EXPERIMENTAL INVESTIGATION OF THERMAL ENERGY STORAGE USING SPHERICAL PCM CAPSULES

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Abstract **-- Conventional fossil fuels on one hand are depleting and on the other, are creating pollution and spoiling the environment and hence the efforts to utilize various renewable energy sources are to be expedited. In countries like India, solar energy is a promising alternate source of energy. The major problem with solar energy is inconsistency between the supply and demand. The method of Thermal Energy Storage system used in the field of solar energy may fulfill the gap . TES technique is achieved by means of Sensible Heat Storage (SHS) and Latent Heat Storage (LHS).**

Several researchers focused to study and analyze the heat transfer of TES system using PCM . Phase change in spherical geometry is of great interest. Good amount of research work has been carried on the solidification and melting with in spherical enclosures. Spherical shapes exhibited the best heat released performance among the other investigated shapes.

In the present work it is proposed to study and analyze the solar TES with PCM encapsulated in spherical geometry. Line focusing concentrating collector are used under high mass flow rates with continuous circulation. Also as the part of study, the experiment have been conceived to carry out at different flow rates of inlet fluid and two types of PCM .

The present work investigates, experimentally the thermal performance of a packed bed combined sensible and latent heat storage unit integrated with solar heat source. The TES unit consists of paraffin/stearic acid as phase change materials filled in spherical capsules, which are packed in an insulated cylindrical storage tank. Water is used as sensible heat storage material (Heat Transfer Fluid) for transferring heat from solar parabolic collector. A series of charging (heat storage) experiments are conducted at variable inlet temperatures to examine the effect of heat transfer fluid inlet temperature, flow rate, phase change materials. Discharging (heat recovery) experiments are carried out by batch wise method of operation to recover the stored heat. The effect of incubation/retention time on HTF and PCM temperature during discharging process is also studied. The significance of time wise variation of HTF and PCM temperatures during discharging process is discussed in detail. The performance of the present system is compared with that of the storage system that uses flat plate solar collector as varying heat source .

It is observed that out of the two PCMs studied, stearic acid attains higher temperature (equal to HTF inlet temperature) faster compared to paraffin. It is also observed that the thermal energy retrieving time for system using parabolic solar collector is faster when compared with the system using flat plate collector as heat source . Also the system using parabolic solar collector can store large amounts of thermal energy .

***Keywords* -- Thermal energy storage (TES), Phase change material (PCM), Solar parabolic collector, Flow rates**

I. INTRODUCTION

Energy plays an important role in the existence of mankind. Due to continuous usage of fossil fuels their existence has become a question today. This situation has driven the human to search for alternatives that can be used easily and long lastingly. One of these types is the thermal energy storage system.

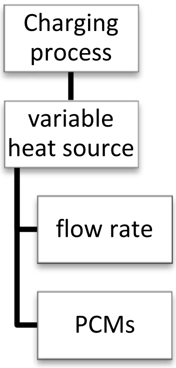
The basic types of TES techniques can be classified as Sensible Heat Storage and Latent Heat Storage. In the first case, where sensible heat storage is concerned, the temperature of the storage material varies with the amount of energy stored. Here, examples of water for heat storage in liquid based systems and rock bed in air based systems can be cited. Latent heat storage is an attractive technique since it provides a high energy storage density at a constant temperature, corresponding to the phase transformation temperature of the phase change material (PCM). This means that a much smaller weight and volume of material is needed to store a certain amount of energy.

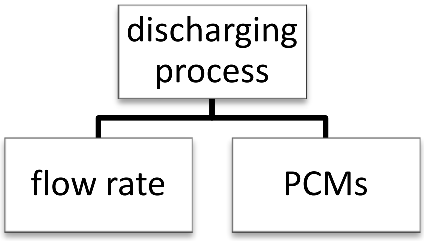
Thermal Energy Storage (TES) systems make use of phase change material (PCM) for efficient storage and release of energies.

Thus the TES systems facilitate use of thermal energy equipment for large scale energy substitution economically. Hence it is an alternate technology for meeting the energy needs and requirements effectively and efficiently.

A. Scope of work

A huge research work had been carried on analysis of SHS and LHS systems for solar energy storage for heating and cooling applications. However, studies on experimental investigation and performance evaluation of combined sensible and latent heat storage system for heating applications are only a few in the literature. After a detailed survey of the literature related to SHS and LHS systems, phase change materials, heat transfer analysis and applications, it is proposed to investigate the thermal performance of a packed bed sensible and latent heat storage .A critical analysis of the literature survey reveals that investigations are done in bits and pieces to satisfy certain goals. The present work attempts to experimentally investigate the variables such as size of the types PCMs in a single system .The system used in the present investigation experiment consists of packed bed combined sensible and latent heat storage unit integrated with solar heat source. The TES unit proposed in this work contains paraffin and stearic acid as PCMs filled in spherical capsules. These are packed in an insulated cylindrical storage tank. Water is used as SHS material (HTF) for transferring heat from variable temperature source such as parabolic solar collector. Series of charging (heat storage) experiments are conducted at constant and variable inlet fluid temperatures to examine the effects of HTF inlet temperature, flow rate, PCMs, on the performance of the TES unit. Discharging (heat recovery) experiments are carried out by batch wise method of operation to recover the stored heat. The effect of incubation/retention time on HTF and PCM temperature during discharging process is also studied. The significance of time wise variation of HTF and PCM temperatures during discharging process is discussed in detail. The scheme of study conducted in the present experimental investigation on the performance of TES system is as given below





II. EXPERIMENTAL SETUP AND DESIGN DETAILS

A thermal energy storage system is designed and evaluated for its thermal performance keeping in mind that the system should be able to supply hot water at an average temperature of 45°C for domestic use in general. The thermal performance of the system is investigated by integrating with variable inlet heat source (parabolic solar collector). Both charging and discharging experiments are carried out for evaluating the performance of the system.

The thermal performance of the system is evaluated based on the heat energy retrieval from the system. In the process the effect of following variables are studied,

- Phase Change Material (PCM):
  - a. Paraffin (type-II), and
  - b. Stearic Acid.
- Mass flow rates of Heat Transfer Fluid (HTF):
  - a. 2 lit/min ,
  - b. 4 lit/min, and
  - c. 6 lit/min.

All above variables are studied in two different stages

1. Charging process
2. Discharging Process

A. Experimental setup

A storage system is designed with a heat capacity of 10,000 KJ. This storage system is expected to supply about 160 lit of water at 45°C±1 temperature.

Figures 2.1 & 2.2 show the set-up used in the study of thermal performance of TES system using latent heat and sensible heat of the PCMs (commercial grades of paraffin and stearic acid). Investigations are carried out by integrating this storage system with variable heat source (parabolic solar collector). To meet the above requirement a cylindrical tank of 51 liters capacity is used, dimensions are Φ360 X 504 mm .Thermal performance is good for aspect ratio less than 3.0. In the present investigation as aspect ratio of 1.4 is chosen as Φ360X504 mm tanks are readily available in the market.

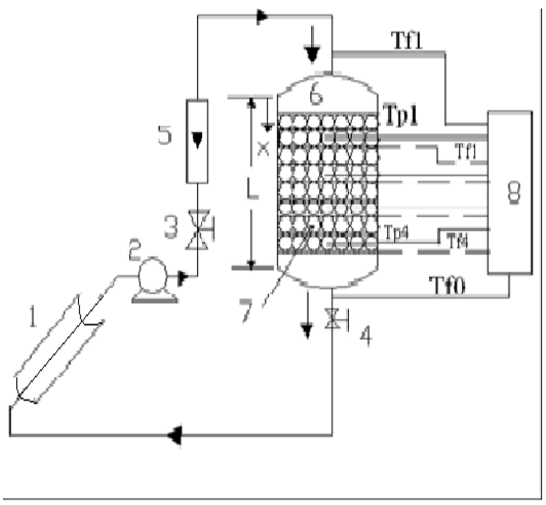
For the purpose of registering the temperature of HTF and PCM thermo couples (Pt 100) are located along the axis of the tank. For this purpose four (different sets of) temperature detectors having an accuracy of ± 0.1°C are located at x/L =0.25, 0.5, 0.75 and 1.0 (L is length of the TES tank in mm; x is 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) for measuring temperature of HTF. Thermo couples are also inserted inside the spherical capsules for measuring the temperature of the PCM. 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 located for measuring the inlet and outlet temperatures of HTF. These thermocouples are connected to a digital temperature (3 1/2 digit) indicator through a 12 point selector switch.

Assuming that 33% of heat capacity is stored as sensible heat (by HTF) and 67% as sensible heat and latent heat by PCM, the amount of PCM is estimated as 20 kgs for filling the spherical capsules. The discussion to go for spherical capsules is influenced by the conclusions drawn by G.A.Lane (1986) , Saitosh(1983), Saitosh and Hirose (1986) and jinjia wei et al (2005),through their numerical and experimental investigations . The details of encapsulated spherical capsules are:38 mm diameter of HDPE (high density polyethylene) balls.

To fill the capsule with PCM, a hole of size 8 mm diameter is made on each spherical capsule. The PCM heated to liquid state is transferred into the spherical capsule up to 90% of its volume. The filling hole is then closed with parent capsule material. Enough care is taken to prevent leakage of PCM material in liquid state. The capsule filled with PCM is immersed for 30 mins in hot water at 95^{o}C to check for leakages . Faulty capsules are rejected.

The number of spherical capsules used for accommodating 20 kgs of PCM in 38 mm diameter of ball is 870 for paraffin type II and 830 for stearic acid.

It is 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 amount of HTF flowing in the system is noted by means of a flow meter (item 7 in Fig. 2.1 a) of an accuracy of 0.51ph is included in the system. Mass flow rates of HTF at 2, 4 and 6 lit/min are used in the experiments conducted. The flow is controlled by the control valves (item 5 & item 6-Fig.3.1) arranged in the flow line at inlet and outlet. A single stage centrifugal pump is employed to circulate the HTF through the storage tank.



1. Parabolic solar plate collector 2. Pump 3 & 4. Flow control valves 5. Flow meter 6. TES tank 7.PCM Capsules; 8. Temperature indicator, T_p & Tr: Temperature sensors (RTDs)

Fig. 2.1 Schematic diagram of experimental set up

Fig 2.2 Photographic view of experimental setup

A parabolic solar collector of 2.5 m^2 area is used to supply the HTF to the storage tank. The collector inclination with horizontal is maintained at 0^o , equivalent to the latitude of the work place (chittoor). it is oriented facing due south. Depending upon the time of the day and the temperature of ambience, the temperature of the HTF varies . Thus variable temperature of HTF is provided by means of a parabolic solar collector. Fig. 2.2 shows parabolic solar collector along with TES system .

B.Experimental procedure

1) Charging process

The heat is transferred to or from HTF as it flows through the voids in the bed. During charging the hot HTF is circulated through the tank by the pump employed in the circuit. The PCM inside the capsules absorbs latent heat and melts. The difference between the mean temperature of HTF and PCM must be sufficient to obtain a satisfactory rate of heat transfer.

The supply water temperature to the parabolic solar collector is around 32°C. However, when the experiments are conducted on different days, the supply water temperature could not be controlled exactly at 32°C. But once the HTF from solar collector attains 38°C the experiment for charging the TES tank is started, so that the effect of inlet temperature to parabolic solar collector has no influence on the experiment. HTF is supplied through the parabolic solar collector during charging process. Referring to Fig. 2.1, through the inlet valve 3 hot water (HTF) is sent to TES tank at the given flow rate. Initially the outlet valve 4 is kept closed till the TES tank is filled. During this process at various levels (as mentioned earlier) the HTF temperature and PCM temperatures are noted. After the tank is full, the outlet valve 4 is opened and adjusted such that the water level in the tank is maintained constant. The circulation of HTF is continued at a given flow rate (2, 4 and 6 lit/min), till the same (HTF) temperature is attained by the PCM (all segments in the TES tank). Care is taken to conduct the experiments during hot season of the year so that the temperature of the HTF is above 70°C. The charging process is terminated once the temperature of the PCM reaches the temperature of the HTF, being circulated.

Initially the energy is stored in the PCM as sensible heat until the PCM reaches its melting temperature. As the charging process proceeds, energy storage (as latent heat) is achieved by melting the PCM at a constant temperature. Finally, the PCM becomes superheated. The energy is then stored as sensible heat in liquid PCM. Temperature of PCM (T_p) and HTF (T_f) at different locations of the TES tank is recorded at an interval of 5 min in the variable heat source method. This is because HTF is drawn from a solar collector and hence its inlet temperatures are expected to be in the range of 40-70°C.

2) Discharging process

The discharging process can be by continuous/batch wise process. However, it is reported in the literature that batch wise process is more effective where the requirement is intermittent (Nallusamy et al. 2006). During discharging HTF at room temperature from the load is circulated through the tank; at a fixed flow rate of 2 lit/min. However the hot HTF is withdrawn from the system at 2, 4 and 6 lit/min. A certain quantity of hot water (20 Lit) is withdrawn from TES tank and the tank is again filled with cold water of quantity equal to the amount of water withdrawn. This fixed quantity of 20 lit of water which is withdrawn from the TES tank to facilitate filling up of fresh cold water is termed as batch. After a time interval of 20 minutes allowing for transfer of energy from PCM, another batch of 20 lit of water is withdrawn from the TES tank. This process is continued until the average temperature of the complete amount of water withdrawn is about 45°C. Thus, the discharging experiments (energy retrieval) are carried out in batch wise process. During the discharging process also the temperature of HTF & PCM at various levels of the tank are noted at fixed intervals of time.

III. RESULTS AND DISCUSSION

The effective heat storage of TES tank is studied employing both paraffin and stearic acid as PCMs . Spherical shapes are used for storing the PCM with High Density Poly Ethylene (HDPE) as encapsulation material. Selection of best material for encapsulation of PCMs keeping in view the cost, durability, ease of handling and sustainability is reported.

The temperature distribution of heat transfer fluid (HTF, water which acts as sensible heat storage material) and PCM at various levels of the TES tank for different mass flow rates and HTF inlet temperatures is reported during storage and retrieval of energy from the TES tank.

The temperature histories of both HTF & PCM during the process of charging and discharging are reported in details .

Experiments are designed with the following variables for determining the performance of the PCMs employed.

- HDPE spherical capsule Φ38 mm,
- Paraffin and Stearic Acid,
- During charging mass flow rates 2,4 and 6 lit/min were used,
- At inlet flow rate 2 lit/min, and outlet flow rates are varied (2, 4 and 6 lit/min) during discharging.
- Temperature histories of both PCMs arid HTF at various levels of the TES tank are reported using HDPE spherical capsule size 38 mm diameter.

A. Charging process

1) Effect of flow rate

The experiment is carried for different flow rates like 2lit/min , 4 lit/min and 6 lit/min the effect of this flow rate on heat transfer is illustrated using the graph shown in figs 3.1 and 3.2 . fig 3.1 refers when paraffin is used as PCM and fig 3.2 refers when stearic acid is used as PCM

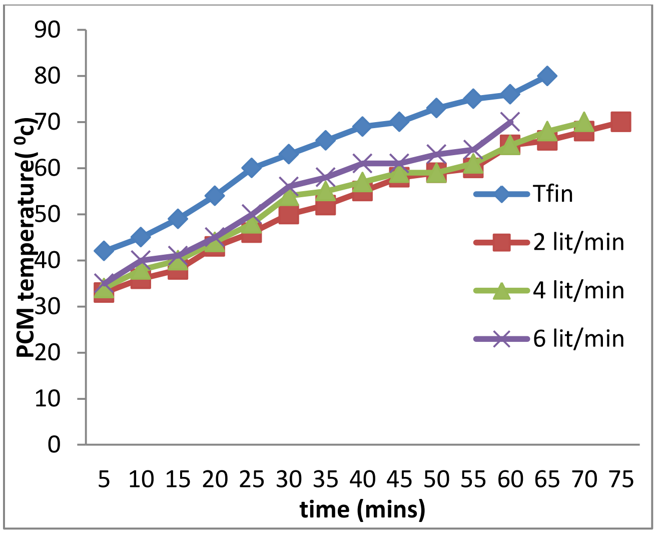


Fig 3.1 Effect of mass flow rate of HTF on charging time (Φ38mm , X/L=1 , paraffin)

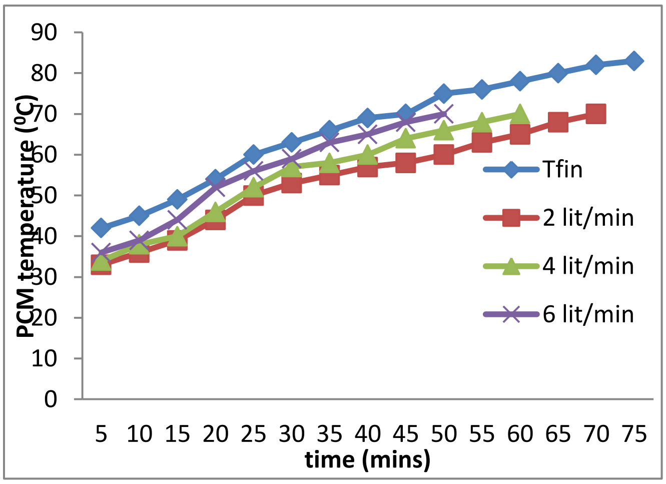


Fig 3.2 Effect of mass flow rate of HTF on charging time (Φ38 mm , X/L=1 , stearic acid)

It is observed from the above that the charging time charging time decreases with the increase in mass flow rate from 2 to 6 lit/min. This is because as the mass flow rate is increased , the thermal energy supplied to the TES tank through HTF in a given time increases and as there always exists a temperature difference between HTF and PCM. This causing reduction in charging time with increased mass flow rates .

It is seen from the above graphs that the time taken for rising the PCM temperature material to phase change temperature is around 25-30% of the total time of charging. The time taken for melting the PCM material is around 45-50% , the time taken to rise above the melting temperature is around 15-20%

2) Temperature histories

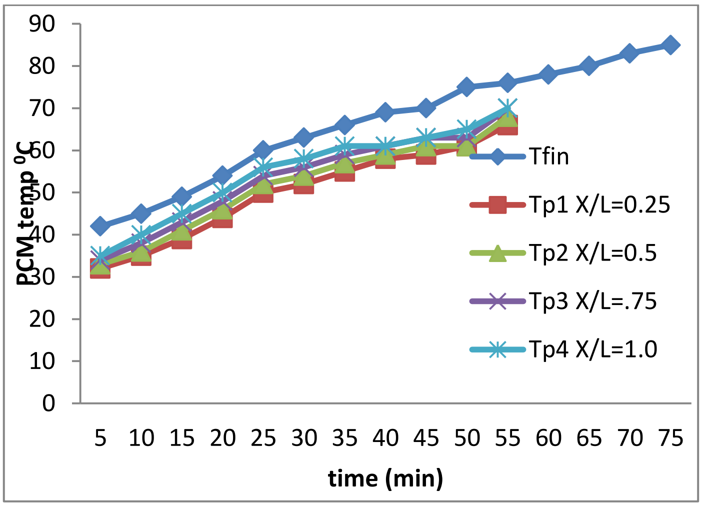


Fig 3.3 temperature histories of PCM during charging process (Φ38mm , paraffin , 6 lit/min)

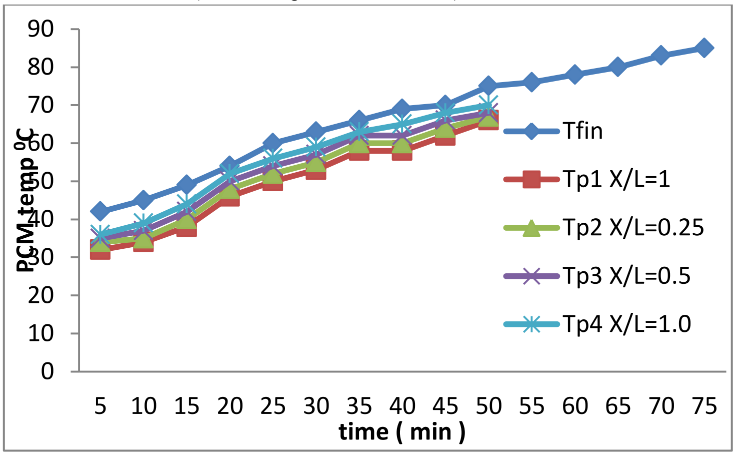


Fig 3.4 temperature histories of PCM during charging process (Φ38mm , stearic acid , 6 lit/min)

The temperature distribution of HTF and PCM in four segments of the TES tank, i.e., at x/L =0.25, 0.5, 0.75 and 1.0 is shown in Figs.3.3 and 3.4 (L is length of the TES tank, mm; x is axial distance from the top of the TES tank, mm; x/L is the dimensionless axial distance from the top of the TES tank). Figure 4.3 represents the temperature variation of PCM during the charging process for mass flow rate of 6 lit/min and paraffin as PCM. It may be noted from the above that the PCM temperature (T_p) increases gradually at the beginning of the charging period, remains nearly constant around 61°C during melting process and increases sharply during heating of liquid PCM. The PCM in the first segment (x/L=0.25) is completely charged, is 72% of the total charging time. This charging process is terminated when the PCM temperature in all segments reaches 70°C.

Figure 3.4 represents the temperature variation of the HTF inside, the storage tank for mass flow rate of 6 lit/min and stearic acid as PCM. It is observed from figure 4.4 that the temperature of the HTF at all segments increases gradually until it reaches the temperature of 62°C and then remains nearly constant around for a period of minutes during which the PCM undergoes phase change. Consequently HTF temperature (Tr) increases up to 72°C. It is also observed from figures 3.3 and 3.4 that there is no significant temperature difference between the segments of the storage tank during the sensible heating of the solid PCM and also during phase change period.

The reason being the water temperature in the storage tank and PCM temperature increases gradually in accordance with HTF inlet temperature (Tr_m) supplied from the solar collector. Thermal energy absorbed by the HTF through solar collector is a time consuming process and very slow. Thus sufficient time is given for the raise in temperature of HTF and PCM in all segments of TES tank. Thus significant temperature difference in various segments is not noticed. It is possible to reduce the charging time further by increasing solar collector surface area.

3) Effect of PCM

Figure 3.5 shows the relation between charging time and PCM temperature for paraffin and stearic acid. The charging time of stearic acid is 12% less compared to that of paraffin. This is due to the influence of thermal properties of stearic acid.

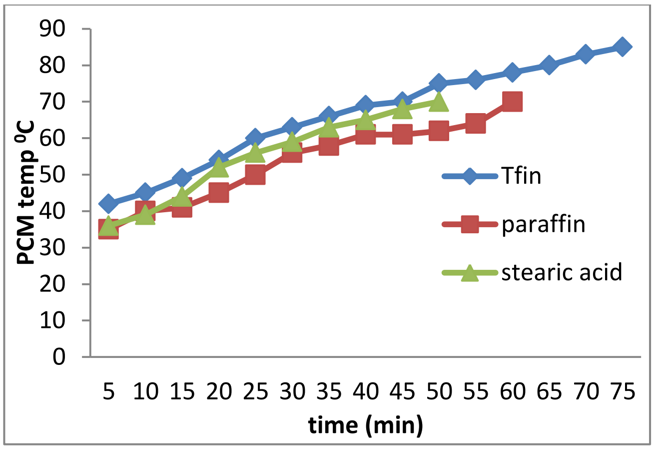


Fig 3.5 Effect of PCMs on charging time for variable HTF inlet temperature (Φ38 mm , 6 lit/min , X/L=1.0)

B. 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. In this case a quantity (20 Lit) of hot water is withdrawn from the storage tank and same amount of cold water is filled in the storage tank. Withdrawn hot water is collected into an insulated drum the temperature is noted and finally after collecting all the batches the average temperature of hot water is measured. Collection of 20 liter batch of water is made at 2, 4 and 6 lit/min in a particular set of experiments. However, the inlet to the TES tank is kept constant at 2 lit/min only and once the inlet water into the tank is equal to the water withdrawn (20 lit), the inlet is stopped. The 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.

1) Effect of flow rate

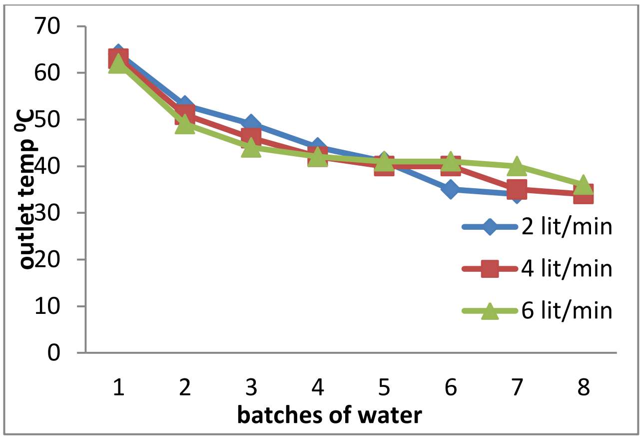


fig 3.6 variation of output(lit) for different mass flow rates paraffin as PCM (HDPE , Φ38mm)

Figures 3.6 and 3.7 show the batches of water collected Vs temperature. The temperature of water discharged decreases gradually from 64°C to 34°C. The quantity of water collected at 2 lit/min and 61it/min flow rate is 156 lit and 130 lit respectively. It shows that the temperature of water collected at 21it/min is less than the temperature of water collected at 61it/min. Higher outlet temperature of water is achieved at a withdrawal rate of 6 lit/min due the time given for mixing of cold water is less.

It is observed from the figure 3.6 that a total of 156 lit of water is collected (before the outlet temperature drops to 34°C) at 2 lit/min and it is 130 lit at 61it/min. The average temperature of water withdrawn is 45°C at 21it/min and it is 46.5°C at 6 lit/min.

Hence, it may be concluded that water collected at 21it/min is able to extract more thermal energy from the TES tank compared to other rates. This is due to for collecting 20 lit (batch size) 10 minutes is needed at 21it/min and at 61it/min it needs only 3.5 minutes. During the slow process of withdrawal, more time is given for heat extraction from PCM to HTF.

The higher mass flow rates of with drawl viz., 6 lit/min and 4 lit/min results good convection heat transfer consideration in the storage tank and by the end of 5th batch considerable amount of heat stored in PCMs are withdrawn. By the 6th batch of withdrawal it is noticed that the outlet temperatures are sharply falling in cases of 6 lit/min and 4 lit/min results crossing over the temperature profiles of 2 lit/min case.

The output results when stearic acid is used as PCM are shown in figure 3.7. The difference is not significant.

The same could be observed from figure 3.8 which relates the results obtained with paraffin and stearic acid PCMs using 2 lit/min withdrawal rate. The Temperature of each batch of water withdrawn and thus the average temperature of the water withdrawn is slightly more when paraffin is used as PCM compared to the case where stearic acid is used as PCM. But the difference is not appreciable.

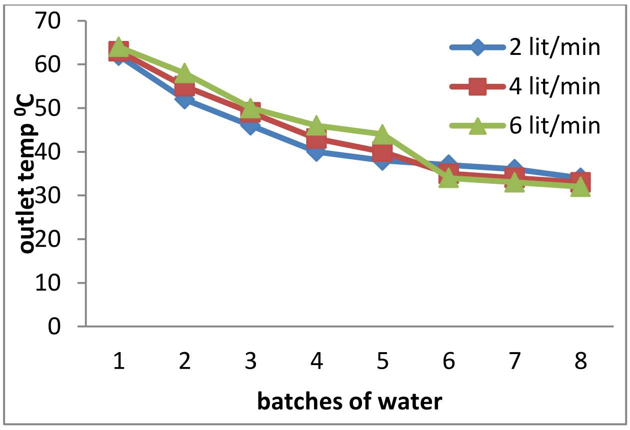


fig 3.7 variation of output (lit) for different flow rates stearic acid as PCM (HDPE , Φ38 mm)

2) Effect of PCMs

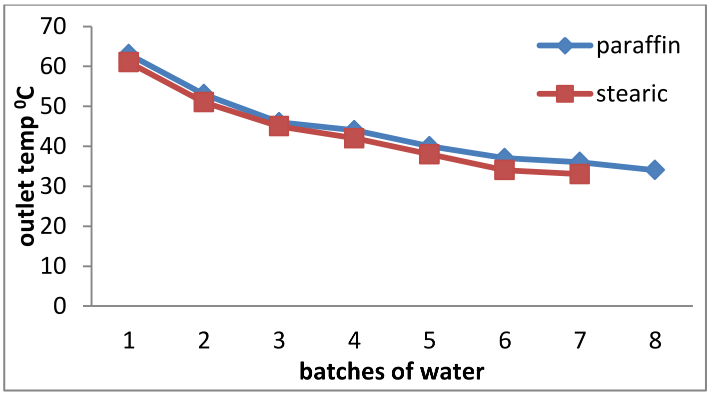


fig 3.8 variation of outlet (lit) for the different PCMs (HDPE , Φ38mm , 2 lit/min)

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 is recommend as the PCM as its cost for heating one litre of water is 33.47% less as compared to paraffin.

IV. CONCLUSIONS

A thermal energy storage system using the concept of combined sensible and latent heat is developed for the supply of hot water at an average temperature of *45°C* for various applications such as solar water heating, air heating, solar cooking, building applications, printing on the cotton cloths and dying the threads and kitchen purpose etc. Experiments were conducted on the TES unit to study its performance by integrating it with variable heat source (parabolic solar collector). The variables studied include PCMs, mass flow rate, and inlet temperature of HTF, on the performance of TES. The conclusions drawn from the experiment are listed below

- 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 .
- Out of the mass flow rates employed (2, 4 and 6 lit/min) it is observed that the mass flow rate 2 lit/min requires more charging time than other mass flow rates. Hence, it is concluded that by increasing the mass flow rate, the charging times can be reduced.
- Out of the HTF inlet temperatures employed, it is found that at 66°C, the charging times needed are more compared. Hence, it is concluded that by increasing the HTF inlet temperature the charging times are reduced.
- Both the temperatures of PCM and HTF along axial direction of TES tank raise rapidly till phase change temperature is attained during charging. However, both the PCM and HTF reach higher temperatures in the topmost segment of TES tank earlier.
- Availability of water of high temperature at the top of the TES tank and water of a lower temperature at bottom of the tank is known as thermal stratification. Thermal stratification in HTF is observed till the phase change temperature of PCM is attained. Thermal stratification is observed first in the top segment of TES tank and later proceeds to other segments. The existence of thermal stratification improves both system efficiency and solar collector efficiency.
- A similar trend (thermal stratification) also is found to exist in the PCM during sensible heating period and is not noticeable during the phase change.
- The mass flow rate has significant effect on **charging** times when the TES tank is integrated variable heat source.
- Both the energy storage and energy retrieval are more in combined SHS and LHS system than conventional Sensible Heat Storage (SHS) system, while other parameters such as TES tank capacity and HTF temperature constant.
- Out of the two PCMs used in the experiments, stearic acid attains maximum temperature (equal to HTF inlet temperature) faster compared to paraffin (12% less).This is due to the phase change temperature and latent heat of stearic acid being less compared to paraffin.

Cost of heating 1 liter of water with paraffin as PCM is INR 9.62 where as it is INR 6.4 with stearic acid as PCM. Hence, stearic acid is recommended for use in thermal energy storage tank as PCM.

In the present analysis, paraffin and stearic acid are used as PCMs for combined (SHS+LHS) storage system. Such systems can be adopted where the requirement of heat is within the temperature range 50-75°C. For higher temperature applications suitable materials may be selected. Many applications are possible with the combined sensible and latent heat storage system such as waste heat recovery utilization, food preservation and air conditioning applications, electronic cooling etc. Each application requires careful attention in the selection of PCM material and the design of the storage system. Among the two PCMs used (paraffin and stearic acid), stearic acid as PCM is noticed to be better, because its maximum temperature is attained at a faster rate (12% lesser time) compared to that of paraffin. With stearic acid as PCM another advantage noticed is the amount of hot water with drawn is found to be 10% more.

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