An Improvement in the Solar Water Heating Systems using Phase Change Materials

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Abstract

The present work has been undertaken to study the feasibility of storing solar energy using Phase Change Materials (PCMs) and utilizing this energy to heat water for domestic purposes during nighttime. This ensures that hot water is available through out the day. The system consists of two simultaneously functioning heat-absorbing units. One of them is a solar water heater and the other a heat storage unit consisting of PCM (paraffin). The water heater functions normally and supplies hot water during the day. The storage unit stores the heat in PCMs during the day supplies hot water during the night. The storage unit utilizes small cylinders, made of aluminium, filled with paraffin wax as the heat storage medium. It also consists of a Solar Collector to absorb solar heat. At the start of the day the storage unit is filled with water completely. This water is made to circulate between the heating panel (Solar collector) and the PCMs. The water in the storage unit receives heat form the heating panel and transfers it to the PCM. The PCM undergoes a phase change by absorbing latent heat, excess heat being stored as sensible heat. Using parabolic mirrors accelerates the charging of the tower. The water supply in the night is routed to the storage unit using a suitable control device. The heat is recovered from the unit by passing water at room temp through it. As water is drawn from the storage tower, fresh water enters the unit disturbing the thermal equilibrium, causing flow of heat from PCM to the water. The storage tower is completely insulated to prevent loss of heat. The efficiency of this system is scrutinized for the solar conditions

1 Introduction

The effective use of solar energy is hindered by the intermittent nature of its availability, limiting its use and effectiveness in domestic applications, notably, water heating. Some throughway has been obtained through Sensible Heat Storage (SHS) systems. However, these require large storage capacity in order to cover a minimum of a couple of days with intermittent usage. Storage of solar energy as sensible heat has been a cheap but inefficient means of Thermal Energy Storage (TES). Conversely, Latent Heat Thermal Energy Storage (LHTES) systems using Phase Change Materials (PCMs) as a storage medium offers advantages such as high heat storage capacity, small unit size and isothermal behavior during charging and discharging. However, these systems are not in commercial use as in the case of SHS systems due to poor heat transfer rates during heat storage and recovery processes. Using combined sensible and latent heat storage system eliminates some of the difficulties experienced in the SHS and LHTES systems and possesses most of the advantages of both.

Latent heat storage has been receiving considerable attention only over the last two decades, yielding promising results. Previous research on LHTES and SHS systems has pertained to the study of the performance characteristics of these systems, theoretically and experimentally, predominantly using artificial heat sources. The majority of the literature research on the LHTES system has been performed for shell and tube arrangement, and more recently for spherical shells. Saitoh and Hirose[1] performed a theoretical and experimental investigation of transient thermal characteristics of a phase change thermal energy storage unit using spherical capsules. Takayuki Watanabe et al.[2] developed a numerical model for prediction of the transient behavior of the latent heat storage module. The model is one-dimensional with a finite overall heat transfer coefficient between the PCM and the Heat Transfer Fluid (HTF). They conducted the experiments on the heat storage module consisted of PCM (paraffin waxes) with different melting temperatures using water as HTF. Both the experimental and numerical results showed some improvements in charging and discharging rates by use of the "three-type" PCM. Velraj et al.[3] presented a numerical study on the solidification of PCM inside vertical, internally finned tubes and proposed a two-dimensional model based on the enthalpy formulation. They recommended that for a given quantity of heat to be extracted, the PCM, HTF and flow parameters are to be selected in such a way to attain a combination of lower Biot number and higher Stefan number (within the practical range) for the uniform extraction of heat. Cho and Choi[4] investigated the thermal characteristics of paraffin in a spherical capsule during freeing and melting processes. Experiments were performed with paraffin, i.e. n-tetradecane, and a mixture of n-tetradecane (40%) and n-hexadecane (60%) and water. The parameters were Reynolds Number and the inlet temperature during the freezing and melting process of the PCM-thermal energy storage system. Effective utilization of solar energy for water heating applications using combined sensible heat and latent heat storage system presented by Nallusamy N. et al.[5].

However, a very limited number of studies have been published on the thermal performance of the LHTES systems (employing PCM in various geometries) integrated with solar heating systems. Fouda et al.[6] studied the characteristics of Glauber's salt as the PCM in the 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.. Bellacci and Conti[7], using enthalpy method, numerically analyzed the cyclic behavior of a phase change solar shell and tube energy storage system. Mehling et al.[8] presented experimental and numerical simulation results of 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 heat loss in the top layer. Thermal performance of LHTES systems integrated with solar heating systems was also investigated by Ghoneim et al.[9], Hoogendoorn et al.[10] and Bansal et al.[11].

The objective of the present work is to experimentally investigate the thermal behavior and feasibility of a cylindrically encapsulated PCM as a LHTES medium. A storage tank containing latent heat storage material is constructed to analyze the performance of latent heat thermal energy storage system. Experiments have been carried out at a constant flow rate of HTF for which the thermal characteristics of the LHTES system and efficiency of the system is calculated. The discharge characteristics for batch-wise discharge are also studied. The results obtained from the experiment are presented.

2 Experimental Investigations

2.1 Experiment setup

Photographs of the experimental setup shown with the solar collector connected to the TES tank are shown in Figures 1 and 2. The setup consists of a cylindrical TES tank which holds the PCM capsules, solar flat plate collector, flow meter and a circulating pump. The stainless steel TES tank has a capacity of about 47 litres, capable of supplying water for a family of four. With an internal diameter of 360mm and a height of 460mm, it houses the PCM capsules and allows for heat transfer between the capsules and the Heat Transfer Fluid (HTF). The tank is insulated with 50mm of glass wool and is provided with an aluminium cladding.

The PCM is encapsulated in Aluminium cylinders of internal diameter 34mm and height 110mm, with wall thickness 2mm. Each cylinder contains 75gm of PCM by wt. The cylinders are packed in layers one over the other, with every two layers separated by a wire mesh to enhance the rigidity of the setup. The setup consisted of 4 layers of cylinders.

RTDs are provided at four different locations of the storage tank and inside four PCM capsules to measure temperature changes for every 2 layers of the PCM capsules, with an accuracy of ±0.3°C. The flow rate of the HTF through the system is measured using a Rota meter. The PCM used is industrial grade granulated paraffin wax with a melting point range of 58-61°C and water is used as both the HTF and the SHS material. The temperatures of the PCM and the HTF are continuously recorded at different locations (8 RTD inputs). Solar radiation is measured using a Pyranometer.

Fig 1: View of setup during experimentation

Fig. 2: Pyranometer with TES tank

The TES tank is connected to a solar flat plate collector of 2 m^2 area and the PCM capsules in the TES tank are surrounded by water. During the experiment, the HTF inlet varies in accordance with solar radiation.

2.2 Experiment trial

During the charging process the HTF is circulated through the TES tank and the solar collector unit continuously. The HTF absorbs solar energy sensibly, and exchanges this heat with the PCM in the PCM storage tank, which is initially at room temperature. The PCM slowly gets heated, sensibly at first, until it reaches its melting point temperature. As the charging proceeds, energy storage as Latent heat is achieved as the Paraffin wax melts at constant temperature (59±2°C). After complete melting is achieved, further heat addition from the HTF causes the PCM to superheat, thereby again storing heat sensibly. The charging process continues till the PCM and the HTF attain thermal equilibrium. Temperatures of the PCM and HTF at the different locations are recorded at intervals of 10 minutes. The PCM is charged through the day, whenever hot water is not demanded by the user.

The discharging process used is termed as batch wise process. In this method, a certain quantity of hot water is withdrawn from the TES tank and mixed with cold water to obtain a nominal temperature of 45 ± 0.5°C for direct use and the tank is refilled with cold water to maintain a constant amount of water in tank. This is then repeated for intervals of 10 minutes, in which time transfer of energy from the PCM would have occurred. This procedure is continued till PCM reaches a temperature of 45°C.

3 Results and Discussion

The temperature distributions of HTF and the PCM in the TES tank for different mass flow rates are recorded during charging and discharging processes. The cumulative heat stored and system efficiency of process is studied in detail during the charging process.

3.1 Charging Process

3.1.1 Temperature histories of HTF and PCM

The temperature histories of HTF and PCM at the four segments of the tank at $(x/L) = 0.25, 0.5, 0.75, 1.0$ are shown in Fig. 3 and 4. Fig 3 represents the temperature variation of HTF inside the storage tank for a mass flow rate of 2 litre/minute and porosity $\varepsilon = 0.49$. It is observed from the figure that the temperature of HTF at all segments increases gradually until it reaches the temperature of 62- 63°C, where it remains constant for a period of 45 to 50 minutes. During this time, the phase change material undergoes an isothermal phase transformation at 60±1°C. After that, the HTF temperature increases by up to 7°C, reaching a maximum of about 69°C.

Fig 4 represents the temperature variation of PCM during the charging process for a mass flow rate of 2 litre/minute and porosity of 0.49. The gradual increase in wax temperature during the charging process is followed by a period of isothermal melting. The heating of liquid PCM shows a rapid change in temperature. It is also noted that the melting of the first layer (or segment) of PCM is completely charged when 70% of the charging has been completed. The charging process is terminated when the PCM temperature in all the segments is above 68°C. It should also be observed that there is no significant temperature difference between each PCM segment during the sensible heating and phase change period. From the temperature histories of PCM and HTF, it is inferred that, for the present system, the heat transfer rate possible from the HTF to PCM in the storage tank is higher than the solar heating rate of the HTF from the solar collector. Hence, it is possible to reduce the charging time by either increasing the surface area of the solar collector, or by using one with a higher efficiency, such as parabolic mirrors.

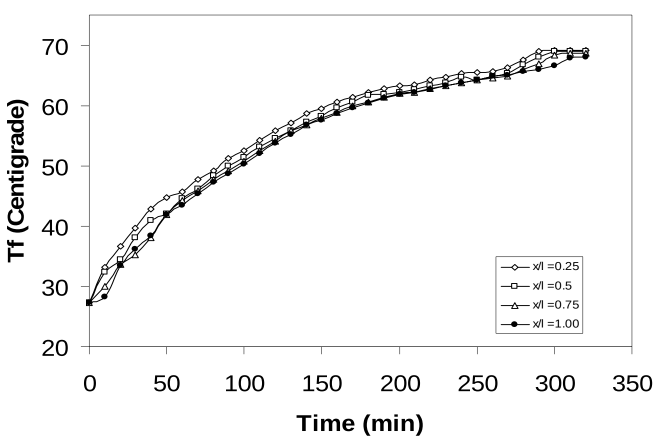

Fig. 3: Temperature distribution of HTF (m=2 l/min, ε=0.49)

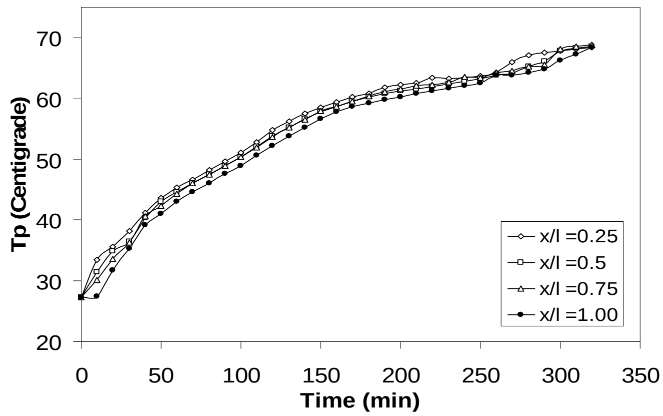

Fig. 4: Temperature distribution of PCM
(m=2 l/min, ε=0.49)

3.1.2 Instantaneous heat stored

Fig 5 graphically represents the instantaneous heat stored in the storage tank during the charging process of PCM with ε=0.49. This is estimated based on the instantaneous inlet and outlet temperatures of the HTF. It is observed that during the initial period of charging the heat stored is high, but decreases there on end. During the phase change period of PCM, the drop in heat stored is less drastic, almost a constant. This is a major advantage of the LHTES system where a uniform rate of charging and discharging is possible for a longer period, which will be useful for practical applications.

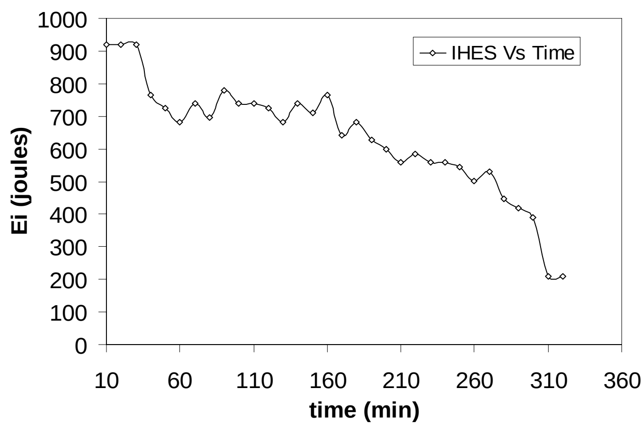

Fig. 5: Instantaneous Heat Energy Stored Vs Time
(m= 2 l/min, ε=0.49)

3.1.3 System Efficiency

System efficiency is defined as the ratio of the amount of energy stored by the TES tank to the heat energy available from solar radiation. The system efficiency of the TES system for the mass flow rate of 2 L/min of HTF is plotted in figure 6. It is seen that the system efficiency decreases with time during the sensible heating of solid PCM, remains nearly constant during phase change period and then further decreases during sensible heating of liquid PCM. The decreasing efficiency can be accredited to decreasing temperature differences between PCM and HTF during charging, which lowers the amount of heat transferred to the TES tank. Also, the increase in HTF temperature at the inlet of solar collector in turn decreases the heat absorption rate from the collector. A further drop in system efficiency arises due to increasing heat losses from TES tank as the HTF temperature increases over time.

3.2 Discharging process

The present work is an effort to evaluate the feasibility of applying LHTES systems for domestic water heating purposes. Thus, we confine ourselves to the study of the discharge characteristics of the HTF alone.

3.2.1 Variation of HTF temperatures

Fig. 7 shows the temperature histories of HTF during batch-wise discharging processes. A certain quantity of hot water is withdrawn from the storage tank and mixed with cold water to obtain hot water of 20 litres at an 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 and after a retention period of 10 minutes, another batch of hot water is withdrawn and mixed with cold water. The batch-wise discharging process is continued until the PCM temperature reaches 45°C. The variation of temperature of the HTF during retention period is also shown in the graph.

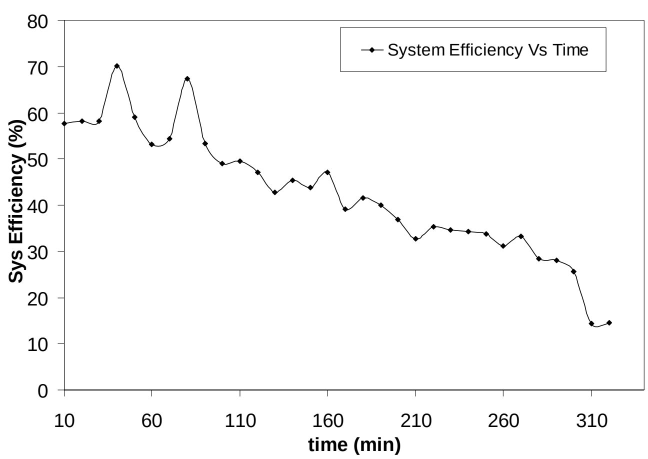

Fig. 6: System Efficiency Vs Time
(m= 2 l/min, ε=0.49)

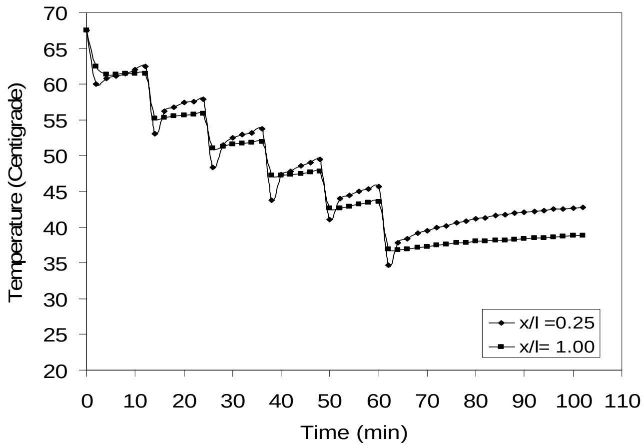

Fig. 7: Temperature distribution of HTF during discharge (m= 2 l/min, ε=0.49)

4 Conclusions

A packed LHTES system containing PCM in cylindrical capsules is designed and fabricated with an effective water storage capacity of about 7 litres, enough to meet the needs of a family of four. The thermal behavior of the LHTES system is investigated experimentally for various operating conditions. The system's discharge characteristics with respect to the HTF are analyzed batch-wise discharge. It is concluded that LHTES systems are a commercially viable option for solar heat energy storage with further research in this area.

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