THERMAL ENERGY STORAGE SYSTEM USING PHASE CHANGE MATERIALS – CONSTANT HEAT SOURCE

by

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Original scientific papre
DOI: 10.2298/TSCI100520078R

The usage of phase change materials to store the heat in the form of latent heat is increased, because large quantity of thermal energy is stored in smaller volumes. In the present experimental investigation paraffin and stearic acid are employed as change materials in thermal energy storage system to store the heat as sensible and latent heat also. A constant heat source is used to supply heat transfer fluid at constant temperature to the thermal energy storag system. In the thermal energy storag system change materials are stored in the form of spherical capsules of 38 mm diameter made of high density poly ethylene. The results of the investigation are related to the charging time and recovery of stored energy from the thermal energy storag system.

Key words: *phase change material, latent heat, heat transfer fluid, paraffin, stearic acid, thermal energy storage, constant heat source*

Introduction

Thermal energy storage (TES) system using phase change materials (PCM) as a storage medium offers advantages such as high heat storage capacity, small unit size and isothermal behavior during charging and discharging when compared to the sensible heat storage (SHS) system. However, latent heat TES systems are used to a limited extent in commercial use due to poor heat transfer rates during heat storage and recovery process. The efforts are on to overcome this problem.

Cho *et al.* [1] investigated the thermal characteristics of paraffin in a spherical capsule during freezing and melting process. Experiments were performed with paraffin. The study has shown that the heat transfer coefficients increase with increase in inlet temperature and the Reynolds number of heat transfer fluid (HTF) flow. However, they were less affected during freezing process due to free convection effect. Nallusamy *et al*. [2] , Mehling *et al.* [3] studied effective utilization of solar energy for water heating applications using combined sensible heat and latent heat storage system. Results show that adding PCM modules at the top of the water

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tank would give the system higher storage density and compensate heat loss in the top layer. Fouda *et al*. [4] studied the characteristics of Glauber's salt as the PCM in the solar storage system. The effect of several variables was observed over many complete cycles of the unit, including variable HTF flow rate, inlet temperature, wall thickness, *etc*. Thermal efficiencies generally exceeded 85 per cent and were often greater than 90 per cent. These values are higher than those reported for smaller heat storage vessels.

Ghoneim *et al.* [5], Hoogendoorn *et al.* [6], and Bansal *et al.* [7] studied thermal performance of latent heat thermal energy storage (LHTES) systems integrated with solar heating systems was also investigated. One major conclusion reported is that PCM has low thermal conductivity, leading to slow charging and discharging rates. Hisham Ettouney *et al*. [8] studied the performance of TES system filling paraffin wax and metal beads in spherical capsules. It was shown that the heat transfer rate is increased because of placing the metal beads. Farid *et al.* [9] and Farid *et al.* [10] have proposed the use of PCM with different melting temperatures in latent heat storage (LHS) module with air as HTF. The PCM was encapsulated in multi rows of vertical cylinders. Both experimental and numerical results showed improvement in the heat transfer rates during both heat charge and discharge when three types of PCM were used. Watanabe *et al*. [11] extended the experiments of Farid *et al.* [10] by using water as the HTF and proved that there was obvious enhancement of the charging-discharging rates in the LHS system using three PCM.

The objective of the present work is to select suitable PCM among paraffin and stearic acid for sensible and latent heat TES. The influence of both flow rates and inlet temperatures of HTF, water on the performance of storage unit is studied. The performance of the storage unit is determined by the study of energy storage and recovery of energy.

Experimental set-up

A storage system is designed with a heat capacity of 10,000 kJ to supply about 160 l of water at 45 ± 10 °C temperature.

Figure 1 shows the set-up used in the study of thermal performance of TES system using latent heat and sensible heat of the PCM (commercial grades of paraffin and stearic acid). Investigations are carried out by integrating this storage system with constant heat source. To meet the above requirement a cylindrical tank of 51 l capacity is used, dimensions are ∅360 × 504 mm. The storage tank is insulated with glass wool of 50 mm thick to prevent loss of heat. An all round aluminum cladding is provided on top of the glass wool insulation. For the purpose of measuring the temperature of HTF, thermocouples (Pt 100) are located along the axis of the tank at x/L = 0.25, 0.5, 0.75, and 1.0 where L is the length of the TES tank in mm and x – the axial distance from the top of the TES tank in mm; x/L is the dimensionless axial distance from the top of the TES tank. Thermocouples are also located inside the spherical capsules for measuring the tempera-

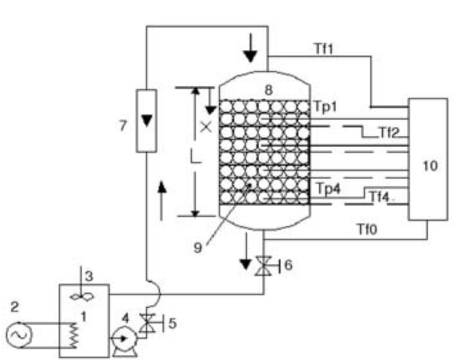

Figure 1. Schematic experimental set-up; *1 – constant temperature bath; 2 – electric heater; 3 – stirrer; 4 – pump; 5 and 6 – flow control valves; 7 – flow meter; 8 – TES tank; 9 – PCM capsules; 10 – temperature indicator; Tp and Tf – temperature sensors (RTD)*

ture of the PCM at $x/L = 0.25$, 0.5, 0.75, and 1.0. Wire mesh is used between each layer of spherical capsules to provide/create uniform void space between capsules and layers as well. Thermocouples are also used for measuring the inlet and outlet temperatures of HTF. 38 mm diameter spherical capsules filled with PCM are used to determine the performance of the TES system. Details of spherical capsules employed are given in tab. 1.

Table 1. Details of spherical capsules

Size of the capsule (diameter)	No. of spherical capsules needed	
	Paraffin (type-II)	Stearic acid
38 mm	870	836

From tab. 1 it may be noted that less number of spherical capsules are used for stearic acid PCM as its density (840 kg/m^3) is more than that of liquid paraffin (778 kg/m^3). The thermophysical properties of PCM are given in tab. 2.

Table 2. Thermophysical properties of PCM

Phase change material	Melting temperature [°C]	Latent heat of fusion [kJkg^{-1}]	Density [kgm^{-3}]		Specific heat [Jkg^{-1}°C^{-1}]		Thermal conductivity [Wm^{-1}°C^{-1}]	
			Solid	Liquid	Solid	Liquid	Solid	Liquid
Paraffin wax Type-II*	61	213.0	861	778	1850	2384	0.40	0.15
Stearic acid** (GRADE-TGV-MP)	57	198.91	960	840	1600	2300	0.3	0.172

Manufactures: *Chennai Petroleum Corporation Ltd., Chennai, India; ** Sree Rayalaseema Alkalies and Allied Chemicals Ltd., Kurnool, A.P, India

The amount of HTF flowing in the system is noted by means of a flow meter (item 7 in fig. 1) of an accuracy of 0.5 lph. Mass flow rates of HTF at 2, 4, and 6 l/min. are used in the experiments. The flow is controlled by the control valves (items 5 and 6 in fig. 1) arranged in the flow line at inlet and outlet. A single stage centrifugal pump (item 4 in fig. 1) is employed to circulate the HTF through the storage tank. An insulated tank of 70 l capacity is used (item 1 in fig. 1) to supply water at constant temperature fitted with three electric heaters of 1 kW, 2 kW, and 3 kW capacity with thermostat control. The photograph of experimental set-up integrated with constant temperature bath is shown in fig. 2.

The variables studied include, different PCM, HTF inlet temperature and its flow rate. During the charging process, the HTF is circulated through the TES tank continuously. Initially, temperature of PCM capsule is 32 °C and as the HTF exchanges its heat en-

Figure 2. Photograph of TES tank with constant heat source

ergy to PCM, the PCM gets heated up to melting temperature (storing the energy as sensible heat). Later, heat is stored as latent heat once the PCM melts and becomes liquid. The energy is then stored as sensible heat in liquid PCM. Temperature of the PCM and HTF are recorded at intervals of 3 minutes. The charging process is continued until the PCM temperature reaches 70 °C.

Results and discussion

Charging process

The charging experiments are conducted considering the variables such as mass flow rate, different PCM and HTF inlet temperature.

Effect of HTF flow rate

Figures 3 and 4 depict the relation between charging time and the PCM temperature for HTF mass flow rates of 2, 4, and 6 l/min. when circulated from a constant heat source, with paraffin and stearic acid PCM, respectively.

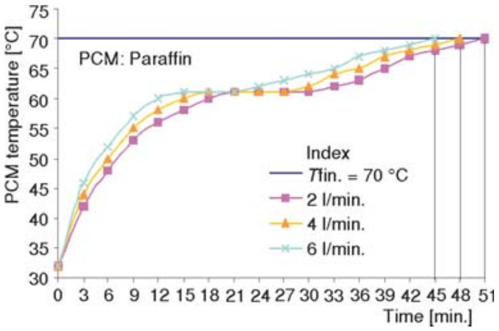

Figure 3. Effect of mass flow rate (HTF) on charging time (x/L = 1.0)

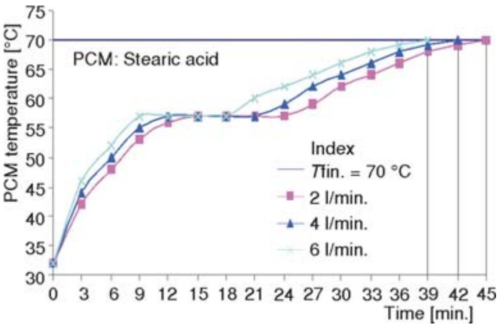

Figure 4. Effect of mass flow rate (HTF) on charging time, (x/L = 1.0)

It can be observed that the rate of rise of PCM temperature is high initially due to high temperature difference between HTF and PCM (initial temperature is 32 °C). At the mass flow rate of 6 l/min. reduction in both the charging time and the phase change duration is seen. The variation in charging time is about 14% when varied from 2 l/min. to 6 l/min. of flow rate.

Effect of HTF inlet temperature

Figures 5 and 6 relate the charging time with PCM temperature of paraffin and stearic acid respectively. It may be noted that though the HTF temperature is varied from 66 to 70 °C for the purpose of making the comparison, the charging times needed to reach 66 °C is considered.

It may be observed that the PCM temperature rises rapidly with increase in HTF temperature. A temperature of 66 °C is reached in 36, 42, and 51 minutes when the inlet temperature is 70, 68, and 66 °C for paraffin as PCM (tab. 3). It may be seen that in 70% time paraffin reaches

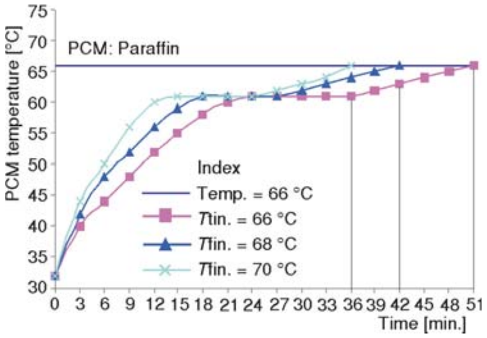

Figure 5. Time *vs.* PCM temperature for the different inlet temperatures (x/L = 1.0)

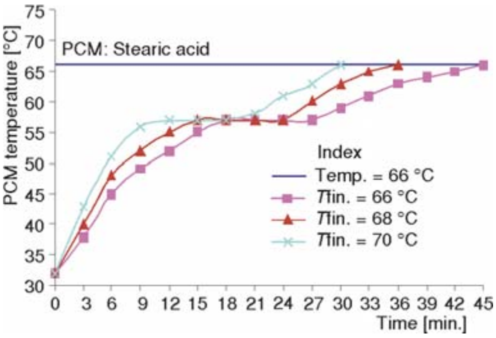

Figure 6. Time *vs.* PCM temperature for the different inlet temperatures (x/L = 1.0)

66 °C when inlet temperature is 70 °C, where as it takes 82% of time when the inlet temperature is 68 °C.

When Stearic acid is used as PCM, the time taken to reach 66 °C are 30, 36, and 45 minutes with the inlet temperatures 70, 68, and 66 °C respectively. In about 65% time and 80% time PCM reaches 66 °C, when the inlet temperature is 70 and 68 °C.

About 30% time could be saved for raising the PCM temperature to 66 °C when inlet temperature of 70 °C is employed irrespective of the PCM used.

Table 3. Effect of HTF inlet temperature

Inlet temperature In [°C]	Time needed to reach 66 °C of PCM	
	Paraffin	Stearic acid
66	51	45
68	42	36
70	36	30

Thermal histories

Figures 7 and 8 relate the charging time with PCM temperature and HTF temperature in TES tank at x/L = 0.25, 0.5, 0.75, and 1.0 when mass flow rate of 6 l/min., maintained at HTF inlet temperature of 70 °C, with paraffin PCM. It may be noted from the above that both the PCM and HTF temperature raise rapidly till the phase change temperature is attained. The temperature of the both PCM and HTF in the top segments is observed to be higher than in other seg-

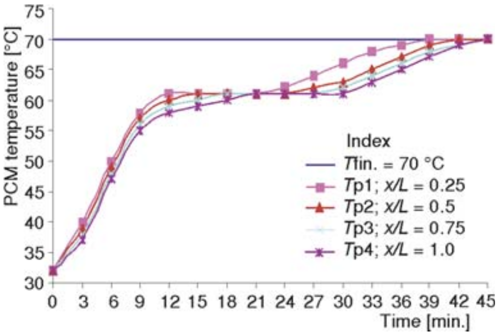

Figure 7. Time *vs.* PCM temperature with constant HTF inlet temperature (paraffin)

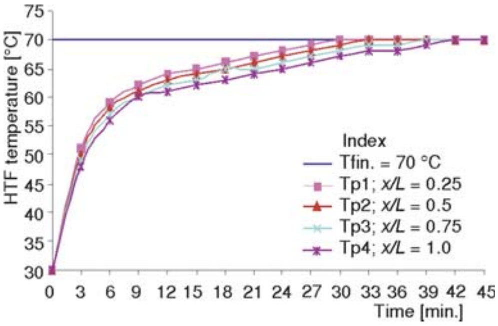

Figure 8. Time *vs.* HTF temperature with constant HTF inlet temperature (paraffin)

ments at any given time. However, in the later period the raise in temperature with time becomes slower. This is because during phase change, PCM absorbs thermal energy as latent heat and hence reduces the rate of raise of temperature of HTF.

From fig. 7, it may be observed that PCM temperature (in all segments of TES tank) increases rapidly till the phase change temperature is reached and remain constant during phase change and later the temperature of the liquid PCM raises gradually and attains HTF temperature. PCM temperature in the top segment attains charging temperature in 39 minutes where as 45 minutes are needed for charging the other segments.

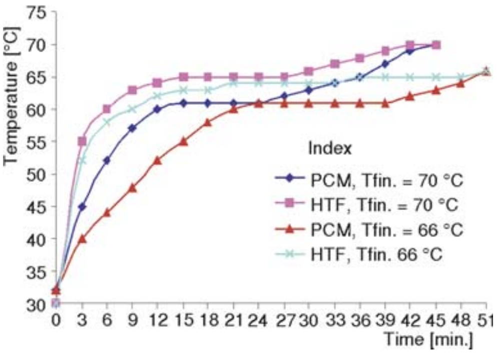

Figure 9. Variation of HTF and PCM temperature during charging process for two different constant HTF inlet temperatures (paraffin, *x/L* = 1.0)

In the top segment PCM not only reaches the phase change temperature early but also and the phase change is completed earlier.

Figure 9 shows the variation of both HTF and PCM temperatures with time at segment $x/L = 1.0$ for two constant HTF inlet temperatures ($T_{\text{fin.}}$ = 66 and 70 °C). The instantaneous amount of heat transfer to the PCM depends on the temperature difference prevailing between HTF and PCM at any given time.

During the temperature raise when PCM is solid, (sensible heat raise):

- temperature of HTF and PCM raise rapidly,
- HTF temperature is higher than the PCM temperature,
- the difference in temperature of HTF & PCM also increases with time.

During phase change period:

- rate of raise in HTF temperature is reduced.

After the phase change period:

- rate of raise of PCM temperature increases and attains that of HTF as time progresses.

In first stage PCM absorbs heat by conduction a slow process, In the second stage PCM absorbs latent heat and thus the rate of raise in HTF temperature is reduced. In final stage PCM absorbs heat by convection and the rate of heat absorption is more and finally attains the temperature of HTF. In this stage only sensible heat of PCM is increased.

Discharging process

The discharging experiments are carried out by batch wise method. This method of discharge permits the full extraction of heat from the storage tank. A quantity (20 l) of hot water is withdrawn from the storage tank and same amount of cold water is filled in to the storage tank. Withdrawn hot water is collected into an insulated drum and the temperature is noted and finally after collecting all the batches the average temperature of hot water is measured. Collection of water is made at 2, 4, and 6 l/min. However, the inlet to the TES tank is kept constant at 2 l/min., only. An optimum retention period of 20 minutes between batches is allowed. The batches of withdrawing hot water is continued till the out let temperature reaches 34 °C. The average temperature of the total withdrawn water is 45 ± 10 °C.

Effect of rate of water withdrawal from TES

Figures 10 and 11 show the batches of water collected *vs.* outlet water temperature. The outlet water temperature decreases gradually from 64 °C to 34 °C. The quantity of water collected at 2 l/min. and 6 l/min. flow rate is 156 l and 130 l, respectively.

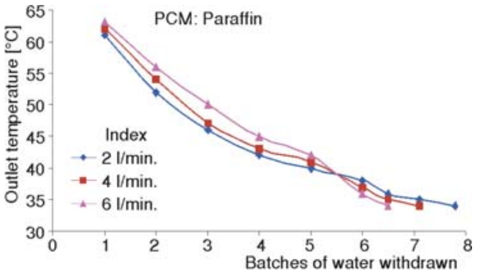

Figure 10. Effect on outlet water temperature (*x/L* = 1.0)

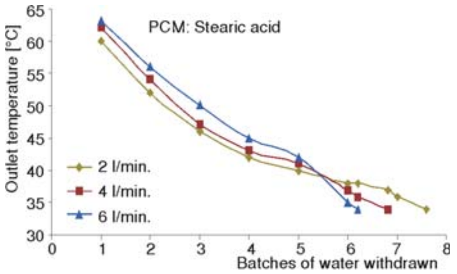

Figure 11. Effect on outlet water temperature (*x/L* = 1.0)

It is observed that:

- when the rate of water withdrawal is equal to the rate of water inlet to the TES system (2 l/min.), the outlet temperature of water is less compared to when the rate of withdrawal is more,
- total amount of water withdrawn before it attains 34 °C is more at lower withdrawal rates, and
- as the rate of withdrawal of water is increased, though the outlet water temperature is high, total amount of water that could be withdrawn is less.

This is because in a given period of time, when the rate of water withdrawn is equal to rate of filling the TES system, the system is kept full always, thus the outlet water temperature is less as total amount heat energy is distributed to full capacity of the system. However, sufficient time is given for the realization of both sensible and latent heat of water, at lower rates of withdrawal of water and more amount of water could be made available at 34 °C. As the rate of withdrawal of water is increased, the temperature of water withdrawn is high an expected, because at any given time, the tank never full.

Effect of phase change material

Figure 12 relates the results obtained with paraffin and stearic acid PCM using 2 l/min. withdrawal rate. It may be observed that the temperature of each batch of water withdrawn from TES is slightly higher with paraffin as PCM compared to stearic acid as PCM. Hence, total amount of water that could be withdrawn also is more with paraffin as PCM (156 lit as compared to 150 lit with stearic acid PCM).

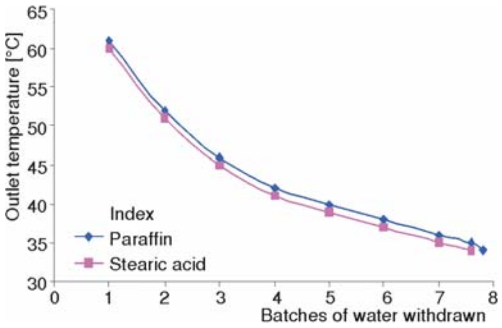

Figure 12. Effect on outlet water temperature (2 l/min.)

Economic reasons for employing/recommending a PCM: with initial cost of the set-up remaining the same, the cost per unit liter of water heating with paraffin as PCM is 1500/156 = INR 9.62 and with stearic acid it is 960/150 = = INR 6.4. Hence stearic acid recommend as the PCM as its cost for heating one litre of water is 33.47% less as compared to paraffin.

Conclusions

A TES system using the concept of combined sensible and latent heat is developed for the supply of hot water at an average temperature of 450 °C for various applications. Experiments were conducted on the TES unit to study its performance by integrating it with constant heat source. The variables studied include PCM, mass flow rate, and inlet temperature of HTF.

- PCM temperature gradually increases with time and remains constant during the phase change and continues to increase after the phase change before it attains charging temperature.
- The charging times can be reduced with increased mass flow rates of HTF (from 2 l/min. to 6 lit/min.).
- By increasing the HTF inlet temperature the charging times are reduced (66 to 70 °C).
- Stearic acid attains maximum temperature (equal to HTF inlet temperature) faster compared to paraffin (12% less). This is due to higher density of stearic acid compared to paraffin.
- From economic point of view, the stearic acid is recommended as PCM for TES system.

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Paper submitted: May 20, 2010
Paper revised: September 26, 2010
Paper accepted: November 16, 2010