Phase Change Material (PCM) Based Thermal Energy Storage with Hybrid Salts

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Abstract

Latent energy based Thermal energy storages have got attention in this era because they require lesser temperature variations, greater storage density and more suitable for solar assisted power plants. This study focuses on the performance of PCM based thermal energy storage system with hybrid inorganic salts for a solar power plant where peak temperature of heat transfer fluid (HTF) lies between 250ºC-300ºC. The system has been analysed in terms of charging/discharging cycle time and energy storage density. Selection of PCM, HTF is made according to requirement and effect of different parameters like flow rate, density and inlet temperature of HTF has been studied.

Results show that by increasing in flow rate from 0.1 kg/s to 0.5 kg/s enhanced rate of heat transfer and thermal energy storages from 1.35 kW to 1.6kW, and from 5 MJ to 7.5 MJ respectively has been achieved using H-220 as a PCM with Shell S-2 HTF. When inlet temperature of HTF is increased from 250 ºC to 300 ºC both the heat transfer rate as well as Energy storage capacity rises from values of 1.14 kW to 1.58 kW and 6 MJ to 8.2 MJ respectively for inlet temperatures of HTF.

Keywords:

Thermal Energy Storage, Encapsulated Phase Change Material, Latent Heat Thermal Energy Storage, hybrid salts Plus ICE H-220

Introduction:

Current day, the world is dependent mostly on fossil reserves to fulfil energy demands. However, rapid depletion of these reserves as well as their hostile nature for environment in form of greenhouse gases' emission, are reasons behind the need to introduce and develop Renewable energy technologies [1]. Solar energy, the most abundant renewable energy is available nearly everywhere on earth in form of solar flux and need greater area and more capital investment for exploitation. Another problem with solar energy along with different energies is their nature of discontinuity, which makes it essential to use a storage mechanism to compensate the difference between supply and demand [2]. Solar energy is being harnessed for power production in two forms: (I) direct conversion to electricity using photovoltaic panels, and (ii) thermal energy conversion technologies. Thermal energy conversion technologies are promising for their greater conversion efficiencies and wide applications [3]. Renewable energy resources are abundant on our earth but no attention in past has been paid towards their utilization for fulfilling energy needs on a larger scale. However current developments have introduced such systems for partial fulfilment of energy needs. All renewable energy resources inherently have intermittent nature and are spread in form of flux. Unlike conventional fuel fired power plants, a vast area is needed for their harnessing requiring greater capital investment and longer pay back periods. A storage is also necessary to fill demand and supply gap of such systems and to increase the capacity factor of power plants. Solar energy being the most abundant and clean resource on our earth deserves the most attention[3, 4]. Energy from solar radiations can be harnessed in two ways (I) by converting the electromagnetic radiation directly into voltage and current using photovoltaic panels, [5-8]and (ii) absorbing the radiation in active or passive systems in form of thermal energy which may subsequently be utilized for power generation, heating and cooling or many other applications[9, 10]. Of these, concentrated solar power technologies seems most promising as they offer greater Carnot efficiency and is implementable for very large-scale power generation to meet entire nation’s needs[11]. These include parabolic trough, solar dish, Fresnel reflectors, heliostat power tower and solar sterling engine. Recent years have shown exponential increase in use of solar power plants with thermal energy storages. Sensible heat based thermal energy storage systems have been developed in various forms and are successfully implemented in commercial power plants. Examples include two-tank and single-tank thermal energy storages[15, 16]. These storages incorporate an insulated tank (considered thermal battery) to store a high temperature fluid like molten salt. The shortcomings of these storages are: (I) since only sensible heat capacity is utilized, greater sizes and capital investment is necessary and a storage at a very large scale may be practically difficult, and (ii) greater temperature variations are observed with these storages.

Sensible heat-based energy storages have got commercial acceptance, however latent heat and Phase Change Material (PCM) based storages are more viable due to: lesser temperature variations, greater storage density, lesser capital investment needed, and more suitable for large scale power plants [12-14]. Using the latent heat capacity of a phase change material (PCM) of a suitable phase change temperature, would not only reduce the thermal battery size manifolds, but also greatly reduce the temperature variations because phase change occurs essentially at a constant temperature or in a narrow temperature range for some materials. Unlike sensible heat based thermal storages where the same fluid may play a role of both the heat transfer fluid and storage medium, latent heat-based storages incorporate a phase change material, a different heat transfer fluid and physical boundary between them. Shell and tube heat exchangers and other different designs may be constructed for PCM latent heat-based TES [17]. These systems have very slow charging and discharging rates due to low thermal conductivities of most phase change materials and limited heat transfer area. This low thermal conductivity is of most concern in discharging phase when molten PCM at surface solidifies first reducing further heat transfer[18]. Three methods may be adopted to solve this difficulty[13, 19]. First, encapsulating the PCM material in smaller containers would enhance heat transfer by reducing the barrier to heat transfer within the container[20-23]. Second heat transfer geometries like fins may be integrated with heat transfer surface for enhanced heat transfer rates[24]. Third, a composite PCM by mixing a high thermal conductivity material, would also enhance the heat transfer rate[25-29]. The first and third method is focus of current study, in which case the increased rate of heat transfer balances the additional cost of design and fabrication of capsules.

In a previous work[18], air has been used as heat transfer fluid. Considering the lower thermal conductivity of air compared with liquids, there is much room for enhancing the heat transfer characteristics. The main work in this research will be on selection of a liquid heat transfer fluid and hybrid inorganic PCM for the application of CSP plants, and design of a thermal energy storage for the selected HTF-PCM combination and experimental analysis of this

EPCM based thermal energy storage on the basis of design parameters. This study includes performance of an Encapsulated inorganic hybrid PCM (EPCM) based thermal energy storage system for different applications where HTF is as high as 200°C-400°C. The performance of this system has been tested in terms of charging/discharging cycle time and energy storage density. An analysis is performed to observe performance of this energy storage system for varying input parameter like input fluid temperature and mass flow rate. This work establishes effectiveness of inorganic hybrid EPCM based thermal energy storage (EPCM-TES)

Experimental setup

Experimental setup's two-dimensional view is shown in Fig.1. All components of experimental setupe are labeled to show their position .K-type thermocouple are used to measure the temperature reading inside and out side of capsule and also in the insulation. thermocouple inside the capsule are measuring the PCM temperature and are placed in the thermocouple well (TC) at specific distance.As this is pilot scale setupe and energy storage of PCM is being studied so three heaters of 6 KW used to heat the heat transfer fluid. To circulate the HFT from oil storage tank to the TES motor of 3 HP along with centrifugal pump is used and proper tubing is done from tank to the TES section. To avoid heat losses from the tubes to atmosphere these are also insulated with insulation as illustrated in Fig.2.

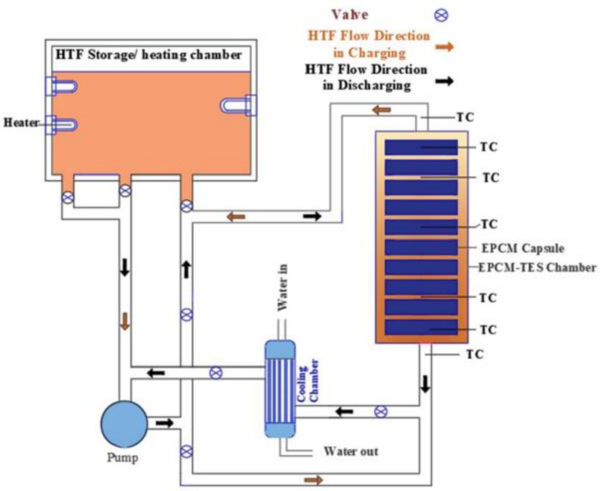


Figure 1 two-dimensional view of setup

This flow is controlled by multiple ball type flow control valves. Opening and closing of valves should be in proper order before and after the charging, discharging to avoid any accident. After charging is completed then heaters are switched off, valves arrangement is changed, and flow direction is reversed to get the heat energy from the TES which was stored in the capsules during the charging process. Length, diameter and other dimensions of capsule are taken according to the literature which Zheng et al explained in the paper [18].

Figure 2 Experimental setup

Figure 3 Data acquisition and recording system

Reading from thermocouples is collected by data acquisition system(DAQ) having 16 ports in each and two DAQ systems are used for the reading as shown in Fig.3. These two DAQ systems are connected to the computer by USB cable. This data is decoded by LabVIEW software and saved in the excel file. Complete setup view is shown in Fig.2 and 3. Figure.4 consists of the thermal energy storage (TES) of mild steel, inside of which 10 capsules of stainless steel are fixed with the help of supporting structure. TES is insulated with glass wool insulation with thickness 150 mm. All capsules contain PCM H-220 filled up to 80% space and 20% void space.

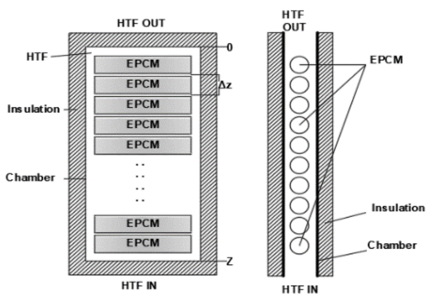


Figure 4(a) Capsules arrangement in thermal energy storage

Materials

For the current work, NaNO3-KNO3 (50:50, commercial name Plus ICE H220 obtained from PCM products limited was used as the PCM whereas Shell S-2 heat transfer oil was used as the HTF. The selection of PCM and HTF was based on desired thermophysical properties, availability and economic considerations for the geographical location of the apparatus. Tables 1 and 2 presents important thermophysical properties of these materials.

Material selection is made according to the operating conditions defined and H220 is selected as a PCM from PCM products limited which starts melting at 220°C and goes up to 390 °C. For exchange of heat from solar to PCM heating oil is used, which is Shell S-2 and can handle high temperature range.

Table 1: Properties of (NaNO3–KNO3 (50:50)[38]

PCM	**Phase Change Temperature**	**Density**	**Latent Heat Capacity**	**Specific Heat Capacity**	**Thermal Conductivity**	**Maximum Temperature**
	(°C)	(kg/m3)	(kJ/kg)	(kJ/kg K)	(W/m K)	(°C)
H220	220	2,000	100	1.515	0.515	390

Table 2: Properties of Shell-S2 oil[39]

Temperature	**(°C)**	**0**	**20**	**40**	**100**	**150**	**200**	**250**	**300**	**340**
Density	(kg/m^3)	876	863	850	811	778	746	713	681	655
Specific Heat Capacity	(kJ/kg.K)	1.809	1.882	1.954	2.173	2.355	2.538	2.72	2.902	3.048
Thermal Conductivity	(W/m.K)	0.136	0.134	0.133	0.128	0.125	0.121	0.118	0.114	0.111
Prandtl No.	(Pr)	3375	919	375	69	32	20	14	11	9

Results and Discussion:

It is important to validate the experimental results to determine how accurately, it predicts desired characteristics of EPCM-TES. The results of experiment are compared with the simulated results of EPCM-TES developed by Zheng et. al[18].

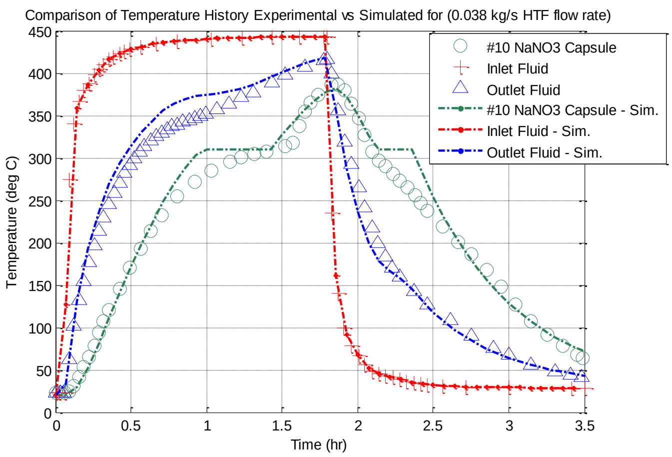


Figure 5 Temperature History Experimental and Simulated [18]

Effect of HTF Mass Flow Rate

Study of flow rate is made from 0.1 to 0.5kg/s to choose the optimum flow rate at which maximum energy can be stored in PCM. Mean while other parameters have taken constant. Based on results shown below it is found that thermal energy stored increased for range of flow and then decreased so an optimum flow rate is to be selected. At 0.3kg/s flow rate PCM melts and latent portion of heat is also obtained as shown in Fig 6(a) and inlet temperature variation is achieved up to 280^{0}C while on lower flow rates it reaches only to 250^{0}C at which PCM will not melt. Thermal energy stored is achieved to value of 9.5 MJ at higher flow rates and rate of heat transfer is also high at high flow rate but charging and discharging time is varied Fig(6.d)

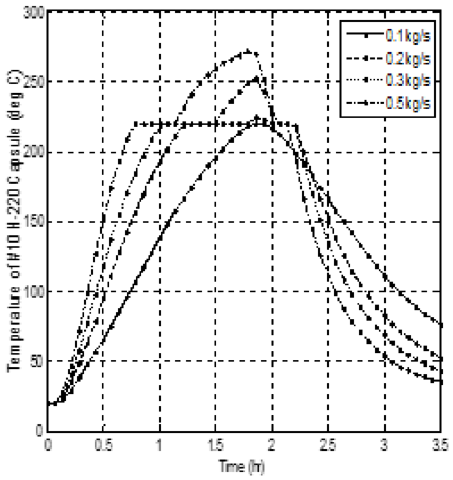


Figure 6(a)Temperature of #10 H-220 Capsule for different HTF flow rates

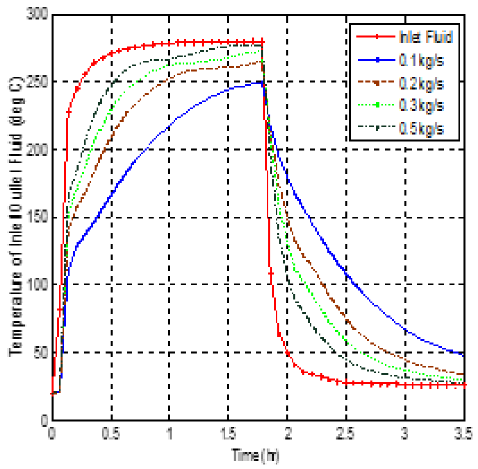


Figure 6(b)At Inlet and outlet temperature variations HTF for different flow rates

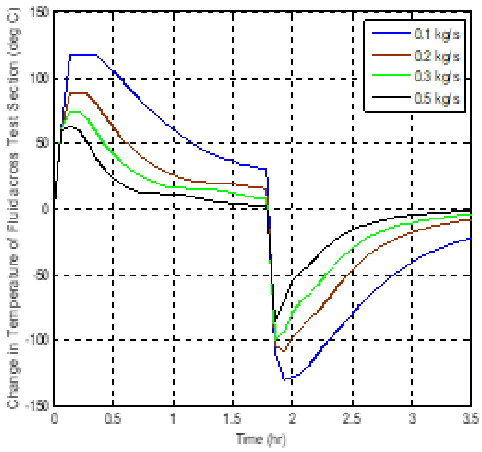


Figure 6(c)Change in temperature of HTF across the test section for different HTF flow rates

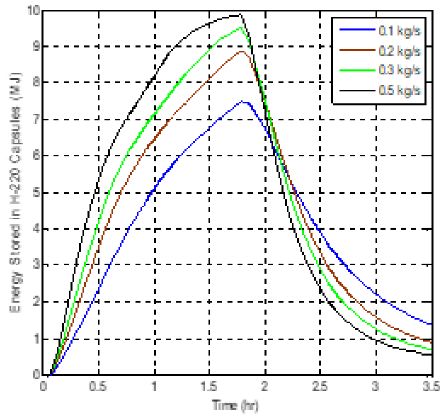
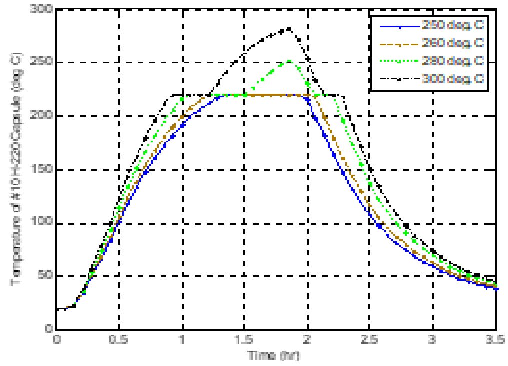


Figure 6(d)Thermal Energy Stored in H-220 Capsules for different HTF flow rates

Effect of HTF Inlet Temperature

The inlet temperature of HTF is changed from values: 250 ℃, 260 ℃, 280 ℃ and 300 ℃ for simulation (Fig.7). At start inlet temperature of HTF rises swiftly until it is reached to set value, and then remain constant until the charging half cycle is finished. The temperature then decreases quickly to a value initial condition at the starting of discharging cycle shown in Fig.7(a). This smooth variation in temperature is because of continuous nature of temperature function, which may have no jumps over time. Fig:7 shows the melting temperature of the PCM under observation lies at 220 ℃, the maximum of heat to the EPCMs occurs nearly about the melting temperature.



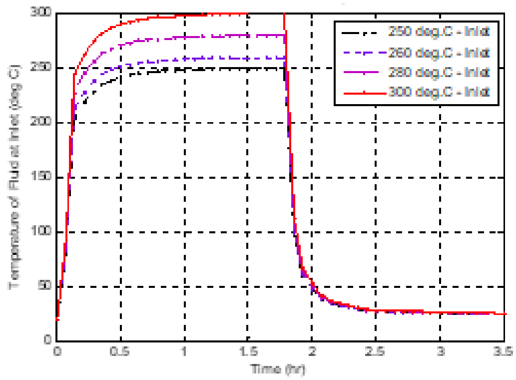
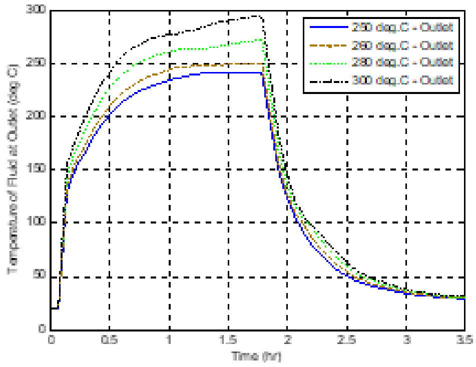


Figure 7(a)Temperature of #10 H-220 Capsule for different Fluid Inlet Temperatures

Figure 7(b)Variation of Fluid Inlet Temperature



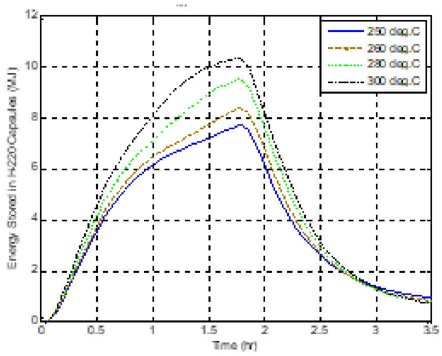


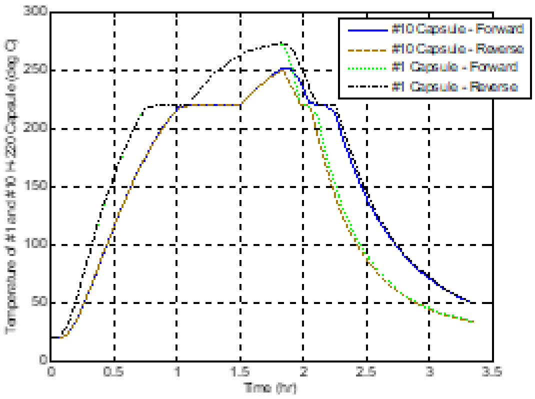
Figure 7(c)Temperature of HTF at outlet for different Fluid Inlet Temperatures

Figure 7(d)Thermal Energy Stored in H-220 Capsules for different Fluid Inlet Temperatures

Direction of Flow Effects in Discharging

To study direction of HTF on the overall system two directions have been chosen, one is forward in which both PCM and heating oil have parallelly heat transfer, while on the other hand reverse direction in which both have counter flow.

Figures 8 compares the two cases by means of variations in temperatures, heat transfer rate and amount of energy stored. By reversing the direction did not effect on the performance of system and the two cases showed same results overall.So there is no effect of reversing HFT direction of flow on system.



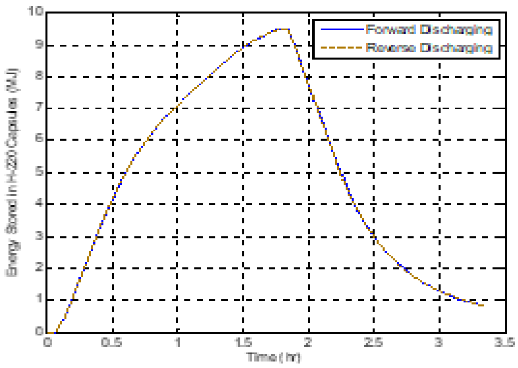


Figure 8(a)Temperature of #1 and #10 H-220 Capsule for different modes of Discharging

Figure 8(b)Thermal Energy Stored in H-220 Capsules for different modes of Discharging

Number of Capsules variation

The effect of changing number of capsules on EPCM-TES has been investigated using five, ten and fifteen number of capsules respectively inside the TES, while keeping other parameters same and in experimentation 10 capsules are used to get data. Figures 9 present, HTF inlet temperature, energy stored, heat transfer rate and percentage of energy captured by EPCMs from the HTF respectively for systems with different number of capsules. For systems with different number of capsules of same size the amount of PCM and thus the energy storage capacity is simply proportional to the number of capsules depicted in Fig. 9(a). Using greater number of capsules increases the time of charging and discharging and rate of heat transfer is also less in this case as shown in Fig.9(b).Likewise inlet and exit temperatures of the HTF also less for higher number of capsules but this difference is less prominent as shown in Fig.9(c).Change in temperature across the test section is higher for the greater number of the capsules which is beneficial for output gaining and it is shown in Fig.9(d).

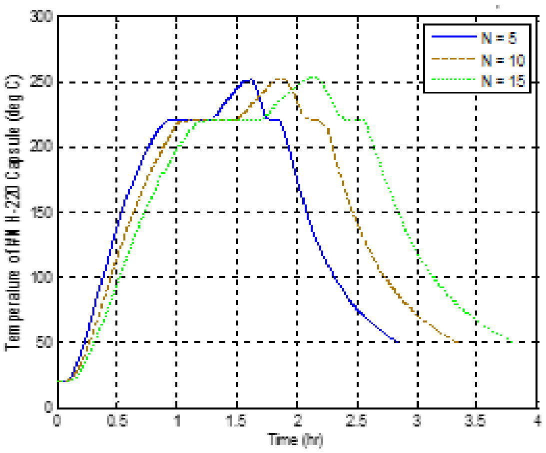


Figure 9(a)Temperature of #10 H-220 Capsule for different No. of Capsules

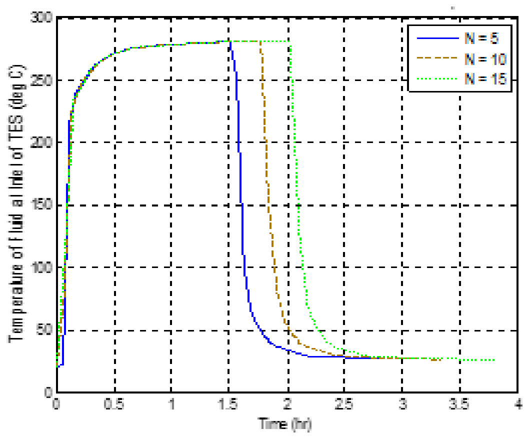


Figure 9(b)Temperature of HTF at Inlet for different No. of Capsules

Conclusion

The current study deals with the performance evaluation of EPCM-TES system for concentrated solar plant for medium temperature applications.The results of this research matched to the previously published[35] literature to greater extend.These experimental results are better than those for which air is used as HTF and single PCM is used without encapsulation. An inline arrangement of 10 EPCMs arranged vertically in a rectangular test section is taken for investigation. PCM obtained from UK is selected and Shell-S2 as Heat Transfer Fluid. Since this investigation considers use of EPCM-TES for CSP applications, the input parameters are selected those that vary as output of solar collector. The output fluid from solar collector is characterized by its Temperature and mass flow rate, which becomes input conditions for TES section. The performance of TES is evaluated by varying following input and design parameters:

- HTF mass flow rate 0.1 to 0.4kg/s.
- Temperature at inlet of fluid (250 ^oC, 260 ^oC, 280 ^oC and 300 ^oC)
- Flow direction during discharging in reversed to compare its effect with performance obtained without reversing flow direction
- Number of capsules (5, 10 and 15)

For investigating the effect of first two parameters, a pre-set charging-discharging cycle time of 3.5 hours is selected. While for rest three, a criterion is defined that is charging phase will be completed when #10 PCM capsule reaches a temperature of 250^oC because allowing the capsule temperature to rise even further won't have any count due to diminished heat transfer rate at elevated capsule temperatures compared with inlet fluid temperature of 280 ^oC.

Similarly discharging is said to end when temperature of last capsule reaches sufficiently close to cooler fluid inlet temperature.

The following conclusions are made from current investigations:

- The increase in flow rate from 0.1 to 0.5 kg/s enhanced heat transfer rate and thermal energy storages from 1.35 kW to 1.6kW, and from 5 MJ to 10 MJ respectively.
- However, it is found that enhancement of both parameters are less above the 0.3kg/s and therefore a best suited mass flow rate of 0.3 kg/s is used for further investigation of other parameters.
- When HTF temperature is increased from 250 ^{o}C to 300 ^{o}C both the heat transfer and storage capacity rises from values of 8 MJ, 8.4 MJ, 9.5 MJ and 10.2 MJ respectively for inlet temperatures of 1.14 kW 1.58kW and from 8 MJ to 10.2 MJ (21% increase).
- The trend in increasing both heat transfer rate as well as Energy stored in EPCM capsules is linear rise with increase in temperature. However, given stability limit of Shell S-2 HTF used under current investigation, the temperature cannot be increased beyond 300 ^{o}C. Use of a different fluid with greater upper temperature is therefore recommended in future investigation.
- The percentage of Energy from HTF that is stored in EPCMs remains intact at a value of 70% for any change in either mass flow rate or inlet temperature of heating oil.
- Although with increase in number of capsules from 5 to 10 Rate of heat transfer and Energy Storage capacity increase from 0.8 kW to 1.95 kW and from 4.8 MJ to 14.3 MJ respectively. However, this is accompanied with decrease in percentage of Energy from HTF that is stored in EPCM capsules from 75% to 72%.
- The charging-discharging cycle time also increase from 2.7 hours to 4.8 hours with increase in number of capsules from 5 to 10. Moreover, increase in number of capsules is not associated with any increase in Energy storage density, which remains nearly constant at a value of 0.29 MJ/kg.
- Therefore, whenever enhancement in thermal performance is sought, it is preferred to obtain this using increase in size of capsule rather than increase in number of capsules. Therefore, an enhancement in thermal conductivity of capsules using either fins, metal matrix or any other technique is highly recommended to enhance heat transfer rate and reduce charging-discharging cycle time.
- Finally, there is no effect of choosing to allow heat transfer fluid to flow in discharging phase either in like or un-like manner to that during charging phase. It is therefore un-necessary to do so.

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