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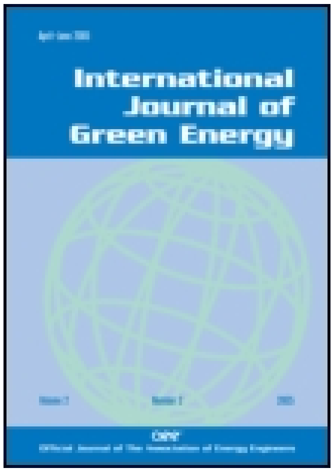

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An Experimental Study of PCM-Incorporated Thermosyphon Solar Water Heating System

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In the contemporary era, phase change material (PCM) is used in solar water heaters to store the extra amount of heat energy available during the full sunshine hours. The primary purpose of this study is to examine the performance of PCM-incorporated thermosyphon solar water heating system using flat plate collector as a heat source. In this study, a cylindrical aluminium PCM tank acts as a thermal energy storage unit. It is employed in the top portion of the insulated storage tank containing water. Paraffin wax is used as a PCM. Water is used as heat transfer fluid (HTF) to transfer heat from flat plate collector to storage tank. The charging and discharging experiments are carried out on clear days with and without PCM under actual operating conditions. The significance of time wide variation of HTF and PCM temperatures during experiments are discussed in detail and the performance parameters, such as charging energy efficiency, stratification number, and thermal efficiency, were also studied. The simulation of the discharging experiments is done in Computational Fluid Dynamic for validation purpose. It is shown from the experiments that the PCM improves the performance of the system by bettering stratification number, charging energy efficiency, and thermal efficiency of storage tank.

Keywords: Solar energy, PCM, Thrmosyphon solar water heater, Charging, Discharging, Charging efficiency

Introduction

Solar energy has been identified as one of the excellent and sustainable alternate energy sources for the future. However, the effective use of solar radiation is hindered by the intermittent nature of its availability, limiting its use and effectiveness in domestic applications, notably water heating. Water heating is one of the qualities of the direct use of solar energy, and it is an alternate thermal application from an economic viewpoint. It is necessary to develop an efficient solar water heating system for economical usage. Nowadays researchers are (Hedayatizadeh et al. 2013; Dubey, Andrew, and Tay 2014) focusing their attention on innovative design changes in order to improve the performance of solar water heating system. Latent heat thermal energy storage (LHTES) systems using phase change materials (PCM) as a storage medium offer advantages such as high heat storage capacity, small unit, and isothermal behavior during charging and discharging. PCMs can be integrated with solar water heater tanks to improve stratification. The behavior of PCM in real conditions (Cabeza et al. 2006) has been studied by adding a PCM module at the top of a hot water storage tank with stratification. The conditions under which an absence of advantage of the use of PCMs in a domestic hot water (DHW) system are analyzed to propose some possibilities of improvement for demonstrating the interest in using PCMs in solar-based DHW systems (Kousksou et al. 2011). The effects of using PCM as storage medium on the performance of a solar water heater (Fazilati and Alemrajabi 2013) have been investigated experimentally. Many researchers studied about the usage of PCMs as energy storage applications to improve thermal energy storage (TES) systems (Dinçer and Rosen 2002; Zalba et al. 2003; Farid et al. 2004; Talmatsky and Kribus 2008).

The thermal performance of phase change micro-encapsulated paraffin-based slurry with a phase-change temperature of 65ºC and heat storage with different rates of heat input have been studied in order to enable improved system designs to be developed for intermittent thermal energy storage (Huang et al. 2011). The dynamic characteristics of the solar heat storage system with spherical capsules-packed bed have been studied during the discharging process with paraffin as PCM and water as heat transfer fluid (HTF). The effects of inlet temperature of HTF, flow rate of HTF, and porosity of packed bed on the time for discharging and heat released rate have also been discussed (Wu, Fang, and Liu 2011). The performance of a natural circulation solar domestic water heater (Rezania, Taherian, and Ganji 2012) has been investigated experimentally under standard consumption rate. The effect of PCM modules in a stratified solar household hot water system (Mazman et al. 2009) has been studied by using 3 kg mixtures of paraffin–stearic acid, paraffin–palmitic acid, and paraffin–myristic acid with 80:20 weight percentage ratio as phase change material.

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It was concluded that paraffin–stearic acid gave the best results in the thermal performance enhancement of solar DHW system.

Thermally stratified water tanks are widely used for short-term thermal energy storage applications. In such systems, hot water remains separated from cold water by means of buoyancy forces and is stored in top portion of the tank. This method is usually used for solar energy and waste heat recovery systems (Gretarsson, Pedersen, and Strand 1994; Rosen 2001; Cabeza et al. 2006). In stratified water tanks heat can be supplied from the highest available temperature at the upper part of the tank for usage. The heat transfer coefficient (Castell et al. 2008) has been calculated experimentally for PCM module in a thermally stratified tank by adding vertical fins. A low temperature at the bottom of the tank is connected to the solar collector inlet, which will yield better collector efficiency (Nelson, Balakrishnan, and Murthy 1999). Thermal energy storage has always been one of the most critical components of residential solar space heating and cooling applications. Solar radiation is a time-dependent energy source with an intermittent character. The heating demands of a residential house are also time-dependent. However, the energy source and demands of a house, in general, do not match each other, especially in solar heating applications. The peak solar radiation occurs near noon, but the peak demand is in the late evening or the early morning when solar radiation available is not sufficient. Thermal energy storage provides a reservoir of energy to adjust this mismatch and to meet the energy needs at all times, and it is used to minimize the gap between supply and demand of energy. So this energy storage is essential in solar water heater for improving its efficiency.

Hot water is used for domestic purposes or for meeting the needs of industries and commercial applications. Residential, commercial, and industrial buildings often have the hot water requirement of around 60°C, and bathing, laundry, and cleaning operations in the domestic sector generally need it at about 50°C. PCMs with a melting range of 50–60°C can be used in the solar DHW system to meet hot water demands in buildings. Phase change energy storage with higher energy densities is another alternative for small storage (Castell et al. 2008). Thus, thermal energy storage unit integration with solar water heater fulfils the needs of efficient energy utilization. Throughout the survey, it has been noted that electrical heater was used as a heat source to heat water during their experiments to study the performance of solar water heaters. It will not produce the effect of real operating conditions. So in order to produce actual conditions, a flat plate collector has been used as a heat source for heating water during the experiments of this study. Charging and discharging experiments were performed with and without PCM to study the performance of the system. No water can be taken out during the experiments. The main objectives of this study are (i) to evaluate the thermal performance of solar DHW system with PCM using flat plate collector as heat source, (ii) to find the effect of PCM cylinder in a stratified thermopyphon solar water heater, and (iii) to develop a Computational Fluid Dynamic (CFD) model to predict the performance of solar water heater with PCM cylinder.

Experimental Work

Experimental Setup

The experiments were performed during the month of February at Hosur in South India (latitude: 12.7200° N, longitude: 77.8200° E), which is located 900 meters above the sea level and is on Deccan Plateau. The average temperature of Hosur during summer is 25 to 35°C, and during the winter the temperature is 13 to 25°C. A schematic diagram of the experimental setup and photographic view are shown in Figures 1 and 2 respectively. The experimental setup consists of an insulated cylindrical stainless steel tank, solar flat plate collector, aluminium PCM cylinder, temperature data logger, thermocouples, and insulated inlet and outlet pipes. The stainless steel thermal energy storage tank has the capacity of 78 liters and is insulated with coconut coir and thermocoal, each 20-mm thick, capable of supplying water for a family of three. It comprises the PCM cylinder to allow heat transfer between the PCM cylinder and HTF. Coconut coir is used as an insulation because of its easy availability from agricultural waste and very low thermal conductivity (varying between 0.054 and 0.143 W/mK). Thermal energy storage tank is integrated with a flat plate collector of 2 m^2 area for heating

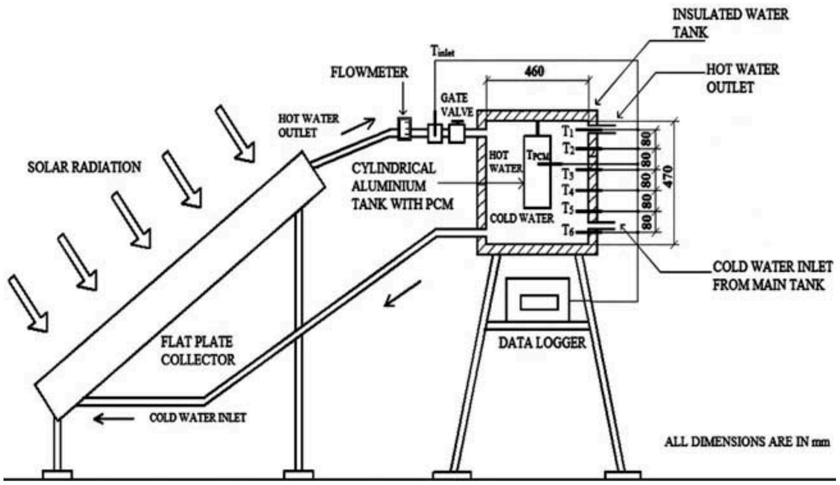

Fig. 1. Schematic diagram of experimental setup.

Fig. 2. Photographic view of experimental setup.

Table 1. Technical Specifications of Flat Plate Collector

Collector area	2 m^2 (2 m × 1 m)
Collector cover material	Single tempered glass, 3-mm thickness
Glass cover emissivity/absorptivity	0.85
Refractive index of glass relative to air	1.5
Length of the absorber plate	1.95 m
Width of the absorber plate	0.95 m
Material of the absorber plate	Copper
Thermal conductivity of the plate material	386 W/mK
Density of the plate material	8954 kg/m^3
Plate thickness	0.16 mm
Diameter of the tube	6.35 mm
Tube center to center distance	100 mm
Number of tubes used	9
Diameter of header pipes	12.7 mm
Location of collector tray	Hosur
Collector angle	30^o

water by absorbing solar radiation. The technical specifications of flat plate collector for the solar water heater are given in Table 1.

When solar radiation falls on flat plate collector, the absorber plate absorbs the heat from solar energy, and the heat is transferred to a HTF passing through pipes attached to the absorber plate. Here water is used as HTF to transfer heat from tubes to storage tank. Due to density difference, the heated water will rise through pipe, and the hot water is supplied to an insulated storage tank. Simultaneously cold water from the bottom of the storage tank enters the flat plate collector. The system works on the thermosyphon principle. The hot water outlet and cold water inlet of the insulated storage tank were closed to study the stratification.

Table 2. Properties of Paraffin Wax

Properties	Solid phase	Liquid phase
Melting point	56 (^{o}C)	56 (^{o}C)
Latent heat	142.7 (kJ/kg)	142.7 (kJ/kg)ß
Thermal conductivity (k)	0.4 (W/m ^{o}C)	0.2 (W/m ^{o}C)
Density (ρ)	670 (kg/m^3)	640 (kg/m^3)
Specific heat (C_p)	2.4 (kJ/kg ^{o}C)	1.6 (kJ/kg ^{o}C)

Actually the PCMs fall in three categories: (1) salt hydrates, (2) paraffins, and (3) non-paraffin organics. For this study, paraffin wax Grade 56 is used as a PCM, which has a melting temperature of 56^{o}C and its properties are listed in the Table 2. This is due to the fact that paraffin is readily available from manufactures and is usually less expensive than some salt hydrates. Several works have been carried out to study the thermal characteristics of paraffin during solidification and melting processes. Paraffin is known to be an attractive and chemically stable nontoxic material without regular degradation and has high latent heat storage capacities over a narrow temperature range. The PCM is placed in an aluminium cylinder of 121-mm internal diameter and 300-mm height, with a wall thickness of 3 mm. The aluminium cylinder contains 2.5 kg of PCM by weight. The PCM was heated above its melting point before it is put in the cylinder in order to avoid any problems that may arise due to volume expansion. Temperatures of PCM and HTF are recorded at intervals of 30 min using an HEATCON 8003/USB data-logger, which could measure the temperature with a precision of 1^{o}C. Also, the flow rate of HTF through the system is measured at an interval of 30 min. Solar radiation is measured by using a TES-1333 solar power meter with the accuracy of ±10 W/m^2.The specifications of measuring instruments used in this study are listed in Table 3.There are six thermocouples placed inside the storage tank for measuring temperatures of water at six different layers with uniform distances. The thermocouples are placed at a distance of 170 mm away from the center axis of the storage tank, and the distance between each thermocouple is 80 mm. In addition, two thermocouples are used to measure temperature of hot water inlet and PCM.

Table 3. Specifications of the Measuring Devices Used in This Study

Name of the device	Type	Accuracy	Percentage of error
Data logger	Type: HEATCON 8003/USB Eight channels (capable of recording temperature over a defined period of time).	±1^{o}C	4.5%
Thermocouple	Type: K (a positive chrome wire and a negative alumel wire combination). It can measure up to 150^{o}C.	±0.01^{o}C	0.4%
Solar power meter	Type: TES-1333	±10 W/m^2	0.38%
Flow meter	Glass tube variable area flow meter Water capacity: 0 .032 to 114 L/h Maximum pressure: 14 bar Maximum temperature: 1 to 121^{o}C	10% FS	2.5%

Charging Process

The HTF is circulated continuously through the water storage tank and the collector plate by natural circulation. The HTF absorbs solar energy and exchanges this heat with PCM in the PCM storage tank, which is initially at room temperature. The PCM gets heated sensibly at first until it reaches its melting point. As the charging proceeds, energy storage as latent heat is achieved as the paraffin wax melts at a constant temperature (56°C). After complete melting is achieved, further addition of heat from HTF causes the PCM to superheat, thereby again storing heat sensibly. The charging process continues until the PCM and HTF attain an average temperature of 65°C. Here the water is heated up to 65°C, which is above the melting range of PCM. This is as per the requirements of the application. The charging experiment is done with and without PCM cylinder to study the performance of thermal energy storage tank.

Discharging Process

The discharging process is the process of cooling the HTF inside the storage tank naturally in the absence of heat source. Due to the temperature difference between the HTF and the surrounding atmosphere, the heat transfer takes place and eventually the temperature of HTF decreases. At the end of the charging experiment, the flat plate collector is covered with a thick covering, and the hot water inlet pipe into the storage tank is closed by a gate valve. Therefore, the storage tank becomes an isolated system. The discharging is done until the average temperature of HTF reaches 45°C. When the outlet temperature of water decreases below 45°C, the water is not fit for application. This discharging is done with and without PCM to study the stratification. The discharging process is carried out to check the improvement of domestic solar water heater by comparing the time taken between the discharging of heat with and without aluminium PCM cylinder, and also to determine the time taken by the stratification process which separates hot and cold water in the same tank.

Charging Energy Efficiency

The charging energy efficiency is based on the first law of thermodynamics and is defined as the ratio of the amount of heat absorbed by water to the amount of heat supplied to the water (Haller et al. 2009).

$$\text{The charging energy efficiency, } \eta_{\text{ch}} = \frac{T_{\text{avg}(t)} - T_{\text{ini}}}{T_{\text{inlet}} - T_{\text{ini}}}. \tag{1}$$

Stratification Number

Stratification number (Fernandez-Seara, Uhia, and Sieres 2007) evaluates the thermal stratification of water inside the storage tank. It is defined as the ratio of the mean of temperature gradients at each time interval to that of the beginning.

$$\text{Stratification number, } \text{Str} = \frac{(\overline{\partial T/\partial Z})_t}{(\overline{\partial T/\partial Z})_{t=0}}, \tag{2}$$

$$\overline{\frac{\partial T}{\partial Z}} = \frac{1}{j-1}\left[\sum_{j=1}^{j-1}\left(\frac{T_{j+1}-T_j}{\Delta z}\right)\right]. \tag{3}$$

Thermal Efficiency

The thermal efficiency gives the performance of storage tank and is defined as the ratio of useful heat absorbed by a solar water heater to incoming solar energy with 0.55 collection efficiency of flat plate collector.

$$\text{Thermal efficiency, } \eta_{\text{th}} = \frac{mc_p(T_{\text{f}} - T_{\text{ini}})}{A_{\text{c}}G}. \tag{4}$$

Results and Discussions

The effect of using PCM cylinder in a stratified thermosyphon solar domestic water tank was investigated. Charging and discharging experiments were performed with and without PCM cylinder on clear days. The days of the experiments were chosen in such a way that the global solar radiation falling on the collector should be almost similar to the one given in Figure 8. This was to assure the convenience of comparing the charging experiments conducted on different days. The charging and discharging experiments were carried out in solar water heater without PCM cylinder on 11 February 2013 and 12 February 2013, and with PCM cylinder on 27 February 2013 and 28 February 2013. The temperature variations of different layers in the storage tank during charging experiments with and without PCM are given in Figures 3 and 4 respectively. The readings were taken at a frequency of 30 min, and the points in the temperature plots are not as much close to each other. So the energy absorption by PCM is not visible in the plots. In case the readings are very close, the lower slope might be visible. But the plot shows that the tank is well stratified in the mid-day and the temperatures of the six layers are uniformly distributed throughout the charging. However, in case of charging with PCM, the temperatures of top three layers and bottom three layers are distributed with considerable gaps throughout the charging process. It is understood that

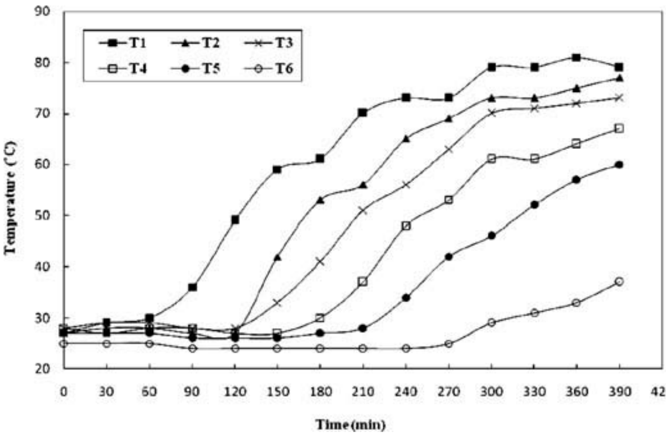

Fig. 3. Temperature vatiations during Charging without PCM cylinder.

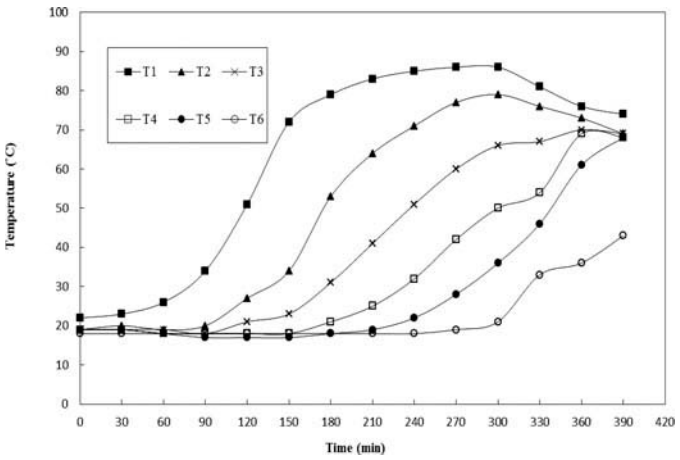

Fig. 4. Temperature vatiations during Charging with PCM cylinder.

the temperature stratification of the storage tank is improved with PCM presence.

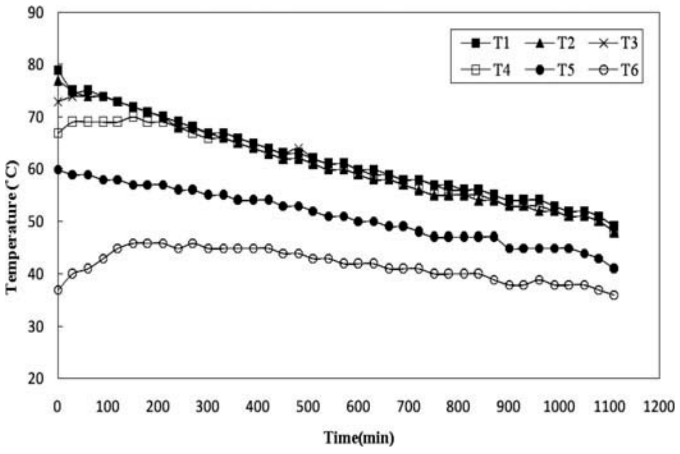

Fig. 5. Temperature vatiations during Discharging without PCM cylinder.

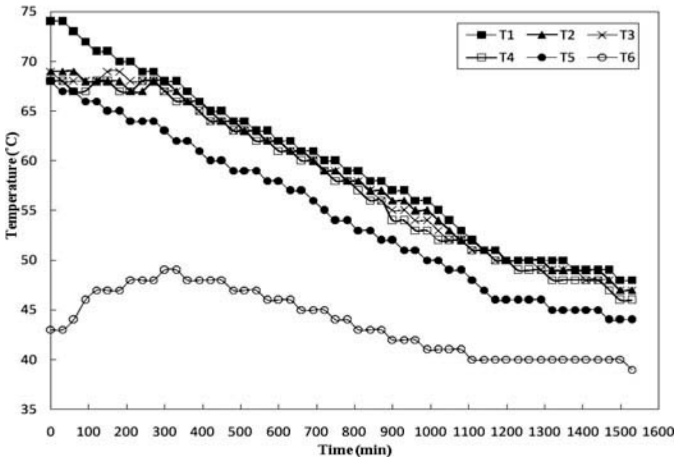

Fig. 6. Temperature vatiations during discharging with PCM cylinder.

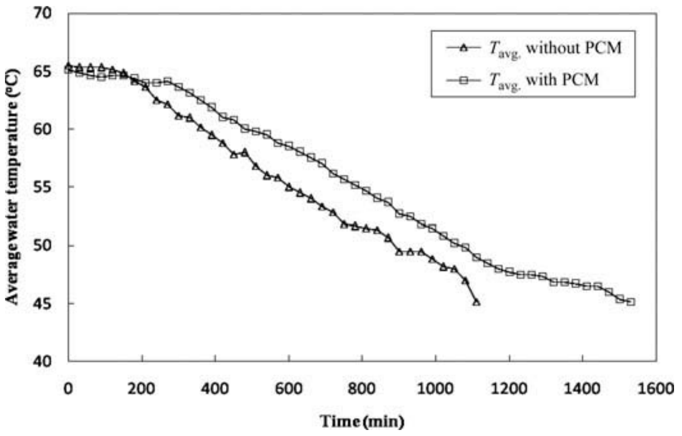

Fig. 7. Comparison of T_{avg} with and without PCM during discharging experiments.

The temperature variations of different layers in the storage tank during the discharging experiments with and without PCM are given in Figures 5 and 6 respectively. It can be seen from the figures that the temperature variations of top and bottom layers without PCM converge quickly than with PCM. During the charging experiment of solar water heater with and without PCM, it took 390 min to heat water in the tank to approximately 65°C. But during the discharging experiment without PCM, it took 1110 minutes for the same. With PCM, cylinder discharging process took 1530 minutes to release heat from hot water from 65 to 45°C. This shows there is a considerable time gap between the cooling of water with and without PCM. This can be clearly understood from the average water temperature variations of storage tank given in Figure 7. It can be understood from the average water temperature variations graph that the discharging without PCM reached required temperature faster than the discharging with PCM. Also, it is found that there is a delay of 420 min between discharging with and without PCM. This time delay occurred due to low heat transfer rate caused by less temperature gradient between PCM and its surroundings during discharging. It clearly shows that the excess amount of energy stored by the PCM improved the performance of solar water heater. It is clearly understood that the PCM improves stratification and leads to considerable improvement in the performance of the system.

The graph shown in Figure 9 compares the stratification number of solar water heater with PCM cylinder and without PCM. Stratification number evaluates the thermal stratification of water inside the storage tank. From the graphs, it can be understood that the stratification number distribution of discharging experiments with PCM is always 10% higher than without PCM throughout the process. Therefore, incorporation of PCM cylinder improves the performance of the system by improving the temperature stratification.

The charging energy efficiency is a term used to study the stratification efficiency of solar water heater tank. The graph given in Figure 10 shows the comparison of charging efficiency of water in the thermal energy storage system with and without PCM. Initially, charging efficiency of water with PCM is less because part of heat is used to melt the PCM. After complete melting of PCM the charging efficiency of water increases

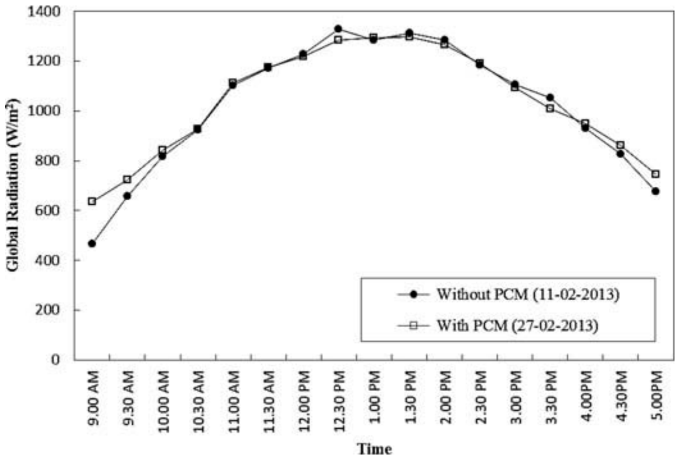

Fig. 8. Comparison of global radiation during the charging experiments.

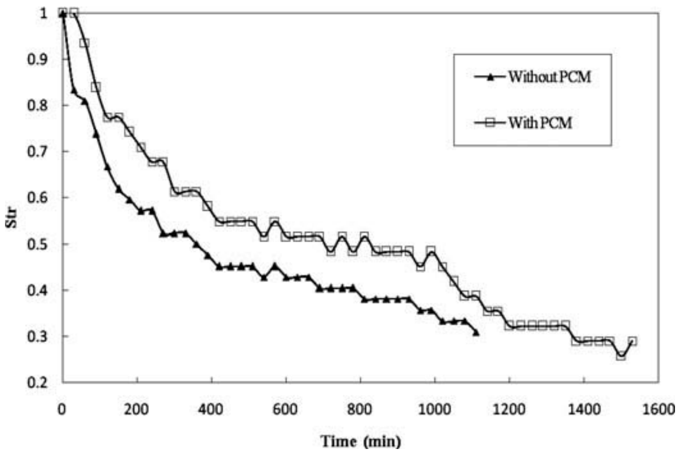

Fig. 9. Comparison of stratification number during the charging experiments.

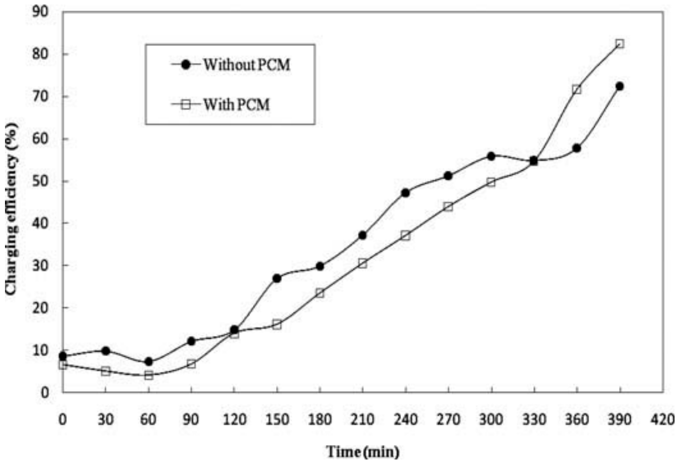

Fig. 10. Comparison of charging efficiency during the charging experiments.

and reaches the highest efficiency. It can be seen that the thermal energy storage system with cylindrical PCM tank has the highest charging energy efficiency as compared with the solar water heater tank without PCM. This is due to the latent heat stored by the melting of PCM in the storage tank.

The thermal efficiency is a term used to study the efficiency of solar water heater storage tank with and without PCM during the discharging experiments. Figure 10 shows the comparison of thermal efficiency of a thermal energy storage system without PCM and with a cylindrical PCM tank. It can be seen graphically that there is an appreciable difference between thermal efficiency of the storage tank with and without PCM cylinder, that is, the thermal efficiency of the system with PCM is always higher than the system without PCM throughout the discharging experiments. It was found that the difference in thermal efficiency is 10% in the starting of the experiments, then this efficiency difference increased gradually and finally reached 16%. This reveals that the latent heat stored in 2.5 kg of PCM improved the thermal efficiency of the storage tank by 10–16%.

Simulation of Discharging Experiments

The discharging experiments of storage tank with and without PCM are validated by simulation in CFD-Fluent (Version 6.3.26) software.The three-dimensional modeling of storage tank has been done in SOLIDWORKS (Version 10) software according to original dimensions. Then the three-dimensional model is imported into CFD-Fluent and the meshing is done in Fluent itself. The meshing element used is a hexagonal mesh with element size two. The simulation of the discharging experiment without PCM is carried out by giving the boundary conditions of wall convective heat flux and ambient temperature. The insulation layers are given by their respective properties, and the temperature layers are given as T1 to T6. The simulation is carried out with respect to time, and the temperature distributions of T1 to T6 are obtained over time with 60 as the time step size for 1110 time steps. Heat losses are taken into account while simulating. The simulation of discharging experiments without PCM is carried out in 1110 time steps since it took 1110 min for discharging. Figure 11 shows the temperature distribution of different layers of HTF in the storage tank without PCM when discharging starts, i.e., the time is equal to zero.

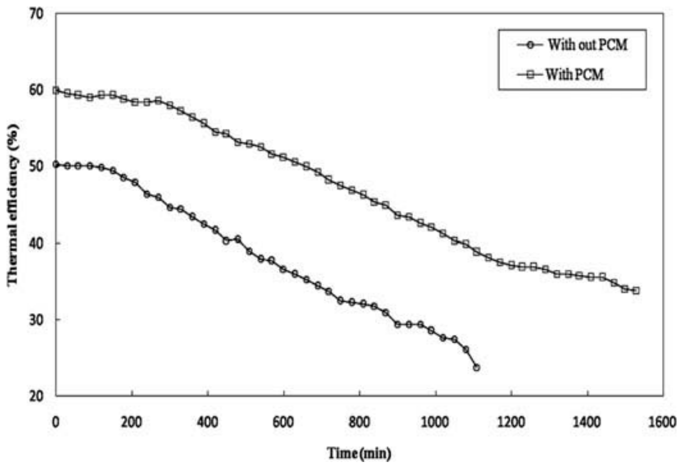

Fig. 11. Comparison of thermal efficiency of the storage tank during discharging experiments.

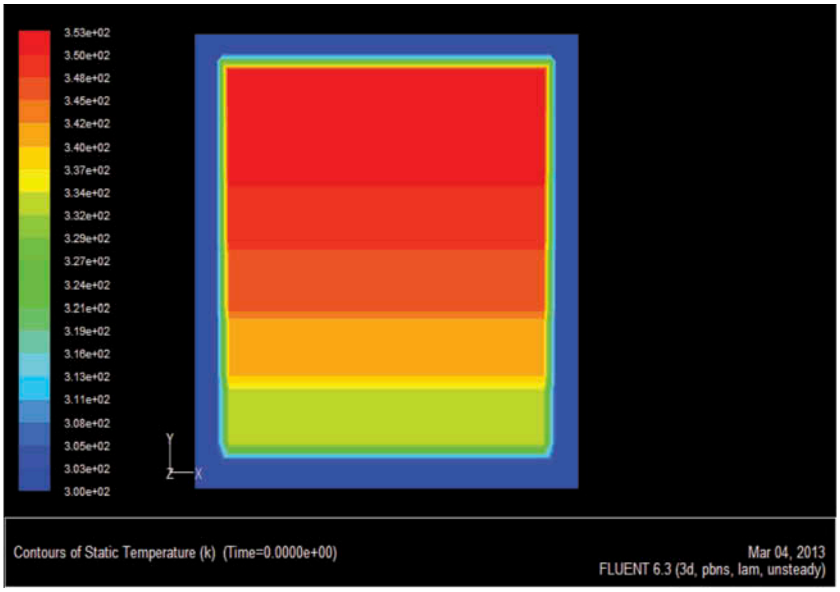

Fig. 12. Temperature distribution of HTF at the beginning of discharging experiment without PCM.

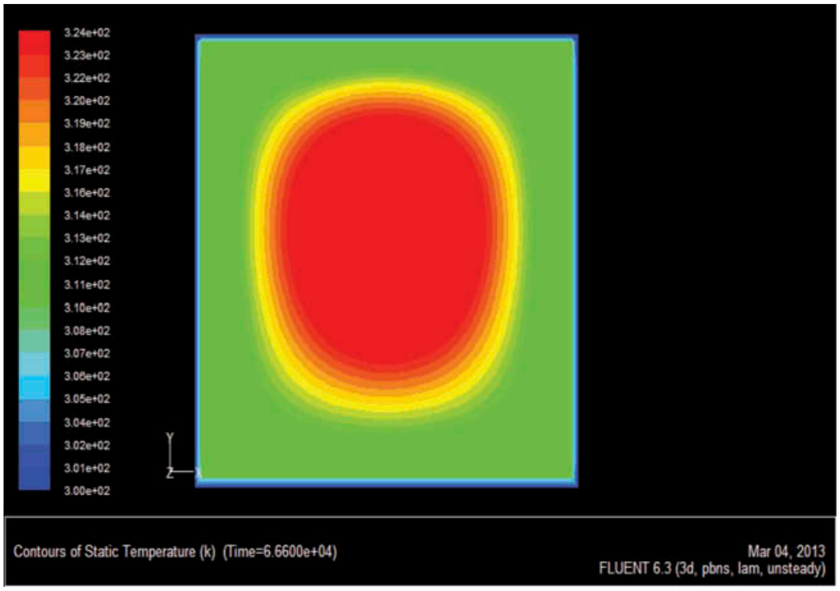

Fig. 13. Temperature distribution of HTF at the end of discharging experiment without PCM.

Figure 12 shows the temperature distribution of different layers of HTF in the storage tank without PCM when discharging finishes, that is, the time is equal to 1080 min. The simulated temperatures at the end of discharging experiment are found to be matching the experimental results. Figure 13 shows the temperature distribution of different layers of HTF in the storage tank with PCM cylinder when discharging starts, that is, the time is equal to zero.

Figure 14 shows the temperature distribution of different layers of HTF in the storage tank with PCM cylinder when discharging finishes, i.e., the time is equal to 1580 minutes. The temperatures at the end of the discharging experiment simulation are found to be matching the experimental outputs. Also, it is clearly understood from Figure 15 that the discharging experimental results are very close to the CFD results. It can be clearly seen from Figure 16 that the simulated results match the experimental results within permissible errors. The analysis shows that the agreement between analytical and experimental results has significantly improved. By analyzing the results, it was found that the PCM acts as an excellent thermal energy storage unit.

Conclusions

In this experimental investigation, the performance study on thermosyphon solar water heater incorporated with a thermal energy storage tank with cylindrical PCM tank was conducted

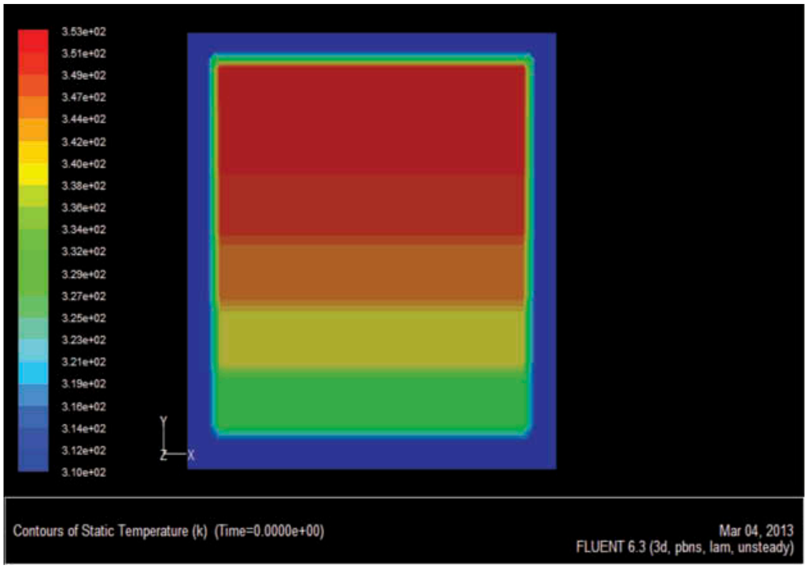

Fig. 14. Temperature distribution of HTF at the beginning of discharging experiment with PCM.

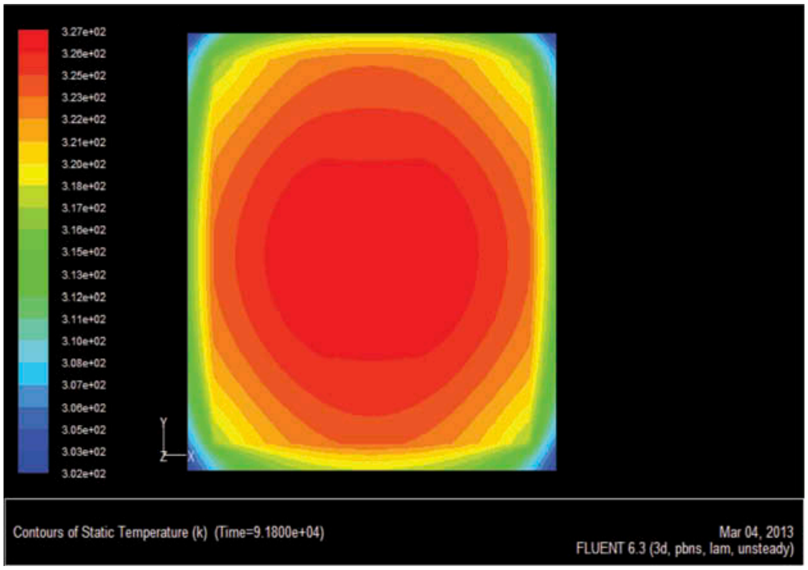

Fig. 15. Temperature distribution of HTF at the end of discharging experiment with PCM.

using a flat plate collector as heat source, and the hourly based charging efficiency, stratification number, and thermal efficiency of the storage tank were calculated for these cases and the results are compared. It was found from the stratification study that the thermal energy storage tank with PCM cylinder gave better performance compared with the thermal energy storage tank without PCM. Discharging without PCM took 1110 minutes, while discharging with PCM took 1530 minutes. It clearly indicates that the PCM improves the performance of a solar hot water system as the discharging is prolonged by additional 420 minutes. Also, the charging energy efficiency increases when radiation increases and it reaches a maximum efficiency of 82.44% in the afternoon around 2 PM. It can be understood that the stratification number distribution of discharging experiments with PCM is always 10% higher than without PCM throughout the process. So the incorporation of PCM cylinder improves the performance of the system by improving temperature stratification. Further, the thermal efficiency of the system with PCM is always higher than that of the system without PCM throughout the discharging experiments. This reveals that the latent heat stored in 2.5-kg PCM improved the thermal efficiency of storage tank by 10–16%. The simulation of discharging experiments with and without PCM is carried out and the results are found to be matching the experimental outputs. This study shows that the performance improvement by amended stratification of a thermosyphon solar water heater using PCM when flat plate collector used as heat source. Alternate energy resources and energy storage systems are the need of the hour, so the PCM is an added advantage for solar water heaters and the PCM-incorporated solar water heater will be a scope for the future.

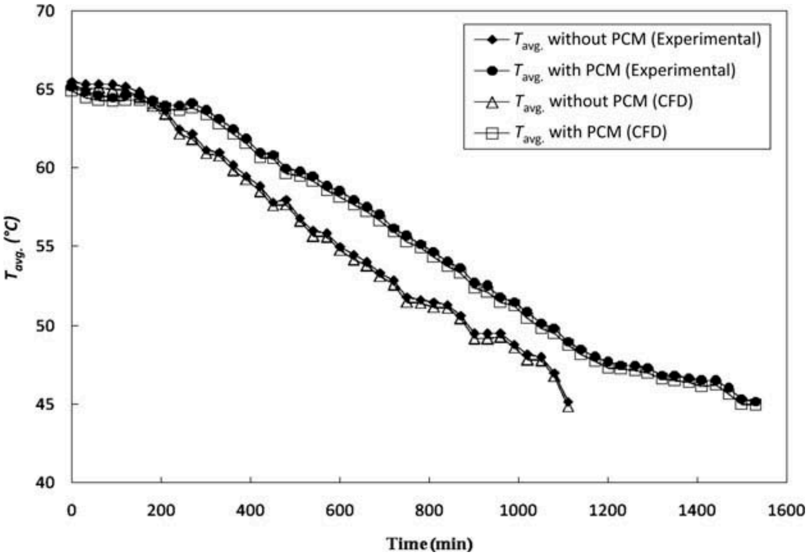

Fig. 16. Comparison of average temperature during discharging experiments.

Nomenclature

A_c	Area of the collector in m^2
G	Global radiation in W/m^2
j	Number of water layers
Str	Stratification number
$T_{avg(t)}$	The time-dependant average temperature of the storage tank in °C
T_{ini}	The initial average temperature of the storage tank in °C
T_f	Final temperature of the storage after the experiments in °C
T_{inlet}	The inlet temperature at the top of the storage tank in °C
t	Time in minutes
Δz	Distance between temperature sensors in mm
η_{ch}	Charging energy efficiency in %
η_{th}	Thermal efficiency of the storage tank in %
m	Mass of water in the storage tank in kg

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