Performance analysis of a hybrid-coated solar water heater with and without beeswax phase change material at 15^0 and 30^0 tilt angles

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Abstract – *The present study investigates the performance enhancement of a solar water heater integrated with a beeswax-based Phase Change Material (PCM) at tilt angles of 15° and 30°. Experiments were carried out at three different flow rates 60 kg/hr, 90 kg/hr, and 120 kg/hr to evaluate both hourly and overall thermal efficiencies. The system incorporating PCM (WPCM) demonstrated superior efficiency compared to the system without PCM (WOPCM) under all test conditions. The maximum efficiencies achieved for the WPCM system were approximately 20.56%, 25.11%, and 29.90% at flow rates of 60 kg/hr, 90 kg/hr, and 120 kg/hr, respectively, while the corresponding values for the WOPCM system were around 17.67%, 22.32%, and 26.17%. The observed enhancement in efficiency is attributed to the PCM's capacity to absorb excess thermal energy during peak solar radiation periods and release it gradually during the evening, thereby maintaining stable thermal performance. These findings confirm that integrating beeswax-based PCM significantly improves overall energy utilization and extends the effective operating duration of the solar water heater.*

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

1.INTRODUCTION

In line with the rapid pace of development and changing lifestyle patterns, energy consumption in Indonesia has continued to rise. This growth has occurred across nearly all sectors, including industry, transportation, commerce, households, power generation, and others. Between 2003 and 2013, the country's total national energy consumption increased at an average annual rate of 4.1%, rising from 117 million TOE in 2003 to 174 million TOE in 2013 [1]. The commercial sector includes trade, hotels, restaurants, finance, government institutions, schools, hospitals, communication services, and other related activities. Data from 2004 to 2011 indicate that this sector grew at an average rate of 8% per year. However, this growth did not directly correspond to the increase in energy consumption, which rose at a slower average rate of 4% per year during the same period. In 2014, the commercial sector consumed approximately 5.22 million TOE, accounting for about 3% of the total final energy consumption. According to the National Energy Conservation Master Plan, this sector has an energy-saving potential ranging from 10% to 30%. Reducing energy consumption and its associated impacts can be achieved through several strategies, such as using low-carbon building materials, enhancing insulation, installing energy-efficient lighting, integrating renewable technologies, employing intelligent control systems, and utilizing low-carbon fuels. The integration of renewable energy within building components should be designed to ensure both reliable performance and cost-effective energy savings. Building Integrated Photovoltaic (BIPV) systems represent one such approach, where photovoltaic modules are incorporated into the building envelope such as the roof or façade. By functioning simultaneously as a structural element and a power generator, BIPV systems help reduce material and electricity costs, lower fossil fuel dependence and greenhouse gas emissions, and enhance the architectural aesthetics of the building [2]. However, BIPV systems face a significant challenge related to temperature rise, which leads to reduced electrical efficiency and overheating. This efficiency loss primarily occurs due to the decline in open-circuit voltage (Voc), which possesses a negative temperature coefficient. At present, only about 15–20% of the solar energy incident on a photovoltaic (PV) panel is converted into electricity, while the remaining energy is converted into heat. This accumulated heat can raise the operating temperature of the PV module to as high as 80°C, resulting in a decrease in conversion efficiency of approximately 0.4–0.65% for each degree of temperature increase [3]. Consequently, many researchers are exploring ways to minimize the adverse effects of high temperatures on PV conversion efficiency by effectively dissipating heat from the module surfaces. The goal is to maintain optimal performance and ensure the system meets expected efficiency levels. Most of these studies have concentrated on various cooling approaches, including natural or forced air circulation, heat pipe systems, and hydraulic or refrigerant-based cooling methods [4-7].

Emphasizes on the thermal properties of PCMs, techniques of heat transfer augmentation, and applications in solar water heating systems, all of which contribute to hot water requirements [8]. Studied the TES employing solid liquid phase transition was conducted, focusing on possible materials, thermophysical characteristics, heat transfer, and applications. Commercial PCMs were also featured. Different methods for determining thermal properties are covered, as well as issues with long-term material stability and encapsulation [9].Inorganic phase change materials (PCMs) have a thermal conductivity of 0.3-1 W/mk and significant latent heat across a specified temperature range. However, organic PCMs, despite being the preferred choice for thermal energy storage (TES) due to their low vapor pressure, high energy storage capacity, chemical stability, self-nucleating behaviour, and commercial availability, have significant drawbacks such as significant supercooling and corrosive properties [10,11]. Biological PCMs are the carbon-based fuel variant, with price disparities and sociopolitical implications. Because of these factors, motivation must be transferred from commercial biological PCMs to auxiliary bio-based PCM (BPCM) [12]. Biological PCMs are suited for TES due to their small vapour pressure, substantial energy storage capacity, chemical durability, tendency to self-nucleate, and economical affordability. Biological PCMs, on the other hand, are derivatives of fossil fuels with price differences and geopolitical implications. Because of these factors, there is an urgent need to shift motivation away from commercial organic PCMs and toward (BPCMs). As a promising material for TES, BPCMs composites have been concerned with energy storage since BPCMs have certain unique qualities such as less polluting, excellent energy storage, highly stable, little volume change, and eco-friendly [13-16]. Phase change materials (PCMs) are materials having the capacity for latent heat thermal energy storage (LHTES). They can be employed as creative ways to TES and satisfying the world's energy needs [17]. Solar thermal energy systems absorb sunlight and convert it into heat, which is then transferred to a fluid for usage. Many Solar thermal energy systems additionally have a heat storage system, which might be sensible or latent heat [18]. compared the duration intervals between PCM and standard samples at specific time increments. The approach known as the "heat latency technique" provides accurate, temperature-dependent thermal data unique to PCMs. This method delivers comprehensive information needed to construct an enthalpy–temperature curve, essential for PCM characterization [19]. Studied the phase change materials and their applications in solar thermal energy storage [20].

2. EXPERIMENTAL SETUP

The experiment is designed to test a flat plate solar water heater that incorporates beeswax as a phase change material (PCM) and nano-enhanced components to improve heat storage and transfer. The setup includes a water tank, pump, and rotameter, which together control and measure the water flow through the system. By adjusting the flow rate (60, 90, and 120 kg/hr) and the tilt angle of the collector (15^0 and 30^0), the experiment can study how these variables affect the heater's performance. Copper tubes with fins are used as the main channels for water flow. The fins and the black paint increase heat absorption from the absorber plate. Heat from the sun warms the water as it flows through the tubes. Beeswax PCM is installed under the absorber plate. Temperature measurements are taken at multiple points using thermocouples: at the water inlet and outlet, along the copper tubes, the absorber plate, the glass cover, the air gap, the PCM, and ambient air.

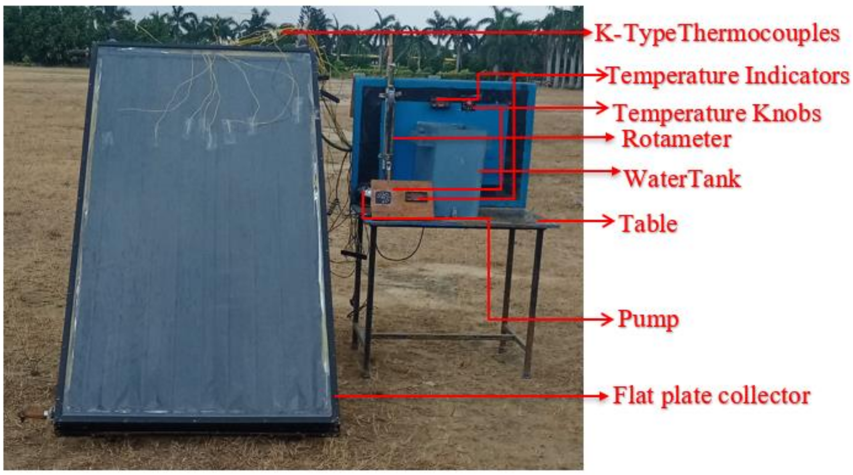

Fig-1: Solar water heater Experimental setup with names

a) b)

Fig-2: Solar water heater for different Tilt angles a) 15^0 b) 30^0

3. RESULTS AND DISCUSSIONS:

3.1 Efficiency Evaluation of Solar Water Heaters with out and with Beeswax-Based Phase Change Material at 15^0Tilt Angle:

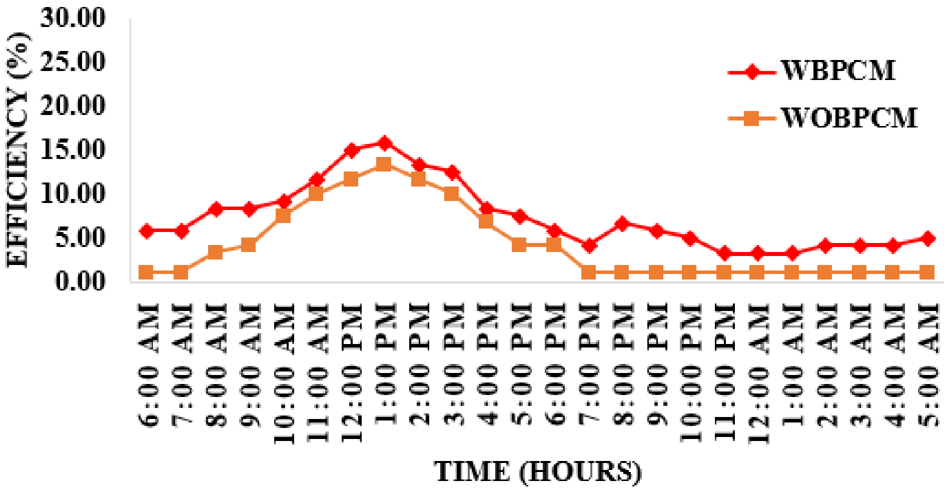

Chart-1: Efficiency Curve at a 15^0 Tilt Angle with a Flow Rate 60 kg/hr

The graph Chart-1 illustrates the the variation in efficiency (%) with respect to time for 60 Kg/hr at an inclination angle of 45^0 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–11:00 AM): WBPCM shows slightly higher efficiency than WOBPCM because PCM starts absorbing heat early. Noon (12:00–1:00 PM): Both systems reach peak efficiency; WBPCM is slightly higher. Afternoon & Evening (2:00 PM–8:00 PM): Efficiency drops for both systems, but WBPCM maintains a better level due to PCM heat retention. Night (9:00 PM–5:00 AM): WBPCM maintains efficiency (~4–5%), while WOBPCM drops to almost 1%, showing the energy storage advantage of PCM. With Bees wax Phase change material (WBPCM) efficiency starts around 5–6% at 6:00 AM, increases sharply during the morning as solar radiation increases, peaking around 12:00–1:00 PM (~15%). Efficiency then gradually decreases in the afternoon but remains higher than the WOBPCM system in the evening and night due to the latent heat storage effect of the PCM. Maintains some efficiency even after sunset (e.g., 1:00–5:00 AM), because the PCM releases stored heat. With out Bees wax Phase change material (WOBPCM) Efficiency rises with sunlight, peaking around 12:00–1:00 PM (~13%). After sunset, efficiency drops sharply and stays almost negligible (~1%) during the night. No PCM means no thermal energy storage, so the system cannot continue releasing heat after solar input ends. Bees Wax PCM to a flat plate solar collector enhances thermal efficiency, especially during late afternoon and nighttime, by storing solar energy during the day and releasing it gradually.

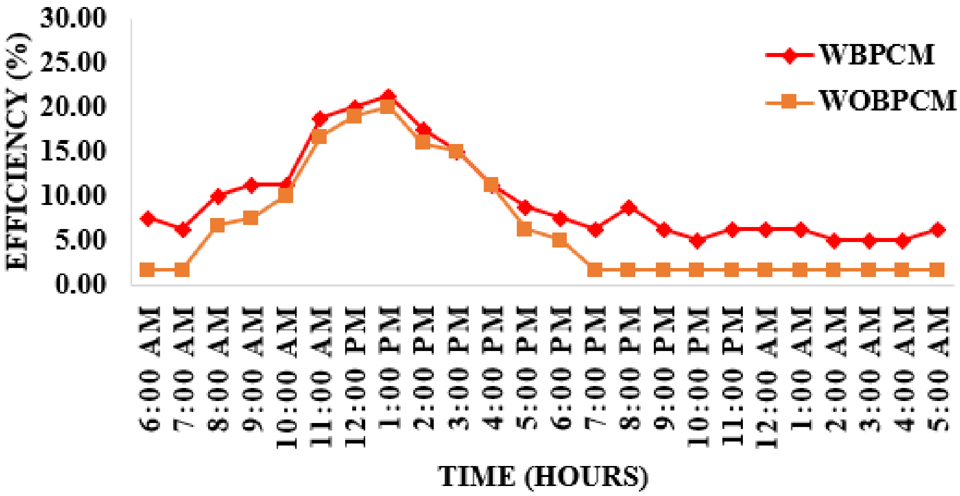

Chart-2: Efficiency Curve at a 15^0 Tilt Angle with a Flow Rate 90 kg/hr

The graph Chart-2 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): The WBPCM system exhibits a slightly higher efficiency, as the beeswax PCM begins absorbing and storing heat even at lower temperatures. Mid-Morning to Noon (9:00 AM – 12:00 PM): The WBPCM system consistently outperforms the WOBPCM one due to the additional thermal storage capability of beeswax PCM, which captures excess heat. Afternoon (12:00 PM – 2:00 PM): The maximum efficiency is observed around 12:00 PM – 1:00 PM, with WBPCM reaching around 21%, while WOBPCM peaks near 18%. This indicates enhanced heat retention and better energy utilization with PCM. Evening (3:00 PM – 6:00 PM): Efficiency starts to decline as solar radiation decreases. The WBPCM system maintains higher efficiency for a longer duration because the PCM releases stored heat gradually, extending useful operation time. Night to Early Morning (7:00 PM – 5:00 AM): Efficiency of WOBPCM drops nearly to zero. WBPCM maintains a small residual efficiency due to the release of stored heat from the PCM, showing its advantage in heat retention. This improvement is due to the PCM's ability to store heat during peak sunlight and release it when solar radiation decreases, resulting in stable and extended performance of the solar collector.

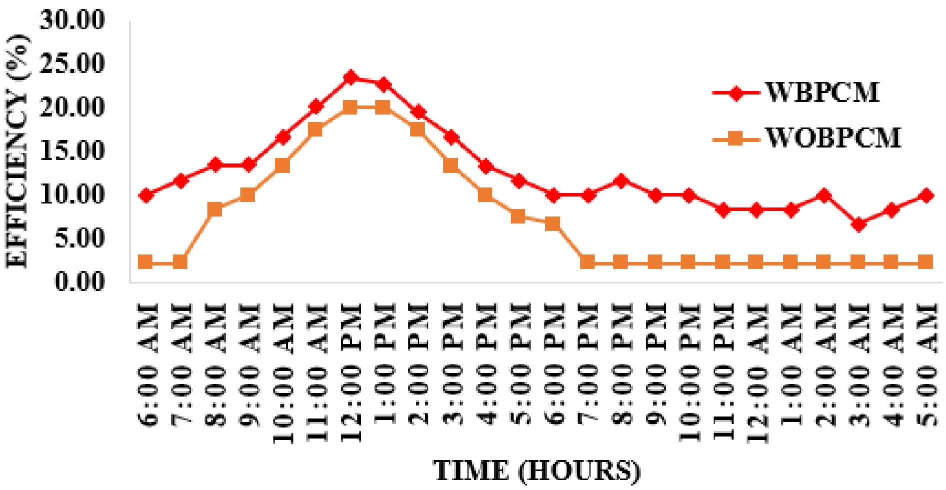

Chart-3: Efficiency Curve at a 15^0 Tilt Angle with a Flow Rate 120 kg/hr

The graph Chart-3 illustrates 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): The WBPCM system shows slightly higher efficiency, as the beeswax PCM begins to absorb and store solar energy even at lower temperatures. Morning to Noon (9:00 AM – 12:00 PM): Solar intensity increases, leading to a rapid rise in efficiency for both systems. The WBPCM system reaches higher efficiency levels compared to WOBPCM, due to enhanced heat absorption and thermal storage in the PCM. Noon to Early Afternoon (12:00 PM – 2:00 PM): The WBPCM system peaks at around 22% efficiency, while the WOBPCM system reaches around 18%. The beeswax PCM effectively stores excess heat, preventing overheating and maintaining stable performance. Late Afternoon (3:00 PM – 6:00 PM): As solar radiation decreases, efficiency for both systems decline. The WBPCM system maintains higher efficiency for a longer period since the PCM releases stored heat gradually, extending the useful heating duration. Evening to Early Morning (7:00 PM – 5:00 AM): The WOBPCM system efficiency drops nearly to zero after sunset, as it lacks thermal storage capability. The WBPCM system continues to show a small but consistent efficiency level, attributed to the release of stored heat from the phase change material during discharge. The PCM enhances the collector's performance by storing heat during peak sunlight hours and releasing it during low solar radiation periods, ensuring extended operation and improved energy utilization.

3.2 Efficiency Evaluation of Solar Water Heaters with out and with Beeswax-Based Phase Change Material at 30⁰Tilt Angle:

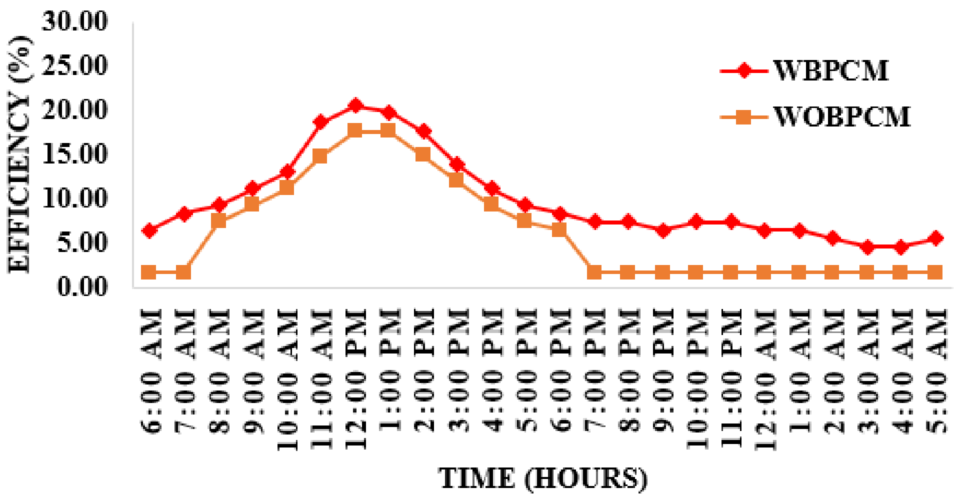

Chart-4: Efficiency Curve at a 30⁰ Tilt Angle with a Flow Rate 60 kg/hr

The graph Chart-4 represents 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): At sunrise, both systems show low efficiency due to minimal solar radiation. The WBPCM system begins absorbing heat earlier and exhibits slightly higher efficiency because the beeswax PCM stores heat even at low temperatures. Morning to Noon (9:00 AM – 12:00 PM): Solar intensity increases steadily, resulting in a sharp rise in efficiency for both systems. The WBPCM system achieves higher efficiency than the WOBPCM system, as the PCM absorbs and stores part of the incoming solar energy, preventing heat loss. Noon to Afternoon (12:00 PM – 2:00 PM): Both systems reach their maximum efficiency around 12:00 PM – 1:00 PM. The WBPCM system peaks near 20–21% efficiency, while the WOBPCM system reaches around 16–17%. The stored heat in the PCM helps maintain stable operation during peak sunlight. Evening (3:00 PM – 6:00 PM): The WBPCM system retains higher efficiency because it releases stored heat gradually, sustaining useful output after solar intensity drops. The WOBPCM system efficiency falls more rapidly due to the absence of heat storage. Night to Early Morning (7:00 PM – 5:00 AM): The WOBPCM system efficiency approaches zero after sunset.

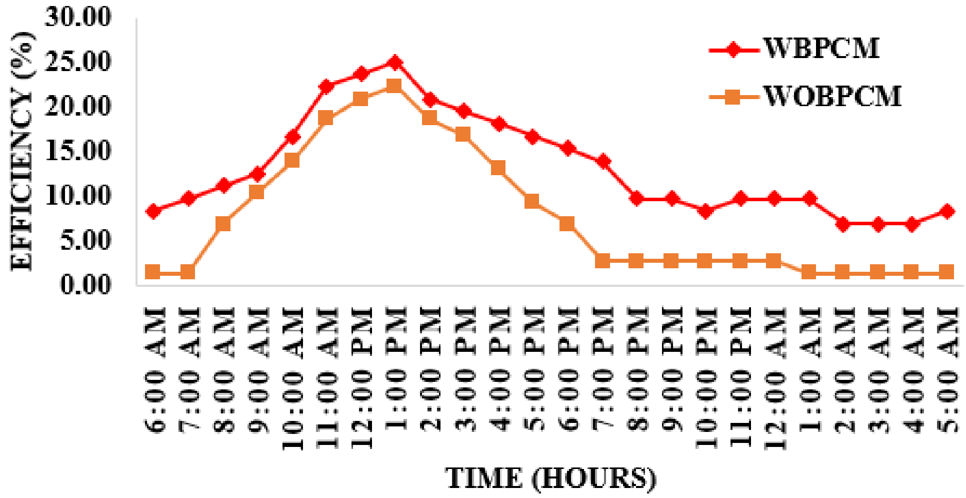

Chart-5: Efficiency Curve at a 30⁰ Tilt Angle with a Flow Rate 90 kg/hr

The graph Chart-5 shows how efficiency (%) varies with time (hours) for two different systems WBPCM and WOBPCM over a 24-hour period. Morning (6:00 AM – 9:00 AM): Both systems start with low efficiency. WBPCM efficiency rises earlier and faster than WOBPCM. Midday (10:00 AM – 1:00 PM): Efficiency peaks for both systems around 12:00 PM. WBPCM reaches around 25%, while WOBPCM peaks around 20–22%. This indicates that WBPCM performs better during peak solar hours. Afternoon (2:00 PM – 6:00 PM): Efficiency declines gradually for both. WBPCM maintains higher efficiency compared to WOBPCM. Evening to Early Morning (7:00 PM – 5:00 AM): Efficiency drops significantly. WBPCM remains slightly more efficient even during night hours, while WOBPCM efficiency nears zero. WBPCM (With Phase Change Material) shows consistently higher efficiency throughout the day. PCM helps store thermal energy during peak hours and release it later, maintaining efficiency longer. WOBPCM (Without PCM) loses efficiency quickly once solar input decreases. No thermal storage capability.

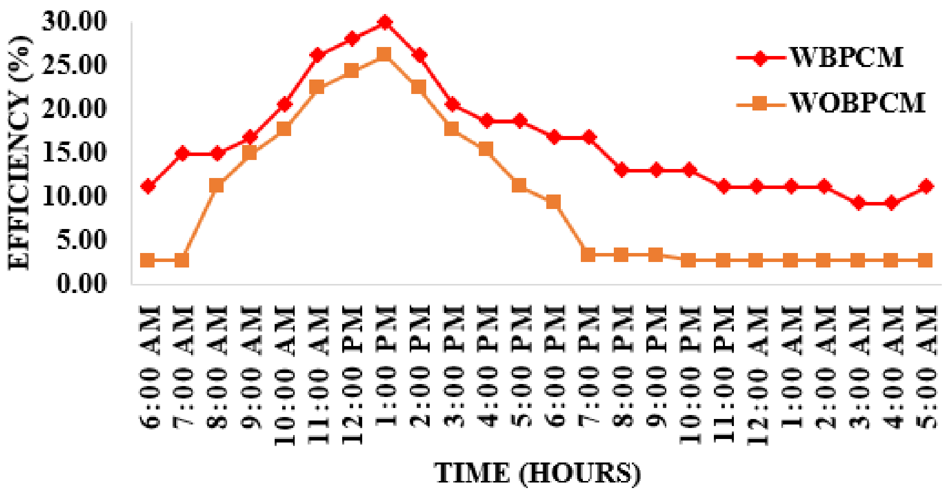

Chart-6: Efficiency Curve at a 30⁰ Tilt Angle with a Flow Rate 60 kg/hr

The graph Chart-6 illustrates the variation of efficiency (%) with time (hours) for two systems WBPCM (With Phase Change Material) and WOBPCM (Without Phase Change Material) over a 24-hour period. Early Morning (6:00 AM-8:00 AM) Both systems start at low efficiency. WBPCM begins around 12%, while WOBPCM starts near 3%. Morning to Noon (8:00 AM -12:00 PM) Efficiency increases rapidly for both. WBPCM peaks around 28% at 12:00 PM. WOBPCM peaks around 22% at the same time. Afternoon (1:00 PM to 6:00PM) WBPCM maintains higher values (between 15–20%) compared to WOBPCM (5–15%). Evening to early morning (7:00 PM-5:00 AM) WBPCM sustains a small efficiency level (~10–12%) due to thermal energy storage while WOBPCM efficiency remains nearly constant at a very low level (~3–4%). WBPCM having higher efficiency throughout the day and maintains useful performance after sunset. This indicates that PCM absorbs heat during the day and releases it later, improving overall thermal regulation and performance stability. WOBPCM Shows lower and more fluctuating efficiency, dropping quickly once sunlight diminishes, as it lacks thermal storage capability.

3. CONCLUSIONS

The thermal performance of a hybrid-coated solar flat-plate water heater was evaluated from 6:00 a.m. to 5:00 a.m., comparing systems with and without beeswax as a phase change material (PCM). The PCM was positioned beneath the absorber plate to optimize thermal energy storage. Beeswax PCM significantly enhanced thermal efficiency compared to the non-PCM system. Copper tubes outperformed steel tubes due to their superior thermal conductivity. A 30° tilt angle yielded the highest efficiencies for the beeswax PCM (WBPCM) system compared to 15° and 30° angles. The maximum efficiencies recorded at a30^0 tilt angle were:120 kg/hr flow rate: WBPCM: 29.90%, Without Beeswax PCM (WOBPCM): 26.17%, 90 kg/hr flow rate: WBPCM: 25.11%, WOBPCM: 22.32% ,60 kg/hr flow rate: WBPCM: 20.56%, WOBPCM: 17.67% Efficiency. peaked around midday and declined in the afternoon due to reduced solar radiation. A sharper efficiency drops after 1:00 p.m. suggested either increased heat loss or diminished solar gain. Systems with beeswax PCM maintained marginally higher efficiency than non-PCM setups, demonstrating the material's ability to store and gradually release thermal energy.

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