PCM), the glass top surface, the absorber plate, the space between the glass and absorber plate, ambient air, and five locations along the copper tubes. Measurements are taken hourly. Fig. 2 illustrate beeswax PCM placed bottom of the absorber plate. This Bees wax PCM absorbs heat from the copper tubes and absorber plate during the day, storing it for gradual release at night.

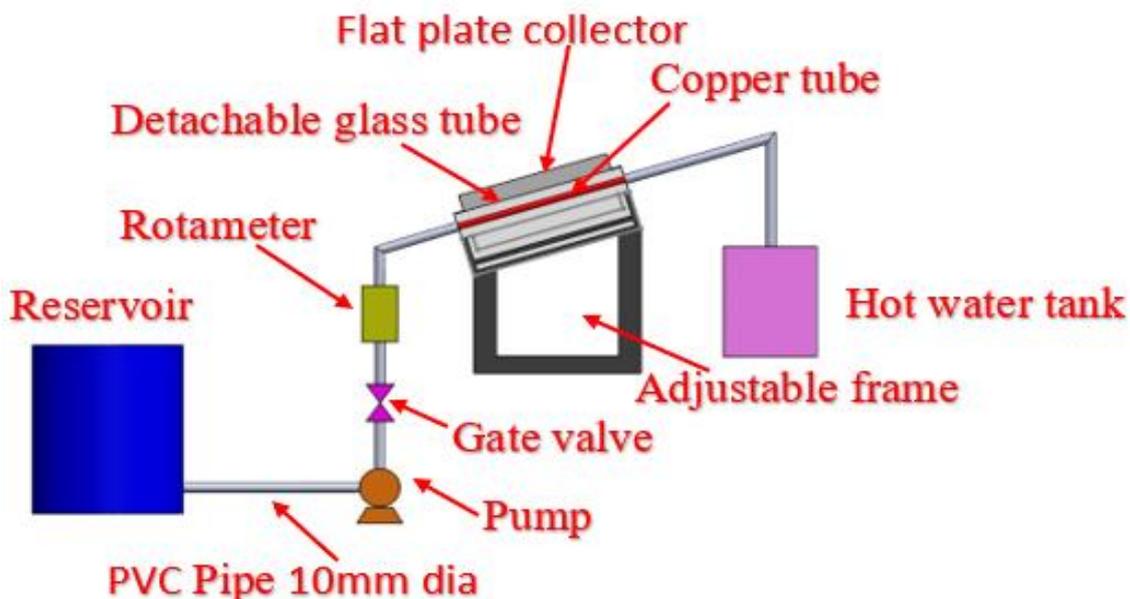


Fig.1: Experimental setup

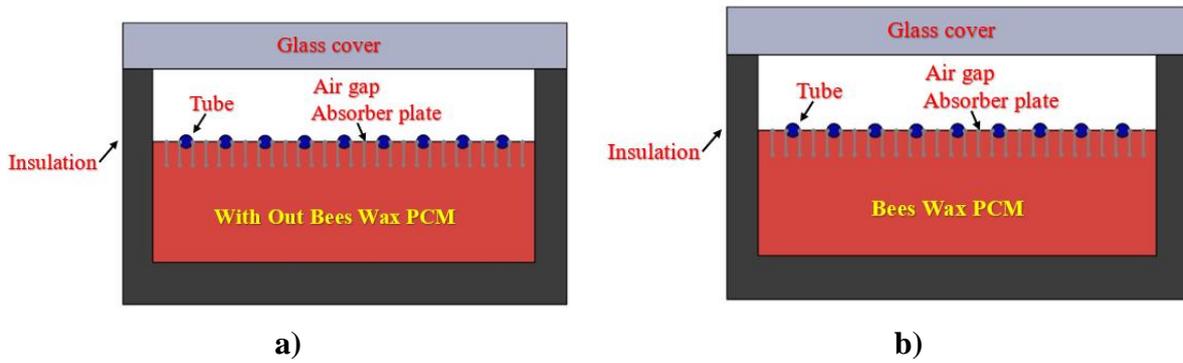


Fig.2: Flat plate collector a) With out Bees Wax b) With Bees Wax PCM

4.1 Data simplifying

Thermal efficiency is the rate of heat output relative to the rate of heat input. The percentage of thermal efficiency ( $\eta\%$ ) of the Flat plate collector is determined by

1. Energy that can be used or heat gained by the operating fluid:

$$Q_c = m_c \times c_{pc} \times \Delta T \text{ Watts}$$

$m_c$  = Mass flow of cold fluid kg/s

$C_{pc}$  = Specific heat of cold fluid = 4186.8 j/kg-k.

2. Energy absorbed by the Collector's Heat:

$$Q_a = I \times A \text{ watts}$$

$I$  = Intensity of solar radiation in W/m<sup>2</sup>

average solar power in India is 5 Kw.

but  $I = 5 \cos \alpha$  ( $\alpha$ = angle of tilt)

Flat plate collector Surface Area = 0.1x2=0.2 m<sup>2</sup>

Total collector area (A) = Surface area x number of tubes (n)

$$A = 0.2 \times 9 = 1.8 \text{ m}^2$$

3. Efficiency of the unit:  $(\eta\%) = \left( \frac{Q_c}{Q_a} \right) \times 100$

5. Results and Discussions:

5.1 Efficiency Evaluation of Solar Water Heaters with out and with Beeswax-Based Phase Change Material at 45°Tilt Angle:

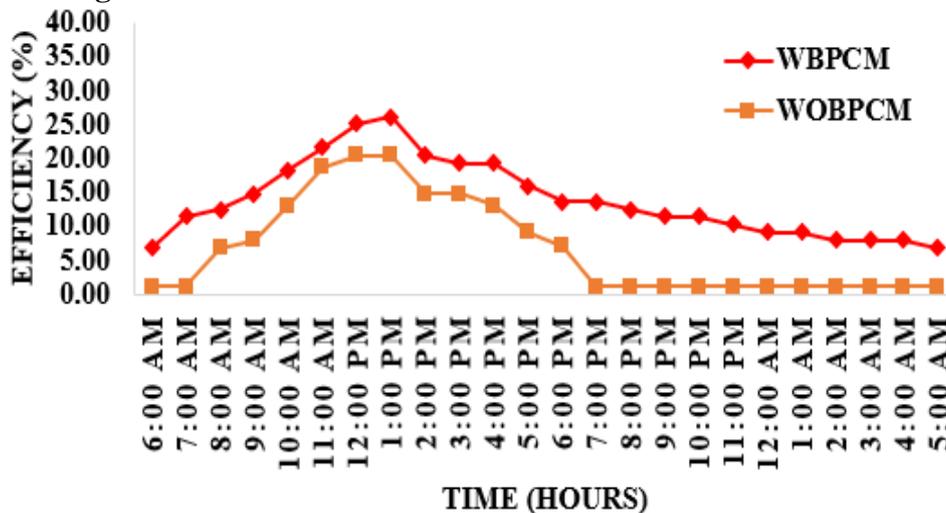
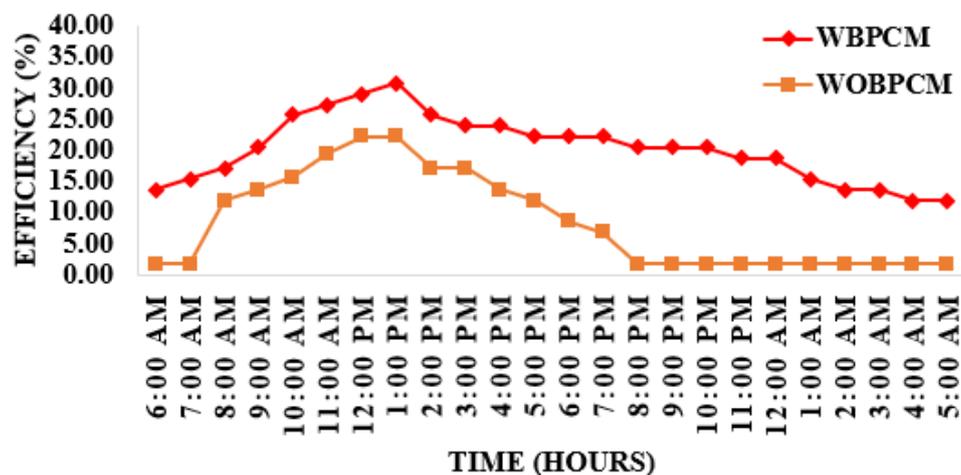


Fig.5: Efficiency Curve at a 45° Tilt Angle with a Flow Rate 60 kg/hr

The graph Fig.5 illustrates the the variation in efficiency (%) with respect to time for 60 Kg/hr at an inclination angle of  $45^{\circ}$  of a solar water heating system, comparing two conditions With Bees wax Phase Change material (WOB) and Without Bees wax Phase Change Material (WOPCM). The readings are taken from 6:00 AM to 5:00 AM the next day, representing a full 24-hour performance cycle. Morning (6:00 AM – 9:00 AM): Both systems start with low efficiency as solar radiation is weak. The WPCM system begins to absorb and store heat more quickly than the WOPCM system, showing an early rise in efficiency. Midday (10:00 AM – 2:00 PM): Efficiency peaks during this period due to maximum solar intensity. The WPCM system reaches around 25–30% efficiency, higher than the WOPCM system (15–20%), because beeswax PCM stores excess thermal energy and releases it gradually. Evening (3:00 PM – 7:00 PM): As solar radiation decreases, the WOPCM efficiency drops rapidly. In contrast, the WPCM system maintains higher efficiency for a longer duration due to the stored latent heat in the PCM, which continues to transfer heat to the water. Nighttime (after 7:00 PM): The WOPCM system shows almost zero efficiency since there is no sunlight. The WPCM system continues to operate with residual efficiency, utilizing the stored thermal energy in beeswax PCM for nighttime heating. The graph clearly demonstrates that the system with beeswax PCM (WPCM) provides higher and more sustained efficiency throughout the day and extends useful heat delivery into the evening. This confirms the effectiveness of beeswax PCM in enhancing energy storage and improving the overall thermal performance of the solar water heater.



**Fig.6: Efficiency Curve at a  $45^{\circ}$  Tilt Angle with a Flow Rate 90 Kg/hr**

The graph in Fig. 7 shows the variation of efficiency (%) with time (hours) for a solar water heating system with (WBPCM) and without (WOBPCM) Bees Wax Phase Change Material (PCM). Morning (6:00 AM – 9:00 AM): Efficiency starts low for both systems because solar radiation is weak. WBPCM shows a slightly higher efficiency due to the PCM's ability to absorb and store early solar heat. Midday (10:00 AM – 1:00 PM): Both systems show a rise in efficiency as solar intensity increases. The maximum efficiency occurs around 12:00 PM WBPCM Peaks around 30–32%, WOBPCM: Peaks around 20–22%. The PCM helps maintain better heat absorption and storage, leading to improved performance. Afternoon (2:00 PM – 5:00 PM): Efficiency decreases as sunlight intensity reduces. The WBPCM system maintains a gradual decline, while WOBPCM drops faster, showing that PCM delays heat loss by releasing stored energy. Evening to Night (6:00 PM – 5:00 AM): WOBPCM efficiency drops nearly to zero, as there is no solar input. WBPCM still maintains residual efficiency (~10–15%), due to the latent heat release from Bees Wax PCM, which continues to transfer heat to the water even after sunset. The system with Bees Wax PCM (WBPCM) performs significantly better throughout the day. PCM acts as a thermal buffer, storing heat during the day and releasing it gradually at night, leading to higher overall efficiency and extended operation hours. The system without PCM (WOBPCM) shows a sharp decline after sunset, highlighting the advantage of incorporating PCM in solar water heating systems.

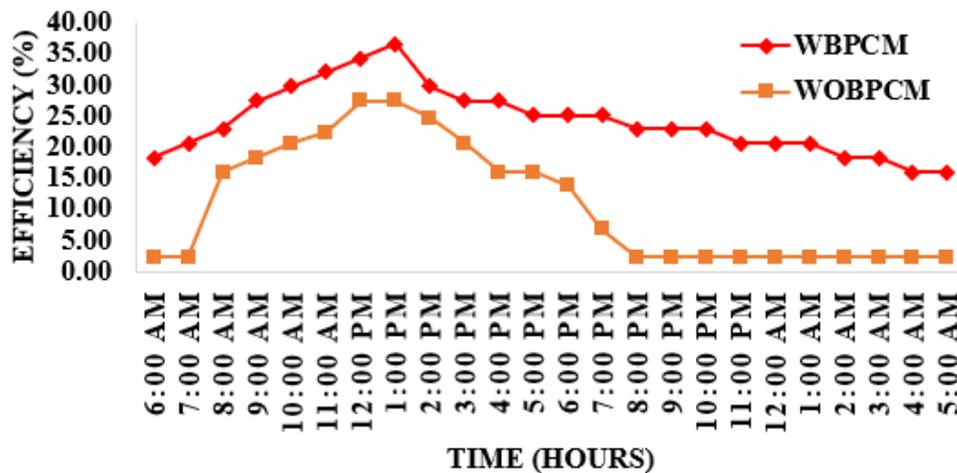


Fig.7: Efficiency Curve at a 45° Tilt Angle with a Flow Rate 120 Kg/hr

The graph Fig.8 shows the variation of efficiency (%) with time (hours) for a Flat Plate Solar Collector (FPSC) system tested with Bees Wax Phase Change Material (WBPCM) and without Bees Wax Phase Change Material (WOBPCM). Early Morning (6:00 AM – 8:00 AM): Both systems start with low efficiency due to low solar radiation. The WBPCM system quickly gains efficiency because the Bees Wax PCM starts absorbing heat even at lower temperatures. Mid-Morning to Noon (9:00 AM – 1:00 PM): Efficiency of both systems increases as solar intensity rises. The WBPCM system reaches a peak efficiency of around 32–33%, whereas the WOBPCM system peaks around 22–24%. The PCM improves heat absorption and storage, enhancing system performance. Afternoon (2:00 PM – 6:00 PM): Efficiency gradually declines as sunlight intensity reduces. The WBPCM system maintains a slower decline, showing sustained performance due to the stored thermal energy in the PCM. The WOBPCM system efficiency drops faster, as it relies only on direct solar input. Evening to Night (7:00 PM – 5:00 AM): The WOBPCM system efficiency nearly drops to zero since there is no sunlight. The WBPCM system still shows around 10–15% efficiency for a few hours, as the PCM releases stored latent heat, maintaining water temperature during non-sunlight hours. The integration of Bees Wax PCM significantly enhances the thermal efficiency of the solar collector by enabling heat storage during peak sunlight and gradual heat release after sunset, resulting in improved performance and prolonged heat availability.

## Conclusion

From the experimental analysis at a 45° tilt angle and varying flow rates, the following conclusions are drawn: **Efficiency Improvement with PCM:** The inclusion of beeswax-based PCM consistently increased the thermal efficiency of the solar water heater compared to the system without PCM. At 60 kg/hr, efficiency improved from 24% (WOPCM) to 31% (WPCM) an increase of approximately 29%. At 90 kg/hr, efficiency improved from 27% (WOPCM) to 36% (WPCM) an increase of about 33%. At 120 kg/hr, efficiency improved from 29% (WOPCM) to 38% (WPCM) an increase of roughly 31%. **Effect of Flow Rate:** Increasing the flow rate enhanced the overall efficiency because higher flow rates improved the rate of heat transfer and reduced temperature rise in the collector, minimizing thermal losses. **Thermal Stability:** The beeswax-based PCM acted as a thermal buffer storing heat during peak solar radiation and releasing it after sunset resulting in extended operational hours and smoother efficiency variation. **Observed Deviation:** The efficiency deviation between WPCM and WOPCM is mainly due to the latent heat storage capacity of the PCM, which delayed temperature drop during the evening. Without PCM, efficiency declined sharply after 3:00 PM, while WPCM maintained higher performance levels well into late hours. Hence, the integration of beeswax-based PCM significantly enhances both the instantaneous and overall thermal efficiency of solar water heaters, making it an effective solution for improving energy storage and utilization in solar thermal systems.

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