Performance Analysis of Solar Water Heater at Possible Flow Rates with and Without Phase Change Material

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ABSTRACT

To store excess solar energy from the sun, in this project we provide phase change materials (PCM) at the bottom of the absorber plate. Experiments were conducted in the cascaded solar water heater with and without phase change materials at different flow rates. During the sun-shine hours, the phase change material (PCM) absorbs latent heat of solar energy and stores the same energy up to its melting point. Similarly during off-sunshine hours, the phase change material releases the energy, which is used to heat the water. The set up can result a higher efficiency of the solar collector system. In this work, the paraffin wax has been selected as a phase change material due to its low cost, easily availability and considerable thermo-physical properties. The PCM unit stores the heat during the sun-shine hours and supplies hot water during the night and overcast periods. An attempt was made to produce hot water even after sun-shine hours every day. The performance of this PCM based thermal energy storage system is compared with conventional latent heat storage system and the conclusions drawn from them are presented. The conventional solar water heater gives better efficiency during day time because of the energy absorbed by phase change material. Thus a solar water heater integrated with phase change material unit gives little better efficiency during off sun-shine hours due to the presence of thermal energy storage system.

Keywords: Thermal energy storage, phase change material, solar water heater, paraffin wax, n-tricosane

INTRODUCTION

The past few years have witnessed a rapid growth in global population putting a tremendous burden on energy resources. Due to fast growth of the India's economy, the country's energy demand has grown to an average of 3.65% per annum over the past 30 years, so it has become a need to harness alternate and renewable energy sources. Thus the country has invested heavily in recent years in renewable energy utilization. Solar energy being simple to use, clean, non polluting and inexhaustible has received wide spread attention in recent times and provides well abundant energy source if utilized efficiently. But this energy is a time dependent energy source with an intermittent character [1, 12, 15, 24&31], hence some form of thermal energy storage (TES) is necessary for more effective utilization of this energy source. Phase Change Materials (PCM) is one of the techniques to store this thermal energy in the form of latent heat. Inorganic phase change materials (PCM) are hydrated salts that have large amount of heat energy stored in the form of latent heat which is absorbed or released when materials changes state from liquid to solid or solid to liquid [2 & 33]. The PCM retains its latent heat without any change in physical or chemical properties over thousands of cycles and has wide range of applications.

Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy. Performance improvement with TES results from right sizing all energy systems components (e.g. heat exchangers and pumps) and operating them at optimal efficiency range and within their design intent specifications, which minimize losses. Phase change materials (PCM) uses this energy to heat water for domestic purposes during night time. This ensures that hot water is available throughout the day. The system consists of two simultaneously functioning heat-absorbing units. One of them is a solar water heater and the other a heat storage unit consisting of PCM (paraffin). India Energy storage not only plays an important role in conservation of the energy but also improves the performance and reliability in wide range of energy systems and becomes more important where the energy source is intermittent in nature such as solar. TES can be used in such places where more variation in temperature difference between day and night. The problem of high compressor discharge temperature caused by high pressure ratios across the compressor can be solved by operating cascade mode at low ambient temperature. The corrugated surface based solar water heater is determined to have a higher operating temperature for longer time than the plane surface [5, 14, 18 & 20]. A thorough literature investigation into the use of phase change material (PCM) in solar water heating has been considered. It has been demonstrated that for a better thermal performance of solar water heater a phase change material with high latent heat and with large surface area for heat transfer is required.

SOLAR WATER HEATER

Solar domestic water heaters are cost competitive in many applications when we account for the total energy costs over the life of the system. Although the initial cost of solar water heaters is higher than that of conventional water heaters, the fuel (sun-shine) is free, plus, they are environmentally friendly. To take advantage of these heaters, we must have an unshaded, south-facing location (a roof, for example) on our property. These systems use the sun to heat either water or a heat-transfer fluid, such as a water-glycol antifreeze mixture, in collectors generally mounted on a roof. Some systems use an electric pump to circulate the fluid through the collectors. Solar water heaters can operate in any climate. Performance varies depending, in part, on how much solar energy is available at the site, but also on how cold the water coming into the system is. The colder the water, the more efficiently the system operates [6, 11, 21 & 29].

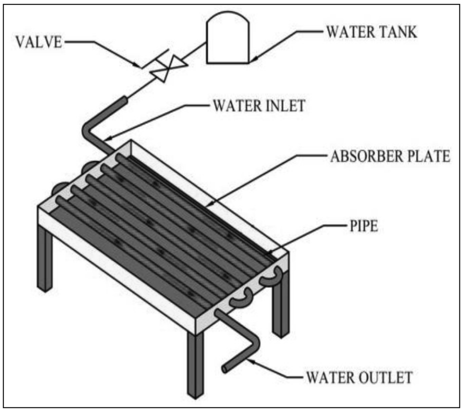


Figure 1. Solar water heater without PCM

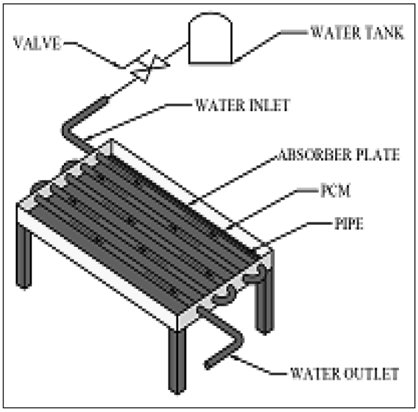


Figure 2. Solar water heater with PCM

PHASE CHANGE MATERIALS (PCM)

These materials can store energy by melting at a constant temperature. No material has all the optimal characteristics for a PCM, and the selection of a PCM for a given application requires careful consideration of the properties of various 20,000 compounds and/or mixtures have been considered in PCM, including single component systems, congruent mixtures, and eutectics. The isothermal operating characteristics (i.e. charging/discharging heat at a nearly constant temperature) during the solidification and melting processes, which is desirable for efficient operation of thermal systems[7,12,19 & 22]. One of the most important aspects during the selecting of the material is the convertible melting point and the high latent heat of fusion. The choice of the substances used largely depends upon the temperature level of the application. Residential, commercial and industrial buildings often have hot water requirements at around 60°C and bathing, laundry and cleaning operations in the domestic sector generally need it at about 50°C [34]. The right melting point enables that the phase Changing comes off during every usage cycle. Thereby the latent heat could be fully utilized. According to the required temperature of the domestic hot water the melting point should be between 40°C and 50°C. Storage systems using these heat accumulator materials can store the energy from the solar collector at lower temperature level, too in winter. The stored energy can be used for pre-heating the cold incoming water and the solar water heating system with and without PCM is shown in Figures 1 and 2 respectively.

CLASSIFICATION OF PCM

Organic Phase Change Materials

Organic materials are further described as paraffin and non-paraffins. Organic materials include congruent melting, which means melting and freezing repeatedly without phase segregation and consequent degradation of their latent heat of fusion.

Paraffins

Paraffin is safe, reliable, predictable, less expensive and non-corrosive. [8,13 & 28]. These are hydrocarbons and increasing the number of C-atoms increases the melting point too. The non paraffins of type

C_nH_{2n+2} are a family of saturated hydrocarbons with very similar properties. Paraffin's between C5 and CI5 are liquids, and the rest are waxy solids. Paraffin wax is the most commonly used commercial organic heat storage PCM. Paraffin waxes are cheap and have moderate thermal energy storage density but low thermal conductivity and hence it requires large surface area.

Non-Paraffins

The non-paraffin organic are the most numerous of the phase change materials with highly varied properties. Each of these materials will have its own properties unlike the paraffin's, which have very similar properties. This is the largest category of candidate's materials for phase change storage.

SOLAR ENERGY ANALYSIS

Heat Transfer Analysis

Heat in a solar thermal system is guided by five basic principles: heat gain, heat transfer, heat storage, and heat insulation. Here, heat is the measure of the amount of thermal energy an object contains and is determined by the temperature, mass and specific heat of the object. Solar thermal power plants use heat exchangers that are designed for constant working conditions, to provide heat exchange. Heat gain is the heat accumulated from the sun in the system. Solar thermal heat is trapped using the greenhouse effect. The green house effect in this case is the ability of a reflective surface to transmit short wave radiation and reflect long wave radiation. Heat and infrared radiation (IR) are produced when short wave radiation light hits the absorber plate, which is trapped inside the collector. Fluid, usually water in the absorber tubes collect the trapped heat and transfer it to a heat storage system.

Energy Analysis

The energy analysis is based on the first law of thermodynamics and the corresponding first law efficiency has been calculated and the energy analysis is based on the fact that it is an upper limit of efficiency [9,17 & 27].

Exergy Analysis

The rate at which exergy is collected by the solar collector can be increased by increasing the mass flow rate of the working fluid. Since the collector tubes are the most expensive component of any solar thermal system which needs advanced material and associated technology to build, therefore, it requires large invest¬ment. In order to reduce the capital cost, we need to optimize the dryer area, as the fuel (sunlight) is free[10,32]. Again, for large mass flow rates, the fluid outlet temperature is very low and requires more power to pump/blow air/fluid through it. On the other hand, low flow rate results in high outlet temperature of the working fluid with high specific work potential. But due to the nature of entropy generation, exergy losses increase due to the temperature differences and hence, the optimum mass flow rate is required. The exergy analysis has been performed based on the configuration of solar air heater collector.

EXPERIMENTAL SET-UP

The set-up is essentially similar to conventional, commercially available, solar water heating systems with a few differences. It consists of four south-facing flat plates (1.94 x 0.76 x 0.15) m, collectors with a tilt angle of 25° to the horizontal. The collectors, which have ordinary single glass covers and black painted absorber plates, are connected to the main water supply and the hot water storage tank through a set of three valves enabling open-loop and closed-loop operation. In addition to natural circulation, a forced circulation is introduced in the tank loop by using standard 80W circulation pump with a capacity of 9 /min

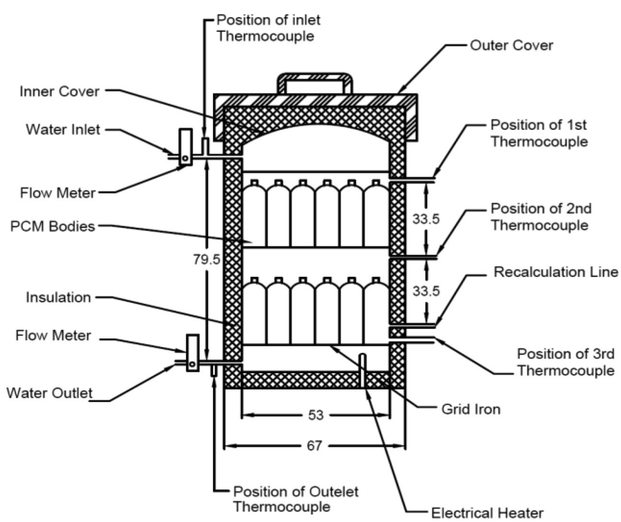


Figure 3. Schematic line diagram of solar water heater

[11].The galvanized steel storage tank is cylindrical in shape having a length of 645 mm, an inner diameter of 470 mm and a volume of 109.4 litres and it is insulated with 80-mm thick layer of rock wool insulation. A detailed cross-sectional view of the storage tank is shown in Figure 3. The tank contains a total of 38 thin walled, cylindrical, aluminium containers. Each container has a volume of 1.4 litres, and contains 2.0 kg of paraffin wax which was used in this investigation as the PCM.

The PCM is encapsulated in aluminum cylinders of internal diameter 36mm and height 120mm, with wall thickness 4mm. Each cylinder contains 75gm of PCM by wt. The cylinders are packed in layers one over the other, with every two layers separated by a wire mesh to enhance the rigidity of the set-up The PCM containers are arranged in the tank on two levels, each containing 17 containers, with the aid of two perforated sheet metal separators. The choice of these containers was meant to reach a relatively large heat transfer surface area in comparison with the volume of the PCM, and to minimize the thermal resistance between water and the PCM. The total volume of the PCM containers is 49.4 l, with water occupying the remaining 58 litres in the storage tank. The bottom section of the storage tank also contains an auxiliary 4 kW electrical heater, in order to enable controlled conditions. Paraffin wax and n-tricosane was selected as a LHTESS due to its thermal storage, safety, reliability and low solar reduction is measured by using a pyranometers.

The schematic line diagram of solar water hear integrated with thermocouples is shown in figure 4 and the measurement system includes a total of seven pre-calibrated K-type thermocouples: One at the inlet line and the other at the outlet line of the storage tank, three distributed at the upper, middle, and lower sections of the storage tank, one thermocouple inserted in a PCM container at the central section of the tank, and one to measure the ambient air temperature. All thermocouples are connected to an HP 34970A-type data logger is connected to a PC to enable the continuous recording of the temperature readings during various test scenarios. In the experiments described in the following section, temperature readings were continuously recorded with 1, 5, or 10 min intervals between each reading and the other, depending on the experiment requirements. The specification of experimental set-up is shown in table 1 and the photographic view of experimental set-up,paraffin wax plate is shown in figures 5 and 6 respectively.

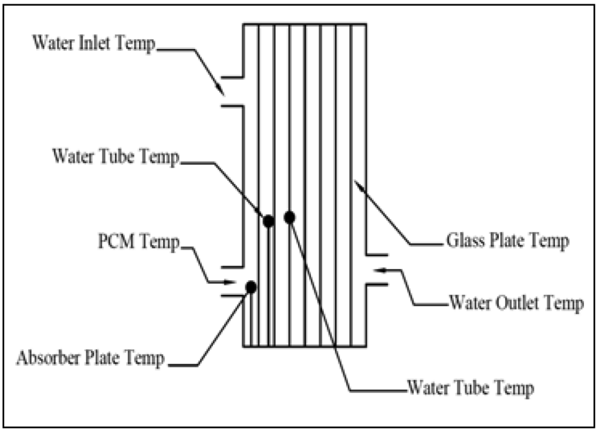


Figure 4. Details of thermocouple position in the experimental set-up

Table 1. Specification of experimental setup

Material for collector	Stainless steel
Length of collector	1m
Width of the collector	0.5m
Area of the collector	$0.5m^2$
Air gap between glass plate	0.05m
Total Quantity of PCM	3kg
Total number of heat reservoir	12

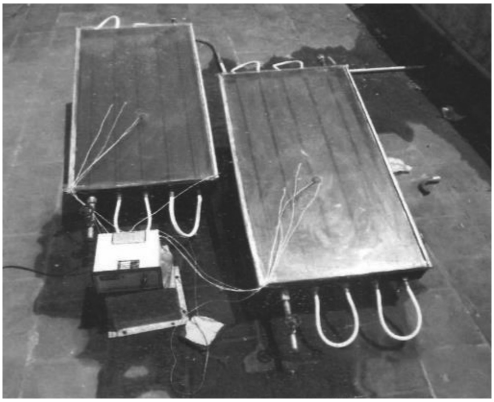


Figure 5. Photograph of experimental setup

Figure 6. Photograph of Paraffin wax plate

RESULTS AND DISCUSSIONS

Figure 7 shows the variation in absorber plate temperature with time for Solar Water heater with and without PCM. It is observed that on 13.02.2014 the value of absorber plates temperatures obtained for with PCM was 89°C and for without PCM was 103°C respectively. Absorber plate temperature has less value in PCM unit, because of the fact that the storage medium absorbs some amount of energy during sun-shine hours. Absorber plate temp has higher value during the flow rate of 400 ml/min than 200 ml/min flow rate. Even though the absorber plate temperature is purely depends upon the solar intensity and irrespective of flow rate.

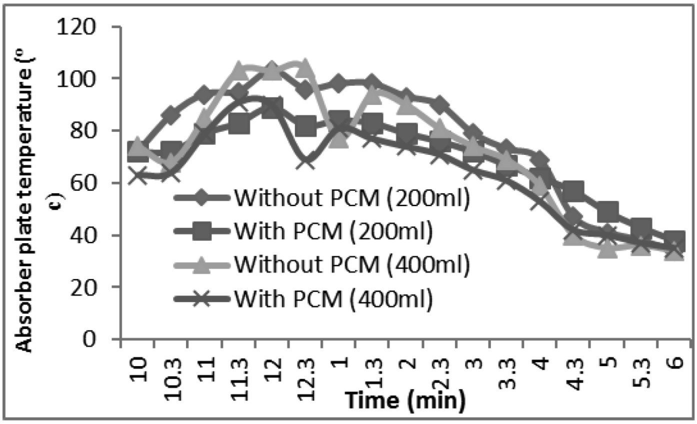


Figure 7. Variations of time Vs Absorber plate temperature (°C)

Figure 8 shows the variation in glass plate temperature with time for solar water heater with and without PCM. It is observed that on 13.02.2014 the value of Absorber plates temperatures obtained for with PCM was 69°C and for without PCM was 89°C respectively. Glass plate temperature has higher value in the flow rate of 400 ml/min than 200 ml/min flow rate. Even though the absorber plate temperature is purely depends upon the solar intensity and also irrespective of flow rate.

Figure 9 show the variation of PCM Temperature with time. It is observed that on 13.02.2014 the value of PCM Temperature obtained was 72°C respectively. The maximum value of PCM temperature obtained on 14.02.2014 at 400 ml/ min, it may due to the higher heat transfer area with high flow rates.

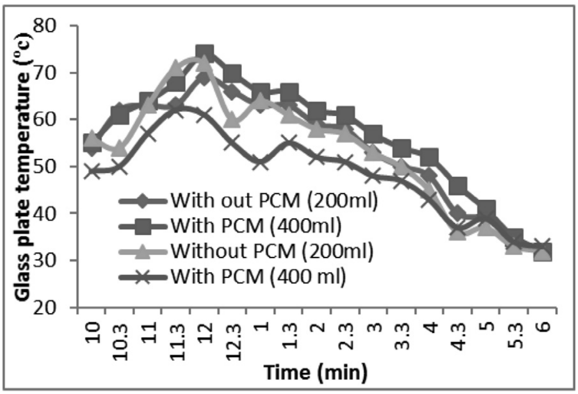


Figure 8. Variations of time Vs Glass plate temperature (°c)

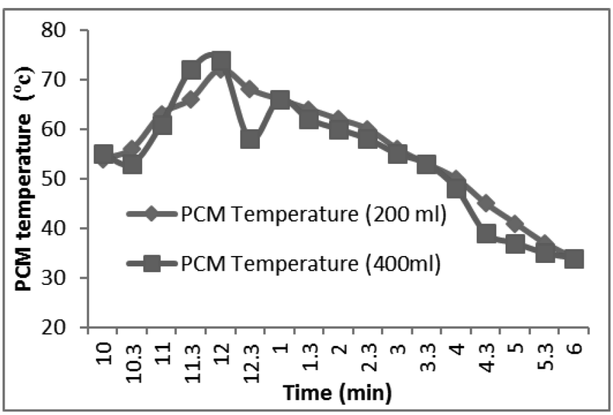


Figure 9. Variations of time Vs PCM temperature (°C)

Figure 10 show the variation of heat available in collector with time. It is observed that on 13.02.2014 the value of Heat available in collector was 1490.695 KJ/hr respectively, The maximum value of heat available in the collector with time is obtained on 14.02.2014 due to the fact of higher flow rate. Heat available in the collector is same for both units with and without PCM due to the same intensities.

Figure 11 shows the variation in heat gained by water with time for solar water heater with and without PCM .It is observed that on 13.02.2014 the value of heat gained by water for with PCM was 502.32 KJ / hr and for without PCM was 753.48 KJ/hr respectively. Heat gained by water is higher for higher flow rates due to the fact of higher heat transfer area.

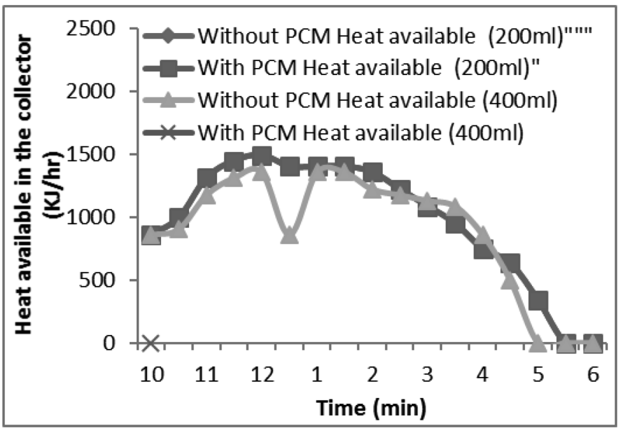


Figure 10. Variations of time Vs Heat available in the collector (KJ/hr)

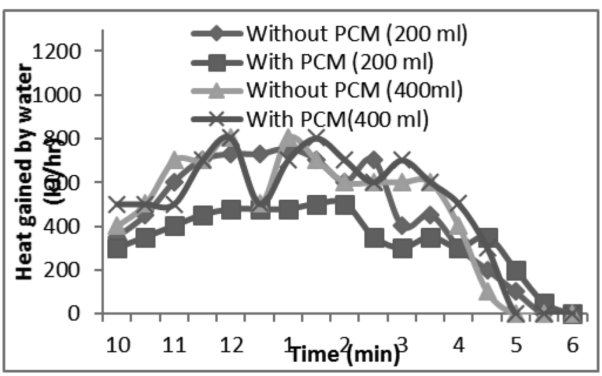


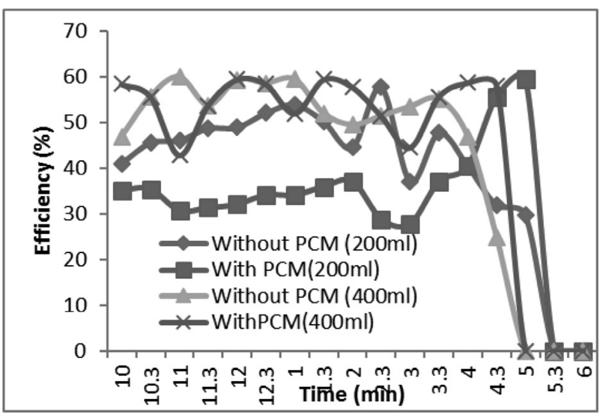
Figure 11. Variations of time Vs Heat gained by water (kJ/hr)

Figure 12 shows the variation in efficiency with time for solar water heater with and without PCM. It is observed that on 14.02.2014 the value of efficiency for with PCM was 59.3% and for without PCM was 57.68% respectively. The efficiency of solar water heater with PCM increases with higher flow rates throughout the day. When the flow rate increases in the solar water heater, the efficiency of unit with and without PCM almost same nearly during sun-shine hours. The set-up with PCM gives better efficiency during off sun-shine hours at higher flow rates. The conventional unit has comparatively high efficiency than unit with PCM during sun-shine hours. Similarly the unit with PCM produces little better efficiency due to the presence of thermal energy during evening hours.

CONCLUSIONS

The performance of solar water heater without PCM is slightly higher than the solar water heater with PCM in typical sunny days. But the solar water heater with PCM enhances in heat transfer which gives good performance especially during off sun-shine hours. The efficiency of solar water heater increases with and without PCM at higher flow rates. The set-up with PCM gives better efficiency at higher flow rates during off sun-shine hours due to higher heat transfer area presence. The conventional solar water system is proposed for sun-shine hour due to its simple construction, better efficiency and low cost. Similarly the unit with PCM is proposed for evening hours or partially cloudy days due to the presence of thermal energy storage medium which yields better efficiency.

Figure 12. Variations of time Vs efficiency (%)



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