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Study on performance of a packed bed latent heat thermal energy storage unit integrated with solar water heating system*

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Abstract: In thermal systems such as solar thermal and waste heat recovery systems, the available energy supply does not usually coincide in time with the process demand. Hence some form of thermal energy storage (TES) is necessary for the most effective utilization of the energy source. This study deals with the experimental evaluation of thermal performance of a packed bed latent heat TES unit integrated with solar flat plate collector. The TES unit contains paraffin as phase change material (PCM) filled in spherical capsules, which are packed in an insulated cylindrical storage tank. The water used as heat transfer fluid (HTF) to transfer heat from the solar collector to the storage tank also acts as sensible heat storage material. Charging experiments were carried out at varying inlet fluid temperatures to examine the effects of porosity and HTF flow rate on the storage unit performance. The performance parameters such as instantaneous heat stored, cumulative heat stored, charging rate and system efficiency are studied. Discharging experiments were carried out by both continuous and batchwise processes to recover the stored heat, and the results are presented.

Key words: Charging, Discharging, Heat transfer fluid (HTF), Latent heat, Phase change material (PCM), Packed bed, Thermal energy storage (TES)

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INTRODUCTION

Efforts of rational and effective energy management, as well as environmental considerations, increase the interest in using renewable energy sources, especially solar energy. Because of discrepancy between the energy supply and demand in solar heating applications, a thermal energy storage (TES) device has to be used for the most effective utilization of the energy source. Energy storage combined with solar collectors and photovoltaic systems have been developed over the years for homes and large buildings. Although these systems provide energy at a higher cost than fossil fuels, the main advantage is their limited impact on the environment and sustainability of the energy source.

The most commonly used TES methods are sensible heat storage (SHS) and latent heat storage (LHS). Much research work was carried out on SHS materials and systems in the past and the technology for their utilization was also well developed. However SHS systems have the following disadvantages: (1) low heat storage capacity per unit volume of the storage medium and (2) non-isothermal behaviour during heat storage (charging) and heat release (discharging) processes. On the other hand, LHS, with solid-liquid phase change, has received considerable attention due to its advantages such as storing a large amount of energy in a small volume, i.e., high storage density and heat charging/discharging at a nearly constant temperature.

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Several investigators have studied, theoretically and experimentally, the performance of TES employing phase-change material in various geometries. Most literature research on the LHS system is performed for the shell and tube configuration as well as the plate and frame system. Recently Trp (2005) carried out numerical and experimental investigation of transient heat transfer phenomenon during paraffin melting and solidification in a shell-and-tube LHS unit with water as heat transfer fluid (HTF). A mathematical model for non-isothermal phase transition has been developed based on the enthalpy formulation. Numerical prediction and experimental results are shown to be in good agreement.

A very limited number of studies on the energy storage in spherical capsules are found. Saitoh and Hirose (1986) performed theoretical and experimental investigation of the transient thermal characteristics of a phase-change TES unit using spherical capsules. The effects of variation in the capsule diameter, the flow rate of the HTF, the inlet temperature difference, the capsule material, and the PCM, on the thermal performance of this storage unit were studied in detail using computer simulation and compared with the experimental results of a prototype LHS unit with a capacity of 300 L. Ananthanarayanan *et al.*(1987) developed a computer model for the estimation of temperature profiles of the solid and the fluid along the length of the packed bed of self-encapsulated Al-Si PCM shots as functions of distance along the bed and time during a series of heat storage and utilization cycles. Air was used as HTF in their study. Beasley and Ramanarayanan (1989) developed a computational model to study the transient thermal response of a packed bed of spheres containing a phase change material using one dimensional separate phases formulation. Results from the model were compared with the experimental results of a commercial size thermal storage bed packed with polypropylene spheres containing paraffin wax for both the energy storage and recovery periods using air as HTF.

Chen and Yue (1991) developed a 1D porous-medium model to determine the thermal characteristics of ice-water cool storage in packed capsules for air conditioning. Comparisons of this theory with experimental data of temperature profiles of PCM (water) and coolant (alcohol) for various porosities, flow rates and different inlet coolant temperatures showed good agreements. Sozen *et al.*(1991) investigated the TES characteristics of an SHS and an LHS packed bed consisting of a horizontal channel filled with randomly packed particles of PCM encapsulated spherical capsules. The HTF was refrigerant-12, which was modelled as an ideal gas. The SHS material used was 1% carbon-steel and PCM was myristic acid. Ismail and Stuginsky (1999) presented a comparative study on six possible models for fixed bed storage systems for PCM and sensible heat storage. The models were first evaluated regarding the computational time consumed to solve a specific test problem, then compared with regard to the influence of particle size, void fraction, particle material, flow rate variations, HTF inlet temperature variations and finally the wall thermal losses.

Ismail and Henriquez (2002) presented a numerical model to simulate the process of heat transfer (charging and discharging) in an LHS system of packed bed of spherical capsules filled with PCM (water). The effect of HTF (ethylene glycol) entry temperature, the mass flow rate and material of the spherical capsule on the performance of the storage unit were investigated numerically and experimentally. Barba and Spiga (2003) analysed the behaviour of encapsulated salt hydrates used as PCM in a heat transfer system of a domestic hot water tank employing three different geometrical configurations of the PCM containers. Their study showed that spherical capsules yielded the largest energy density and the most rapid charge and release times, when compared against the slab or the cylindrical geometry. Ettouney *et al.*(2005) presented a detailed picture of the temperature field inside the PCM encapsulated spherical capsule during melting and solidification processes using paraffin as PCM and air as HTF. The results indicated that the Nusselt number for melting has strong dependence on the sphere diameter, lower dependence on the air temperature and negligible dependence on the air velocity. Works in the related area (i.e. energy storage in spherical capsules) are also reported by Prudhomme *et al.*(1989) and Cho and Choi (2000). He *et al.*(2004) used the liquid-solid phase diagram of the binary system of tetradecane and hexadecane to obtain information on the phase transition processes and differential scanning calorimetry to determine the thermo-physical properties of the binary system. They presented a reliable method to incorporate both the heat of phase change and the temperature range of paraffin by combining phase equilibrium considerations with DSC measurements.

A very limited number of studies are found on the thermal performance of LHS systems (employing PCM in various geometries) integrated with solar heating applications. Fouda *et al.*(1984) studied the characteristics of Glauber's salt as an LHS medium in solar storage system. The effect of several variables was studied over many complete cycles of the unit, including variable HTF flow rate and inlet temperature, wall thickness, etc. Bellecci and Conti (1993), using enthalpy method, numerically studied the cyclic behaviour of a phase change solar shell-and-tube energy storage system. Esen *et al.*(1998) numerically investigated the thermal performance of solar water heating systems integrated with cylindrical LHS unit using various PCMs. Mehling *et al.*(2003) presented experimental and numerical simulation results on the energy storage density of solar hot water system using different cylindrical PCM modules. Their results showed that adding PCM modules at the top of the water tank would give the system higher storage density and compensate for heat loss in the top layer. Thermal performance of LHS systems integrated with solar heating systems were also investigated in (Ghoneim *et al.*, 1989; Hoogendoorn and Bart, 1992; Bansal and Buddhi, 1992).

The objective of the present work is to study the thermal performance of a packed bed latent heat thermal energy storage unit integrated with solar water heating system. The packed bed contained encapsulated PCM in spherical capsules, surrounded by SHS material. Parametric studies were carried out to examine the effects of porosity and HTF flow rates on the performance of the storage unit for varying inlet fluid temperatures. Discharging experiments were carried out by both continuous and batchwise processes to recover the stored heat.

EXPERIMENTAL INVESTIGATION

Experimental setup

The schematic diagram of the experimental setup shown in Fig.1 consists of an insulated cylindrical TES tank containing PCM encapsulated spherical capsules, solar flat plate collector, flow meter, and circulating pump. A photographic view of the experimental setup is shown in Fig.2. The 360 mm diameter and 470 mm height stainless steel TES tank has a capacity of 48 L to supply hot water for a family of 5~6 persons. There are two plenum chambers on the top and the bottom of the tank and a flow distributor is provided on the top of the tank to achieve uniform flow of HTF. The storage tank is insulated with 50 mm thick glass wool. The 55 mm outer diameter of the spherical capsule is made of high-density polyethylene (HDPE) with wall thickness of 0.8 mm. The total number of capsules in the TES tank is 264 for the case with porosity ε=0.49 and 209 for the case with porosity ε=0.61. The spherical capsules are uniformly packed in eight layers each supported by wire mesh. When ε is 0.49, the PCM capsules occupy 51% of the storage tank total volume and the remaining volume is occupied by SHS material. Paraffin is used as PCM with melting temperature of 60±1 °C and water is used as both SHS material and HTF. The thermo-physical properties of paraffin are given in Table 1 and the specifications and heat storage capacity of the storage tank are given in Table 2.

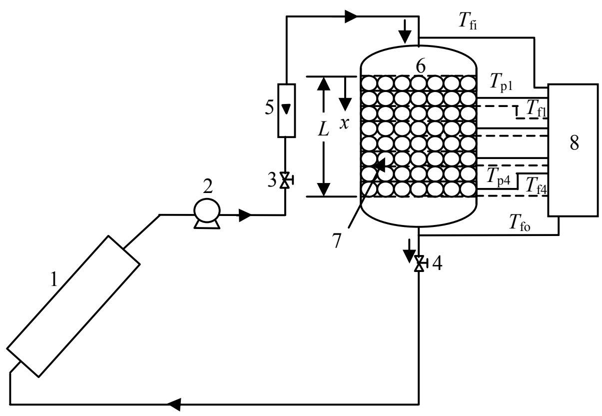
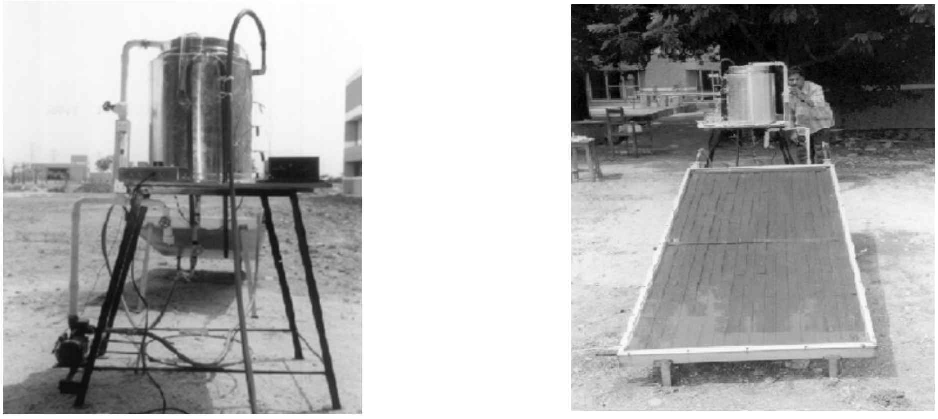


Fig.1 Schematic of experimental setup
1: Solar flat plate collector; 2: Pump; 3 & 4: Flow control valves; 5: Flow meter; 6: TES tank; 7: PCM capsules; 8: Temperature indicator; T_p & T_f: Temperature sensors (RTDs).

A flow meter with accuracy of ±2% is used to measure the flow rate of HTF and a centrifugal pump is employed to circulate the HTF through the storage tank. The TES tank is divided into four segments along its axial direction and RTDs with accuracy of ±0.2 °C are placed at the inlet, outlet and four segments



(a) (b)

Fig.2 Photograph of (a) TES tank and (b) Solar collector

Table 1 Thermo-physical properties of PCM (Paraffin*)

Melting temperature (°C)	Latent heat of fusion (kJ/kg)	Density (kg/m^3)		Specific heat (J/(kg·°C))		Thermal conductivity (W/(m·°C))	
		Solid	Liquid	Solid	Liquid	Solid	Liquid
60	213	861	778	1850	2384	0.40	0.15

* Manufacturer: Chennai Petroleum Corporation Ltd., Chennai

Table 2 Specifications and heat storage capacity of the TES tank

Parameter	Value	
	ε=0.49	ε=0.61
Volume of the storage tank for diameter=360 mm and length=470 mm (m^3)	0.048	0.048
No. of spherical capsules of 55 mm diameter	264	209
Volume of PCM in the spherical capsules (m^3)	0.024	0.018
Volume of HTF (water) in the storage tank (m^3)	0.023	0.029
Mass of HDPE spherical capsules (kg)	4.00	3.14
Energy stored in the TES tank when fully charged (above 32 °C) at average temperature of PCM=70 °C and average temperature of HTF=70 °C (MJ)		
Energy stored in PCM	6.90	4.28
Energy available in the HTF	3.62	4.61
Energy content of capsule material	0.38	0.30

of the TES tank to measure the temperatures of HTF. Another four RTDs are inserted into the PCM capsules and placed at the four segments of the TES tank to measure the temperatures of PCM. The position and number of RTDs are also designated in Fig.1. The RTDs are connected to a temperature indicator, which provides instantaneous digital outputs. The solar radiation is measured using a pyranometer.

Experimental trial

The TES tank is connected with 2 m^2 active solar flat plate collector, with the PCM capsules in the TES tank being immersed in water. The key experimental parameters are porosity (ε), HTF inlet temperature (T_{fi}) and flow rate (m). Several experiments were conducted with different HTF flow rates. During the experiments, T_{fi} varied in accordance with the solar radiation.

During the charging process (storing of heat energy) the HTF is circulated through the TES tank continuously. The HTF transfers its energy to PCM capsules and at the beginning of the charging process, the temperature of the PCM (T_{pi}) inside the packed bed capsules is 32 °C, which is lower than the melting temperature. 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 at different locations of the TES tank as shown in Fig.1 are recorded at interval of 5 min. The charging process is continued until the PCM temperature T_p reaches 70 °C.

Discharging process (the energy retrieval) experiments were carried out in two methods. In the first method referred to as a continuous process, the cold water at a temperature of 32 °C is circulated continuously through the TES tank to recover the stored heat energy. In the second method referred to as a batchwise process, a certain quantity of hot water is withdrawn from TES tank and mixed with cold water at 32 °C to get the required hot water of 20 L at an average temperature of 45±0.5 °C 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 10 min allowing transfer of energy from PCM, another batch of hot water is withdrawn and mixed with cold water to get 20 L hot water at 45±0.5 °C. This process is continued until the PCM temperature reaches 45 °C.

RESULTS AND DISCUSSION

The temperature distributions of HTF (water in the TES tank serving as SHS material) and PCM in the TES tank for different porosities and mass flow rates during charging and discharging processes are recorded. The instantaneous heat stored, cumulative heat stored and system efficiency during the charging process are studied in detail.

Charging process

1. Temperature histories of HTF and PCM

The temperature histories of HTF and PCM at four segments of the TES tank, i.e., at x/L=0.25, 0.50, 0.75 and 1.0 are shown in Figs.3a and 3b (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). Fig.3a represents the temperature variation of the HTF inside the storage tank for a mass flow rate of 6 kg/min and porosity of 0.49. It is observed from Fig.3a that the temperature of the HTF at all the segments increases gradually until it reaches the temperature of 62 °C or 63 °C and then remains nearly constant around 65 °C for a period of 45 min during which the PCM undergoes phase change at 60±1 °C. After that the HTF temperature (T_f) increases up to 71 °C or 72 °C.

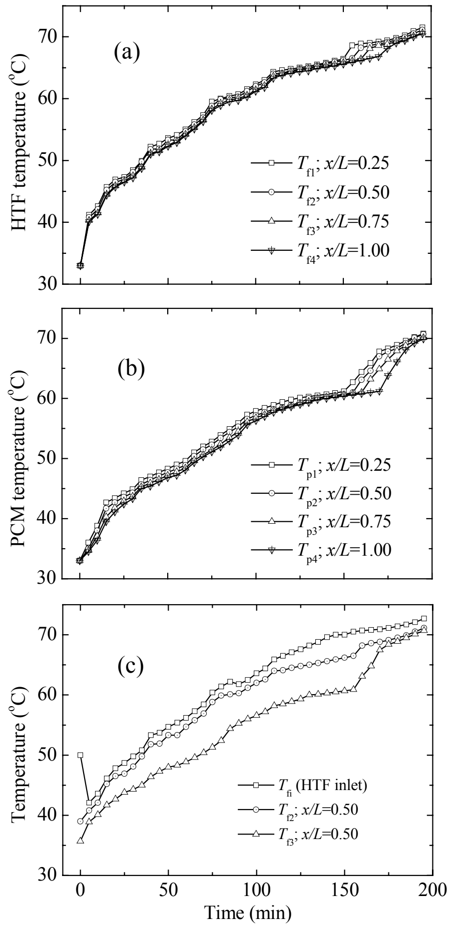


Fig.3 Temperature histories during charging process (m= 6 kg/min; ε=0.49). (a) HTF; (b) PCM; (c) HTF & PCM

Fig.3b represents the temperature variation of PCM during the charging process for mass flow rate of 6 kg/min and porosity of 0.49. It is seen from the figure that the PCM temperature (T_p) increases gradually at the beginning of the charging period, remains nearly constant around 60 °C during melting process and increases sharply during heating of liquid PCM, and that the PCM in the first segment is completely charged nearly 85% of the total charging time. The charging process is terminated when the PCM temperature in all the segments reaches 70 °C. It is also observed from Figs.3a and 3b that there is no significant temperature difference between each segment from top to bottom of the storage tank during the sensible heating of the solid PCM and also during phase change period. The reason is that the water temperature in the storage tank increases gradually in accordance with HTF inlet temperature (T_{fi}) supplied from the solar collector and that the PCM temperature also increases gradually along with HTF temperature. From the temperature histories it is inferred that in the present system, the heat transfer rate possible from the HTF to the PCM in the storage tank is higher than the heat-receiving rate of HTF from the solar collector. Hence it is possible to reduce the charging time further by increasing solar collector surface area.

Fig.3c shows the variation of both HTF and PCM temperatures at Segment 2 (x/L=0.50) with HTF inlet temperature. The instantaneous amount of heat transfer to the PCM depends on the temperature difference prevailing between HTF and PCM at a given time. During the sensible heating of solid PCM, the temperature of both HTF and PCM increases at a faster rate and the temperature difference between them also increases continuously until the PCM reaches its melting temperature of 60±1 °C. The increase in temperature is higher in water than in the PCM as a more quantity of heat is absorbed by the water than the amount of heat it gives to the PCM. This is due to the higher resistance offered by the solid PCM for heat flow. A stage is reached when the entire heat in the HTF is transferred to PCM by convection. Hence beyond this stage, HTF temperature also remains nearly constant, i.e., after a time period of 105 min for the case with a mass flow rate of 6 kg/min as observed from Fig.3c. After the completion of the melting process, the HTF and PCM temperatures further increase and the charging process is continued until the PCM attains 70 °C.

2. Effect of HTF flow rate

Fig.4 illustrates the effect of varying the mass flow rate of HTF (2, 4 and 6 kg/min) during the charging of the storage tank. Increase in mass flow rate has large influence on the phase transition process of PCM. As the flow rate increases the time required for the complete charging becomes smaller. It is seen from the figure that the charging time is decreased by 16% and 24% when the flow rate is increased from 2 to 4 kg/min and 2 to 6 kg/min respectively. This is because an increase in fluid flow rates (from 2 to 6 kg/min) translates into an increase in surface heat transfer coefficient between the HTF and PCM capsules. Hence mass flow rate has significant effect on the time for charging the storage tank.

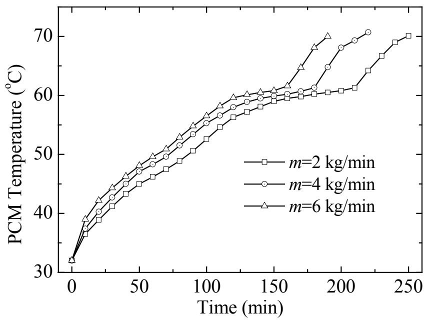


Fig.4 Effect of HTF flow rate on charging time (ε=0.49; x/L=0.50)

3. Effect of varying porosity

Porosity determines the quantity of thermal energy that can be stored and the surface area of heat transfer between particle and fluid per unit volume. For a given volume of the storage tank and size of the spherical capsules, porosity is varied by changing the number of PCM capsules in the storage tank. Fig.5 shows the comparison of the temperature histories of PCM for ε=0.49 and ε=0.61. It is noted from the figure that the charging time of PCM capsules reduces for the higher porosities as the PCM mass reduces with increase in porosity. The charging time is reduced by 18% for the mass flow rate of 6 kg/min when ε is increased from 0.49 to 0.61. It is observed from Table 2 that the energy content of the storage tank is 10.90 MJ when ε is 0.49 and is 9.19 MJ when ε is 0.61. However, the charging rate is almost the same for both cases for a particular flow rate. The charging rate is 0.956 kW when ε is 0.49 and is 0.928 kW when ε is 0.61 for a mass flow rate of 6 kg/min.

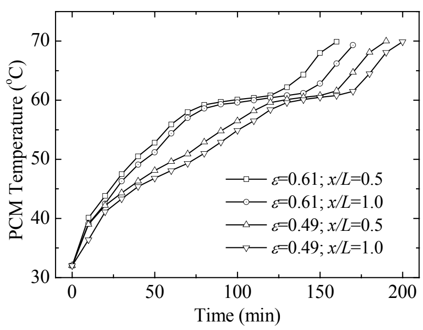


Fig.5 Effect of porosity on the time required for complete charging (m=6 kg/min)

4. Instantaneous heat stored

Fig.6a shows the instantaneous heat stored in the storage tank during the charging process for various mass flow rates of HTF with ε=0.49. This is estimated based on the instantaneous inlet and outlet temperatures of the HTF (T_{fi} and T_{fo} respectively). It was observed that during the initial period of charging the instantaneous heat stored is high and decreases till 50~60 min. This drop in heat stored is due to the decrease in temperature difference between the HTF and the temperature of the storage tank. As the charging process proceeds, the PCM starts melting and the heat stored remains almost uniform due to constant temperature difference between the HTF and the storage tank. This is the major advantage of an LHS system where a uniform rate of charging and discharging is possible for a longer period, which will be useful for many practical applications.

Fig.6b shows the cumulative heat stored in the storage tank for the case of ε=0.49. It is seen that the time required for storing 11 MJ is 240, 210 and 190 min for mass flow rates of 2, 4 and 6 kg/min respectively, and at average charging rates of 0.764, 0.873 and 0.965 kW respectively. It is observed from the figure that the mass flow rate has significant effect on the average charging rate. This is due to higher heat extraction rate of HTF from the solar collector when the flow rate is increased.

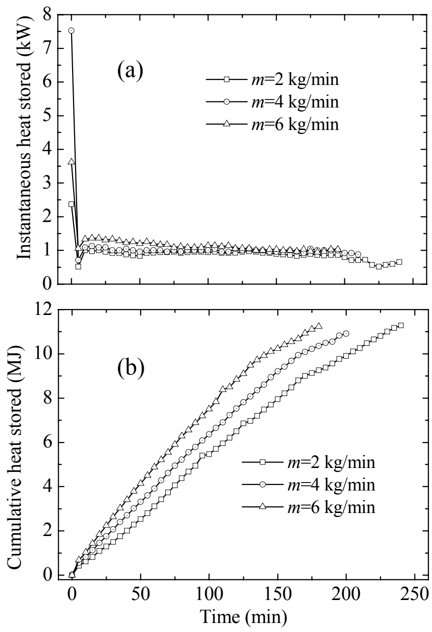


Fig.6 Instantaneous (a) and cumulative (b) heat stored during the charging process for ε=0.49

5. System efficiency

Fig.7 shows the system efficiency of the storage system for various HTF mass flow rates. System efficiency is defined as the amount of energy stored in the storage tank and the heat energy available from the solar radiation. As time increases the system efficiency decreases during sensible heating of solid PCM and it remains nearly constant during phase change period and then it further decreases during sensible heating of liquid PCM. This is due to the fact that as charging proceeds the temperature difference between the HTF and the PCM in the storage tank decreases. This decreases the amount of heat transferred to the storage tank and thus the energy stored decreases with increase in time. Also the increase in HTF temperature at the inlet of solar collector in turn decreases the heat absorption rate from the collector. In addition, as the time increases the temperature of the water in the storage tank increases, which results in increasing heat loss from the storage tank. This also contributes to the decrease in system efficiency.

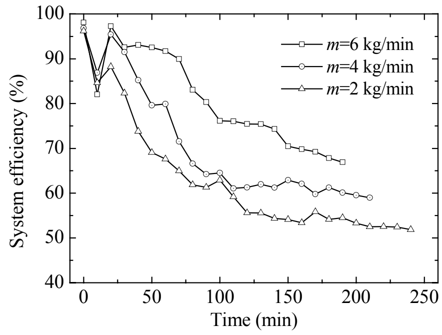


Fig.7 Comparison of system efficiency for various HTF mass flow rates for ε=0.49

Discharging process

1. Variation of PCM temperatures

Fig.8a represents the temperature histories of PCM during batchwise discharging process. It is seen from the figure that the temperature drop is large until the PCM reaches its phase transition temperature as the hot water in the storage tank loses its sensible heat due to the mixing of inlet water at a temperature of 32 °C. After that the temperature drop in the PCM is negligible for a long duration as the PCM releases its latent heat. In the case of continuous discharging process the PCM temperature is nearly constant for 25 min whereas in the case of batchwise method it occurs over a duration of 40 min as the inlet water is supplied intermittently to extract heat from the storage tank. After complete solidification of the PCM, its temperature starts decreasing, however, the rate of temperature drop is not as high as in the beginning of the discharging process. This is due to low temperature difference between the PCM and HTF inlet temperature though the solid PCM releases its sensible heat.

2. Variation of HTF temperatures

Fig.8b shows the temperature histories of HTF during continuous and batchwise discharging processes. The rate of heat recovery is large at the beginning of the discharging process and decreases with time because of the change in the thermal resistance of the solidified layer of the PCM and decrease in temperature difference between the solidified PCM and HTF. In the case of continuous discharging process as the HTF outlet temperature decreases continuously with time, this type of process is not suitable for practical applications.

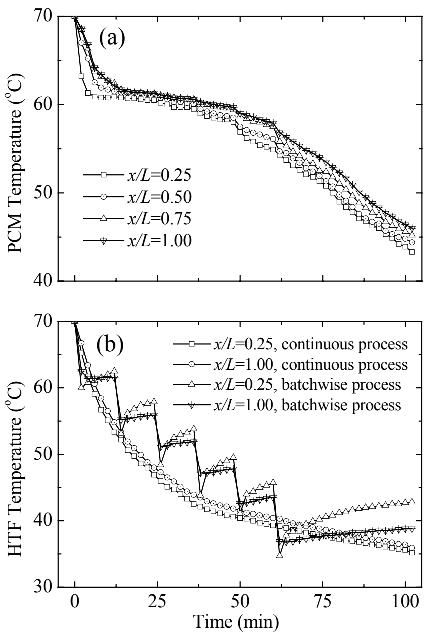


Fig.8 Temperature histories of PCM during batchwise discharging process (a) and HTF during continuous and batchwise discharging process (b)

In the case of batchwise discharging process a certain quantity of hot water is withdrawn from the storage tank and mixed with cold water to obtain 20 L hot water at average temperature of 45 °C. Then the storage tank is again filled with cold water of quantity equal to the amount of water withdrawn. Now the temperature of HTF (water) in the tank increases by gaining heat from PCM capsules and after a retention period of 10 min, another batch of hot water is withdrawn and mixed with cold water. The batchwise discharging process is continued until the PCM temperature reaches 45 °C. The variation of HTF temperature during retention period is also shown in the graph.

Six batches of 20 L of hot water at average temperature of 45 °C can be obtained in a period of 60 min from the TES tank whose capacity is 48 L with 23 L of water and 24 L of paraffin (i.e. 20.66 kg). Another batch of hot water (23 L) at a temperature of 43 °C is also withdrawn after 40 min. The time duration is very high as large quantity of cold water is added during this batch (i.e. 20 L at 32 °C) and the rate of heat extraction from the PCM becomes very slow as the temperature difference between the PCM and HTF is small. The total system approaches an equilibrium temperature of around 43~45 °C. When considering the above modes of operation of discharging processes, the packed bed LHS system employing batchwise discharging method is best suited for applications where the requirement is intermittent as in solar water heating systems.

3. Energy stored and size of the storage tank

The amount of heat stored in the present system when both PCM and HTF attain the temperature value of 70 °C is 10.9 MJ and the total volume of the storage tank required is 0.048 m^3 with a porosity of 0.49. In order to store the same quantity of heat using the SHS system with water as storage medium, the storage tank volume required will be 0.069 m^3. This shows that the packed bed LHS system reduces the size of the storage tank by 28% without any losses. The size can be further reduced by decreasing the porosity in the storage tank.

CONCLUSION

A thermal energy storage system has been developed for the use of hot water at average temperature of 45 °C for domestic applications using packed bed LHS concept. Charging experiments were conducted on the TES unit to study its performance by integrating it with solar flat plate collector. The temperature histories of HTF & PCM and energy storage characteristics during charging process for different porosities and flow rates are discussed. It is concluded that the mass flow rate has significant effect on the heat extraction rate from the solar collector, which in turn affects the rate of charging of the TES tank. Experiments were conducted for continuous and batchwise discharging processes for both SHS and LHS systems. It is concluded from the experimental results that the packed bed LHS system reduces the size of the storage tank appreciably compared to conventional storage system and that the LHS system employing batchwise discharging of hot water from the TES tank is best suited for applications where the requirement is intermittent.

References

Ananthanarayanan, V., Sahai, Y., Mobley, C.E., Rapp, R.A., 1987. Modeling of fixed bed heat storage units utilizing phase-change materials. *Metallurgical Trans. B*, **18**:339-346.

Bansal, N.K., Buddhi, D., 1992. Performance equation of a collector cum storage using phase change materials. *Solar Energy*, **48**(3):185-194. [doi:10.1016/0038-092X(92)90137-Y]

Barba, A., Spiga, M., 2003. Discharge mode for encapsulated PCMs in storage tanks. *Solar Energy*, **74**(2):141-148. [doi:10.1016/S0038-092X(03)00117-8]

Beasley, D.E., Ramanarayanan, C., 1989. Thermal response of a packed bed of spheres containing a phase change material. *Int. J. Energy Research*, **13**:253-265.

Bellecci, C., Conti, M., 1993. Phase change thermal storage: transient behaviour analysis of a solar receiver/storage module using the enthalpy method. *Int. J. Heat Mass Transfer*, **36**(8):2157-2163. [doi:10.1016/S0017-9310(05)80146-2]

Chen, S.L., Yue, J.S., 1991. Thermal performance of cool storage in packed capsules for air-conditioning. *Heat Recovery Systems & CHP*, **11**(6):551-561. [doi:10.1016/0890-4332(91)90057-B]

Cho, K., Choi, S.H., 2000. Thermal characteristics of paraffin in a spherical capsule during freezing and melting processes. *Int. J. Heat Mass Transfer*, **43**(17):3183-3196. [doi:10.1016/S0017-9310(99)00329-4]

Esen, M., Durmu, A., Durmu, A., 1998. Geometric design of solar-aided latent heat store depending on various parameters and phase change materials. *Solar Energy*, **62**(1):19-28. [doi:10.1016/S0038-092X(97)00104-7]

Ettouney, H., El-Dessouky, H., Al-Ali, A., 2005. Heat transfer during phase change of paraffin wax stored in spherical shells. *ASME J. Solar Energy Engg.*, **127**(3):357-365. [doi:10.1115/1.1850487]

Fouda, A.E., Despault, G.J.G., Taylor, J.B., Capes, C.E., 1984. Solar storage systems using salt hydrate latent heat and direct contact heat exchange-II characteristics of pilot system operating with sodium sulphate solution. *Solar Energy*, **32**(1):57-65. [doi:10.1016/0038-092X(84)90049-5]

Ghoneim, A.A., Klein, S.A., 1989. The effect of phase-change material properties on the performance of solar air-based heating systems. *Solar Energy*, **42**(6):441-447. [doi:10.1016/0038-092X(89)90044-3]

He, B., Martin, V., Setterwall, F., 2004. Phase transition temperature ranges and storage density of paraffin wax phase change materials. *Energy*, **29**(11):1785-1804. [doi:10.1016/j.energy.2004.03.002]

Hoogendoorn, C.J., Bart, G.C.J., 1992. Performance and modelling of latent heat stores. *Solar Energy*, **48**(1):53-58. [doi:10.1016/0038-092X(92)90176-B]

Ismail, K.A.R., Stuginsky, R., 1999. A parametric study on possible fixed bed models for pcm and sensible heat storage. *Appl. Thermal Eng.*, **19**(7):757-788. [doi:10.1016/S1359-4311(98)00081-7]

Ismail, K.A.R., Henriquez, J.R., 2002. Numerical and experimental study of spherical capsules packed bed latent heat storage system. *Appl. Thermal Eng.*, **22**(15):1705-1716. [doi:10.1016/S1359-4311(02)00080-7]

Mehling, H., Cabeza, L.F., Hippeli, S., Hiebler, S., 2003. PCM-module to improve hot water heat stores with stratification. *Renewable Energy*, **28**(5):699-711. [doi:10.1016/S0960-1481(02)00108-8]

Prudhomme, M., Nguyen, T.H., Nguyen, D.L., 1989. A heat transfer analysis of solidification of slabs, cylinders and spheres. *ASME J. Heat Transfer*, **111**:699-705.

Saitoh, T., Hirose, K., 1986. High performance phase-change thermal energy storage using spherical capsules. *Chemical Engg. Commun.*, **41**:39-58.

Sozen, M., Vafai, K., Kennedy, L.A., 1991. Thermal charging and discharging of sensible and latent heat storage packed beds. *AIAA J. Thermophysics*, **5**(4):623-625.

Trp, A., 2005. An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell-and-tube latent thermal energy storage unit. *Solar Energy*, **79**(6):648-660. [doi:10.1016/j.solener.2005.03.006]