

*Research Article*

# Experimental Studies on Phase Change Material-Based Thermal Energy Storage System for Solar Water Heating Applications\*

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**Abstract** Abundantly available solar energy utilization for domestic and industrial applications is hindered because of its intermittent nature. The thermal energy storage (TES) system using both sensible and latent heat has many advantages like large heat storage capacity in a unit volume and its isothermal behavior during the charging and discharging processes. Because of these advantages, in recent years, a lot of research work has been going on to overcome problems like low heat transfer rates between heat transfer fluid and phase change material (PCM) in both charging and discharging processes of the PCM-based TES system. In the present experimental investigation results of a combined sensible and latent heat TES system integrated with a varying (solar) heat source is presented. Investigations are carried out in the TES system for different phase change materials (paraffin and Stearic acid) by varying HTF flow rates and for various sizes of spherical capsules (68, 58, and 38 mm in diameter). Experiments are performed in both charging and discharging processes. The results show that the 38 mm diameter spherical capsule shows better performance compared to spherical capsules of other sizes.

**Keywords** phase change material (PCM); latent heat; heat transfer fluid (HTF); paraffin; stearic acid; thermal energy storage (TES)

## 1 Introduction

In recent years, attention has increased to decrease the cost of solar energy equipment and improve the efficiency of heat energy storage systems. To store the heat energy, basically two types of storage systems are developed. One is a sensible heat storage system and another is a latent heat storage system. To store a large quantity of heat in a small

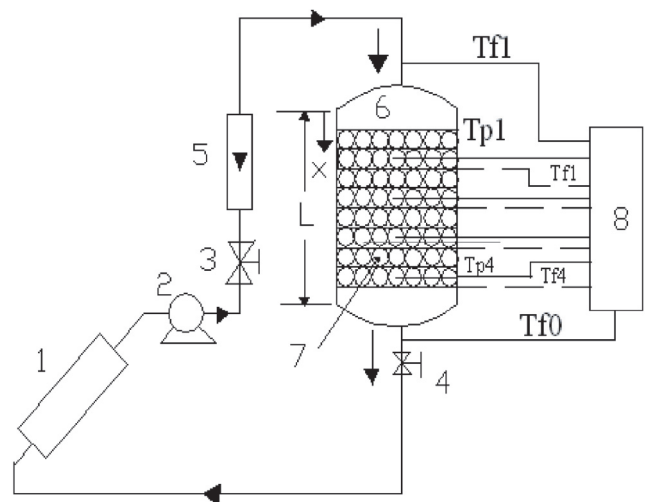
unit volume, combined sensible heat and latent heat storage systems are developed.

These systems have many advantages like large heat storage capacity in a unit volume and their isothermal behavior during the charging and discharging processes. These systems are not in commercial use like sensible heat storage (SHS) systems because of the poor heat transfer rate during the charging and discharging processes and high initial cost. Some of the important contributions in this direction are discussed in the sequel. Al-Jandal and Sayigh [2] studied the thermal performance characteristics of a solar tube collector (STC) system with phase change storage analytically and experimentally. STC performance during charging is studied and it is concluded that fin structures are strongly affecting the melting process. Esen et al. [7] carried out a theoretical analysis to investigate the performance of an LHS unit coupled with a solar water heating system using different PCMs. Banaszek et al. [4] investigated experimentally the solid-liquid phase change in a spiral thermal energy storage unit during charging and discharging processes. Ismail and Henríquez [10] reported the results of numerical and experimental investigations on LHS by varying parameters like heat transfer fluid (HTF) inlet temperature, HTF flow rate, and material of the PCM capsule. In this LHS system water was used as PCM and the heat transfer process during charging and discharging processes was simulated. Mehling et al. [12] concluded that placing PCM modules at the top of the water tank in TES has given higher storage density and compensated the heat loss at the top surface by doing both numerical and experimental investigation. Sharma et al. [16] reported a theoretical analysis on heat transfer phenomena in an LHS system using different heat exchanger materials and different PCMs (fatty acids). The results conclude that the heat exchanger material conductivity does not have much influence on the melting time of PCM. It is also reported that capric acid has good compatibility in

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the LHS system compared to lauric acid, myristic acid, palmitic acid, and stearic acid. Shiina and Inagaki [17] reported a technique improving the thermal conductivity of PCM using saturated porous metals with phase change materials. Results conclude that the melting time of PCM is reduced considerably with low-conductivity PCMs and high-heat-transfer-coefficient porous metals. Halawa et al. [9] presented a numerical analysis of a PCM thermal storage system with varying wall temperature. This last paper discussed typical characteristics of the melting/freezing of PCM slabs in an air stream and presented some results of the numerical simulation in terms of air outlet temperatures and heat transfer rates during the whole periods of melting and freezing. Assis et al. [3] reported a numerical and experimental study of melting in a spherical shell. The results showed the effect of thermal and geometrical parameters on melting/freezing processes. Zukowski [18], Das and Dutta [5], Nallusamy et al. [13], and Akgün et al. [1] reported numerical and experimental investigations about melting and solidification characteristics of different PCMs used in the TES system. Seeniraj and Narasimhan [15] carried out numerical investigations to improve the performance of a TES system by employing multiple PCMs and fins. Jian-you [11] reported a numerical and experimental investigation for heat transfer in a triplex concentric tube with PCM for a thermal energy storage system. The relation between the solid and liquid phases of PCM versus time and axial position, and the time-wise variation of energy stored/released by the system were presented and discussed. Felix Regin et al. [8] developed a numerical model for analyzing the behavior of a packed bed containing spherical capsules filled with paraffin wax as PCM. Nallusamy and Velraj [14] studied both theoretically and experimentally the performance of a combined sensible and latent heat storage unit integrated with a solar water heating system. In this paper, the instantaneous heat stored, cumulative heat stored, and charging rate are studied in detail. El Qarnia [6] performed a numerical analysis to predict the thermal behavior and performance of a solar latent heat storage unit using various PCMs for heating the water. The number of tubes, flow rate of water, mass of the PCM etc. were optimized for given summer climatic conditions of Marrakech city.

The objective of the present work is to predict the optimum spherical sized capsules among three different diameters (68, 58, and 38 mm) for better efficiency of a sensible and latent heat thermal energy storage unit integrated with a varying (solar) heat source. Different diameters of the HDPE spherical capsules were used and surrounded by an SHS material (water). Parametric studies are carried out to examine the effects of the diameter, PCM, and HTF flow rates on the performance of the storage unit for varying inlet fluid temperature. The behavior of the TES



**Figure 1:** Schematic outline of the experimental setup: 1. solar flat plate collector; 2. pump; 3 & 4. flow control valves; 5. flow meter; 6. TES tank; 7. PCM capsules; 8. temperature indicator,  $T_p$  &  $T_f$ : temperature sensors (RTDs).



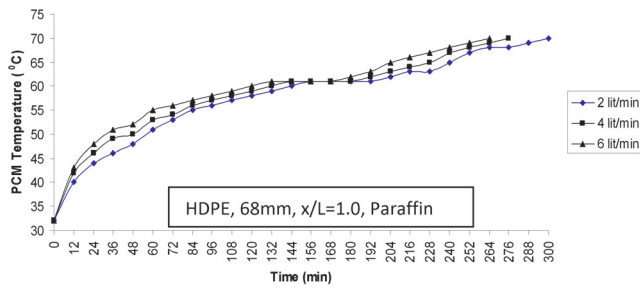
**Figure 2:** Photographic view of the experimental setup.

system is studied during both the energy storage (charging) and recovery (discharging) processes.

## 2 Experimental investigation

### 2.1 Experimental setup

Figure 1 shows a schematic diagram of the experimental setup. The spherical capsules filled with PCM are placed in an insulated cylindrical TES tank. A solar flat plate collector of  $2 \text{ m}^2$  surface area is coupled with the TES system (Figure 2). The capacity of the stainless steel tank is 51 lit (360 mm diameter and 504 mm height) and it is insulated with glass wool of 50 mm thickness. For uniform flow of HTF, a flow distributor is provided on the top of the TES tank. The spherical capsules are stored from top to bottom keeping the wire mesh between each layer for providing the porosity. The total sensible and latent heat storage capacity of the TES tank at  $70^\circ\text{C}$  is around 10,000 KJ. In this



**Figure 3:** Effect of the mass flow rate of HTF on charging time for varying HTF inlet temperature.

experimental investigation paraffin (melting temperature = 61 °C) and stearic acid (melting temperature = 57 °C) are used as PCMs. A flow meter (with accuracy of  $\pm 2\%$ ) and a centrifugal pump (500 lit/hr capacity) are fitted in the pipe connecting the storage tank with flat plate collector. The TES tank is divided into four segments, i.e. at  $x/L = 0.25$ , 0.5, 0.75, and 1.0 ( $L$  is the height of the TES tank, mm;  $x$  is the axial distance from the top of the TES tank, mm;  $x/L$  is the dimensionless axial distance from the top of the TES tank) along its axial direction, and the resistance temperature detectors (RTDs) with an accuracy of  $\pm 0.3$  °C are placed at the inlet, outlet, and four segments of the TES tank to measure the temperatures of HTF. Other four numbers of RTDs are inserted into the PCM capsules and they are placed at four segments of the TES tank to measure the temperatures of PCM. The position and number of RTDs are also designated in Figure 1. The RTDs are connected to a temperature indicator, which provides instantaneous digital outputs.

## 2.2 Experimental details

The performance of the charging of TES is studied using 2 lit/min, 4 lit/min, and 6 lit/min flow rates with varying inlet HTF temperatures. Also batchwise discharging of TES is studied with different discharge flow rates, i.e., 2 lit/min, 4 lit/min, and 6 lit/min, keeping the constant cold water inlet, i.e., 2 lit/min at 30 °C. 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. Temperatures of the PCM and HTF are recorded at an interval of 12 min. The charging process is continued until the PCM temperature reaches the value of 70 °C.

The discharging process (energy retrieval) experiments are carried out in a batchwise process. A certain quantity of hot water (20 lit because an average of one person needs 20 lit for taking a bath) is withdrawn from the TES tank for direct use and the tank is again filled with cold water of quantity equal to the amount of water withdrawn. Again,

after a time interval of 20 min allowing the transfer of energy from the PCM, another 20 lit of water is withdrawn from the TES tank. This process is continued until the PCM temperature reaches 34 °C.

## 3 Results and discussion

The temperature distributions of PCMs in the storage tank for various mass flow rates, different PCMs, and different diameters of capsules are recorded during the charging and discharging processes.

### 3.1 Charging process

The charging experiments are conducted for the combination of various parameters of mass flow rates, various diameters of the spherical capsules, and different PCMs.

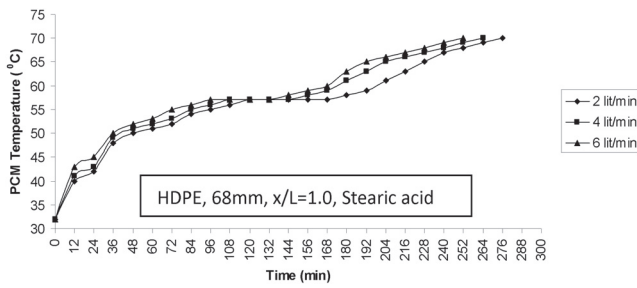
#### 3.1.1 Effect of the flow rate of HTF and paraffin as PCM

Figure 3 illustrates the effect of varying the mass flow rate of HTF (2, 4, and 6 kg/min) during the charging of the storage tank for the varying HTF inlet temperature. The graph shows that the flow rate of the HTF with varying HTF inlet temperature does not have a much significant influence on the charging time. Because the duration needed for charging is around 4 h (i.e., 10:00 a.m. to 2:00 p.m.), which is a long duration, the heat transfer rate influence from HTF to PCM is very low (5–10%).

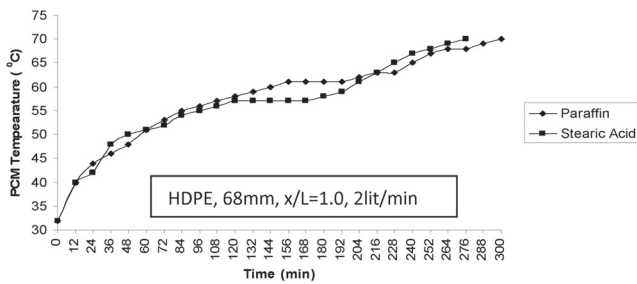
This 10% variation is occurring due to the high heat transfer rate at the high HTF inlet temperature around 1:00 p.m. Figure 3 shows that the temperature of the TES system is reaching around 60 °C after 120 min (i.e., at 12:00 p.m.). During this period the heat energy is stored in water and PCM in the form of sensible heat. At around 60 °C, slope of the curves is nearer to being horizontal because heat is stored in the form of latent heat by melting the PCM. The slope of the curves from 65 °C to 70 °C is not high like the one at low temperatures around 40 °C because the difference between inlet HTF temperature and HTF temperature present in the storage tank is very low, so the time taken to raise the temperature from 65 to 70 °C is more.

#### 3.1.2 Effect of the flow rate of HTF and stearic acid as PCM

Figure 4 shows the variation of PCM temperature and charging time with respect to different flow rates (2, 4, and 6 kg/min) which are very less like the ones in Figure 3. The behavior of the TES tank (stearic acid used as PCM) is almost the same like the TES tank using paraffin as PCM. The charging times in Figure 4 appear slightly less (by around 5%) than the charging times in Figure 3. This is due to less latent heat of stearic acid (198 KJ/Kg as opposed to 213 KJ/Kg for paraffin) and less melting temperature of stearic acid (i.e., 57 °C for stearic acid and 61 °C for paraffin).



**Figure 4:** Effect of the mass flow rate of HTF on charging time for varying HTF inlet temperature.



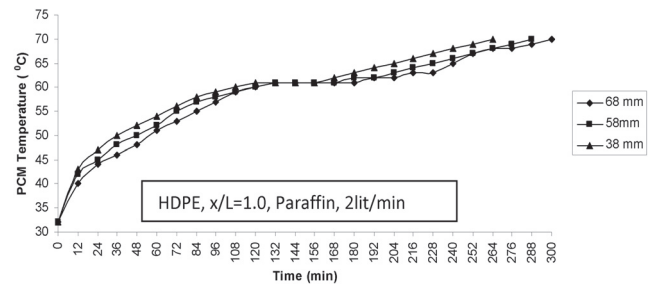
**Figure 5:** Effect of PCMs on charging time for varying HTF inlet temperature.

Figure 5 shows the curves for paraffin and stearic acid PCMs. The charging time of stearic acid is around 8% less when compared to that of paraffin. This is because the latent heat, thermal conductivity, and specific heat quantities for both PCMs have 5–7% variation.

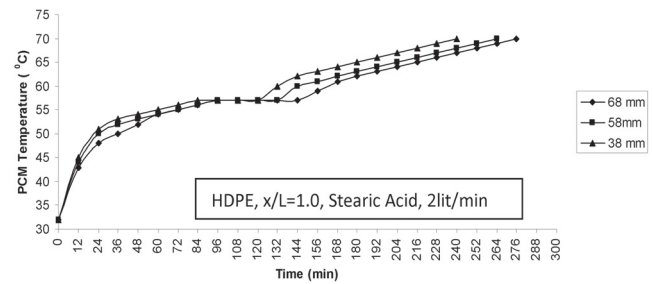
### 3.1.3 Effect of the sizes of the spherical capsules and of paraffin as PCM

Figure 6 represents the variation of charging time and PCM (paraffin) temperature for different capsule diameters (68, 58, and 38 mm). The 38 mm diameter spherical capsule charging time is less (around 10%) compared to that of the 68 mm diameter capsule, and the PCM temperature is also more throughout the charging process compared to that of the 68 mm diameter capsule. Because the total surface area of the 38 mm diameter spherical capsules is around 70% more than that of the 68 mm diameter spherical capsules and the internal heat resistance of the 38 mm diameter spherical capsule is around 45% less than that of the 68 mm diameter spherical capsule, the heat transfer rate will be faster between HTF and PCM in the 38 mm diameter spherical capsule.

In this experimental investigation the variation in diameters of spherical capsules between 68 and 38 mm does not have much effect on the charging time because the heat source (solar flat plate collector) energy supply rate is much less even though the heat transfer rate from HTF to PCM is higher. It is observed that during the experiment from



**Figure 6:** Variation of PCM temperature at  $x/l = 1.0$  for the different capsule diameters.



**Figure 7:** Variation of PCM temperature at  $x/l$  for the different capsule diameters.

10:00 a.m. to 1:00 p.m. (first three hours) the temperature of the inlet HTF increased from 30 °C to 65 °C, i.e., in the charging process the difference in temperature between inlet HTF and PCM is not high.

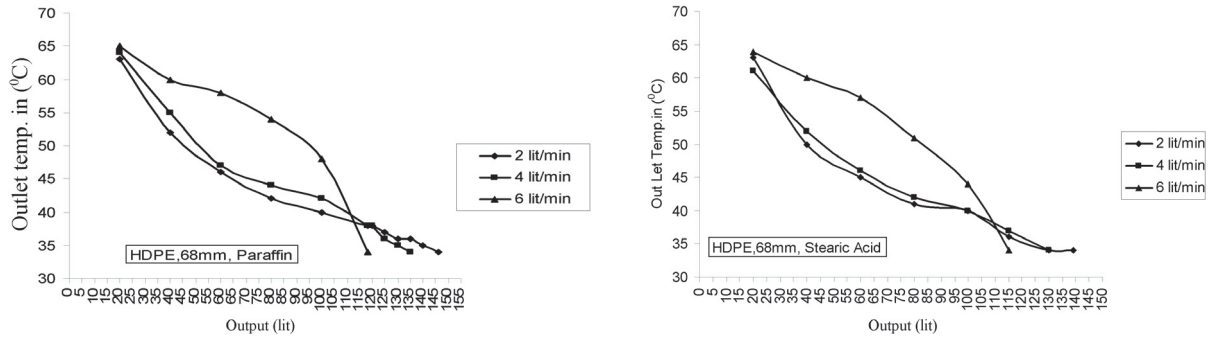
### 3.1.4 Effect of the sizes of spherical capsules and of stearic acid as PCM

Figure 7 represents the variation of PCM temperature for different capsule diameters for stearic acid. Figures 6 and 7 (paraffin as PCM) show that the TES behavior is almost the same for both PCMs. The small variation in charging time in Figure 7 compared to that in Figure 6 is due to the variation in latent heat, thermal conductivity, and specific heat of stearic acid compared to that of paraffin.

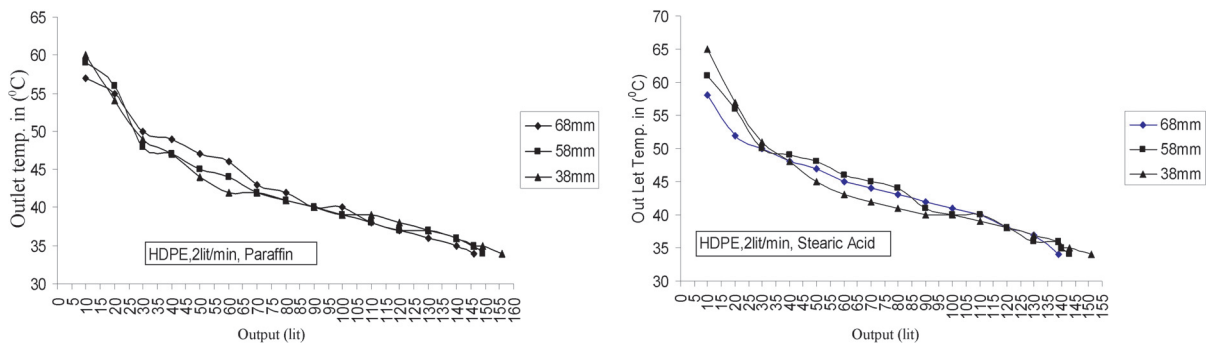
## 3.2 Discharging process

Batchwise discharging experiments are carried out as explained below. In this method hot water (20 lit) is discharged from the storage tank in each batch. The average temperature of the collected discharge water in the bucket is measured using a thermometer. The time difference between the consequent discharges is 20 min. The cold water (30 °C) is supplied (2 lit/min) constantly into the TES tank simultaneously during discharging processes (2, 4, and 6 lit/min). During the experiment the discharge water is equal to the inlet water into the TES tank. The batchwise withdrawing of hot water is continued till the temperature of the outlet water reaches 34 °C.





**Figure 8:** Variation of outlet (lit) for different flow rates at  $x/L = 1.0$  (paraffin and stearic acid).



**Figure 9:** Variation of outlet (lit) for the different capsule diameters (paraffin and stearic acid).

**3.2.1 Effect of flow rate on PCMs**

Figure 8 shows the temperature variation of hot water discharge for different flow rates. The average temperature of hot water discharged batchwise is almost the same in 2 lit/min and 4 lit/min. But the average temperature of hot water discharge in 6 lit/min is high as the graphs show. This is due to the less mixing of inlet cold water in 6 lit/min discharge compared to 4 lit/min and 2 lit/min discharges. The time taken for collecting the batchwise hot water is much less (3.5 min) in case of 6 lit/min discharge, and it is 10 min in case of 2 lit/min discharge. The more the time of discharge the more the mixing of inlet cold water (2 lit/min) with the hot water stored in the TES tank. So it is better to discharge hot water at a high flow rate and keep the low inlet cold water flow rate (2 lit/min) for higher average temperature of hot water.

The output of the stearic acid PCM is 4–5% less for different flow rates. This is because stearic acid has 7% less latent heat of fusion than that of paraffin.

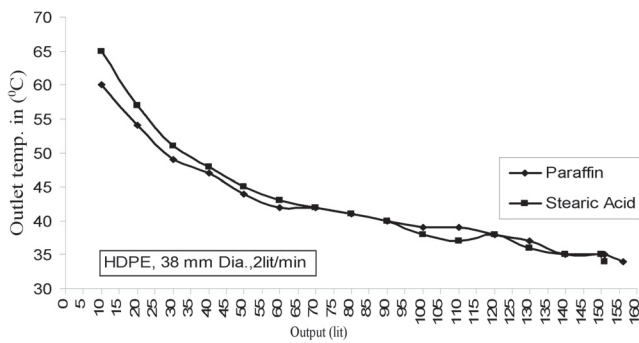
**3.2.2 Effect of spherical capsule’s diameters on PCMs**

Figure 9 shows the variation in output during the batchwise discharging process for 68, 58, and 38 mm diameter spherical capsules. The average temperature of hot water discharge is almost the same for all the three diameters spherical capsules. There is slight variation in the quantity

of discharge around 5–7% between the 68 mm diameter spherical capsule and the 38 mm diameter spherical capsule. This variation is because of the high heat transfer rate (70% increased surface area and 40% reduction in the internal heat resistance of PCMs) from PCM to HTF in the case of the 38 mm diameter spherical capsule. The retention time within the batches is 20 min, so that the heat transferred between PCM capsules and water is sufficient to reach the equilibrium between PCM and water (HTF). The optimum retention time of 20 min within batches is achieved by conducting a number of experiments (with different retention times like 10, 15, 20, 25, and 30 min) for 68 mm and 58 mm diameter capsules. Another experiment showed that the optimum retention time within batches is achieved at 10 min for 38 mm diameter capsules due to the surface area and the less internal heat resistance of PCM. The output of the stearic acid PCM is 3–4% less for different sizes of spherical capsules. This is because stearic acid has around 7% less latent heat of fusion than that of paraffin.

**3.2.3 Effect of PCM material**

Figure 10 shows the outlet variation for paraffin and stearic acid PCMs. The graph shows that the average temperature of batchwise discharged water is almost the same. The quantity of water discharged is also almost the same with slight variation of 3–4%. This is because the latent heat, thermal



**Figure 10:** Variation of outlet (lit) for the different PCMs for the 38 mm diameter capsule.

conductivity, and specific heat quantities for both PCMs are almost the same with 5–7% variation. As for the performance in the discharging process (heat recovery), there is no much difference between paraffin and stearic acid as PCMs.

#### 4 Conclusions

In the charging process using a varying heat source (solar) the results show that the different flow rates (2, 4, and 6 lit/min) of HTF does not have a much significant influence on the charging time. Because the duration for charging is around 4 h (i.e. 10:00 a.m. to 2:00 p.m.), which is a long duration, the heat transfer rate from HTF to PCM has a very low influence (5–10%). For the discharging process there is no much difference in the quantity of thermal energy recovered in the batchwise discharge process for different flow rates (2, 4, and 6 lit/min) even though the quantities of hot water discharged are different. This is because in the 6 lit/min discharge flow rate the average temperature is high and the quantity is low, and in the case of 2 lit/min discharge flow rate the average temperature is low and the quantity is more correspondingly.

The variation in spherical capsule diameters between 68 and 38 mm does not have much effect on charging time because the heat source (solar flat plate collector) energy supply rate is very low (the heat absorption of HTF from the solar flat plate collector is low) even though the heat transfer rate (heat discharge of HTF to PCM) is more in the TES system.

The average temperature of hot water discharge is almost the same for all the three diameters of spherical capsules. But the quantity of hot water discharge is slightly more for the 38 mm capsule diameter compared to the 68 mm diameter capsule.

As for the performance in the charging (heat storing) and discharging processes (heat recovery), there is no much difference between paraffin and stearic acid as PCMs. But paraffin's performance is slightly better (5–7%) because of latent heat and thermal conductivity variation. It means that both PCMs are suitable for TES systems.

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