AN EXPERIMENTAL INVESTIGATION ON THE COMBINED USE OF PHASE CHANGE MATERIAL AND ROCK PARTICLES FOR HIGH TEMPERATURE (~350 ^{O}C) HEAT STORAGE

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Abstract

The intermittent nature of solar energy requires integration of an energy storage system with collector devices in order to have an un-interrupted supply of energy in the absence of the availability of solar energy. The use of Phase Change Materials (PCM) and rock particles for heat storage has been a main topic in research for the past decades. However, little is known on the use of the combination of PCM and rock particles for high temperature heat storage with air as the medium of heat transfer.

The aim of this paper is to show experimentally by means of comparison, the thermal behaviours of thermal energy storage with only rocks and rocks plus copper cylinders containing PCM. A heat storage consisting of both rock particles and phase change material has been designed and built. The PCM material used is a mixture of $NaNO_3$ and KNO_3 in the ratio of 60:40 percent (mol %). The charging and thermal de-stratifications profiles were determined for both cases. The results shows that the introduction of PCM cylinders in rock bed heat storage does not only increase the heat content of the bed but it also act as fins that can be use for heat extraction.

Keywords

PCM cylinders, thermal energy storage, rock particles

1. Introduction

Thermal Energy Storage (TES) is the storing of heat energy that can be drawn at a later time to perform some useful applications. TES systems have the potential of increasing the effective use of thermal energy sources for various applications. Solar energy, a major renewable energy source, is of intermittent nature and its effective use is in fact dependent on efficient and effective energy storage system. The absence of heat storage in solar thermal applications would leave the major part of the energy demand met by auxiliary sources and these would lead to a reduction in the annual solar load.

Different thermal storage techniques are available and a review of different materials suitable for heat storage is provided by Duffie and Beckman (1991). Thermal energy can be stored in the form of sensible heat, latent heat and chemical heat storage. Sensible heat and latent heat are most developed mechanism of heat storage. The choice of the storage media ideally depends on the process or intended use of the energy, the cost of the system, design and safety among other factors. For solar thermal applications suitable for cooking in developing countries that are located within the Sun Belt region, the cost of the system has to be taken into consideration.

Sensible heat storage materials are cheaper and usually have larger thermal conductivities when compared to phase change materials for thermal storage application. Water as sensible heat storage has a high specific heat capacity of 4180 $Jkg^{-1}K^{-1}$ which has made it the best choice for low-temperature heat storage. However, water cannot be easily used at temperatures higher 100 ^{o}C since it would be required expensive pressure equipment in order to raise its operating temperature range.

Rock beds have been largely used as thermal storage mainly for space heating as reported by (Klein et al 1997; Sharma et al 1991 and Abdud et al 1995). Rocks have low energy storage density due to their low heat capacity compared to water and this implies that a bigger heat storage volume is needed when using rocks for heat storage. Rocks have some advantages over other thermal energy storage materials at intermediate to high temperature applications in that they are cheap, readily available and the design of the containment is similar to the conventional cooking oven. In addition, rocks have fairly good heat transfer characteristics when used with air and are able to withstand high temperatures. Fricker (1991) studied rock properties at elevated temperatures and found that gneiss and granite could stand temperatures up to 600 ^{o}C.

The most common PCMs used in solar energy systems are those that undergo a phase change from solid to liquid (Zhen and Suresh 2010; Zalba et al 2003). In comparison to sensible heat storage materials, latent heat thermal storage materials have higher energy storage density and are able to supply heat at nearly constant temperature (Abhat 1983; Lane 1983). This is because the change of phase occurs at a constant temperature and takes some time to complete, so it is possible to smoothen temperature variations in latent heat thermal storage systems (Sharma et al 2005). However, a major disadvantage of PCM materials for heat storage is their low thermal conductivity and some degrades with repeated recycling.

However, existing literature lacks information on the thermal behaviour of a storage containing a mixture of rocks particles and PCM cylinders charged at about 350 ^{o}C. The aim of this study is to examine experimentally the thermal behaviour of a bed containing rock particles and copper PCM cylinders charged with air at about 350 ^{o}C. The advantage of such a system would be having a smaller size heat storage that is able to supply heat at almost constant temperature.

2. Material and Methods

2.1 Preparation of $NaNO_3$-KNO_3 binary mixture

A detailed description on the preparation of $NaNO_3$ and KNO_3 (grade GPR Rectapur, VWR) mixture is reported by Foong et al (2011). The mixture was prepared and stored in copper cylinders of diameter 0.05m and length 0.94 m. A free air space was left on top to allow for expansion and condensation during melting and solidifications. The cylinders were then closed with well designed cylinders tops as shown in Figure 1. The thermo-physical properties of the solar salt mixture were determine using a differential scanning calorimeter as reported by Foong et al (2011). All the experiments on thermo-physical properties were done in triplicate and the mean values were taken.

2.2 Thermal Store

The rock bed store was constructed using two vertical co-axial cylinders made of stainless steel of thickness 0.0015m and length 1.0 m. The diameters of the inner and outer cylinders were 0.3 and 0.4 m respectively. Three thin, parallel, and reflecting steel foils were inserted in the space between the cylinders and the space was evacuated to minimize heat loss by radiation. Additional layers of fibre glass were added to eliminate heat loss to the surroundings. A support screen was placed at bottom to support the rocks. Four copper PCM cylinders shown in figure 1 were inserted in the cylindrical thermal store container and the space between them filled with crushed mountain rocks of approximate diameter of 0.02m as shown in Figure 2. Ten K-type thermocouples were placed vertically along the axis of the cylinder to measure the temperature distribution. Air for a compressed air tank is metered before being introduced to the bed from the top. The initial temperatures of the bed were made uniform by blowing air at room temperature through the bed until all thermocouples reading were the same. The bed was heated by introducing hot air from the top to the bottom in a once through method (without recirculation). Figure 3 shows the block diagram for the experimental setup and data acquisition systems.

Figure 1 showing copper cylinders containing with PCM

Figure 2: showing the Cu PCM cylinders with rocks for heat storage

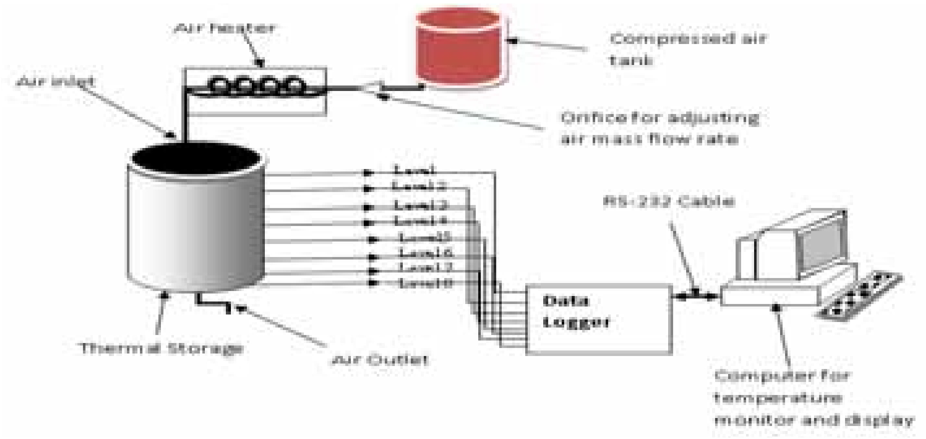

Figure 3: Block diagram of the experimental setup and data acquisition

3. Thermal performance parameters

The thermal performance during charging process is analysed using the charging profiles, which is a plot of axial temperature distribution as function of bed length at different charging times. The energy stored in the bed containing only rocks during the charging cycle is obtained from the expression

$$E_s = \rho_b C_b (1-\varepsilon) V_{stor} (T_{in} - T_{out}) \quad \text{(eq.1)}$$

where C_b is the specific heat capacity of rock, ρ_b is the density of rock, ε is the porosity of the bed, T_{in} is the air inlet temperature (assume to be the temperature of the topmost part of the bed), T_{out} is the temperature of air leaving the bed and V_{stor} is the volume of storage tank.

The energy storage in a bed containing both rocks and copper PCM cylinders is given by the sum of the energy stored in the rocks plus the energy stored in the phase change material. This can be expressed by the equation

$$E_{stored} = \rho_b C_b (1-\varepsilon)(V_{stor} - 4V_{Cu})(T_{in} - T_{out}) + m\left[c_{ps}(T_m - T_{out}) + L_s + L_p + c_{pl}(T_{in} - T_m)\right] \quad \text{(eq.2)}$$

V_{Cu} is the volume of the Cu cylinder, m is the mass of PCM, C_{pl} is the specific heat capacity of the liquid PCM, C_{ps} is the specific heat capacity of the solid PCM, L_s is the latent heat of solid-solid phase transition, L_p is the latent heat of solid-liquid phase transition and T_m is the melting temperature of the solar salt mixture.

Table 1: Thermal energy storage parameters used

Parameter	Value	Units
Rock diameter	0.02	m
Thermal conductivity of rock	2.79	W/m °C
Specific heat capacity of rock	880	J /Kg °C
Void fraction	0.395	
Storage diameter	0.3	m
Storage length	1.0	m
Mass of PCM in each cylinder	2.85	kg
Air-mass flow rate	0.0048	kg/s
Volume of Cu cylinder	0.00184	m^3

4. Results and discussions

4.1 Thermal characteristic of $NaNO_3$ and KNO_3 mixture

The thermal behaviour of the mixture of $NaNO_3$ and KNO_3 salt was determined using differential scanning calorimeter in temperature range from 32 ^{0}C to 496 ^{0}C. The enthalpy of phase transition and phase change were calculated. Table 2 shows the thermo-physical properties of the $NaNO_3$ - KNO_3 binary mixture obtained in the study. The $NaNO_3$ - KNO_3 binary mixture exhibit a relatively high temperature of fusion that is suitable for most cooking applications.

Table 2: Thermo-physical properties of the $NaNO_3$ - KNO_3 binary mixture (60:40 mol %)

Thermo physical property	Value
Temperature of fusion. (^{0}C)	216.73 ± 0.71
Enthalpy of fusion. (kJ/kg)	108.67 ± 1.43
Phase transition enthalpy (kJ/kg)	31.91 ± 0.48
Thermal Conductivity(W/m K)	0.8

4.2 Charging profiles

The temperature profiles for a thermal storage with only rocks are provided in Figure 4. It is observed that the topmost part gets heated up in the first two hours of charging and a large temperature gradient exist showing a highly stratified bed. But as charging is continued at constant rate, the bottom temperature begins to increase. The profile after 5 hours of charging shows the bottom-most part temperature at a distance of 0.9 m from the top-most part rose to about 150 ^{o}C.

The temperature profiles for a combination of copper PCM cylinders and rocks charged at about 350^{o}C are shown in Figure 5. The thermal storage was charged with the same constant flow rate of 0.0048 kg/s that was used in Figure 4. From Figure 4 and 5, one can notice the similarity in the general shapes of the temperature profiles after one hour of charging. However, the profiles begin to change as charging is continued. More stratification in observed in a bed with only rocks (Figure 4), where the temperature gradient between the topmost part of the storage and the bottom-most part is high. The introduction of copper cylinders increases heat conduction down the bed. In this case, the copper cylinders were able to short-circuit the bed.

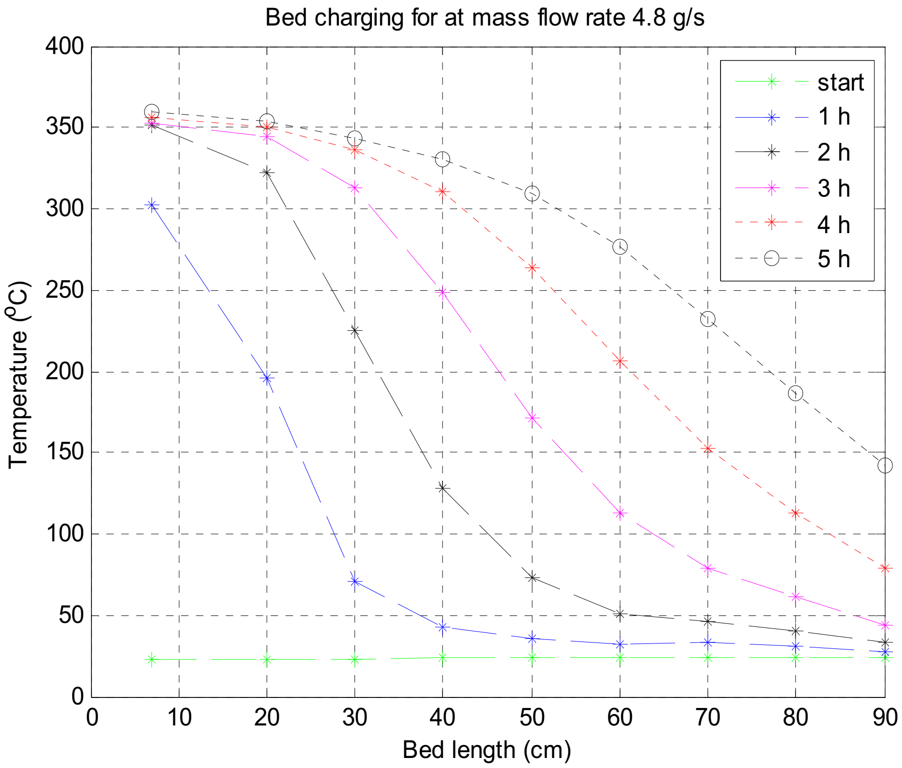

Figure 4: Showing the charging profiles for rock bed charged at a constant mass flow rate of 0.0048 kg/s.

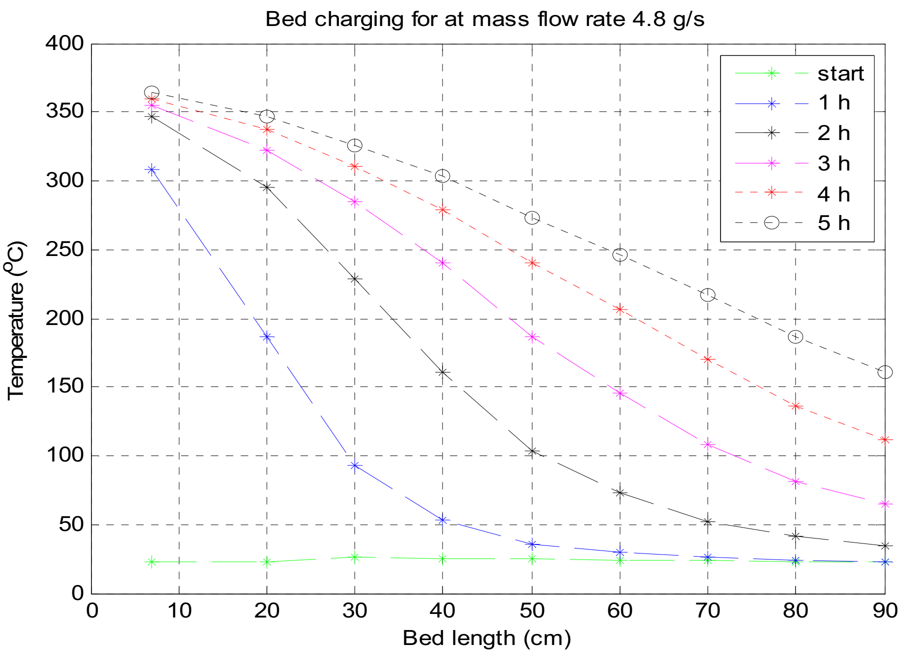

Figure 5: Showing the temperature profiles of a heat storage containing both rock particles and Cu cylinders

4.3 Loss in thermal stratification

To examine the thermal behaviour of the storage after charging, both beds were charged for five hours and then charging was stopped and both the inlet and outlet ports were sealed off. The bed was then left to stay while recording the temperatures along the bed length for 18 hours. The thermal equalisation profiles of a bed consisting of only rock particles is shown in figure 6 while the profile for a bed consisting of both the rock particles and copper cylinders containing PCM shown in Figure 7. The temperature profiles immediately after stopping the heater (indicated by start) and those after 2h, 6h, 12h and 18h are shown in the graphs.

The results indicate faster loss in thermal stratifications in a rock bed containing copper cylinders. Rock storage and solar salt mixture have about the same thermal conductivity in this temperature range. But use of copper cylinders increases the total vertical conductivity of the storage by a factor of about 20. The phase change energy corresponds to about 12 K overall temperature changes in the storage, and will, together with the high copper conductivity, add to the tendency of temperature equalisation in the volume. After 12 hours, the bed is almost at uniform temperature at about 230 ^{o}C. For a bed containing only rock particles, there is little loss in stratification after 6 hours and the bed is observed to exhibit relatively higher temperature at a distance of about 30 cm from the top most part. There is undesirable temperature drop at the storage top of the storage bed caused be heat loss to the surrounding.

The results of the energy stored in the two storage configurations calculated using (eq. 1) and (eq. 2) is plotted in Figure 8. An increment in energy stored by about 6 MJ is observed by the introduction of PCM cylinders.

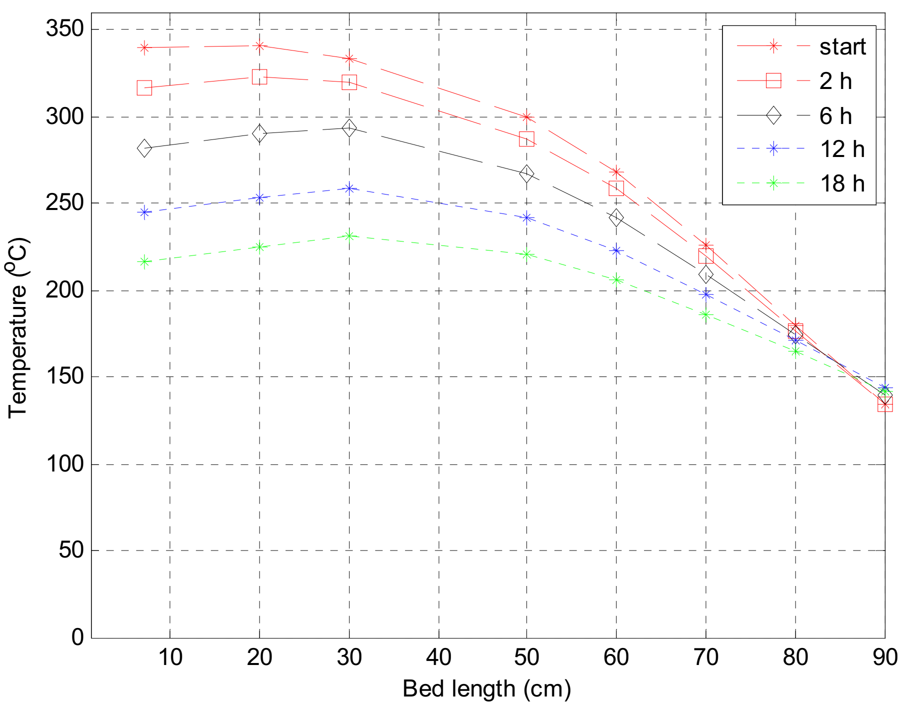

Figure 6: Loss of thermal stratification in rock-bed at different storage times

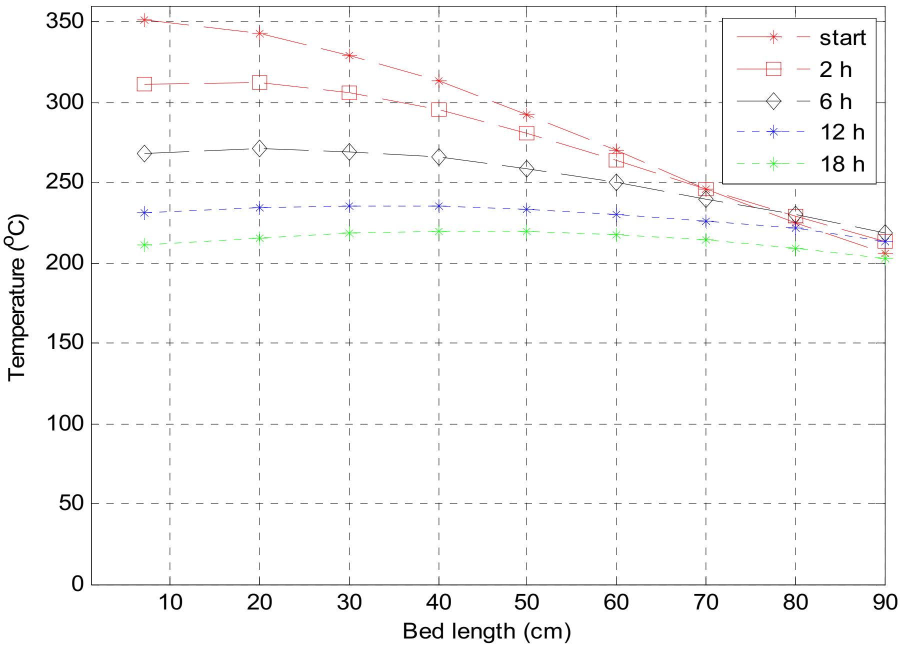

Figure 7: Loss in thermal stratifications in a bed containing both rock particles and Cu cylinders at different storage times

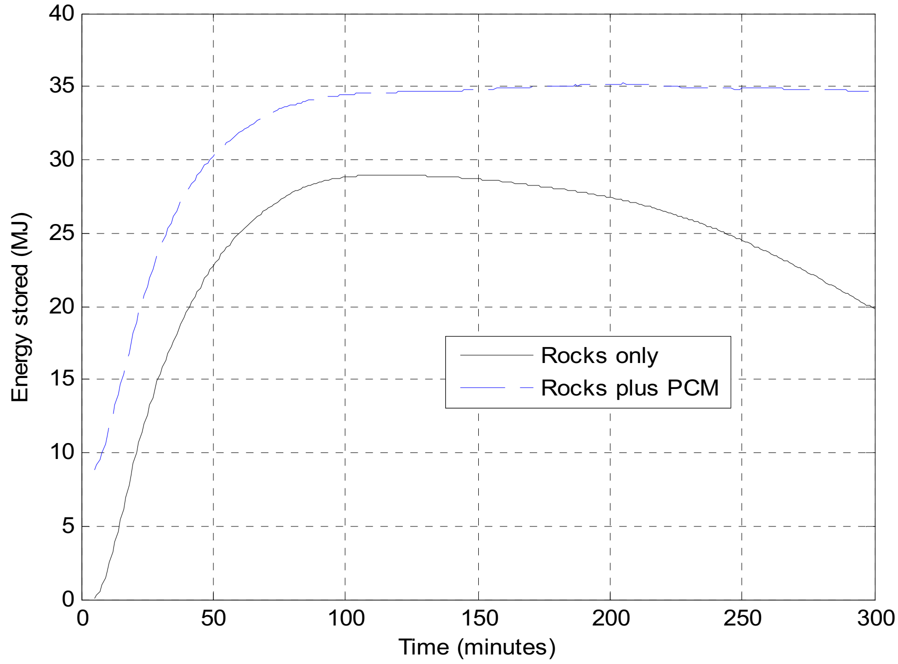

Figure 8: Total energy stored during charging of a bed containing only rocks and rocks plus PCM cylinders

5.0 Conclusions

Limited experiments have been done on the effect of using a combination of phase change material and rocks for high temperature heat storage. The introduction of copper cylinders containing molten solar salt resulted in an increase in the energy content of the storage by about 6 MJ. The use of copper cylinders increases the vertical heat conductivity and the bed was able to equalise thermally after about 12 hours of stay.

Further investigation is needed to find out the possibilities of using highly conductive material (copper cylinders with and without PCM materials) as fins for heat extraction.

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