Air Heating with Latent Heat Storage For Thermal Energy Management Of Solar Applications

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ABSTRACT

Renewable energy, particularly the solar energy, is gaining more importance worldwide for its clean, non polluting, inexhaustible and cost free nature. Though there are many applications possible, an important factor is that solar energy is time dependant in nature. Hence the commercial acceptance and the economics of solar thermal utilities or devices are tied to the design of an efficient thermal storage system to meet the time-dependant supply and end use requirements. Latent heat thermal storage units have received greater attention in recent years, due to their isothermal behavior during the charging and discharging processes, and higher energy storage density. In this study, an experimental investigation is performed to analyze the transient behavior of a packed bed latent heat storage unit, comprised of a cylindrical storage tank filled with Phase Change Material (PCM). PCM is encapsulated in spherical containers for thermal energy management and efficient utilization of solar energy. Applications include space heating and industrial drying. Experimental results are reported and discussed.

Keywords: Air heating, Thermal Energy Storage, Phase Change Material, Spherical capsules, Packedbed, Air heating, Latent heat storage

INTRODUCTION

Among the various sources of renewable energy, solar energy is gaining more importance in the recent years, though it is time dependent in nature. The energy needs for a wide variety of solar applications are also time dependant, but in a different pattern and phase from the solar energy supply. This implies that solar energy based device or utility must be matched dynamically both at the source point and the application point. Once the characteristics of end-use demand and the nature of energy source option are known, the total demand and supply in the time domain have to be brought together through integration of an efficient energy storage and distribution network. Hence the commercial acceptance and the economics of solar thermal utilities or devices are tied to the design of an efficient thermal storage system to meet the time-dependant supply and end use requirements. Thermal energy storage (TES) can be achieved in the form of sensible heat of liquid or solid (water, oil or pebbles) or latent heat of phase change materials (inorganic salts, organic substances like paraffin and fatty acids). Latent heat thermal energy storage units are particularly attractive due to its high energy storage density and its isothermal behavior during the heat storing and retrieving process.

There are various types of latent heat storage systems studied by various researchers for different applications. However the packed bed type storage system filled with spherical capsules has several advantages to overcome the problems associated with low thermal conductivity of the phase change problem and the cavity formation due to the volume change during the solidification process. This type of storage systems are successfully commercialized in central air conditioning applications integrated with storage system. Hence in order to study the suitability of packed bed storage system for solar air heating applications (eg. Drying, space heating) an experimental investigation is made to study the charging and discharging characteristics of a packed bed latent heat storage system filled with PCM encapsulated in spherical containers.

Many researchers have investigated experimentally and theoretically the transient behavior of the PCM encapsulated in different geometries and PCM based storage systems in different configurations of shell and tube and packed bed with capsule of different geometries. Regin et al. [1] presented a review on the heat transfer characteristics of the PCM based thermal energy storage.

Saitoh and Hirose [2] have reported the results of theoretical and experimental investigation on the transient thermal performance of a TES unit based on the capsule diameter, the flow rate of HTF, the type of PCMs, the capsule material and the difference between the inlet HTF temperature and melting temperature of the PCM. Cho and Choi [3] experimentally investigated the thermal characteristics of paraffin in a spherical capsule packed inside a storage tank at different values of the Reynolds number and inlet temperatures. They concluded that the phase change period for the capsule at the edge of the storage tank was shorter than that at the center of the storage tank, because the porosity at the center was smaller than at the edge of the storage tank. Benmansour et al. [4] carried out a two dimensional numerical and experimental analysis to understand the transient axial and radial thermal dispersion on a cylindrical packed bed storage filled with spherical PCM (paraffin) capsules. Air is used as the heat transfer fluid (HTF). Velraj et al. [5] reported a detailed study on the phase change material based cool thermal energy storage system integrated with a large building air conditioning system. The technical information about the encapsulated phase change material based storage system for air conditioning application, importance of load shift operations and its economical benefits are highlighted. They estimated from the study that a cool thermal energy storage system with a capacity of 24000 Ton-hr reduced the installation of air conditioning system from 6000 Ton-hr to 3000 Ton-hr which reduces the monthly demand charges of electricity to around INR 1.2 million and a saving of INR 2.26 million per annum through energy management by scheduling (load shifting) the chiller operation. Nallusamy et al. [6] presented the design and performance of a combined sensible and latent heat storage unit in which the water is used as HTF cum sensible heat storage and encapsulated PCM is used as latent heat storage. They concluded from the discharging experiments conducted based on the daily domestic hot water requirement pattern that such system are best suited where the requirement is intermittent. Cheralathan et al. [7] conducted an experimental investigation on the performance of industrial refrigeration system integratedwith the combined sensible and latent heat encapsulated PCM-based cool thermal storage (CTES) system. The experimental analysis on the effect of inlet temperature of heat transfer fluid (HTF), porosity of storage tank with higher mass flow rate of HTF during charging process has been carried out. The important parameter namely the average rate of charging, time for completion of charging, energy charged were presented and discussed and also a comparison has been made between chiller plant with and without storage using specific energy consumption. Pandiyarajan et al. [8] experimentally investigated the recovery and storage of waste heat from the exhaust gas of the internal combustion engine with a shell and finned tube latent heat storage system. It is found that nearly 10-15% of fuel power is stored as heat in the storage system, which is available at reasonably higher temperature for suitable application. The performance parameters pertaining to the heat exchanger and the storage tank such as amount of heat recovered, heat lost, charging rate, charging efficiency and percentage energy saved are evaluated. Ismail and Henriquez [9] investigated both numerically and experimentally the heat transfer during the charging and discharging process in a packed bed LHS system with spherical capsules filled with PCM (water). The effects of working fluid (ethylene glycol) entry temperature, the mass flow rate and material of the spherical capsule on the performance of the storage unit were reported. Sozen et al. [10] investigated the storage characteristics o fa SHS and LHS packed bed consisting of a horizontal channel filled with randomly packed particles of PCM encapsulated spherical capsules. The heat transfer fluid was refrigerant-12, and the SHS material used was 1% carbon steel and the PCM was myristic acid. Dincer [11] conducted a feasibility study on the selection, evaluation, implementationand operation of a TES system for solar thermal applications. Several issues relating to energy storage were examined from the current perspective. In addition, some criteria, techniques, recommendations, checklists on the selection, implementation and operationof energy storage systems are provided for the use of energy engineers, scientists and policymakers. Chen and Yue [12]compared a one-dimensional porous-medium model with experiment to determine the thermal characteristics of ice-water cool storage in packed capsules for air conditioning with water as PCM and alcohol as coolant for various porosities, flow rates and different inlet coolant temperatures.

EXPERIMENTAL INVESTIGATION

Experimental Setup

A schematic diagram of the experimental setup used in this study is given in Figure 1. The storage tank is made of steel with 0.7 m height and 0.35 m diameter, and is well insulated with glass wool on the outer surface. The tank is shaped like a diffuser at the bottom to provide uniform HTF (air) distribution through the cross section of the tank.

The PCM encapsulated in plastic balls of an outer diameter of 70 mm with a wall thickness of 0.5 mm is packed inside the tank above a grid plate placed at the bottom of the tank. This grid plate acts as a support to the packed balls, and is also useful in the distribution of the HTF.

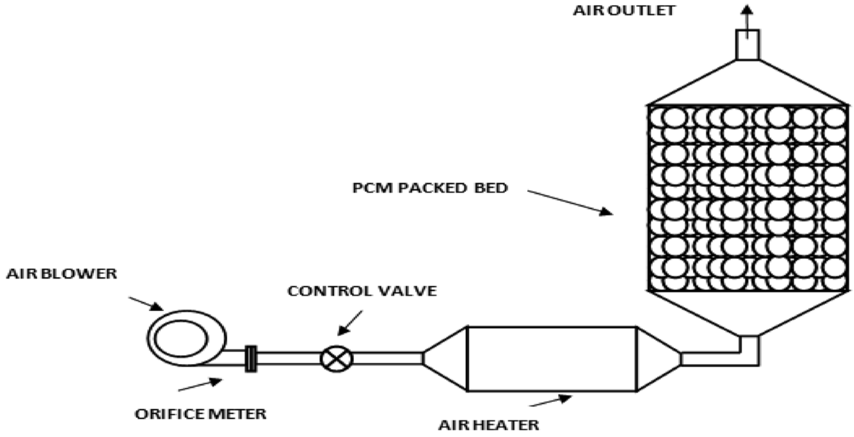


Figure 1. Schematic diagram of the experimental setup

Totally 260 balls are used to fill the tank. Commercially available paraffin is used as the PCM. Most of the paraffin changes its phase in a range of temperature. Table 1 lists the thermo-physical properties of the paraffin-based PCM.

A centrifugal air blower and flow adjusting valves are provided to supply air at varying rates.An orificemeter is used to measure the mass flow rate of air. The air is heated with finned electric heaters fitted inside an insulated enclosure. RTDs are provided at the inlet to the tank, and at five equally spaced locations along the axial direction of the bed, to measure the HTF and PCM temperature variations during the experiment. The photographic view of the experimental setup is shown in Figure 2.

Experimental Trials

The experimental trials consist of two different processes, such as charging and discharging. The charging process is done by heating the

Table 1. Thermophysical properties of the paraffin wax

Phase change temperature (charging)	55.5 ^{0}C – 66.5^{0}C
Phase change temperature (discharging)	47.5^{0}C -60.5^{0}C
Latent heat of fusion	142.7 kJ/kg
Specific heat (Solid / Liquid)	2.4 / 1.8 kJ/kg-K
Density (Solid / Liquid)	670 / 640 kg/m^3
Thermal conductivity (Solid / Liquid)	0.0004 / 0.0002 kW/m K

Figure 2. Photographic view of the experimental setup

PCM bed from room temperature with the supply of hot HTF (at constant temperature), until the PCM in the entire bed changes its phase completely. During the discharging process, the HTF at ambient temperature is supplied through the heated PCM bed to recover the heat. The charging and discharging experiments are carried out at three different HTF flow rates of 0.015, 0.035 and 0.05 kg/s. The inlet temperature of the HTF is maintained at a constant temperature of 70°C during the charging process and at ambient temperature during the discharging process. The temperature histories are recorded continuously during the experiment. Several experiments are conducted for the repeatability of the readings.

Error Analysis

The error associated with primary experimental measurements such as temperature and mass flow rate and the performance parameters evaluated such as instantaneous and cumulative heat transfer using the root sum square method are listed in Table 2.

Table 2. Estimated values of Uncertainties

Parameters	error (%)
Temperature	1.0531
Mass flow rate	0.6
Instantaneous heat transferred	1.212
Cumulative heat transferred	1.2561

RESULTS AND DISCUSSION

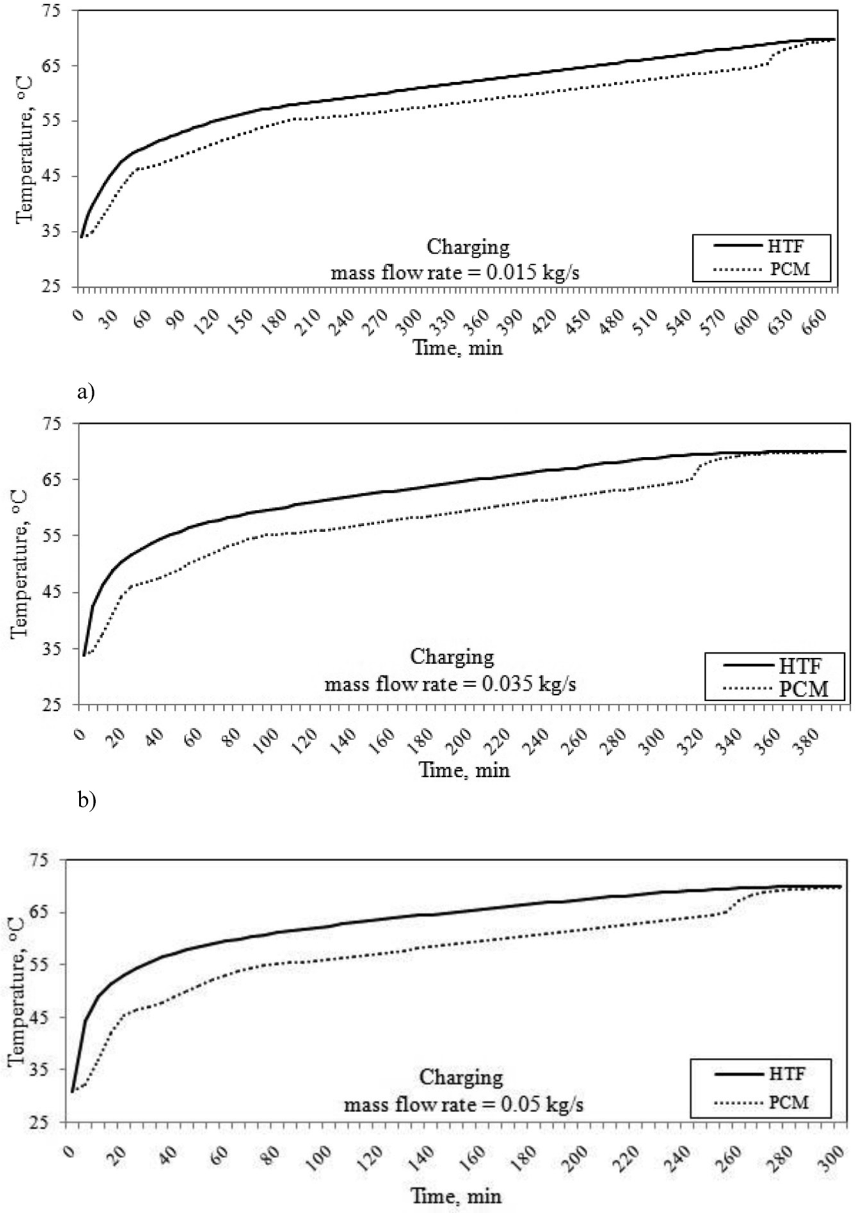
Figure 3 shows the experimental temperature variation of the PCM and the HTF present in the top layer of the storage tank for the mass flow rates of 0.015 kg/s, 0.035 kg/s and 0.05 kg/s respectively, during the charging process. A near constant temperature of 60 0C for the HTF and PCM is seen for a longer duration at which the major phase change occurs. It is seen from the figures that at a higher mass flow rate, a higher temperature difference exists between the HTF and PCM. At a higher mass flow rate, the surface convective heat transfer coefficient for the spherical ball is higher, and hence, more quantity of heat is transferred to the PCM present in the near wall region. Since the thermal conductivity of the PCM is very low, the heat transfer through diffusion from the PCM present near the wall region to the inner region is also low. Hence, a higher ΔT exists between the temperature of the PCM present in the centre of the ball and the HTF surrounding the ball. However, for the case with a low mass flow rate, the low surface heat transfer coefficient transfers comparatively lesser quantity of heat to the PCM present near the wall region, which can be easily transferred to the centre of the PCM ball through diffusion. Hence, the temperature difference between the centre of the ball and the surrounding HTF is quite less.

Figure 4 shows the experimental and numerical temperature variation of the HTF and PCM in the storage tank during the discharging process, for the mass flow rates of 0.015 kg/s, 0.035 kg/s and 0.05 kg/s respectively. It is seen from Figures 3 and 4 that the higher mass flow rate reduces the phase change duration appreciably, during both the charging and discharging processes. This shows that the mass flow rate has a significant effect, which is due is to the higher variation in the heat capacity of the HTF used in the present investigation.

Figure 5 shows the instantaneous heat transferred during the charging and discharging processes respectively, at various mass flow rates. It is evaluated using the equation (1),

$$Q_{\text{inst}} = m_f \cdot c_f \cdot \left(T_{f \cdot in} - T_{f \cdot out}\right) \tag{1}$$

Where $\mathbf{T}_{\boldsymbol{f.in}}$ and $\boldsymbol{T_{f.out}}$ are the HTF temperatures at the inlet and outlet of the storage tank. It is seen from the figures that the variation of heat transfer w.r.t time is very low both during the charging and discharging processes at the lower mass flow rate of 0.015 kg/s, whereas at higher mass flow rates, initially the heat transfer is very high, and it decreases



a)

b)

Figure 3. Experimental temperature variations at the top layer of the storage tank for a mass flow rate of a) 0.015 kg/s b) 0.035 kg/s and c) 0.05 kg/s (Charging process)

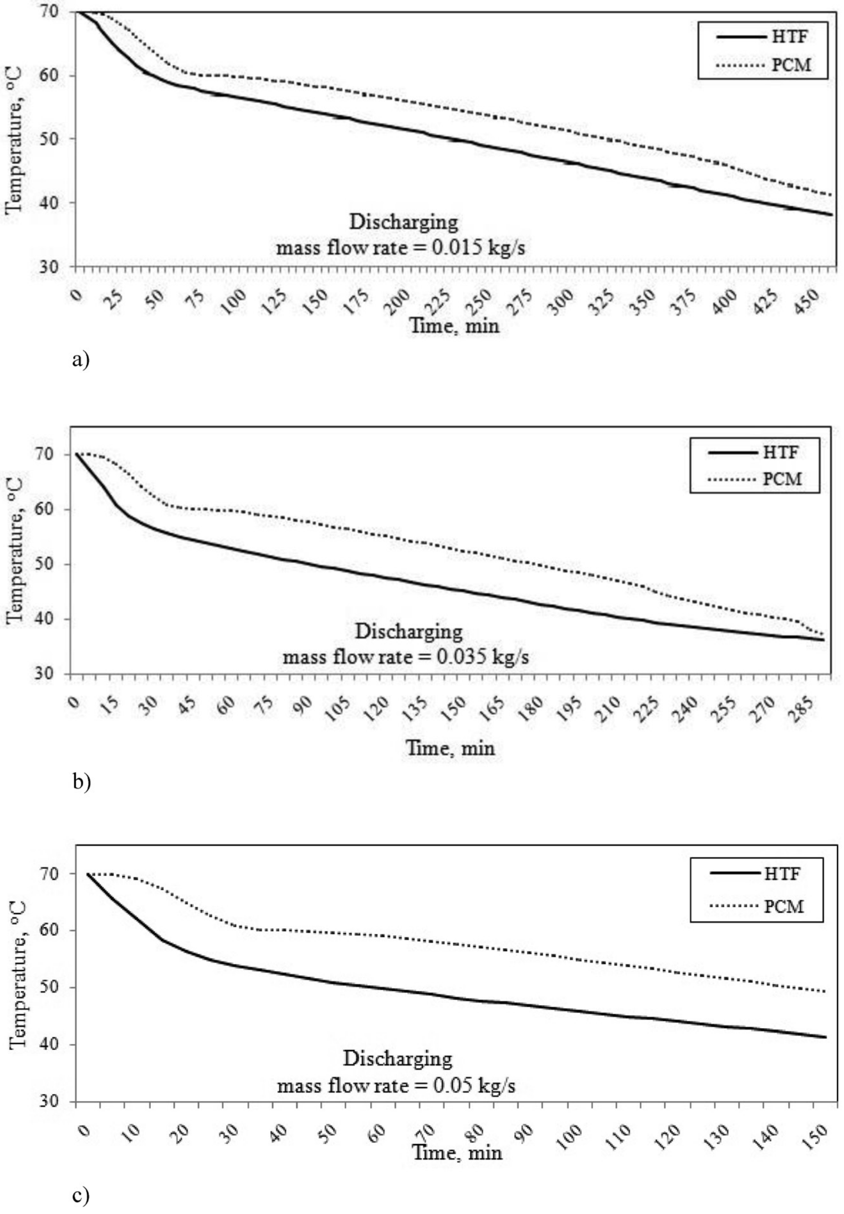


Figure 4. Experimental temperature variations at the top layer of the storage tank for a mass flow rate of a) 0.015 kg/s b) 0.035 kg/s and c) 0.05 kg/s (Discharging process)

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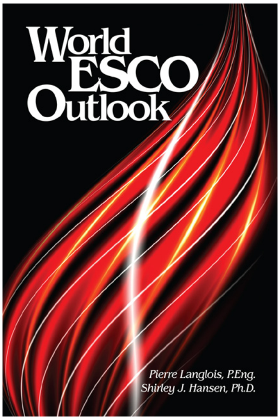

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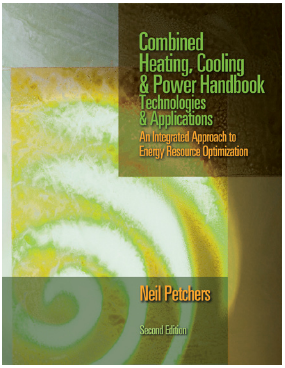

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at a faster rate w.r.t time. At a higher mass flow rate of 0.05 kg/s, initially, the surface heat flux is between 1.6 to 2 kW for both the charging and discharging processes, and it decreases rapidly to 0.8 kW within a duration of 30 min. Further, a linear variation with a higher slope is seen till the end of the charging/discharging process. On the other hand, for a lower mass flow rate of 0.015 kg/s, though initially a low heat transfer rate of 0.5 kW is observed, the variation in the heat transfer rate w.r.t time is very low and an average of 0.25 kW±0.05 is observed during most of the charging/discharging process. Hence, the system with a lower mass flow rate is very useful for applications where a uniform heat transfer rate is required.

Figure 6 shows the cumulative heat transferred during the charging and discharging processes. It is estimated using the equation (2),

$$Q_{\mathrm{cum}} = \sum_{\Delta t=1}^{n} m_f \cdot c_f \cdot \left(T_{f\bullet in} - T_{f\bullet out}\right) \cdot \Delta t \tag{2}$$

Where Δt—time interval between each temperature measurement and—the total number of time interval for complete charging/discharging. The total heat capacity of the storage system is approximately 5000 kJ. It is seen from the figure that the duration for complete charging and discharging is different, and also that it varies with the mass flow rate of the HTF.

Figure 7 is drawn to show the time required for the complete phase change during the charging and discharging processes. It is seen from the figure, that the discharging process requires lesser duration for a given mass flow rate compared to the charging process. This is due to the higher ΔT that exists between the HTF and PCM during the discharging process.

Figure 8 shows the phase change duration of the PCM at various mass flow rates of the HTF for the variation along the bed height during melting and solidification respectively. It is seen from the figure that as the bed height increases, the time required for the phase change increases for both melting and solidification. This is due to the decrease in the temperature difference between the HTF and PCM at the higher bed height location. Further, it is observed that the increase in time required for the phase change along the bed height is appreciable at a lower mass flow rate. This is due to the higher variation in temperature of the HTF along the flow direction, at a lower mass flow rate due to its low heat capacity. Hence, the time required for the phase change is very high at the top of the storage tank, at a lower mass flow rate due to the very low temperature difference between the HTF and PCM.

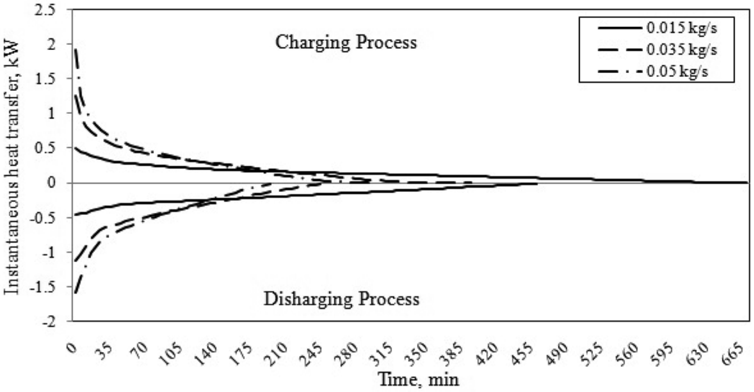

Figure 5. Instantaneous heat transferred during Charging process and Discharging

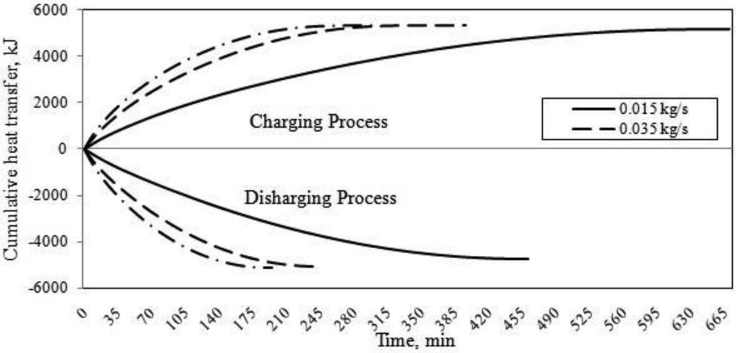

Figure 6. Cumulative heat transferred during Charging process and Discharging process

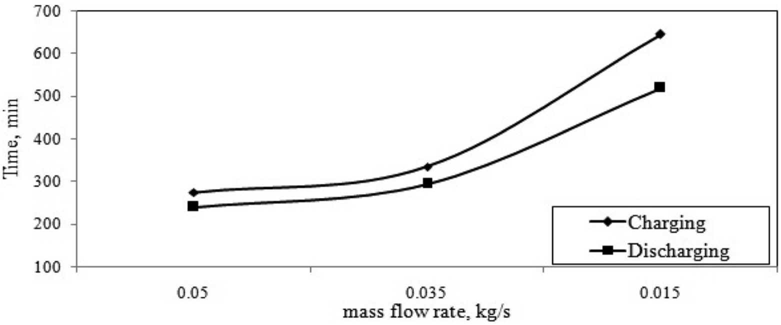

Figure 7. Time required for complete charging and discharging at various mass flow rates of the HTF

CONCLUSION

In this article, the charging and discharging characteristics of a packed bed storage system with air flowing in the axial direction, was investigated experimentally and the results were discussed. It is concluded from the analysis that for the size of the storage unit selected for the experimental investigation, a HTF flow rate of 0.015 kg/s is able to provide a near uniform heat flow during the charging and discharging processes. The results of the present study will be very useful for the design of PCM based thermal storage units with air as the heat transfer fluid for solar drying and space heating applications.

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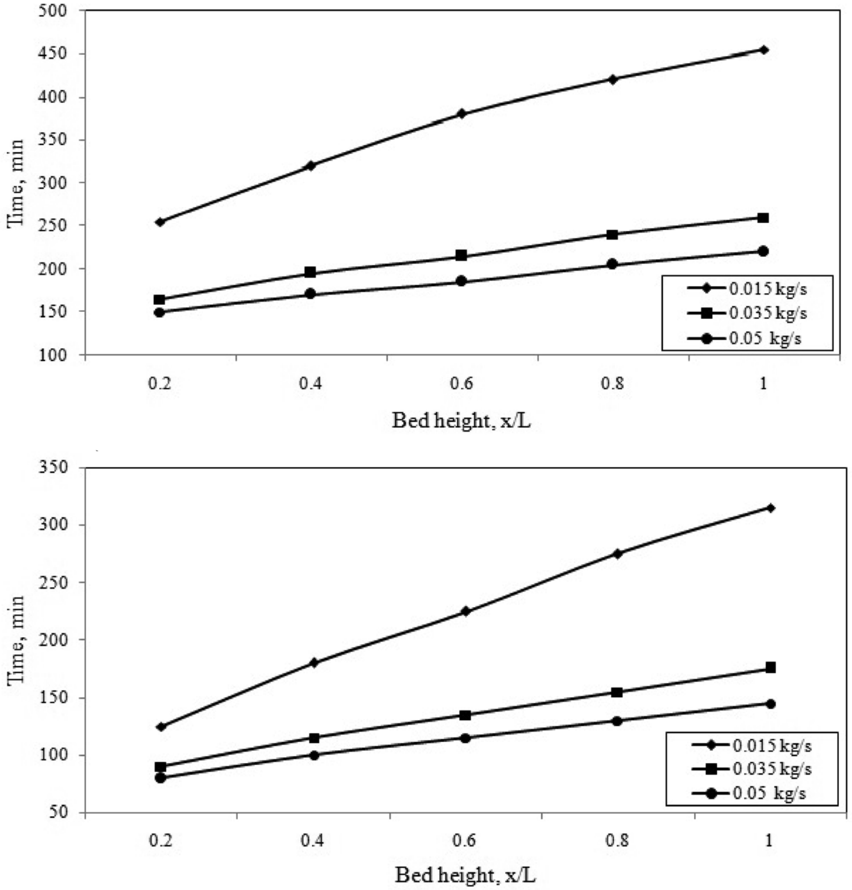

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Figure 8. Phase change duration of the PCM at various mass flow rates of the HTF for the variation along the bed height (a) Melting and (b) Solidification

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