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PCM BASED THERMAL ENERGY STORAGE SYSTEM INTEGRATED WITH SOLAR PARABOLIC TROUGH COLLECTOR

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Abstract

In solar thermal and waste heat recovery systems, the amount of energy supply does not usually match with the process demand. In order to overcome this some form of thermal energy storage (TES) system is necessary for the most effective utilization of the energy sources. Thermal energy storage is the temporary storage unit which stores the heat energy for later use. Among the available technologies for the thermal storage systems, latent heat storage (LHS) systems, using phase change material (PCM) as storage medium, are attractive due to their advantages such as high heat storage capacity and isothermal behavior during charging and discharging processes. The objective of this research work is to study the performance of a TES unit which stores heat energy from available heat sources such as solar heater. For experimental purpose, a solar parabolic trough collector is used as a heat source. A TES unit of 10MJ capacity is designed and fabricated for storing heat and supply hot water for family of 5 to 6 persons. Paraffin wax filled in spherical capsules, is used as PCM in storage tank. Two types of Heat Transfer Fluids (HTFs) such as Water and HP Hytherm 600 are used to transfer heat from the solar parabolic trough collector to the storage tank. They also act as a sensible heat storage material. For different mass flow rates of heat transfer fluid, charging experiments were carried out to verify functioning of the TES unit. It is observed that heat is stored in PCM and water up to a temperature of 65^0 C when TES unit is connected with heat source (solar parabolic trough collector) and it is also observed that charging time is less when Hytherm 600 is used as HTF compared to that of water.

Keywords: Hytherm 600, Parabolic trough collector, PCM, Thermal energy storage.

1. Introduction

The energy demands in the commercial, industrial and utility sectors vary on daily, weekly and seasonal basis. Energy storage units can be used with energy management systems to reduce energy consumption in commercial and industrial establishments by using available waste heat or alternate energy sources (solar energy). Thermal Energy Storage (TES) is one of the key technologies for energy conservation and has recently been developed to a point where it can have a significant impact on modern technologies. TES is the temporary storage of high or low-temperature energy for later use and it appears to be the most appropriate method for correcting the mismatch that occurs between the supply and demand of energy. Increasing societal energy demands, shortages of fossil fuels, and concerns over environmental impact are providing impetus to the development of renewable energy sources such as solar, biomass and wind technologies [1, 2].

Because of their intermittent nature, effective utilization of these and other energy sources is in part dependent on the availability of efficient and effective energy storage systems. In particular, solar energy, being non-polluting, clean and inexhaustible, has received wide attention among scientists and engineers. The mass flow rate of the collector has very less effect on minimum collector area and has significant effect on optimal capacity of storage tank [3]. The high efficiency of the PTC and high flux density of the heat pipe results in lightness when compared to flat plate and evacuated tube collector systems [4, 5].

Sagade et al. [6] suggested that by using fiber reinforced material as parabolic trough material and coated with Aluminium foil then the instantaneous efficiency gets increased. The heat transfer analysis and numerical modeling of the PTC is essential to optimize and to understand its performance effectively. The collector efficiency will be better when the absorber tube is coated with black chrome, but it is less significant when compared to cermet coating on absorber material [1, 7-9]. Kumaresan et al. [10] noted the effect of carbon nanotubes in enhancing the thermal transport properties of PCM during solidification. They have found that enhancement in the thermal conductivity of 30-45% is achieved both in the liquid and solid states of the Nano fluid phase change material compared to that of pure PCM. They have also found that the presence of carbon nanotubes in the PCM at the interior locations suppresses the higher conductive resistance offered by the solidified PCM, and the sub cooling of the PCM that occurs near the wall surface. Though there are many advantages, an important factor is that solar energy is time dependent energy source with an intermittent character.

The energy needs for a wide variety of applications are also time dependent, but in a different pattern and phase from the solar energy supply. This implies that solar energy based device or utility must be matched dynamically both at the source point and the application point. Once the characteristics of end-use demand and the nature of energy source option are known, the total demand and supply in the time domain have to be brought together through integration of an efficient energy storage and distribution network. Among non-concentrating collectors, the PVT solar collectors show the best overall performance and the molten salts with excellent properties are considered to be the ideal materials for high-temperature thermal storage applications [11-14].

There are many applications where there is a time mismatch between energy availability and demand. In such applications TES systems are of great importance.

The other applications of TES are the storage of solar energy for overnight heating, the storage of summer heat for winter use, the storage of winter ice for space cooling in the summer, and the storage of heat or coolness generated electrically during off-peak hours for use during subsequent peak hours. It is therefore a very attractive technology for meeting society's needs and desires for more efficient and environmentally benign energy use.

The use of TES systems for thermal applications such as heating and cooling has recently received much attention. In various energy sectors the potential benefits of TES for heating and cooling applications have been fully realized. Although these systems provide energy at a higher cost than fossil fuels, the major advantages are their limited impact on the environment and sustainability of the energy source [15-18].

2. Materials and Methods

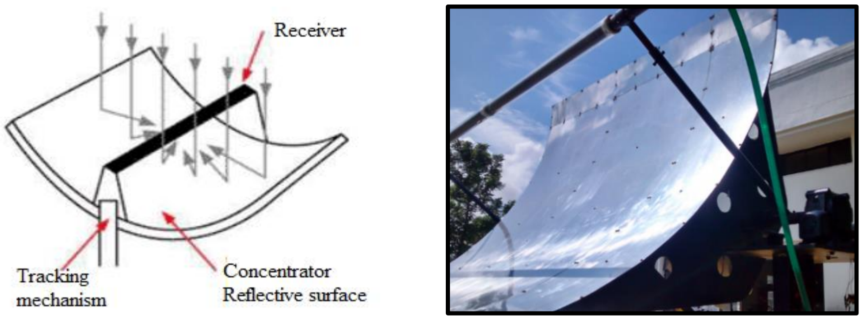
2.1. Parabolic trough collector (PTC)

The PTC system uses mirrored surfaces of a linear parabolic reflector to focus direct solar radiation onto a tubular solar receiver. The receiver is positioned along the focal line of the parabola, and it mainly consists of an absorber tube and a glass cover. The concentrated solar radiation is absorbed and converted into thermal energy by the heat transfer fluid (HTF) flowing through the absorber tube, while the protecting evacuated glass cover is used to reduce the convection heat loss from the absorber. Figure 1(a) shows the schematic view of the parabolic trough collector.

In this work a solar PTC of 7.5 m^2 area is used for collecting solar energy. The Photographic view of parabolic trough collector is shown in Fig. 1(b). Table 1 shows the specifications of PTC used in this experiment.

Table 1. Specifications of parabolic trough collector.

S. No.	Parameters	Value	Units
1	Aperture area of the PT reflector	7.5	m^2
2	Aperture width.	2.5	m
3	Aperture length	3	m
4	Rim angle	70	Deg.
5	Focal length of PTC	0.9	m
6	Length of glass envelope	3	m
7	Length of absorber tube	4	m
8	Absorber tube	$D_o = 0.06$ $D_i = 0.052$	m
9	Glass envelope	$D_o = 0.085$ $D_i = 0.08$	m
10	Collector material	Al sheet(mirror polished)	mm
11	Absorber tube material	Stainless steel coated with heat resistant black paint	
12	Support structure	Mild steel	



(a) (b)

Fig. 1. (a) Schematic view of parabolic trough collector (b) Photographic view of parabolic trough collector

2.2. Tracking mechanism

A tracking mechanism (as shown in Fig. 2) used in this experiment is reliable and can be able to track the sun with a certain degree of accuracy. It also returns the collector to its original position at the end of the experiment. Tracking mechanisms are also used for the protection of collectors, they will protect the collector from the hazardous environmental and working conditions by turning the collector out of focus from wind dust, overheating and failure of the thermal fluid flow mechanism. It is sufficient to use a single axis tracking of the sun and thus long collector modules are produced. The collector can be orientated in an east-west direction, tracking the sun from north to south, or orientated in a north-south direction and tracking the sun from east to west.

Fig. 2. Tracking control unit.

2.3. Heat transfer fluids

Water and HP Hytherm 600 are used as Heat Transfer Fluids (HTFs) to transfer heat from the solar parabolic trough collector to the storage tank and also they act as a sensible heat storage material. Water act as excellent heat transfer fluid in low temperature applications (< 90 °C) such as domestic heating, hospital sterilization purposes, etc. Hytherm 600 is used in the places where operating temperatures reaches up to 305 °C. This product finds extensive application in textile, pharmaceuticals, chemical and processing industries. The physiochemical properties of water and HP Hytherm 600 are compared in Table 2.

Table 2. Physiochemical properties of water and HP Hytherm 600.

Parameters	Water	Hp Hytherm 600
Boiling Point (°C)	100	305
Density (kg/m^3)	997.1	828.57
Thermal conductivity(W/m K)	0.611	0.12
Specific heat (kJ/kg k)	4.187	3.102

2.4. Experimental setup

A schematic diagram of the experimental set-up is shown in Fig. 3. Figure 4 shows the photographic view of the experimental set up. It consists of an insulated cylindrical TES tank, which contains PCM encapsulated spherical capsules, constant temperature bath, solar PTC, storage tank, flow meter, and circulating pump. The cylindrical TES tank is made of stainless steel and has a capacity of 60 litres with a diameter of 370 mm and height of 530 mm. There are two chambers on the top and the bottom of the tank. In order to get the uniform flow of HTF, flow distributor is provided on the top of the tank. The storage tank is insulated with asbestos material of 8 mm thick and provided with aluminium cladding. Spherical capsules made of high-density polyethylene (HDPE) are used as PCM containers as spherical shape gives the best performance among the various types of containers. The outer diameter of spherical capsule is 60 mm and its wall thickness is 0.8 mm. The total number of capsules in the TES tank is 196. The spherical capsules are uniformly packed in seven rows and a wire mesh supports each row. In the analysis two rows of spherical capsules are considered as one segment. The PCM capsules occupy 67% of the total volume (test section) of storage tank and the remaining volume is occupied by SHS material, i.e., water in the present work. RTDs (with an accuracy of 0.1 °C are placed at the inlet, outlet and three segments of the TES tank to measure the temperatures of HTF. In order to measure the temperature of PCM, three RTDs are inserted into the PCM capsules and they are placed at three segments of the TES tank. The RTDs are connected to a temperature indicator, which provides instantaneous digital outputs.

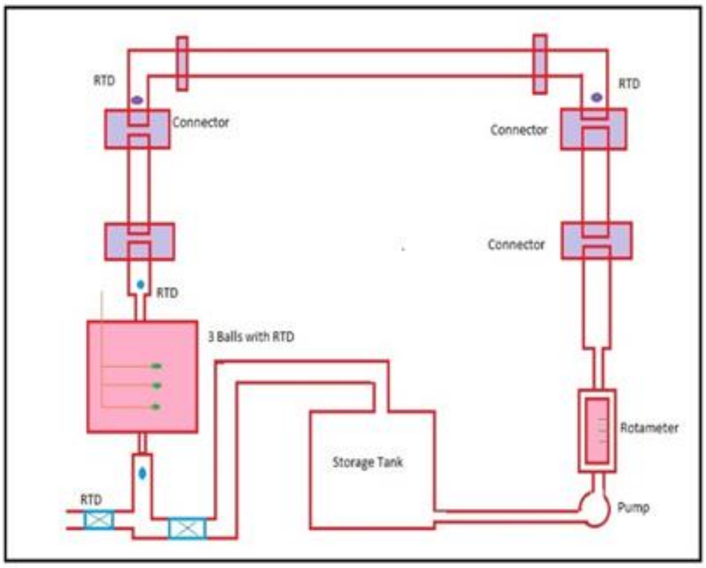


Fig. 3. Schematic view of experimental set-up.

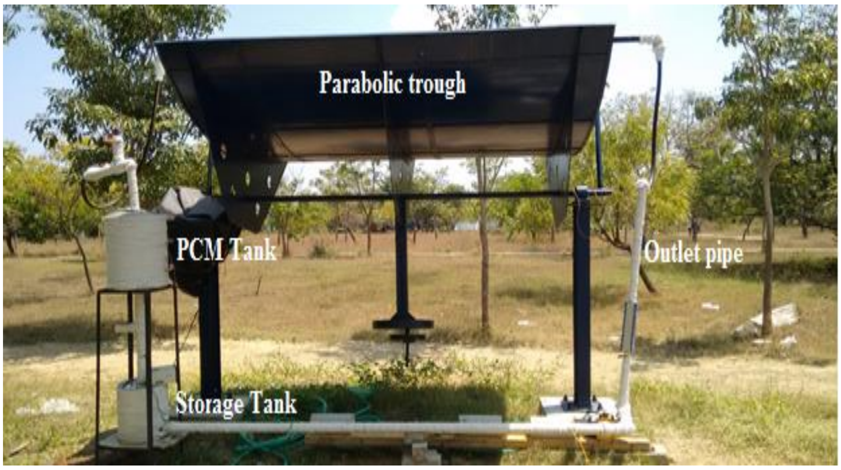


Fig. 4. Photographic view of experimental setup.

2.5. Experimental procedure

The experiments were carried out on the heat storage system with solar parabolic trough collector. The inlet temperature of the HTF varies with change in solar radiation. The HTF is circulated through the TES tank continuously during the charging process and it exchanges its energy to PCM capsules. In the beginning of the charging process, the temperature of the PCM inside the packed bed capsules is in between 30 °C and 32 °C, which is lower than the melting temperature of PCM. Initially the energy is stored inside the capsules as sensible heat until the PCM reaches its melting temperature. As the charging process proceeds, energy storage is achieved by melting the PCM at a constant temperature. Finally the PCM becomes superheated. The energy is then stored as sensible heat in liquid PCM. Temperature of the PCM and HTF at different locations of the TES tank, as shown is recorded at an interval of 20 minutes. The charging process is continued until the thermal equilibrium is attained between HTF and PCM temperatures.

3. Results and Discussions

In this experimental work, water and HP Hytherm 600 are used as heat transfer fluids (HTFs) to transfer the heat from solar parabolic trough collector to the storage tank. The temperature distribution of HTFs and PCM in the TES tank, for various mass flow rates are reported and compared during the charging process. Various parameters like Total energy stored in TES tank, useful heat gain, collector efficiency are reported in detail. The charging processes are conducted for the combination of various parameters of mass flow rates for two different heat transfer fluids (Water and HP Hytherm 600) by varying the flow rates in the range of 2, 4 and 6 liters per minute.

3.1. Water and PCM temperatures

The variation of HTF and PCM temperatures at three segments of the TES tank, that is at x/L = 0.3, 0.6 and 0.9 are shown in figures when the storage tank is connected to the solar PTC. The graphs are drawn for the charging duration, which represents the time from the beginning of the charging process until the last segment (x/L = 0.9) attains thermal equilibrium with the inlet HTF.

The inlet temperature of HTF from the solar PTC increases continuously with time at a uniform rate until the PCM in the storage tank attains the phase change temperature. In the storage tank the water temperature increases with the inlet temperature of HTF supplied from the solar collector. The PCM temperature also increases along with the temperature of heat transfer fluid.

Figure 5(a) represents the variation of HTF temperature inside the storage tank for a flow rate of 2 lpm. It is observed from the figure that the temperature of the HTF at all the segments increases at a faster rate until it reaches the melting temperature of PCM. However, the rise in temperature of HTF in the first segment is very fast as the hot water enters at the top of the storage tank. For this segment the temperature increases up to 65°C in 120 minutes and thereafter remains uniform until the PCM melts completely. It is also observed that a constant temperature difference exist between the segments from top to bottom of the storage tank throughout the period of melting. The temperature of the second segment attains the temperature of the first segment only after the melting process is completed in the first segment. The same trend is observed in the successive segments. This is due to the fact that, after complete melting of the PCM in the first segment, the rate of heat absorbed in the first segment decreases as the local temperature difference between the inlet fluid and PCM in the first segment decreases. Hence, the heat transfer in the second segment increases and the temperature also increases.

Figure 5(b) represents the variation of PCM temperature for a flow rate of 2 lpm. It is seen from the figure that the PCM temperature increases gradually at the beginning of the charging period and remains nearly constant (58 to 62oC) during melting process and increases rapidly during heating of liquid PCM. Also, it is noted from the figure that within 65% of the total charging time of 180 minutes the PCM in the first segment is completely charged.

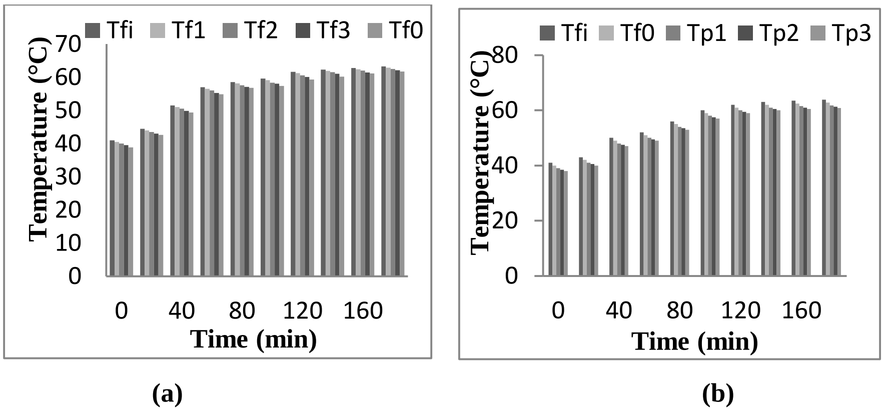
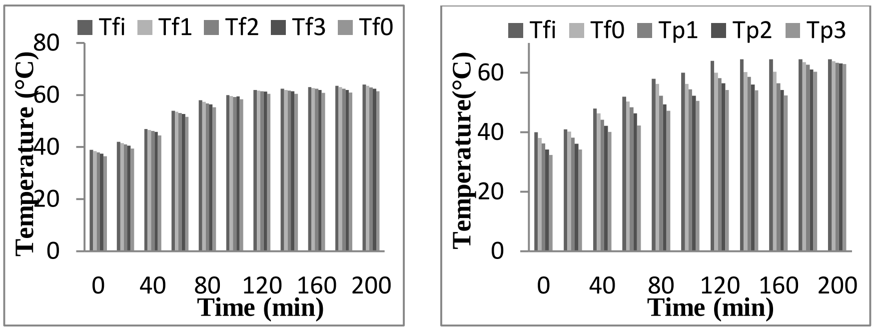


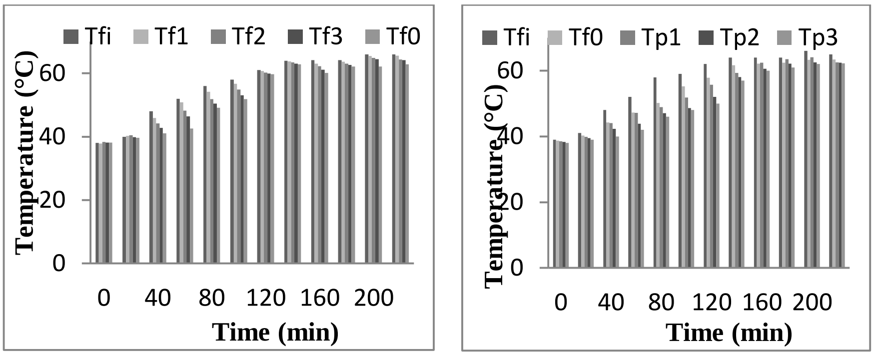
Fig. 5. (a) Variation of HTF temperature (Water) with time for a flow rate of 2 lpm (b) variation of PCM temperature with time for a flow rate of 2 lpm.

Figure 6(a) and 7(a) shows the variation of HTF (water) temperature with time inside the storage tank for a flow rate of 4 and 6 lpm respectively whereas variation of PCM temperature with time for a flow rate of 4 and 6 lpm is shown in Figure 6(b) and 7(b) respectively.



(a) **(b)**

Fig. 6. (a) Variation of HTF temperature (Water) with time for a flow rate of 4 lpm (b) variation of PCM temperature with time for a flow rate of 4 lpm.



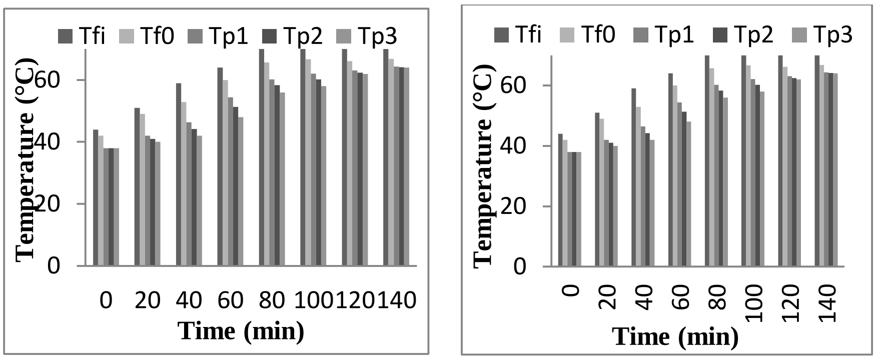
(a) **(b)**

Fig. 7. (a) Variation of HTF temperature (Water) with time for a flow rate of 6 lpm (b) variation of PCM temperature with time for a flow rate of 6 lpm.

3.2. HP Hytherm 600 and PCM temperatures

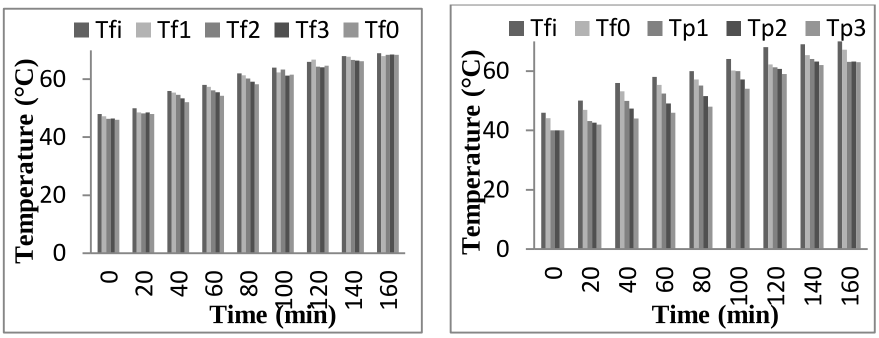
The charging process is repeated for the same mass flow rate with Hytherm 600 as the Heat transfer fluid. The corresponding graphs are drawn and the variations of HTF and PCM temperatures at the segments of the TES tank for Hytherm 600 are shown in Figs. 8, 9 and 10. The charging time of heat storage in PCM for water as HTF is 180, 200 and 220 minutes at flow rates of 2, 4 and 6 lpm respectively, whereas for Hytherm 600 the charging time is 140, 160 and 180 minutes at flow rates of 2, 4 and 6 lpm respectively.

Figures 8(a), 9(a) and 10(a) show the variation of HTF (Hytherm 600) temperature with time inside the storage tank for a flow rate of 2, 4 and 6 lpm respectively whereas variation of PCM temperature with time for a flow rate of 2, 4 and 6 lpm is shown in Figure 8(b), 9(b) and 10(b) respectively. From the above graphs, it is observed that the charging time for HP Hytherm 600 as HTF is less compared to water. This is because thermal diffusivity for HP Hytherm 600 is more compared to that of water.



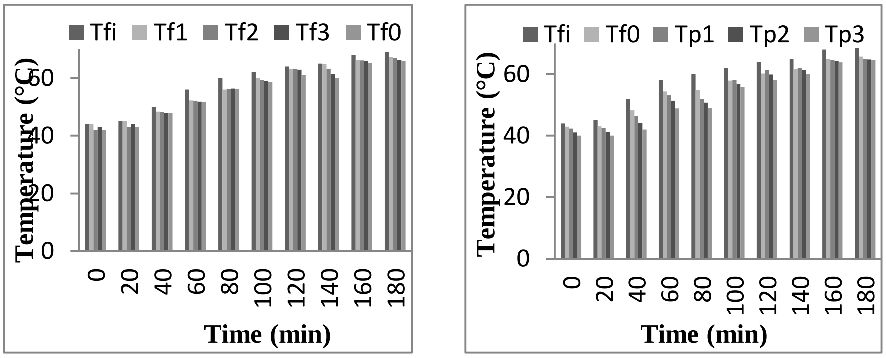
(a) **(b)**

Fig. 8. (a) Variation of HTF (Hytherm 600) temperature with time for a flow rate of 2 lpm (b) variation of PCM temperature with time for a flow rate of 2 lpm.



(a) **(b)**

Fig. 9. (a) Variation of HTF (Hytherm 600) temperature with time for a flow rate of 4 lpm (b) variation of PCM temperature with time for a flow rate of 4 lpm.



(a) **(b)**

Fig. 10. (a) Variation of HTF (Hytherm 600) temperature with time for a flow rate of 6 lpm (b) variation of PCM temperature with time for a flow rate of 6 lpm.

3.3. Performance parameters

The various performance parameters like collector's useful heat gain, collector efficiency, total energy stored in TES unit, and overall efficiency are calculated for both the heat transfer fluids (water and HP Hytherm 600) with flow rate of 4 lpm and compared. Table 3 shows the comparison of performance parameters for both the heat transfer fluids (water and HP Hytherm 600).

Table 3. Performance parameters for water and HP Hytherm 600.

Parameters	Units	Water	Hytherm 600
Useful heat gain	W	3344	2056
Useful heat gain	%	49.5	30.45
Total energy stored in TES tank	kJ	6752.083	5278.97
Overall efficiency	%	27.90	21.72

The above parameters indicate that water is proven effective heat transfer fluid for low temperature applications such as domestic water heating, hospital sterilizations and chemical laboratories, etc. where the temperature requirement is less than 90 °C.

4. Conclusion

A thermal energy storage system using combined sensible and latent storage concept was developed for storing heat energy from solar PTC and use the hot water at an average temperature of 45 ºC for domestic applications. A series of charging experiments were conducted on the TES unit to study its performance by integrating it with solar parabolic trough collector. The significance of time wise variation of HTF inlet temperature and mass flow rate on the system performance was reported. The following conclusions are summarized as follows

- In the Analysis of the temperature distribution of the HTF in the storage tank during melting process, it is found that the temperature of the bottom segment attains the temperature of the previous segment, only after the melting process is completed in the top segment. This is due to the fact that, after the complete melting of the PCM in the top segment, the rate of heat absorbed in the top segment decreases as the local temperature difference between the HTF and PCM in the top segment decreases. Hence the heat transfer in the bottom segment increases and the temperature also increases.
- The existence of thermal stratification in the combined storage tank improves the collector efficiency and hence the system efficiency.
- The charging time duration for water at a flow rate of 2 lpm is 180 minutes and for HP Hytherm 600 it is 140 minutes. This is due to the higher thermal diffusivity of Hytherm 600 when compared with water.
- In the present analysis, water and paraffin are selected as sensible heat and latent heat storage materials respectively. Such systems can be adopted, where the requirement of heat is within the temperature range of 50-80 ºC. For higher temperature applications, Hytherm 600 is more suitable. Many applications are possible with the combined sensible and latent heat storage system like waste heat recovery utilization, food preservation and air conditioning applications, electronic cooling, etc. Each application requires careful attention in the selection of PCM materials and the design of the storage system.

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