Optimizing solar energy utilization and energy efficiency through thermal energy storage with phase change materials in a solar water heating system

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Abstract. Solar energy (SE) is non-polluting and sustainable. However, the strength of the sun's rays shifts as the seasons change, the weather shifts, and the day and night cycles. It is possible to store energy as heat, which can then be used for a variety of applications in the future. The primary objective of this research was to extend the time that high water temperature (HWT) was maintained by using phase change materials (PCM) to reduce energy consumption. To test the efficacy of an FPSWHS using 18 % (63 kg) of PCM condensed paraffin wax of type RT42, an experimental rig was constructed. To further expand PCM surface area and speed up charging and discharging, 18 aluminium cylinders were employed. Given the varying weather patterns in the India, this research was also useful in settling on a suitable PCM for SWHS. At 60°C input temperature of water (Tin) and 0.11 kg.s-1 flow rate of mass in water (mw), including RT42 into a water-PCM storage tank reduced power consumption by as much as 5.75 kWh, for a total system energy consumption of 31.4 kWh. The results showed a 27 % drop

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in daily average carbon footprint and a 27 % increase in overall system efficiency.

Keywords: Phase change material, solar water heater, efficiency, solar energy, flat plate solar collector.

1. Introduction

Several developed nations have turned to solar energy (SE) as the principal means of mitigating climate change by decreasing their reliance on fossil fuels [1]. A yearly savings of 90,014 t of N_2O, 80,042 t of CO_2, and 114 t of methane, CH4 is possible if solar energy is widely used. Most often, SE is used to heat water and the home's interior [2]. During the day, it should be possible to meet the requirements without much trouble. After dark, the stored water is kept at a tolerable temperature with the use of electric heaters [3]. An effective energy storage system is in place, ready to absorb surplus SE and release it when no longer needed [4]. Incorporating PCMs into a SWHS may be done in three different ways. Putting a PCM in the Flat Plate Solar Collector (FPSC) is the first choice. Heat from PCMs was first detected by Carmona and Palacio [4]. The PCM in the second setup is housed in a container. Using this idea, researchers have done a number of empirical experiments [5]. It was shown that water could be kept at a higher temperature when PCM was present compared to when it was absent. The third setup has PCM and water stored in individual containers. Electricity generation, sun cooling/heating of buildings, fish farms, greenhouses, household hot water, and many more applications are only a few of the numerous possible uses for solar LHS systems [6]. The effectiveness of the system, its impact on boosting operating efficiency and lowering module prices, and other such matters have been the subject of much theoretical and practical investigation [7]. Large solar power plants, as well as residential solar water heating systems, used PCMs as a reliable thermal energy storage medium in the 1970s and 1980s [8]. At the same time, scientists have conducted extensive preliminary research on PCMs, probing such phenomena as solidification and melting, as well as the impacts of convection and conductive heat transfer on phase transition processes [9]. In recent years, energy-absorbing apparel for the military and the general public has been developed with polymer ceramic microspheres (PCMs) [10]. What follows is an introduction to several regional frameworks. In order to better the design of such a tank, authors [11] investigated many options. In order to keep water hot throughout the night, researchers [12] examined the effectiveness of solar energy conservation and energy-saving PCMs. At night, a heat storage device made of PCM encased in a cylinder of aluminium is utilized instead of the solar water heaters used during the day. In a PCM investigation, authors [13] encased TES in a cylinder of copper or aluminium. The primary focus of this research is on how much heat energy a SWHS needs to keep the water at a consistent temperature. This research proves that latent heat storage has a unique property (LHS). The 37 fins of the FPSC are arranged beneath the absorber and PCM, and their ideal arrangement was determined through an experimental design [14]. The results demonstrate that high temperatures may be attained with very little adjustments to the tilt angle. However, insulation is crucial in stopping heat from escaping. Since there was no outside heat to produce temperature changes, the water in the tank stayed at a consistent temperature all night long. For the paraffin RT35, for which RUBITHERM provides a melting temperature of 35°C, authors [15] conducted experimental and computational studies of PCM melting in a cylindrical shape. There was a noticeable improvement in energy density and cost reductions as a result. Heat transfer applications in the residential and industrial sectors were studied by researchers [16] using analytical data

and experimental study. The results showed that TES with PCMs is attractive and useful in solar applications. Researchers [17] studied the thermal efficiency of FPSC. According to the results, the thermal efficiency of the system may be greatly improved by combining an FPSC with baffles. Studies of TES systems that use concentrated solar power generation have been looked at in the literature [18]. Larger temperature swings and TES determined by volume are made possible by raising the critical temperature of the storage fluid, as demonstrated by the findings. In order to boost the efficiency of solar air heaters, the authors [19] choose to employ high TES material. The research shows that paraffin wax is more effective at storing heat than cement is at storing sensible heat. The authors [20] used both experimental and computational techniques to investigate the viability of condensed paraffin wax for minimum temperature thermal energy storage applications. Their research found that forced convection might increase melting rates by as much as 87 % compared to settings where heat was allowed to accumulate. To effectively manage the high temperature problem associated with heat pipes, researchers [21] investigated a study employing Phase change material among the heat pipe and absorbing tube in Solar Water Heating system. The results indicated that the two models' exergy efficiency grew by 21-73 % per day while their energy efficiency improved by 37-81 percent per day. One of the main aims of the Paris Agreement is to limit the increase in the average global temperature this century to less than 2 degrees Celsius over pre-industrial levels, with the more ambitious target of limiting the increase to 1.5 degrees Celsius. To better equip governments to combat climate change, the pact seeks to redirect economic flows toward low-greenhouse gas emissions and a climatic- robust path. Reaching these lofty objectives calls for more capacity-building efforts, new technological infrastructure, and greater resource mobilization and provision [22]. Countries in development or peril must also act in their own best interests. Power consumption has a persistent upward trend since it is directly proportional to the ever-increasing population. Thus, the problem of the nighttime cooling of the water at SWHS must be addressed. To maintain a higher water temperature for longer periods of time in SWHS storage tanks, the usage of PCMs has to be researched and optimized. In this research, PCM is encased in a cylinder, which has many practical advantages, most notably increased heat storage capacity. The primary goal of this work is to examine the efficacy of PCMs for thermally enhancing solar energy storage. Saving money on electricity bills and reducing environmental impact, PCM is used to reduce and relocate electrical peak demands in water heating.

2. Experimental setup

The apparatuses used in this study include FPSCs, a big water tank, a water-Phase Change Material storing tank, circulating pumps to move water throughout the system, sensors, a residential water softening system, a pipe system and an expansion vessel. Data from sensors such as thermometers, flow meters, and pressure gauges were visualized using a program called DESIGO INSIGHT. This section provides an overview of SWHS and its key components.

2.1 Flat plate solar collector

As can be seen in Fig. 1(a), the solar collector system used in this investigation comprises of 15 panels; these panels were installed in three parallel rows a top. Each panel had a surface area of (2 m^2), and they were tilted south at an inclination of 60°.

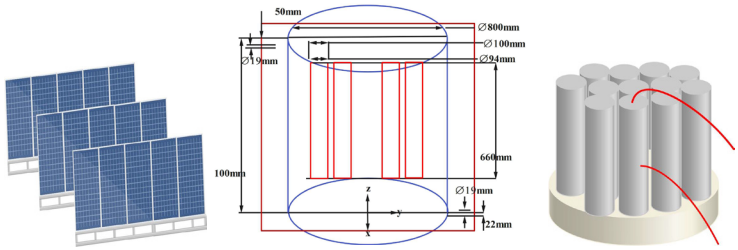

Fig. 1. (a) An overview of flat plate solar collectors **(b)** Water-Phase change material storing tanks with cylindrical PCM dimensions **(c)** Locations of thermocouples in phase change material.

2.2 Water-PCM storing tank

As can be seen in Fig. 1(b), 18 aluminium cylinders with outside diameters of 0.11 m, interior diameters of 0.094 m, and heights of 0.66 m are used to contain water (81 %, 0.405 m^3) and RT42 paraffin PCM (17 %). The foundation of the tank occupies 0.01 m^3 of the total volume (2 percent of tank volume). The Water-Phase Change Material storage tank in front is the primary investigation target. As can be seen in Fig. 1(c), a DS18B20 thermometer was utilized to take readings from three of the twelve temperature sensors in the water-PCM storage tank at the top, midway, and bottom of the cylinder. Flow meter, pressure, and temperature sensors were fitted in the study's closed SWHS (shown schematically in Fig. 2). The purpose of this research was to examine the effects of PCM on energy efficiency and temperature regulation in tank 2, which is positioned after tank 1 and before the load.

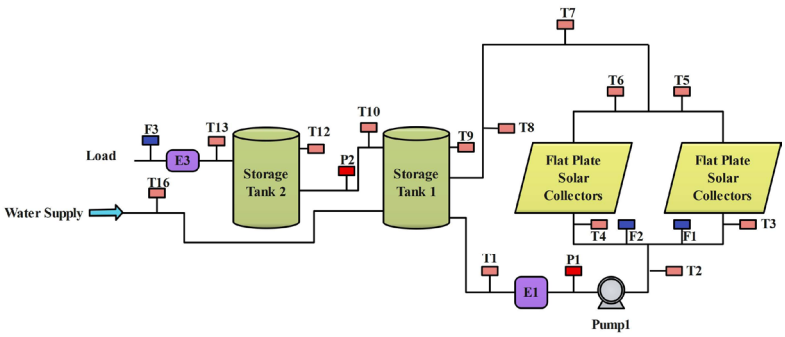

Fig. 2. An outline of the sensors in the solar water heating system.

2.3 Water storage tank

As can be seen in Fig. 3(a), the indirect, non-backup heated water is stored in a WBO 1005 UNO/DUO water storage tank (storage tank 1) with a 1 m^3 capacity. The highest temperature this tank can withstand is 130 degrees Celsius, and its maximum working pressure is 16 bars.

Fig. 3. (a) Water storage tank **(b)** RT42 paraffin wax.

2.4 RT42 PCM

Fig. 3(b) shows that the RUBITHERM company's paraffin wax type RT42 was employed as the phase change material in this study. Table 1 lists some of RT42's characteristics.

Table 1. Properties of RT42 [30].

Properties	Value
Density	880 kg/m^3 (solid) 760 kg/m^3 (liquid)
Latent heat of melting	174 kJ/kg
Thermal expansion coefficient	0.0008 1/K
Specific heat capacity	2 kJ/kg K
Thermal conductivity	0.2 W/m^{2}K

3. Theoretical analysis on energy

For energy analysis, we employ the following sets of equations:

3.1 Energy recovery ratio (ERR)

The energy recovery ratio (ERR) quantifies the amount of heat salvaged after a PCM discharge. A quick discharging procedure or the shortest gap between the discharge and charge periods also significantly contributes to high ERR. During the discharge process, the rejected energy (Q_{rej}) may be calculated:

$$Q\ rejected\ energy\ = M[c_{ps}(Ti\ -\ T_m)\ +\ \Delta h\ +\ c_{pl}(T_m\ -\ Tf)] \quad (1)$$

PCM discharging heat is compared to charging heat to determine the ERR. The formula is as follows [23]:

$$ERR = \frac{Qrej}{Qabs} \quad (2)$$

Considering the charging and discharging times (t), we can calculate the ERR as follows:

$$ERR = \frac{Qrej/timeof\ complete\ discharg}{Qabs/timeof\ complete\ discharge} \quad (3)$$

3.2 Energy accretion

The amount of energy that can be stored depends heavily on the latent heat capacity (Δh) of the PCM, therefore using a PCM with a high h value is essential. The following equation describes the buildup of energy in PCM:

$$Q_{\mathrm{st}} = M[c_{\mathrm{ps}}(T_{\mathrm{m}} - Ti) + x\Delta h + c_{\mathrm{pl}}(Tf - T_{\mathrm{m}})] \quad (4)$$

The melt fraction, denoted by x, may be calculated with the use of the following formula [24]:

$$x = \frac{T - T_S}{T_L - T_S} \quad (5)$$

Where,

T is the polycrystalline metal's average temperature and Ts is its solidus temperature.

The amount of energy accumulated or heat stored (Qst) during charging required for complete melting is as follows:

$$Qabs = Q_{\mathrm{st}} = M[c_{\mathrm{ps}}(T_{\mathrm{m}} - Ti) + \Delta h + c_{\mathrm{pl}}(Tf - T_{\mathrm{m}})] \quad (6)$$

3.3 System efficacy

To calculate the system's efficacy experimentally with and without Phase change material, the following equations were used [25]:

system efficiency without PCM $\eta_{S,no}pcm = \frac{E_{tot,no}pcm}{I*A_c}$ (7)

system efficiency with PCM $\eta_{S,pcm} = \frac{E_{tot,no}pcm}{I*A_c}$ (8)

3.4 System thermal capacity

Water's ability to retain heat depends on the amount of energy it can hold; thus, it makes sense to select a PCM with a large energy storage capacity if you want your water to maintain its high temperature for an extended period of time. With or without PCM, the following [26] equations can be used to determine the total accumulated energy (Etot) in a water storaging tank or a water-Phase Change Material storaging tank.

Total collected energy

without PCM $E_{\mathrm{tot,\,no}}pcm = \dot{m}wCpw(Two - Twi)$ (9)

with PCM $E_{\mathrm{tot}},pcm = \dot{m}w\ Cpw\ (Twav - Twi) + Q_{\mathrm{st}}$ (10)

Thermal storage gain $Q_{ths} = \frac{E_{tot,pcm}}{E_{tot,no}pcm}$ (11)

4. Results and discussions

Improving system performance, energy analysis, and the results of cutting down on carbon emissions are covered. The input water temperature and mass flow rate changed all of these outcomes.

4.1 Charge time

Table 2 displays the nine different RT42 charge times. Using 18 aluminium cylinders led to a lot of PCM surface area, which in turn led to a lot of heat transmission. Because of their rapid heat transfer rate and low volume to surface area ratio, cylindrical batteries take less time to charge. A more efficient system is one that can store as much energy as possible in as little time as possible, hence a shorter charging time is preferable. Maximum values of Tin

and m_w, respectively 70°C and 0.11 kg.s-1, resulted in the most efficient operating conditions for the system. For 60°C and 0.07 kg.s-1 for Tin and w, respectively, maximum charging durations were obtained, but optimal charging times were seen at medium Tin and w. Fig. 4 depicts the duration of the charging process. When can be seen in the graph, as T_{in} levels rise, charging times decrease. The charging time, on the other hand, reduces with increasing w.

Table 2. Charge and Discharge periods (hours)

$T_{in}/\dot{m}_w$	0.07 kg.s^{-1}	0.09 kg.s^{-1}	0.11 kg.s^{-1}
Charging Period			
60°C	2.93	2.35	2
65°C	2.49	2.02	1.8
70°C	1.88	1.75	1.53
Discharging Period			
35°C	3.2	3.05	2.48
30°C	2.68	2.15	2
25°C	2.12	1.98	1.65

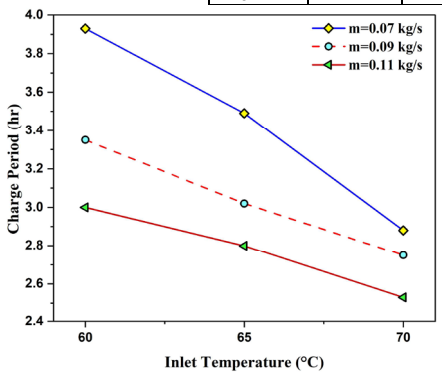

Fig. 4. Comparison of inlet temperature of RT42 and charging period with respect to various of mass flow rate.

4.2 Discharging time

Fig. 5 displays the discharge durations for nine different situations. Discharge timings were longest at 35°C and 0.07 kg. s^{-1} (the highest Tin and lowest w values), whereas they were shortest at 25°C and the highest w values (kg/s). The median discharge times were also calculated at T_{in} and w. The Fig. 5 graph clearly shows that as T_{in} decreases, so does the discharging time. Discharge times, on the other hand, reduce when $\dot{m}_w$ rises because the cooler fluid dissipates heat more quickly. With initial and final PCM charging temperatures of 20°C and 65°C, and initial and final PCM discharging temperatures of 65°C and 20°C, $\dot{m}_w$ =0.11 kg. s^{-1}, and Tin charging and discharging temperatures of 70°C and 35°C, respectively, as shown in Fig. 6, is one instance of the charging and discharging process.

4.3 Reduction in carbon footprint

Electric heaters that use PCM to shorten their run times will save money and reduce their carbon footprint. There are 38,800 kilocalories of heat in one litter of kerosene. Then, the kilowatt-hour (kWh) of CO_2 emissions from electric heaters may be determined: One kilowatt-hour of heat is equal to 0.38 kilos of carbon dioxide. Therefore, RT42 reduces its daily carbon impact by 1.5 kg CO_2 for every 3.82 kWh of energy it stores. If the system can store 20.5 kWh per day, it will lower its annual carbon footprint by 7056 kg CO_2, and its daily effect will be reduced by 28 kg CO_2.

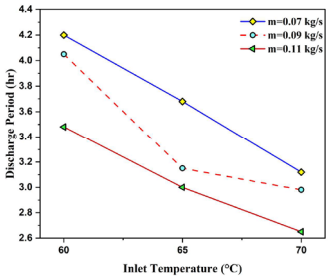

Fig. 5. Comparison of inlet temperature of RT42 and discharging period with respect to various of mass flow rate.

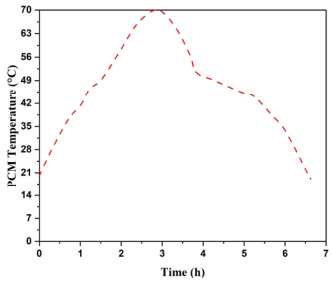

Fig. 6. Evaluation of PCM temperature with mass flow rate = 0.11 kg/s and charging temperature at T_{in} of 70°C and discharging at 35°C.

4.4 Enhancement of efficiency

Integrating PCMs with SWHS has been shown to boost system efficiency. In Fig. 7, we see how the system performs with and without PCM. Using the identical boundary conditions across all scenarios, the outcomes reveal that the energy saved by the phase change material improved system efficacy by 13-26 %, resulting in thermal behaviour.

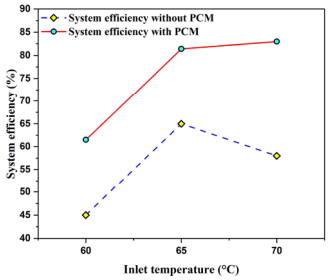

Fig. 7. Evaluation of the system efficacy with respect to phase change material.

Fig. 8 shows how the use of PCM improved system efficiency across all nine scenarios. The graph demonstrates that the system efficiency is raised by a maximum of 27 % for the maximum Tin (70ºC) and minimum m_w (0.07 kg/s) values and by a minimal of 14.1 % for the minimum Tin (60ºC) and minimum m_w (0.07 kg/s) values. It was also shown that the efficiency of the system improves with increasing T_{in}, whereas it can go up or down with increasing m_w owing to energy storaging in the tank 2.

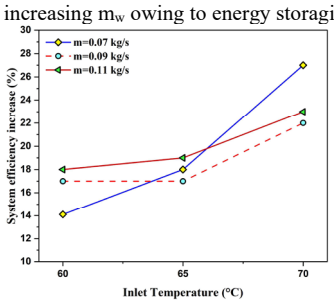

Fig. 8. Evaluation of percentage of system efficacy increment for the various factors with respect to mass flow rate.

4.5 Analysis of Energy

4.5.1 Reduction of electricity consumption

The discharge duration in hours must be multiplied by the kW of energy saved to get an estimate in kWh. Energy storage peaks at 4.2 kWh at minimum Tin (60ºC) and maximum m_w (0.11 kg/s) values and troughs out at 5.75 kWh at maximum Tin (70ºC) and minimum m_w (0.11 kg/s) values, as shown in Fig. 9.

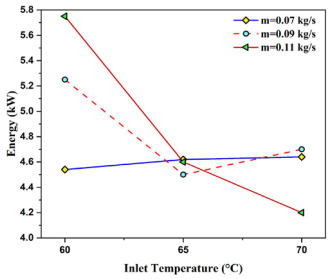

Fig. 9. Comparison of inlet temperature and energy with respect to variation of mass flow rate.

Fig. 10 shows that the system's energy storage capacity peaked at 31.4 kWh on March 22 and its lowest at 11.4 kWh on April 16. The system is able to store an average of 21.1 kWh each day.

4.5.2 Energy saving

The energy stored in PCMs is substantial during the phase transition. Once the substance cools and passes through the phase shift, the stored heat energy is released. When the PCM mass, C_p, Δh and melting percentage are all held constant, the energy savings while charging is affected by the PCM's beginning and ultimate temperatures. Most of the potential energy of PCM can be extracted by starting with a lower temperature and finishing with a higher one. Fig. 11 shows the total energy used by RT42 in kWh across all nine cases. For the highest values of T_{in} and m_w, (70 C° and 0.11 kg. s^{-1}, RT 42) was found to store the most energy (3.11 kW), whereas for the lowest values, (60°C and 0.07 kg. s^{-1}), it stored the least (2.1 kW).

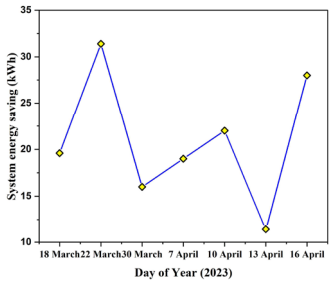

Fig. 10. The system's annual kWh energy savings at different times of the year.

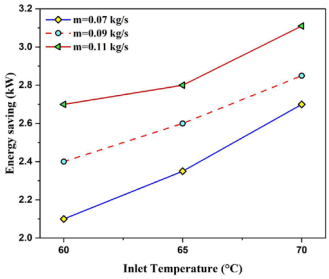

Fig. 11. RT42 Energy saving for variant T_{in} and $\dot{m}_{w.}$

Total energy produced by the system is shown in Fig. 12 as kWh throughout the course of the year. The graph clearly demonstrates that PCM results in greater system energy savings on all days for the same boundary condition than does the absence of PCM. Water-PCM storage tank energy efficiency gains explain this. The data reveal that on April 16, the system energy stored with PCM was at its highest at 11.2 kW, and that on March 30, it was at its lowest at 7.1 kW, mostly because of daily fluctuations in solar radiation and, to a minimum range, depending on the boundaries criteria.

4.5.3 ERR

Fig. 13 displays the outcomes of the nine different scenarios with respect to the ERR. Because of its large ERR and absence of hysteresis, RT42 is easily discernible in the graph. Hysteresis and sub-cooling errors are two examples of the kinds of imprecision that might arise while working with a phase transition material [27].

4.5.4 Thermal storing gain

The Thermal storing Gain (Qths), the ratio of total energy storage with phase change material to total energy storages without phase change material, is additional significant analysis for adopting Phase Change material in Solar Water heating System. The greater thermal increase of the SWHS attributable to the RT42 is seen in Fig. 14. With the similar boundary criteria, the best system efficiency improvement and the highest Q_{ths} were obtained at the maximum inlet temperature of 70ºC and the minimum mass flowrate of 0.07 kg. s^{-1}. Q_{ths} ranged from a maximum of 2.4 at a velocity of 0.11 kg. s^{-1} to a low of 2.2 at 65°C.

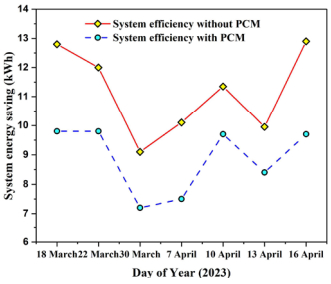

Fig. 12. System energy savings for various days in March and April 2023.

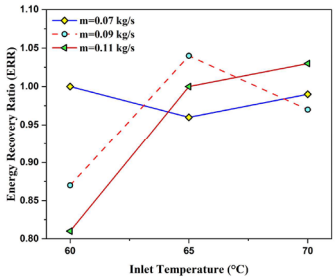

Fig. 13. Difference in energy recovery ratio with varying inlet temperature and variation of mass flow rate.

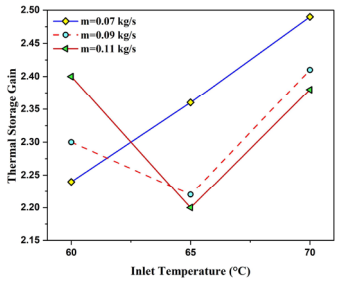

Fig. 14. Comparison of thermal storage gain and inlet temperature as a function of change in mass flow rate.

5. Conclusions

The purpose of this water-PCM storage tank is to increase the effectiveness of the integrated SWHS and PCM system in the climate of India. These are the major findings of this study: Reducing dependency on fossil fuels and increasing use of SE can be accomplished by the usage of PCM in TES storage. Latent heat storage in a PCM during the day can be utilized to retain water at a comfortable temperature for showering, bathing, and other uses at evening. The combination of flat plate solar water heating system with paraffin wax is appropriate for the city of Chennai, since experimental study showed that the maximum energy savings were achieved at 70°C (T_{in}) with 0.11 kg/s (m_w). The system as a whole is now 27 % more efficient. Based on the results of the previous research included in this one, the authors concluded that cylindrical PCM modules perform much better than PCM modules of any other shape. The cylindrical module also has greater installation and production efficiency.

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