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Experimental Studies on the Performance of a Multiple PCM Thermal Storage Unit.

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ABSTRACT

Latent heat thermal storage (LHTS) employing phase change materials (PCMs) has gained significant focus due to its advantages like high energy storage density and easy/inexpensive deployment for different applications. In spite of the advantages, the main drawback of LHTS units is its poor thermal performance owing to low thermal conductivity of PCMs. The present work focuses on employing multiple PCMs as a means for performance improvement of LHTS units. A vertical LHTS unit employing single and multiple PCMs has been designed and tested experimentally for both charging and discharging processes. The experimental results revealed superior performance of the multiple PCM unit compared to the single PCM unit. It has been concluded that the multiple PCM unit yielded faster charging and higher discharge temperature for a longer duration compared to that of the single PCM unit. Based on the results, a lower flow rate of heat transfer fluid (HTF) has been suggested during discharging to achieve higher HTF exit temperatures for a reasonably longer duration.

Keywords: PCM, thermal storage unit, LHTS

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INTRODUCTION

Latent heat thermal storage (LHTS) systems using phase change materials (PCMs) have become promising options for thermal management in different applications ranging space based power generation, solar thermal, HVAC, automobiles, electronic cooling, textiles and so on [1, 2]. PCMs undergo a solid-liquid phase transition in cycles absorbing/releasing latent heat within the LHTS unit. The advantages of latent heat systems are viz. high energy storage, nearly uniform temperature of operation and system compactness. A major drawback with LHTS systems is its poor thermal performance owing to poor thermal conductivity of PCMs [3]. Numerous authors have addressed this issue in the past [4-9] and proposed different methods for performance enhancement of LHTS units.

One among the promising methods is the employment of multiple PCMs. Contrary to single PCM units, a multiple PCM unit employs different PCMs with different melting temperatures as shown in Fig. 1. In general, for a single PCM (1-PCM) unit, the HTF during the charging process undergoes a drop in its temperature along the flow direction which results in a poor bulk temperature difference between the HTF and PCM near the exit section. Therefore, it takes a longer time for the PCM near the exit to melt. To overcome this, a multiple PCM arrangement facilitates faster melting at the exit section through employing PCMs with relatively lower melting temperatures. The number of PCMs employed in a multiple PCM unit can be 2, 3 or more depending on the design.

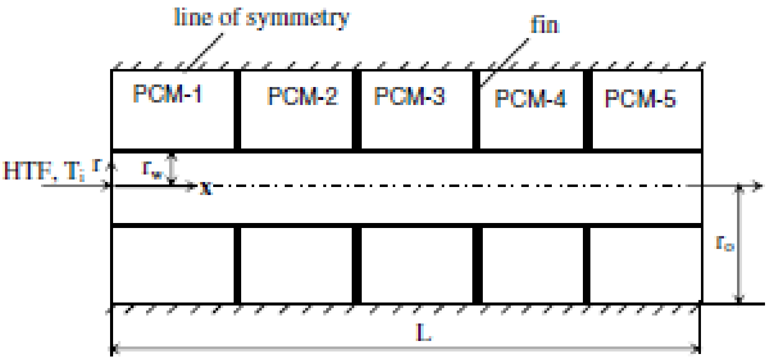

Figure 1: Schematic of a multiple PCM unit.

Pioneering study on multiple PCM units was carried out by Watanabe et al. [10]. A horizontal LHTS unit with 3-PCMs was studied and a 5-30 % enhancement in the performance was reported. Seeniraj and Lakshmi Narasimhan [6] investigated a multiple PCM unit with fins employing numerical technique. They have shown that the multiple PCM unit had resulted in a more uniform exit temperature of the heat transfer fluid with higher heat transfer compared to that of a single PCM with and without fins. Jundika et al. [11] investigated in detail both single and multiple PCM units with (i) single U tube with and without fins (arranged in-line and staggered) and (ii) U tube with festoon type design. Their results show that the U-tube with staggered fins performed better than the in-line case. Lei Yang et al. [12] investigated mathematically the response of a packed bed latent heat unit with both single and multiple PCMs, coupled to a solar water heating unit. Gerard Peiro et al. [13] reviewed briefly about cascaded (multiple) PCM units and conducted experimental studies using d-mannitol and hydroquinone individually as single PCMs and combined as multiple PCMs. Zhipei Hu et al. [14] studied the performance of a novel frustum type thermal storage unit with single and multiple PCMs and compared it against that of a conventional shell and tube type configuration. Based on the literature, it has been found that while studies on single PCM units are vast, it is very scarce on multiple PCM units. Multiple PCM units have been found to perform better compared to that of units with single PCM. Studies so far on multiple PCMs have been largely on horizontal type whereas there are not many on vertical type units. The present work focuses on investigating experimentally the performance of a vertical multiple PCM LHTS unit employing commercial RT type PCMs imported from Rubitherm, Germany.

Experimental Setup

The multiple PCM setup designed and fabricated in this work is presented in Figure 2. It consists of a heater-blower assembly and a LHTS unit comprising PCMs. The PCMs were filled in soft drink (aluminium alloy) canisters arranged on aluminium trays inside the LHTS unit. Pictorial view of the entire system with heater and blower assembly is given in Figure 3. The heat transfer fluid (HTF) employed was air and a blower (radial type, make: EDM Nadi) was employed to deliver the same to the LHTS unit either from bottom to top or from top to bottom. Two flexible bellow type PVC connecting pipes of diameter 0.05 m and length about 3 m have been used for connecting the blower-heater unit with LHTS unit. A 6 kW_e (6 x 1 kWe) finned-coil type electrical heater connected to the exit of the blower has been used to supply hot air at a temperature about 50°C. The heater was switched off during the discharging experiments to ensure cold air entry. The air flow direction in the case of multiple PCMs was reversed (top to bottom instead of bottom to top) interchanging the inlet and exit pipe connections. Seven aluminium trays of size 178 x 170 mm^2 in the form of a wire mesh have been spaced equally along the LHTS unit for placing and supporting the PCM canisters. Commercial soft drink canisters (300 ml) have been used in this work for constructing the PCM canisters. Ten canisters filled with PCMs mounted on the aluminium trays have been arranged in a staggered fashion within the unit as shown later (Figure 3). The canisters have been properly tied to the trays using thin aluminium wires to avoid shaking and lateral movements. Each row has been provided with a maximum of two canisters and the mass of PCM loaded in each canister is about 240 $\pm$ 5grams. The LHTS unit was made using acrylic sheet of thickness 6 mm. It consists of three sections namely the inlet, exit and the middle sections. The middle section is of rectangular cross section and has a height of about 630 mm as shown. It has been divided into seven equal sections with provisions for mounting aluminium trays. PCM canisters have been mounted on the aluminium trays in staggered orientation to facilitate HTF flow around all the canisters throughout the length of the LHTS unit. The front panel of the middle section is removable and screwed airtight for easy mounting/unmounting of the PCM canisters within the LHTS unit. A small hole (2-3 mm) diameter has been drilled at both inlet and exit sections in order to locate the thermocouples for HTF temperature measurements. A central hole of 60 mm diameter has been provided to enable connecting the pipe carrying heat transfer fluid (HTF). K-type thermocouples (accuracy $\pm$ 0.3 °C) were used to measure temperatures at 15 different points viz. (i) at central location in all the 10 canisters (to monitor the temperature of the PCM within) (ii) at one more location near the top surface for three canisters (iii) HTF inlet and (iv) HTF exit. The canisters in the first, fourth and seventh trays have two thermocouples each to measure the temperatures at centre as well as at the top of the PCM. The thermocouples were carefully inserted inside the canisters and sealed using araldite & silicone adhesives to prevent leakage of the PCM. Two temperature indicators were deployed to display the temperatures and readings at every 5 minutes were recorded manually during the experiments.

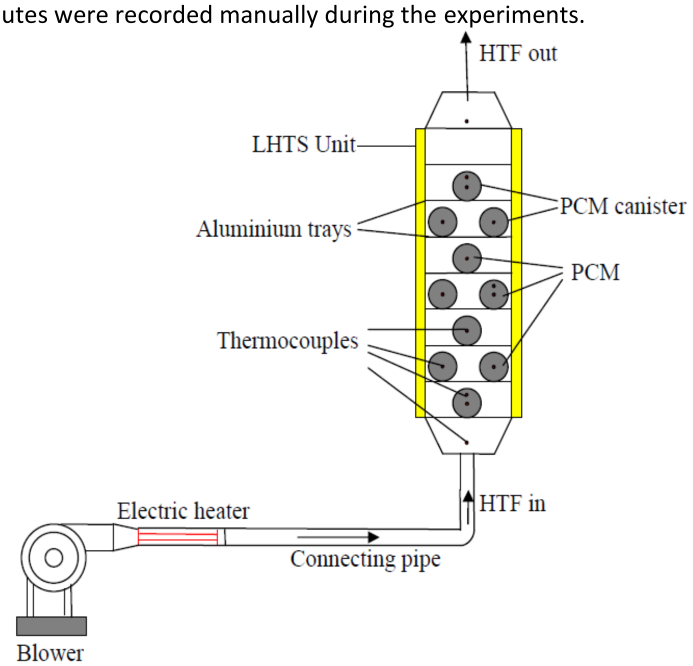

Figure 2: Schematic of the experimental setup

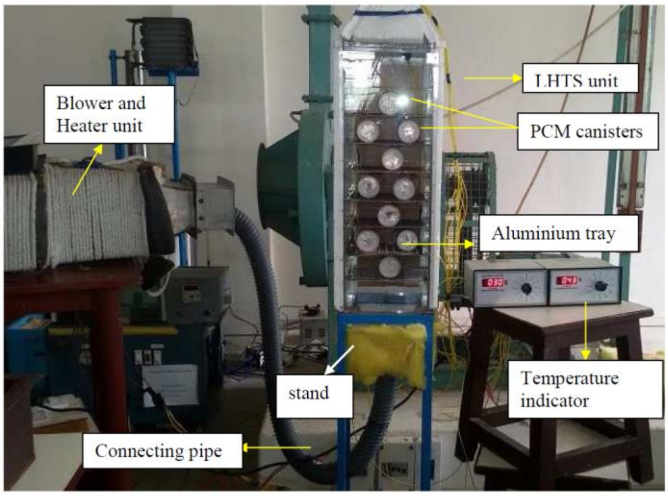

Figure 3: Pictorial view of the experimental setup

Organic PCMs imported from Rubitherm, Germany (commercially known as RT paraffins) have been used in the present work. Three different phase change materials viz. RT 42, RT35 and RT 31 were studied whose meting temperatures are 27-33, 29-36 and 38-43 ^{o}C respectively.

Charging and Discharging

In single PCM experiments, all the 10 canisters were filled with RT 35 PCM and the charging/discharging characteristics were studied. Hot air was passed through the unit from its bottom to top during charging while cold air was passed from top to bottom during discharging. The entire LHTS unit was insulated by using thermocol and glass wool to prevent heat loss via convection.

Charging Process

During charging experiments, hot air was supplied at a constant temperature of about 40 $\pm$ 1^{o}C. Temperatures were recorded at 15 different locations once in every 5 minutes. Experiments with multiple PCMs were performed in the same manner as single PCM except that the PCMs were arranged in their decreasing order of the melting temperatures. The PCMs employed for multiple PCMs were RT31, RT35 and RT42 as discussed earlier. The PCM, RT 42 was filled in the first 4 canisters, while the PCM RT 35 was filled in next 3 canisters followed by PCM RT31 in the last three canisters.

Discharging Process

During discharging experiments, cold air to the LHTS unit was supplied by the blower through a connecting pipe. The heater was switched off during the entire discharging experiments. The temperatures were recorded at 5 minutes interval at all locations till the entire PCM reached steady state of operation. During the discharging process with multiple PCMs, the direction of flow of the heat transfer fluid has been reversed to enable it to be along the increasing order of PCM's melting temperatures.

RESULTS AND DISCUSSION

This section discusses about the experimental results obtained with the single and multiple PCMs. The temperature distribution within the unit and inside the PCM canister and the heat transfer fluid (HTF) exit temperature w.r.t time have been plotted to understand their transient thermal response.

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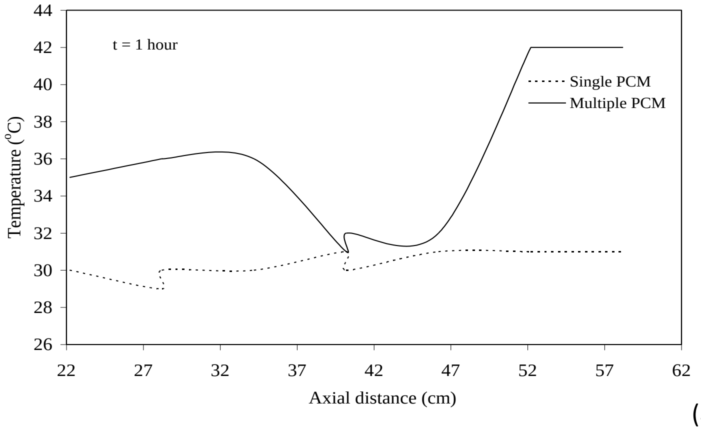
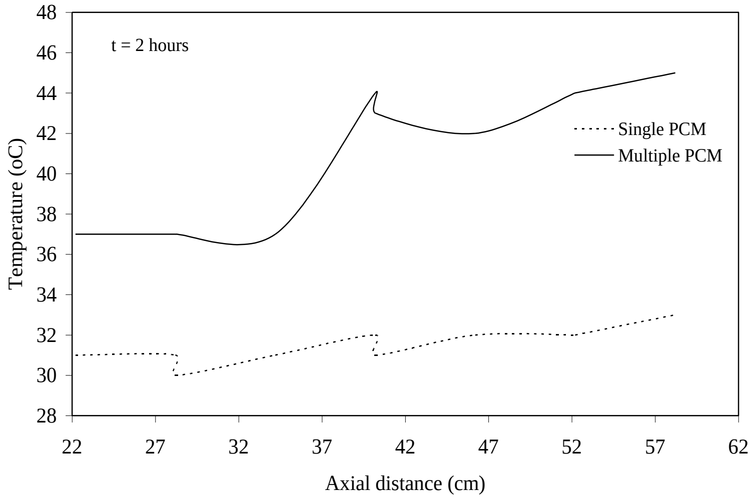
Temperature Distribution During Charging

Figure 4 shows the centreline temperature distribution during charging, for the single and multiple PCM units. Plots have been made for two different time instances 1 hour and 2 hours after commencing the charging process individually for the two cases. While the single PCM unit has been loaded with RT 35 PCM , the multiple PCM unit has been loaded with three different PCMs (RT 31, RT 35 and RT 42) arranged as per the decreasing order of the melting/freezing temperatures from the bottom to top of the unit. The inlet HTF temperature was maintained at 40 ºC for the single PCM case and 46 ºC for the multiple PCM case in order to commence the melting process. It can be seen from Fig. 4 that the temperatures are higher with the multiple PCM case compared to that of single PCM case. Even at time t = 2 hours the temperature within the single PCM throughout the unit along the centreline is nearly uniform (31-33 ºC). In the case of multiple PCM, the central portion and the top portion (RT 35 and RT 31 respectively) undergoes a rapid increase in its temperature. However during the first 1 hour, the PCM at the lower portion of the unit (for multiple PCM case) undergoes a rapid heating as shown in Fig. 4(a), while the middle portion show a slow response. As time progresses, the heating becomes faster in the middle portion of the PCM (RT 35) as shown in Fig 4 (b). The reason for the above is attributed to the axial variation in the temperature difference between the HTF and PCM. Initially, the available HTF to PCM temperature difference is more at the bottom from where the HTF enters the LHTS unit during charging. Therefore the melting is respectively higher at the lower portion compared to the middle portion. Since the top portion is loaded with the low melting point temperature PCM in the case of multiple PCM unit, the melting obtained is much faster owing to relatively higher HTF/PCM temperature difference. On the other hand with the single PCM unit (as shown in Figs. 4 (a) and (b)) the heating of PCM near the top portion is not appreciable owing to lower HTF-PCM temperature difference. It is understood from the figure that incorporating multiple PCMs favours enhancement during the charging process.



(a)



(b)

Figure 4: Centreline temperature distribution during charging for the single and multiple PCM cases at (a) t = 1 hr and (b) t = 2 hrs

Timewise temperature variation of PCM inside canister during charging

Figures 5 and 6 show the timewise temperature variation at the centre and top portion of a single canister located at the bottom, middle and top portions of the single and multiple PCM LHTS unit respectively. It can be observed from Fig. 5 that during the initial stages of melting for the single PCM case, the temperature difference between two locations within the canister located at the bottom end is larger compared to that at the middle and top. The same can be observed from Fig. 4 for the single PCM unit. In the case of multiple PCM, the effect of residence time is overcome by the admission of relatively higher temperature HTF (46 ^oC). The canisters at the middle portion show a distinct temperature difference within the PCM upto 80 minutes, whereas the entire PCM is nearly uniform for the canisters present in the bottom and top sections. The bottom canister show a temperature gradient upto 10 ^oC, whereas for the middle and top canister it is upto 2-3 ^oC as shown in Fig. 6.

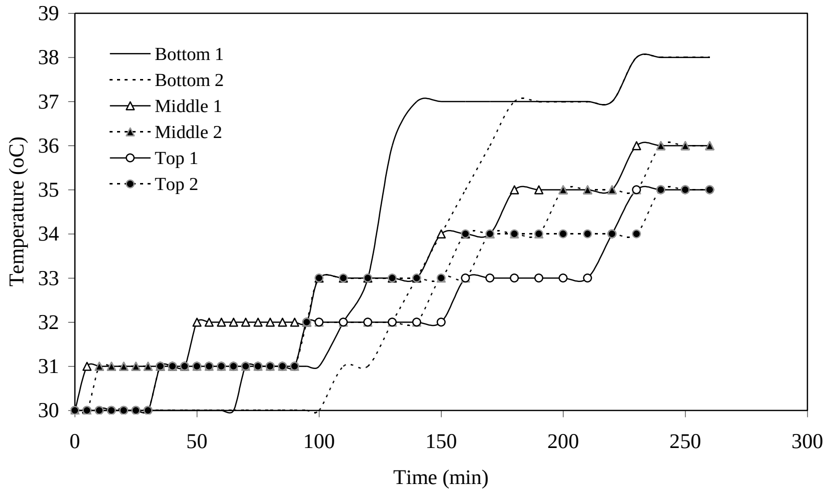


Figure 5: Timewise temperature variation inside the PCM canister at bottom, middle and top sections during charging for the single PCM unit.

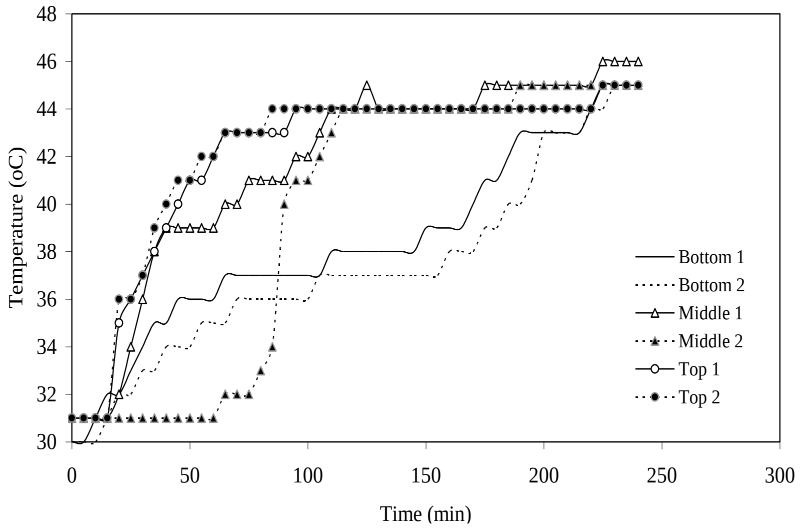
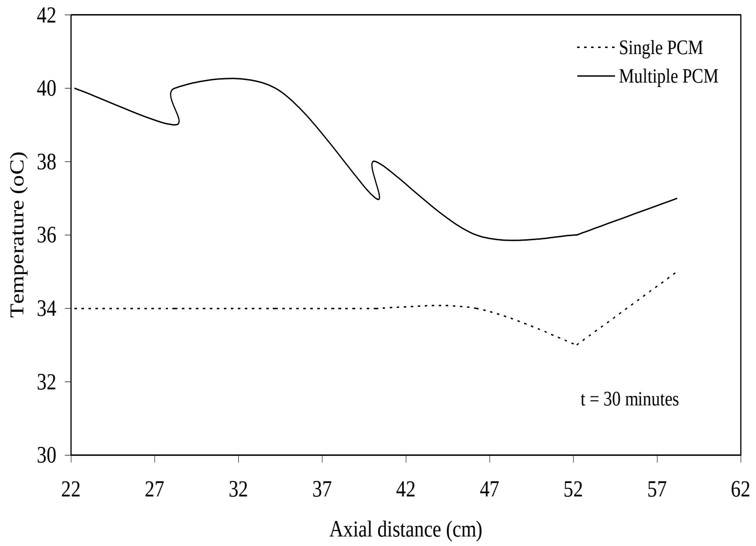


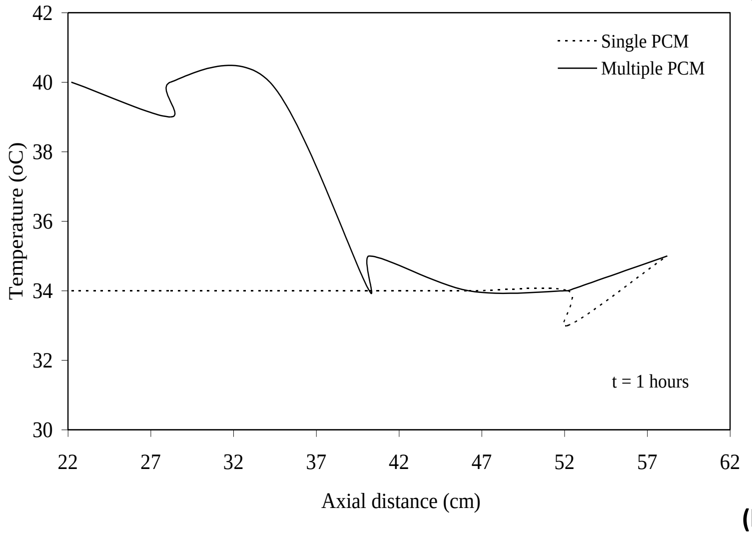
Figure 6: Timewise temperature variation inside the PCM canister at bottom, middle and top sections during charging for the multiple PCM unit

Temperature Distribution During Discharging

Figure 7 shows the centreline temperature distribution along the unit for the single and multiple PCM cases during discharging. The HTF inlet temperature was maintained at 30 ^{o}C throughout the discharging process. During this process, the HTF gains energy from the PCMs. It can be observed that the single PCM unit essentially remains at lower temperature compared to the multiple PCM case. The temperature drop in the middle portion (for multiple PCM case) has been very rapid as time progresses compared to the bottom and top portions. At about 1 hour, both the single and multiple PCM cases drop to a same temperature (34 ^{o}C) in the top half section. However, the bottom half remains at a reasonably higher temperature (about 6 ^{o}C higher than the single PCM case).



(a)



(b)

Figure 7: Centerline temperature distribution during discharging for the single and multiple PCM cases at (a) t = 30 min and (b) t = 1 hr.

CONCLUSIONS

This work reports on the experimental investigations on single and multiple PCM latent heat thermal storage units. It is concluded that the unit with multiple PCMs perform better than those with a single PCM. Employing multiple PCMs results in a faster charging/heat transfer with relatively higher heat transfer fluid exit temperatures during discharging compared to the single PCM unit. Discharging duration can be increased with multiple PCMs for the same HTF inlet temperature compared to the single PCM unit. Lower HTF mass flow rates are suggested for achieving higher exit temperatures for a longer duration when discharging happens.

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