Energy saving of a solar heating system with Phase Change Material (PCM) heat exchanger

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1. Abstract

In the present work, the feasibility of storing solar energy by using latent and sensible heat has been investigated. Phase Change Materials (PCMs) Heat Exchanger is charged by solar collectors during day and discharged when the domestic hot water load is required. The solar heat is firstly charged the PCM tank and the extra heat is stored in a hot water tank. Hot water has been consumed in a sensible heat storage tank from the afternoon to the night.

In this experimental investigation, temperature distributions in the length and radius direction of the PCM capsule and water inside the PCM tank, inlet and outlet temperatures of the PCM tank, the temperature difference of supply water, inlet and outlet temperatures in solar collectors and also solar radiation are measured in order to obtain the solar collector efficiency and the PCM tank efficiency.

Keywords: *Sensible heat store, latent heat store, Phase change materials, PCM tank*

2. Instruction

Effective utilization of time dependent energy resources relies on appropriate energy storage methods to reduce the time and rate mismatch between supply and demand. Solar thermal energy can be stored as a sensible heat, latent heat (water /ice and salt hydrates), heat of reaction or combination of latent and sensible heat.

Lacroix [1,2], Hasan[3], Dimano and Watable [4] as well as Sari and Kaygnsuz [5-7] have investigated experimentally this type of latent storage system. All of them obtained similar PCM temperature profiles and specified governing mechanisms of heat transfer in this type of thermal energy storage system. Latent heat storage system using PCM as a storage medium offers advantages such as high heat storage capacity, small unit sizes and isothermal behavior during charging and discharging processes. But these types of systems aren't in commercial use as much as sensible heat storage systems because of the poor heat transfer rate during storing heat and the recovery process. The main reason is that during Phase Change, the solid-liquid interface moves away from the convective heat transfer surface (during charging in cool storage process and discharging in hot storage process) resulting in poor heat transfer rate. The combined sensible heat storage (SHS) and latent heat storage (LHS) system eliminates the difficulties experienced in the SHS and utilizes the advantage of both systems.

Many research works are reported on SHS materials and TES systems in the past and the technology for their utilization is also well developed. Beaslely and Clark [8] provided an excellent review of such efforts in case of SHS system. LHS systems have received considerable attention in the past decades. Several investigations have studied the performance of TES employing PCM in a variety of geometries theoretically and experimentally. Saith and Hirose [9] performed theoretical and experimental investigations of the transient thermal characteristics of a LHS unit using spherical capsules .Takayuki et al. [10] developed a numerical model for prediction of the transient behavior of the latent heat storage module. The model is one –

dimension with a finite overall heat transfer coefficient between the PCM and the Heat Transfer Fluid (HTF). They conducted the experiments on the heat storage module consisted of PCM (paraffin waxes) with different melting temperatures using water as a Heat Transfer Fluid (HTF). Both experimental and numerical results showed some improvements in charging and discharging rates by use of "three – type" PCM. It is concluded from the literature surveys that most of the research works on TES are concerned with either SHS system or LHS systems only and not much works have been carried out on combined sensible and LHS systems without using electric heater. The objective of the present work is to investigate experimentally the thermal behavior and feasibility of using a cylindrically encapsulated PCM as a medium PCM tank containing latent heat storage material. Experiments are carried out at constant flow rates to the PCM tank where the thermal characteristics of the LHS system and efficiency of the system are calculated. Latent heat storage via Phase Change Material, Paraffin was used in this study. The reason for this selection is the fact that the use of PCM for Thermal Energy Storage in the solar heating system has received considerable attention in the literature. And also Paraffin is cheap, readily available, and melts at different temperature ranges

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3. Experimental Investigations

3.1. Governing equations

The Solar collector efficiency and PCM tank efficiency can be calculated based on the following information.

a) Solar collectors: Solar collector efficiency according to (Eq. (1)) is defined as the ratio of the collected heat by the solar collector over the solar radiation intensity.

$$\dot{Q}_u = \dot{m}_c c_w (T_{ic} - T_{oc}) \qquad \text{Eq. (1)}$$

$$\eta_c = \frac{Q_u}{A_c \;\; G_c} \qquad \text{Eq. (2)}$$

b) PCM tank: PCM tank efficiency defined as the heat transfer in the heat exchanger over the maximum heat transfer that the PCM tank can store (Eq. (5)). As the experimental data have been logged by the data logger every 30 minutes, Eq. (4) needs to be divided by the period of 30 minutes in order to convert it to kW.

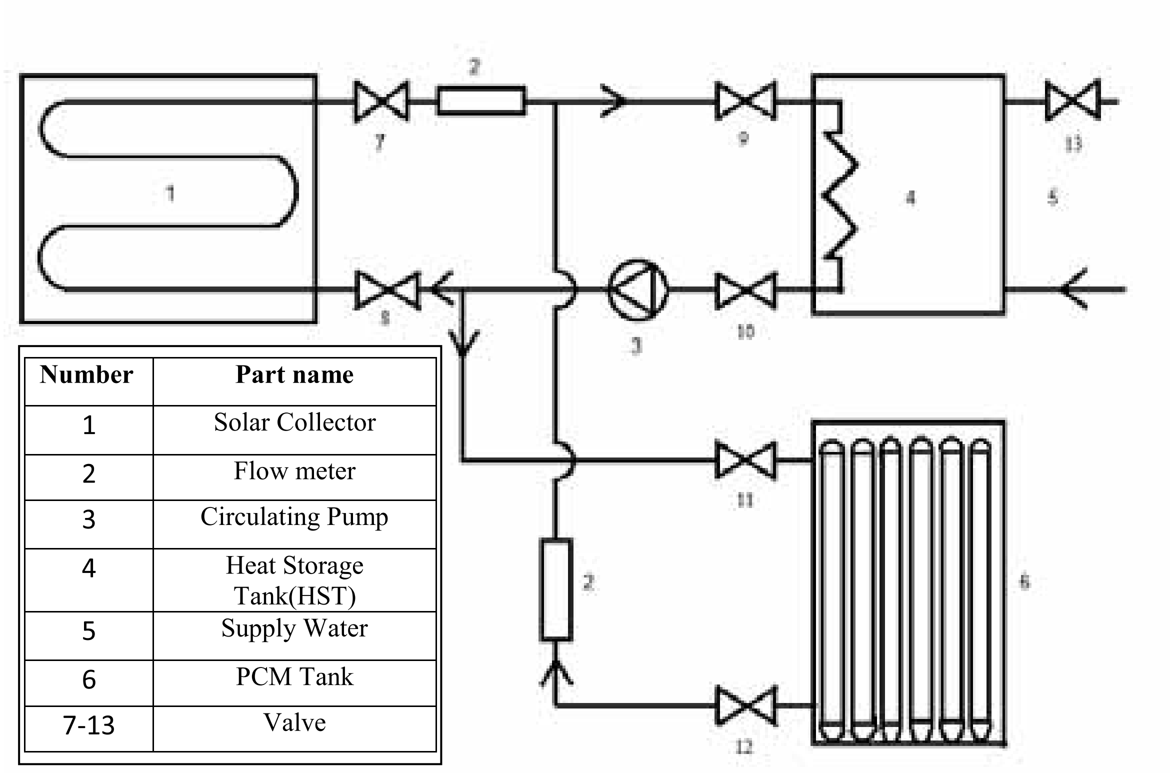
$$\dot{Q}_s = \dot{m}_t c_w (T_{it} - T_{ot}) \qquad \text{Eq. (3)}$$

$$Q_p = m_{pcm}\, c_{pcm}\, (T_{pcm} - T_a) \qquad \text{Eq. (4)}$$

$$\eta_t = \frac{30\times60\dot{Q}_s}{Q_p} \qquad \text{Eq. (5)}$$

3.2. Experimental Setup

A schematic picture of the experimental setup is shown in Fig. 1. The Solar heating system consists of an insulated PCM tank which contains PCM cylinder capsules, circulating pump, solar flat plate collector (total area of $4m^2$), flow meters, valves, and the heat storage tank (HS tank). The experimental setup photo is also shown in Fig 2. The experimental setup location is in the latitude of 35.39, longitude of 53.2 and altitude of 1127.29m.



Number	Part name
1	Solar Collector
2	Flow meter
3	Circulating Pump
4	Heat Storage Tank(HST)
5	Supply Water
6	PCM Tank
7-13	Valve

Fig. 1: Schematic picture of the experimental setup.

The galvanize PCM tank has a capacity of about 55 Liters capable of supplying water for a five family members, with an internal tank diameter of 310 mm and the tank height of 740mm. The tank is insulted with 5.4 cm of glass wool and is covered by a galvanized casing.

Fig. 2. Photographic view of experimental setup.

The PCM tank is encapsulated with aluminum cylinders with the internal diameter of 31mm and the height of 640 mm with wall thickness of 2 mm as shown in Fig. 3. Each cylinder is filled with 371 gr of PCM material and 37 capsules has been used and placed meticulously with the equal distance from the center of the cylinder.

Fig. 3: PCM capsules used in the heat exchanger.

Temperature sensors are placed at four different points of the outer PCM tank (T2, T4, T6 and T8) and inside the four PCM capsules (T1, T3, T5 and T7) are used to measure the temperature distributions at the length direction. And three different locations of the outer PCM tank (T6, T10 and T12) and inside PCM capsules (T5, T9 and T11) are used to measure temperature distributions at the radius direction. The data logger has LM35 temperature sensors with the temperature accuracy of ±0.1°c. A schematic picture of the temperature sensors positions is shown in Fig 4. The flow rate of the PCM tank through the system is measured using coned sinker flow meter. The thermo physical properties of the PCM (paraffin) from Rubitherm are shown in Table 1. Water is also used in both outer PCM tank and the SHS tank. Solar radiation is measured using Kipp & Zonen pyranometer.

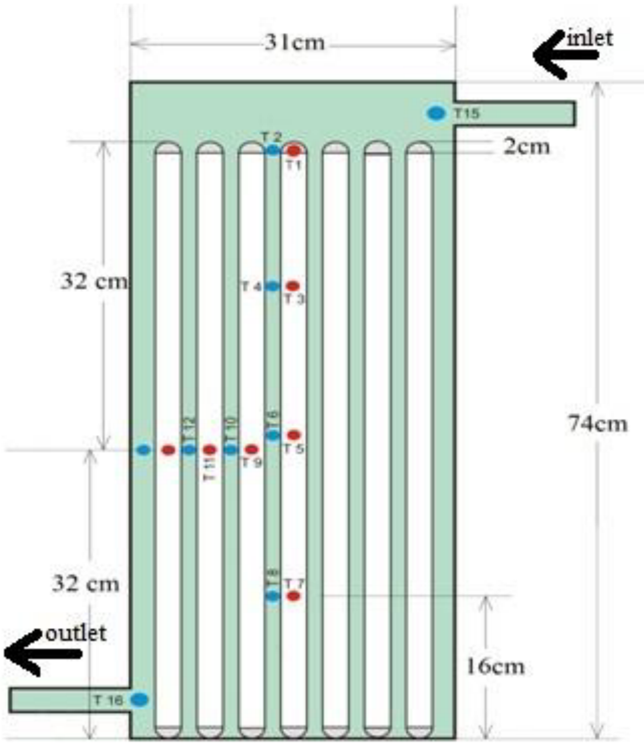


Fig. 4: Locations of temperature sensors.

Table. 1: Thermo physical properties of the PCM (paraffin).

Melting point	Heat storage capacity	Solid Density	Liquid Density	Thermal conductivity
55-59°c	178 (Kj. Kg^{-1})	900 ($m^3.Kg^{-1}$)	770($m^3.Kg^{-1}$)	0.2 ($W.(m°c)^{-1}$)

3.3. Experimental tests

The experimental tests were taken at 5 different days as shown in Table 2 with different flow rates in the closed cycle. In all experiments, the solar collector works with different flow rates between 8:00-17:00 and it stop working between 17:00-1:00. The DHW draw-off in all experiments is between 12:00-1:00 while the valve is closed between 9:00-12:00. The PCM tank valves are always open morning till midnight.

Temperatures are measured at intervals of 30 minutes. The PCM was charged during the day and the hot water is demanded by the user with 0.25 lit/min from 12:00 to 1:00.

Table.2: Experiments specifications.

Experiment name	DHW draw-off (lit/min)		PCM Tank Flow (lit/min)		Solar Collector Flow (l/min)		Radiation Intensity (w/m^2)
	Time 9:00-12:00	Time 12:00-1:00	Time 8:00-17:00	Time 17:00-1:00	Time 8:00-17:00	Time 17:00-1:00	
A1	0	0.25	5	7	4.5	0	500-1100
A2	0	0.25	6	8.5	5	0	500-1100
A3	0	0.25	7	9	7	0	500-1100
B1	0	0.25	5	7	4.5	0	500-1100
B2	0	0.25	0	0	4.5	0	500-1100

4. Results and Discussion

PCM tank efficiency diagrams in A1, A2, A3 experiments are shown in Fig. 5, Fig. 6 and Fig. 7. Based on the experiments, the solar radiation for all experiments is almost the same. The PCM tank efficiency comparison shows that the efficiency in A1 experiment is higher than A2 and A3 experiments. Therefore, solar collector flow rate in A1 experiment is suitable for the solar collector loop and will be used in the next experiments (B1 and B2).

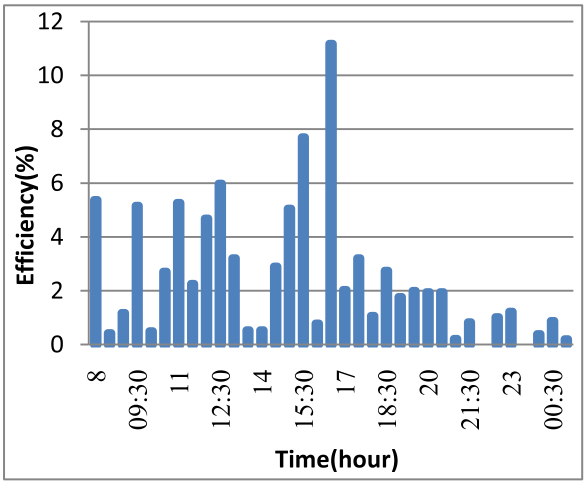


Fig. 5: PCM tank efficiency in A1 experiment.

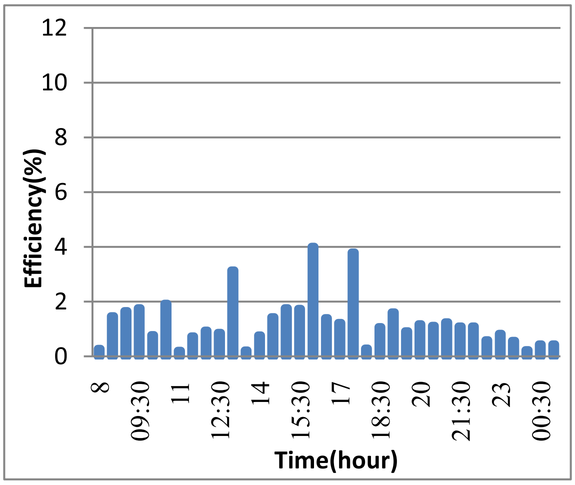


Fig. 6: PCM tank efficiency in A2 experiment.

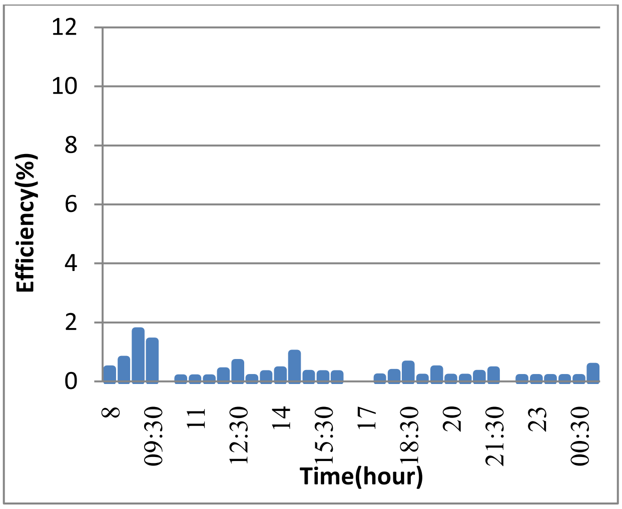


Fig. 7: PCM tank efficiency in A3 experiment.

In B1 experiment both sensible and latent heat storage were used for the study, whereas in experiment B2, only sensible heat storage is used for the experiment. The aim is to find out the benefit of using the PCM heat storage in the solar heating system.

The comparison between solar radiation in experiments B1 and B2 is shown in Fig. 8. It shows that the solar radiation in the experiment B2 is a little bit higher than experiment B1.

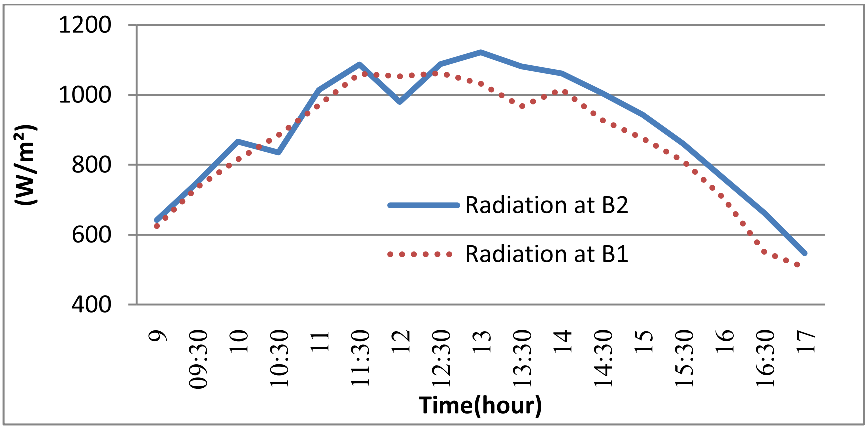


Fig. 8: Solar radiation in B1 and B2 experiments.

Fig. 9 shows that the outlet temperature from the solar collector is higher in experiment B2 than B1 between 9:00 to 15:00 o'clock and it's vice versa between 15:00 to 17:00.

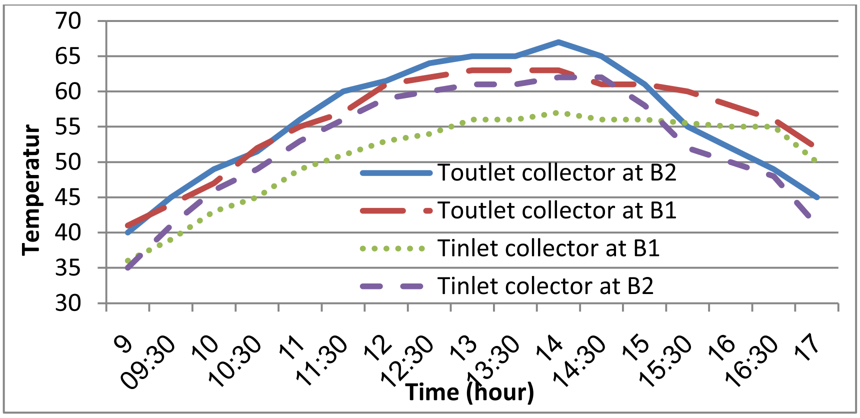


Fig. 9: Inlet and outlet solar collector temperatures in B1 and B2 experiments.

The solar collector efficiency is obtained by Eq. (2). The diagram shows that the efficiency of the solar collector increases when the PCM tank is used.

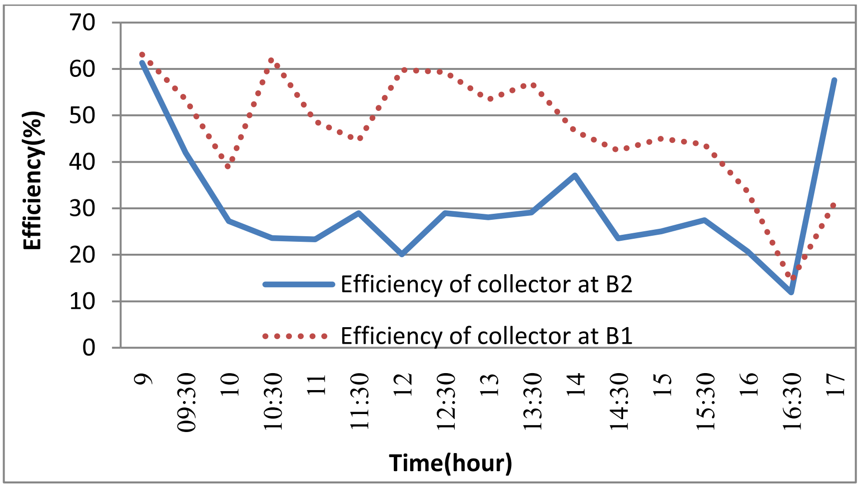


Fig. 10: Solar collector efficiency in B1 and B2 experiments.

Finally, comparison between experiments B1 and B2 is done when the DHW is used for consumption. The results show that the temperature in B1experiment after 17:00 o'clock stays in the higher temperature level and decreases gently than experiment B2. Because the PCM starts to discharge and keeps the water temperature warmer when the solar radiation decreases at 17:00.

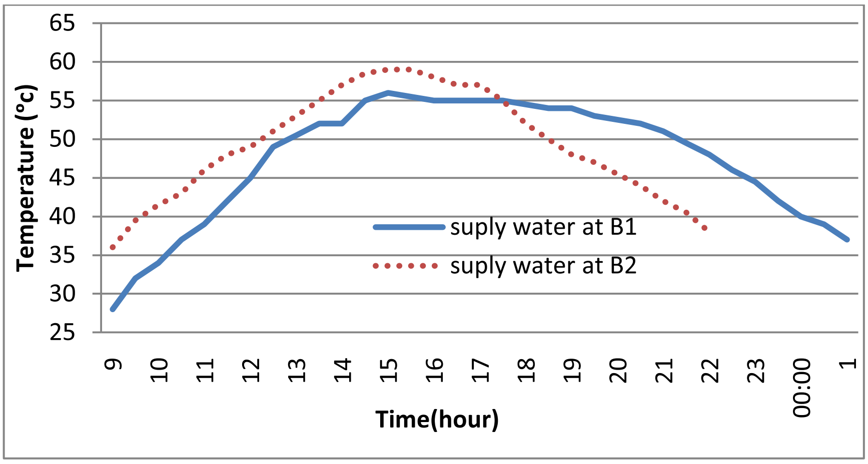


Fig. 11. Supply water outlet temperature in B1 and B2 experiments.

The position of temperature sensors inside and outside of the PCM tank is shown in Fig. 4. The following results is for experiment B1. Fig. 12 shows the temperature distribution of the water inside the PCM tank. As it is shown, the temperature in T2 is higher than T4, T6 and T8 before 15:30. However, after 15:30, the temperature in T8 becomes higher than T6, T4 and T2. Fig. 13 shows the temperature distribution inside the PCM capsules and temperature sensors are positioned exactly in the same level where the temperature sensor in the outer side is located. The result shows that T1 has higher temperature than T3, T5 and T7 before 15:30. But the temperature in T7 will be higher than T5, T3 and T1 after 15:30, respectively. The reason for this behavior is because the temperature inlet to the PCM tank increases till 15:30 and then decreases (Fig. 16). During the inlet temperature increase, due the inlet location at the top of the tank, T2 has higher temperature than T4, T6 and T8 and consequently, the PCM is charged and the PCM temperature at T1 becomes higher than T3, T5 and T7 because they are located close to the inlet. However, after 15:30 when the inlet temperature to the PCM tank decreases, the PCM starts to discharge because the inlet temperature becomes less than 55°C. Therefore, water temperature close to the outlet becomes higher than the temperature close to the inlet. Consequently T8 becomes higher than T6 and T4 and T2.

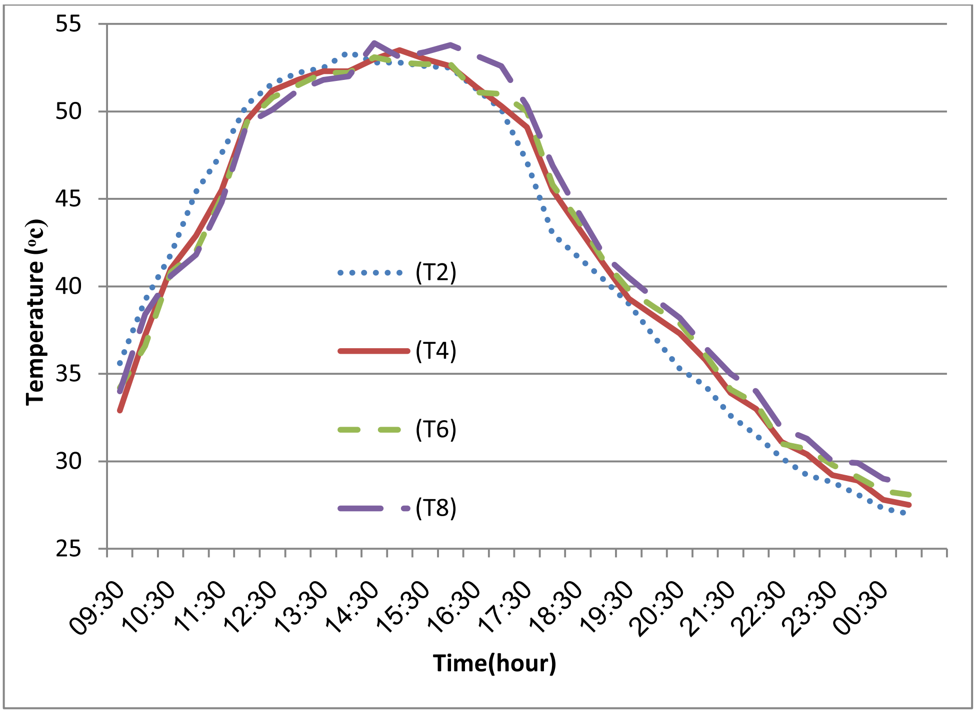


Fig. 12: Temperature distribution of water side of the PCM tank in the length direction. The PCM tank water volume flow rate is 5 l/min from 9:00 to 17:00 and is 7.25 l/min after 17:00.

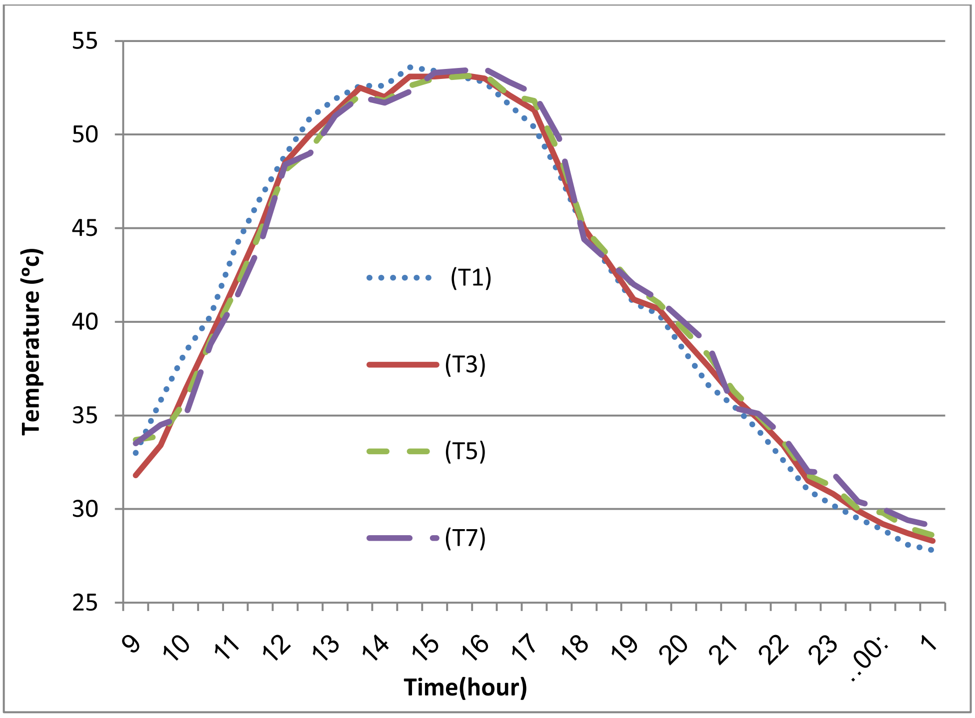


Fig. 13: Temperature distribution inside the PCM capsules in the length direction. The PCM tank water volume flow rate is 5 l/min from 9:00 to 17:00 and is 7.25 l/min after 17:00.

Fig. 14 and Fig. 15 show the temperature distributions in the radius direction in the outer PCM tank and the PCM capsules. The results show that the temperature at the center of the tank is slightly lower than the other part of the tank during the whole experiment. It means that the temperature closer to the tank wall is a bit higher than the center of the tank.

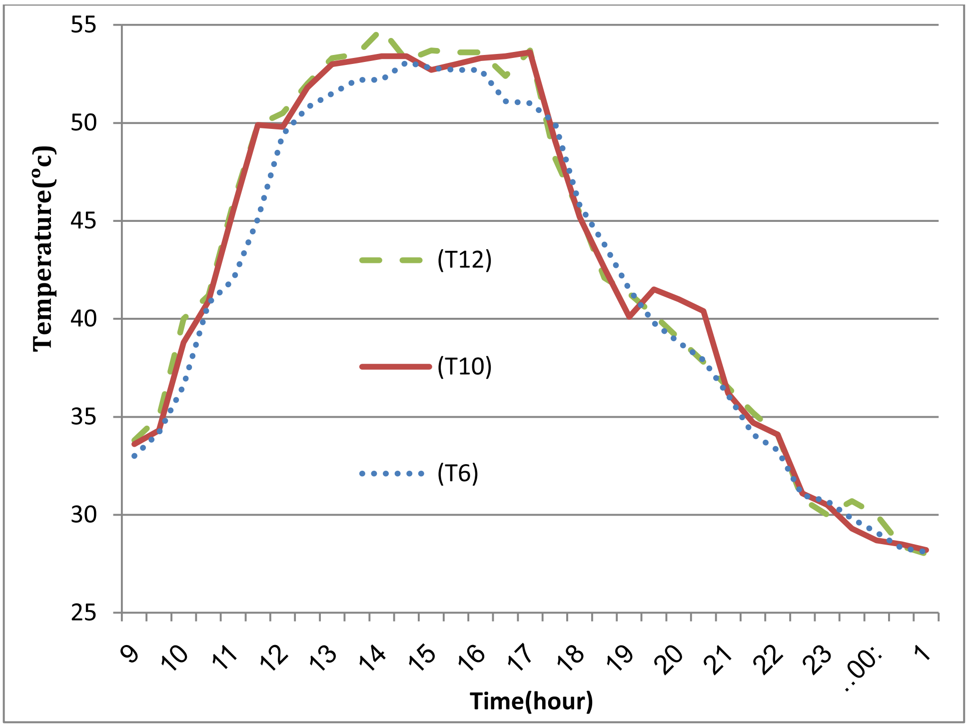


Fig.14: Temperature distribution of water side in the radius direction. The PCM tank water volume flow rate is 5 l/min from 9:00 to 17:00 and is 7.25 l/min after 17:00.

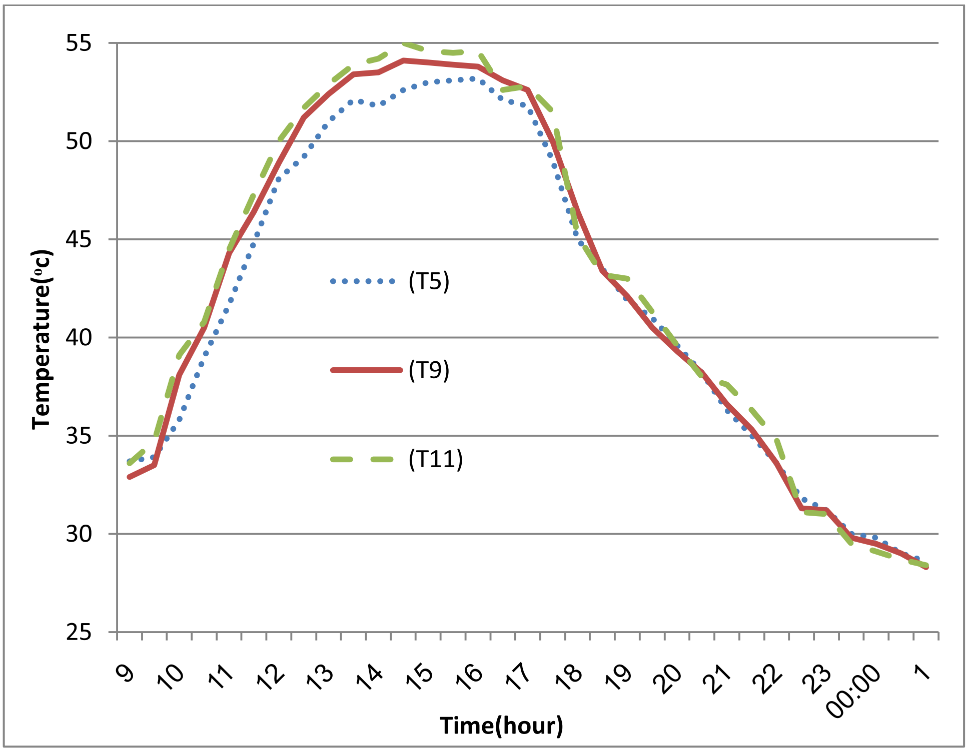


Fig.15: Temperature distribution of PCM in the radius direction. The PCM tank water volume flow rate is 5 l/min from 9:00 to 17:00 and is 7.25 l/min after 17:00.

Fig. 16 shows the inlet and outlet from the PCM tank. The temperature profile before 15:30 shows that the PCM tank is charged by the solar radiation. But after 15:30, the PCM starts to be discharged and heat up the water inside the PCM tank.

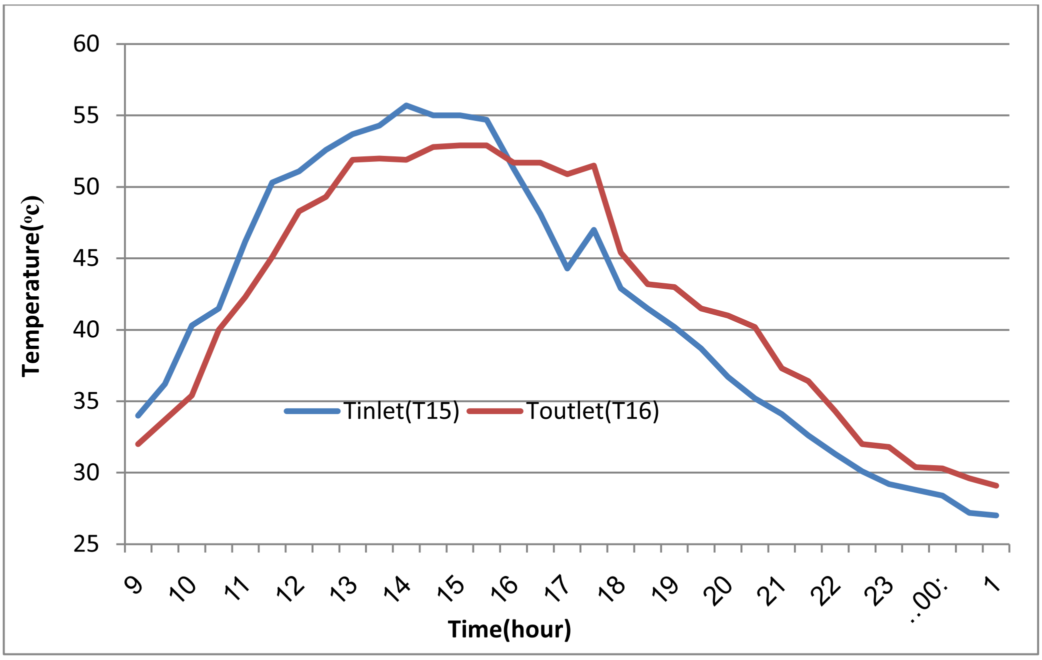


Fig.16: Inlet and outlet temperatures to and from the PCM tank.

Fig. 17 also shows the inlet and outlet temperature from the collector (left Y axis) and also the solar radiation (right Y axis). The temperature is of course a bit higher than the inlet of the PCM tank due to the heat loss.

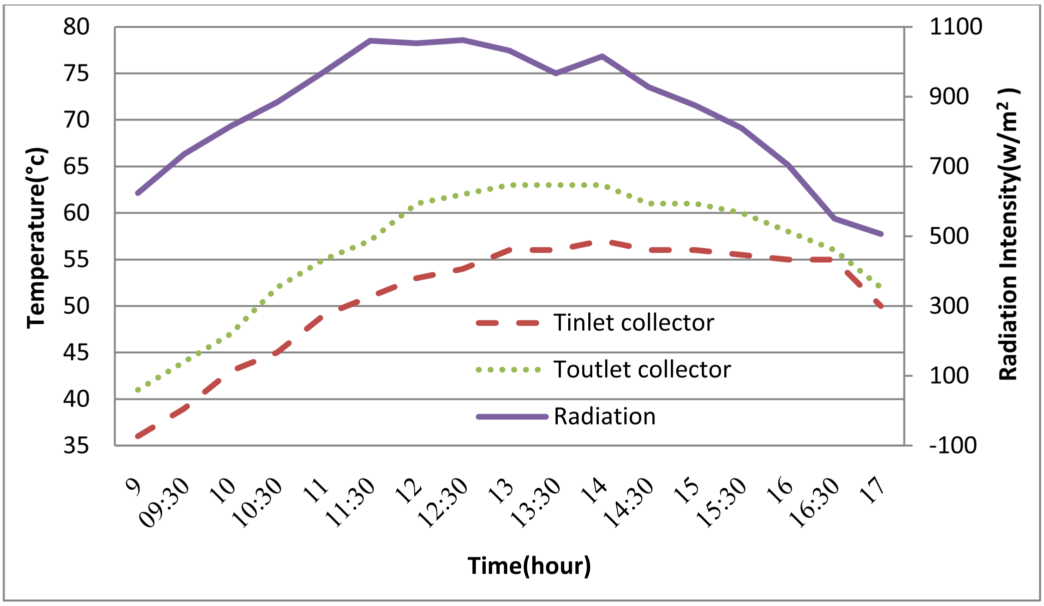


Fig.17 : Inlet and outlet temperatures from the solar collector (to the right), Solar radiation (to the left).

5. Conclusions

In the present study, a combined sensible and latent solar heating system is investigated. In the latent heat store, heat exchangers are used for keeping the PCM. The aim is to store heat as much as possible firstly in the PCM tank heat store and the surplus in the Sensible heat store. The results show that the thermal efficiency of the solar heating system combined with sensible and latent heat store is higher than the system with the sensible heat store alone. The reason is because the PCM tank can store solar energy during day and that makes the hot water temperature draw-off more stable during night. The temperature distributions of the outer PCM tank and inside PCM in the length and radius directions have also been investigated. The authors recommended optimizing the system by different geometries and types of the phase change materials.

6. Nomenclatures

Table 3: Recommended symbols for materials properties

Quantity	Symbol	Unit
Water Specific heat	C_W	J kg^{-1} K^{-1}
PCM Specific heat	C_{PCM}	J kg^{-1} K^{-1}
Water Density	ρ_w	Kgm^{-3}

Table 4: Recommended symbols for radiation quantities

Quantity	Symbol	Unit
Solar radiation	G	W m^{-2}

Table 5: Recommended abbreviation

Quantity	Symbol
Phase Change Material	PCM
Latent Heat Storage	LHS
Sensible Heat Storage	SHS
Thermal Energy Storage	TES
Heat Transfer Fluid	HTF
Latent Heat Storage Energy	LHSE
Heat Storage Tank	HST

Table 6: Recommended symbols for miscellaneous quantities

Quantity	Symbol	Unit
Collector Area	A_C	m^2
PCM mass	m_{pcm}	Kg
Mass Flow rate PCM tank	$\dot{m}_t$	kg s^{-1}
Mass flow rate of Collector	$\dot{m}_c$	kg s^{-1}
collector Heat transfer rate	$\dot{Q}_u$	W
PCM Storage tank Heat transfer rate	$\dot{Q}_s$	W
Max Heat PCM Storage tank	Q_p	J
Collector Inlet temperature	T_{ic}	K
Collector Outlet temperature	T_{oc}	K
PCM tank inlet temperature	T_{it}	K
PCM tank Outlet temperature	T_{ot}	K
Melting temperature of PCM	T_{pcm}	K
Air Temperature	T_a	K
Collector Efficiency	η_C	
PCM tank efficiency	η_t	

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