Exergetic performance of medium temperature metallic solder based cascaded PCM thermal energy storage systems during charging

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Abstract

Metallic phase change materials are attractive candidates for use in thermal energy storage systems, but their high cost per unit volume may prohibit their usage. To reduce the cost, some volume of metallic phase change materials may be replaced with other cheaper phase change materials. Three packed bed cascaded latent heat thermal energy storage (LHTES) systems for medium temperature applications are experimentally evaluated and compared to a single phase change material (PCM) packed bed LHTES of eutectic solder capsules from a charging exergetic rate perspective. Cascaded system 1 comprises of eutectic solder PCM capsules at the top, and erythritol PCM capsules at the bottom in equal storage volumes. Cascaded system 2 consists of eutectic solder PCM capsules at the top and adipic acid PCM capsules at the bottom in equal storage volumes. Cascaded system 3 consists of three PCM capsule layers of eutectic solder at the top, adipic acid in the middle, and erythritol at the bottom in equal storage volumes. Cascaded system 3, the 3 PCM cascaded system shows higher exergy charging rates because of the release of latent heat in 3 phase change transitions. Its thermal performance is, however, comparable to cascaded system 2 with adipic acid at the bottom of the storage tank. The charging times for cascaded system 2 and cascaded system 3 are also shorter as compared to the other storage systems suggesting a better charging performance. The single PCM shows the lowest exergy charging rate at the lowest flowrate but its performance improved to be better than that of cascaded system 1 with an increase in the flowrate.

Keywords: Adipic acid, Charging exergy rates, Cascaded latent heat thermal energy storage, Erythritol, Eutectic solder, Packed bed

1. Introduction

Metallic phase change materials (PCMs) have been suggested for use in latent heat thermal energy storage (LHTES) systems which are useful to address the mismatch between solar energy supply and demand [1]. Solar energy may be utilized for domestic applications like water heating and cooking. Metallic PCMs are particularly attractive due to their high thermal conductivities, high latent heat per unit volume, low vapor pressure, good thermal cycling stability and negligible degrees of sub-cooling [2-6].

The usage of metallic PCMs in practical thermal energy storage (TES) systems may be hampered by their high cost per unit joule of energy storable/deliverable. Cascading different PCMs with different melting temperatures in single/multiple TES tanks has been suggested by a recent comprehensive review as a method that increases the effectiveness of latent heat storage systems [7]. Moreover, including other cheaper PCMs with a metallic PCM in a cascaded configuration in a TES tank has the potential to lower the cost of the overall system. Numerous past studies have investigated different configurations of cascaded LHTES systems from various perspectives, and for different proposed temperature applications as reported in [7]. Studies on packed bed cascaded latent heat storage configurations which are simpler and more efficient are rather limited especially for medium temperature applications [8-13].

doi:10.18086/eurosun.2020.07.02 Available at http://proceedings.ises.org

While numerous previous studies have investigated the optimization of the performance of cascaded LHTES systems from a broad range of parameters for low and high temperatures, a limited number of the systems have been designed for medium temperature applications (100 - 300 ºC). Hence, the objective of this study is to investigate the charging performance of a packed bed LHTES, using a metallic PCM and two organic PCMs, for medium temperature applications. The idea is to combine the advantage of the high thermal conductivity of the metallic PCM with that of the cheapness of the organic PCMs as well as their high latent heats of fusion. Sunflower Oil will be utilized as the heat transfer fluid (HTF) as it has been reported to possess good heat transfer and good stratification properties in a TES tank [14]. The use of vegetable oils such as Sunflower Oil for domestic heating needs is particularly attractive due to their environmental friendliness, cheapness, availability and good thermal reliability within the medium temperature range as highlighted by Mawire [15], Hoffmann et al. [16] and by Hossain et al. [17] in their recent studies.

The eutectic solder, Sn63/Pb37, used in this study has recently been reported to be a good metallic PCM for medium temperature TES applications [18]. In another recent study, a packed bed TES system with the encapsulated eutectic solder alone showed promising thermal performance [19]. In another related study, the performance of the eutectic solder packed bed TES system was compared with a similar TES system incorporating both encapsulated solder cascaded and encapsulated erythritol in a 50:50 ratio in the TES tank [20]. The cascaded TES system generally showed better overall efficiencies at high temperatures and at high HTF flow rates. The performances of three similar packed bed TES systems containing erythritol, eutectic solder and adipic acid, respectively, were compared recently in [21], and the results obtained showed reasonably good performance for these three PCMs. The aim of this comparative study is to compare the performances of the TES systems investigated in [20] with one in which erythritol is replaced by adipic acid and another one comprising of three PCMs cascaded in equal layers in the same TES tank. This is in a bid to obtain an efficient TES system for medium temperature applications in terms of both thermal performance and cost. The exergetic performance is considered in this paper since it gives a true reflection of the quality of the energy stored accounting for heat losses when compared to the energetic performance.

2. Experimental method and procedure

Figure 1 shows schematic diagrams of the four TES configurations considered in this study.

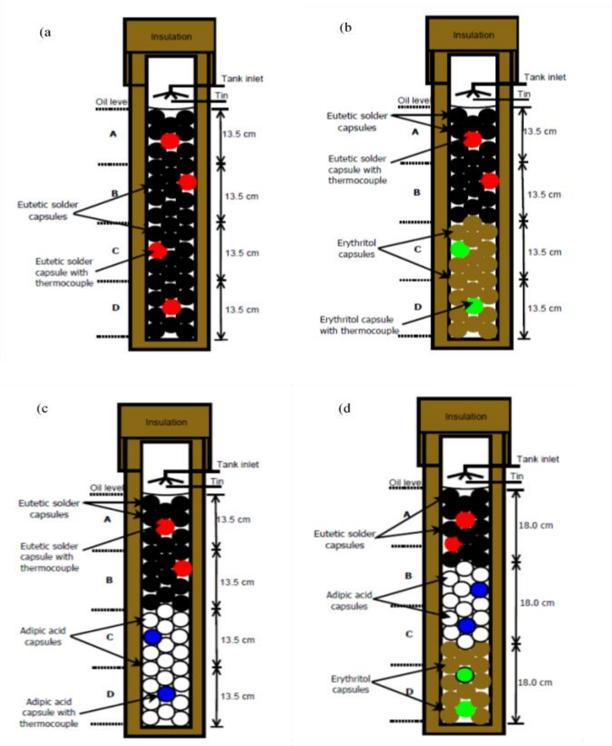

Figure 1: Schematic diagrams of the four storage systems: (a) the single PCM system, (b) cascaded system 1, (c) cascaded system 2 and (d) cascaded system 3.

The single PCM system (a) is composed of 42 eutectic solder (Sn63/Pb37) capsules with four capsules having thermocouples to monitor the PCM temperature, one placed at each of the four levels (A-D). Cascaded TES 1 (b) comprises of 21 eutectic solder PCM capsules at the top and 21 erythritol PCM capsules at the bottom. Two capsules of each PCM have thermocouples to monitor the PCM temperatures at levels A-D. Cascaded TES 2 consists of 21 eutectic solder PCM capsules at the top, and 21 adipic acid PCM capsules at the bottom. Also, two capsules of each PCM have thermocouples to monitor the PCM temperatures at levels A-D. Cascaded system 3 consists of three PCM capsule layers of eutectic solder at the top (14 capsules), adipic acid in the middle (14 capsules) and erythritol at the bottom (14 capsules).

Similar pre-fabricated spherical aluminum capsules, each with a diameter of 0.05 m and a wall thickness of 0.001 m were used for encapsulating the PCMs in this study. Each PCM was melted and then poured into the capsules. Forty-two capsules were filled with eutectic solder (Sn63/Pb37), twenty-one with erythritol, and another twenty-one with adipic acid. Each capsule was filled up to about 80 % of the total volume with liquid PCM to allow for thermal expansion.

Table 1: Thermo-physical properties of the three PCMs used in this study.

Property	Erythritol	Adipic Acid	Eutectic Solder (Sn63Pb37)
Melting Temperature (ºC)	118.4 - 122.0 [22]	151.5-153.0 [24]	183 [26]
Specific Heat Capacity (kJ/kgK)	1.38 (20 ºC) [23] 2.76 (140ºC)	1.59 (20 ºC) [24] 2.26 (150 ºC)	0.21 (30 ºC) [27]
Phase change enthalpy (kJ/kg)	310.6 [22]	238.5 [24]	52.1 [26]
Density (kg/m^3)	1480 (20º C) [23] 1300 (140º C)	1360 (20 ºC) [24] 1093 (163 ºC)	8400 [28]
Thermal conductivity (W/m K)	0.733 (20º C) [23] 0.326 (140º C)	0.16 (150 ºC) [25]	50 [27]
Average mass of PCM in a capsule (g)	64.02	60.03	364.03

Thermo-physical properties of erythritol, adipic acid and the eutectic solder as obtained from open literature are presented in Table 1. The average mass of erythritol in the capsules was almost similar to the average mass of adipic acid in the capsules. The eutectic solder has the largest mass of PCM inside the capsules due its higher density. Erythritol possesses the largest phase change enthalpy, while the eutectic solder has the least. The thermal conductivity of the solder is the highest, while adipic acid shows the lowest thermal conductivity.

The basic experimental setup is shown in Figure 2, and a more detailed description of the setup may be found in our previous studies [20, 21]. The experimental setup consists of an insulated, cylindrical aluminium TES tank whose contents may be any of the configurations depicted in Figure 1. Charging occurs when valves 3, 5 and 7 are open. The electrical heater (f) with embedded oil circulating copper spiral coils heats up the oil which is pumped through the flow pipes to the top of the TES tank (a). The heating power and the maximum temperature of the heating unit is controlled by a temperature controller (g). Charging of the TES system is terminated when the average bottom fluid temperature TD (average of T41, T42, T43) is 190 ºC for the single PCM system to ensure that the bottom PCM is melted since the melting temperature of the eutectic solder is 183 ºC.

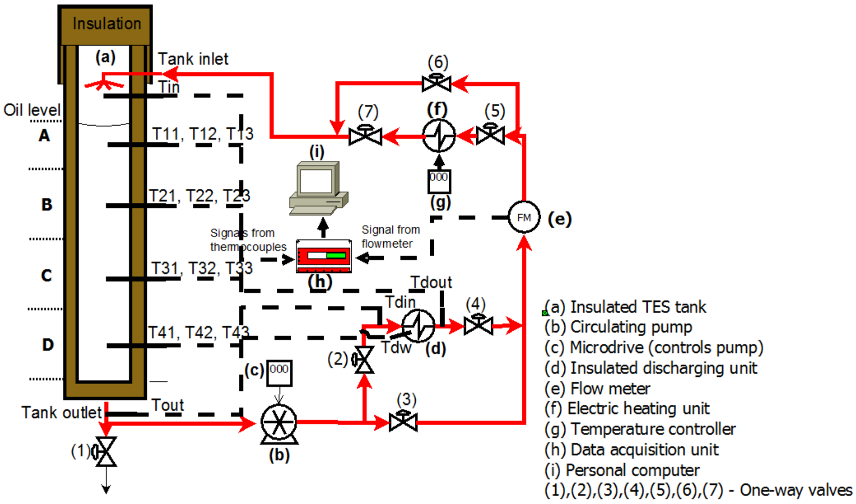

Figure 2: Experimental setup to characterize the four TES systems during charging.

For the cascaded systems, charging is terminated when the average bottom temperature is 180 ^{o}C to ensure the flashpoints of the bottom PCMs (erythritol and adipic acid) are not reached. The flash point temperatures of adipic acid and erythritol are about 196 ^{o}C and 209 ^{o}C, respectively. To investigate the effects of the HTF flowrate on the charging characteristics, the maximum heater temperature was set to 280 ^{o}C. The three different charging flowrates used were 4 ml/s, 6 ml/s and 8 ml/s , respectively. These are referred to low, medium and high charging flowrates in this study. The desired HTF flowrate was regulated via the micro-drive (c) which regulated the pumping power of the circulating pump (b).

3. Exergy analysis

The charging exergy rate which signifies the quality of the energy stored is expressed as [29, 30]:

$$\dot{E}_{XCH} = \rho_{av} c_{av} \dot{V}_{ch} \left[(T_{chin} - T_{chout}) - T_{amb} \, ln \left(\frac{T_{chin}}{T_{chout}} \right) \right] \quad (1)$$

where T_{amb} is the ambient temperature. The average variation of the density and the specific heat capacity of the HTF with temperature is given as [15]:

$$\rho_{av} \ (kg/m^3) = 930.62 - 0.65 T_{av} \quad (2)$$

and

$$c_{av} \ (J/kgK) = 2115.0 + 3.13 T_{av} \quad (3)$$

where T_{av} is the average of the inlet and outlet HTF temperatures.

4. Results and discussion

Figure 3 shows average charging HTF temperature profiles for the four TES systems with the low charging flowrate of 4 ml/s. T_{Chin} is the charging inlet temperature at the top of the storage tank, T_A to T_D are the average HTF temperatures at the four different sections of the TES tanks (taken from the top to the bottom), T_{Chout} is the outlet charging temperature from the bottom of the TES tanks, and T_{amb} is the ambient temperature in the laboratory. The commencement of the phase change processes for the different PCMs in the tanks are pointed out by the arrows on the plots.

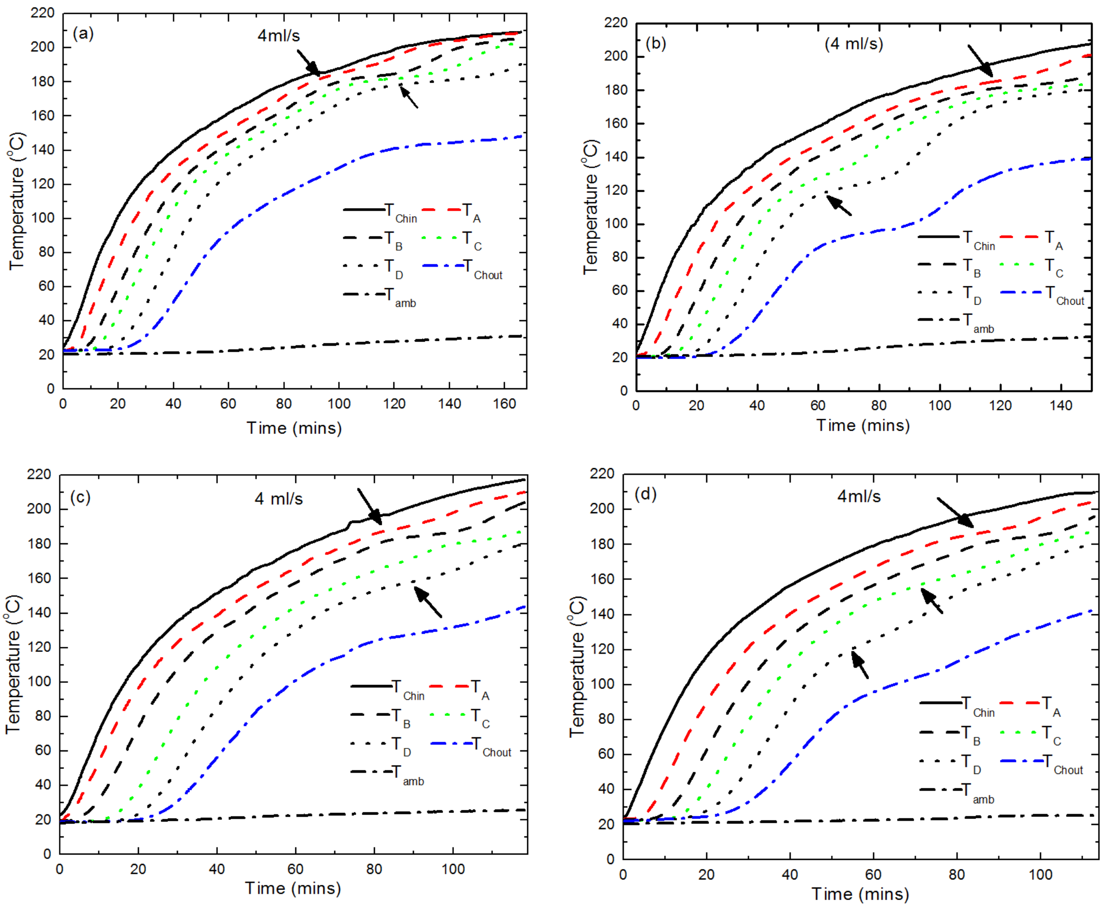

Figure 3: Average charging temperature profiles at a heater set temperature of 280 ºC using a low flowrate of 4 ml/s for (a) a single PCM system, (b) cascaded system 1, (c) cascaded system 2 and (d) cascaded system 3.

The single PCM TES tank shows the longest charging time of around 170 mins due to the larger thermal mass of metallic PCMs in the tank. Cascaded TES 1 with erythritol capsules at the bottom shows a charging time longer than the other cascaded TES systems, due to the lower melting temperature of erythritol which is 120 ºC. The phase change process at the bottom thus occurs earlier and for a longer duration as compared to the other cascaded systems making the bottom limiting temperature to be approached later. One possible explanation is the low thermal conductivity of erythritol in the liquid phase which slows down heat transfer in the liquid phase. The charging time for cascaded TES 1 is comparable to that of single PCM system whereas the charging times of cascaded TES 2 and cascaded TES 3 containing adipic acid are considerably shorter and comparable. The cascaded TES 3 (with the three PCMs) charges up in the shortest duration of about 112 mins. It seems the slightly lower thermal mass of adipic in the liquid phase for cascaded TES 2 and cascaded TES 3 has an effect of lowering the charging time even if the thermal conductivity is lower for adipic acid compared to erythritol.

In terms of the charging phase change transitions, the single PCM shows phase change transitions which commence from the top to bottom since charging occurs from the top to the bottom. In contrast to this behaviour, the cascaded systems with lower meting temperature PCMs at the bottom, show phase change transitions that commence from the bottom lower temperature PCMs to the upper high melting temperature PCMs at the top. The most pronounced phase change transitions at the bottom are seen with cascaded TES 1 consisting of eutectic solder and erythritol. This is probably due to the larger phase change enthalpy of erythritol compared to the other PCMs.

Exergy rate profiles of the TES systems are presented in Figure 4. For the low charging flowrate (Figure 5 (a)), cascaded system 3 shows the highest exergy rate values from around 30 mins to 90 mins as compared to the other TES systems. This is due to the larger degree of thermal stratification during this period induced by the phase change transitions of adipic acid and erythritol during this period. The exergy rate of each TES is seen to increase at steady rates as T_{chin} increases. The rates at which the exergy accumulates in each of the TES system is, however, seen to slow down as T_{chin} approaches a steady state maximum value induced by the set heater temperature, Cascaded TES 2 shows the second best thermal performance in terms of the exergy rate values for the low flowrate, and its exergy rate values become greater than those of cascaded TES 3 after 90 mins of charging. This is possibly due to the earlier phase change of the eutectic solder at section B of the storage tank as compared to the PCM at the same section of cascaded TES 3. Cascaded TES 1 shows the third best thermal performance in terms of useful energy at the low flowrate. The single PCM system possessed the lowest rates of exergy accumulation due to the high phase change temperature of the solder. Exergy rate values range from 0 W to about 225 W. The highest exergy values at the end of charging processes are seen with cascaded TES 2, followed by cascaded TES 3, cascaded TES 1 and lastly by the single PCM system.

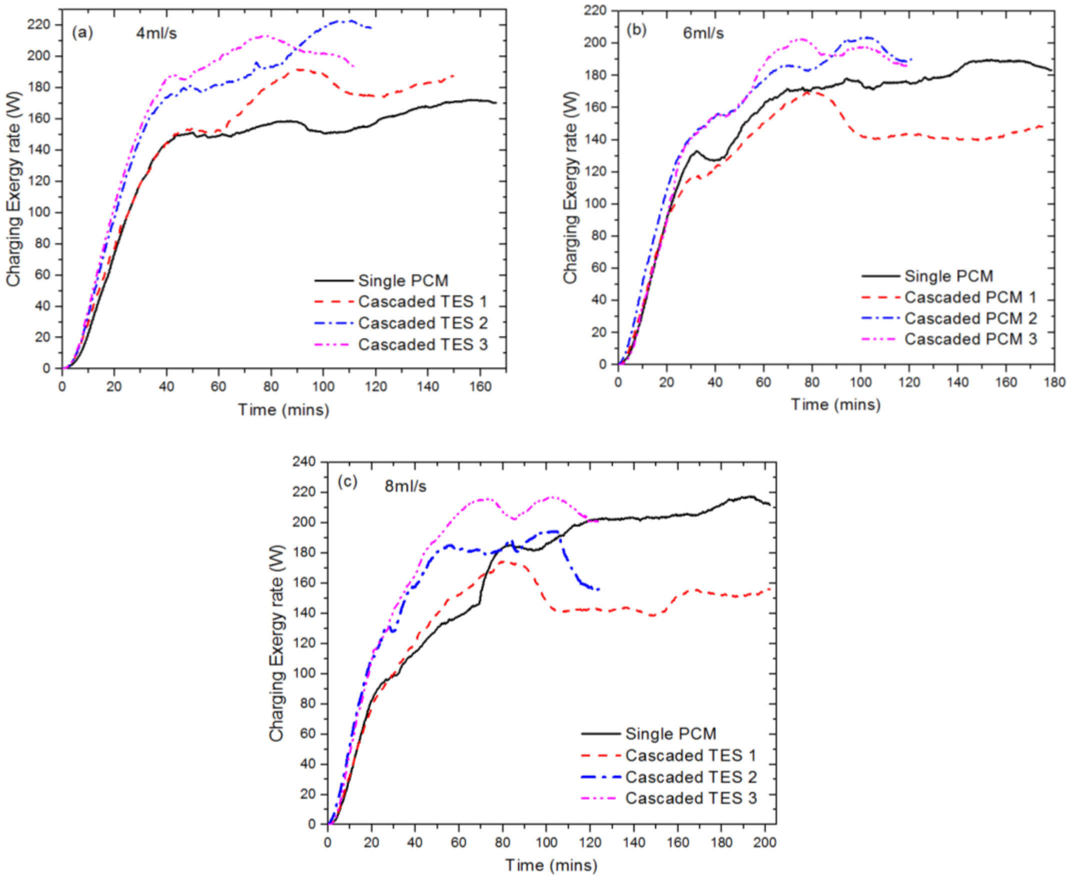

Figure 4: The time-wise variation in the charging exergy rate profiles at (a) low, (b) medium and (c) high HTF flowrate for the four TES systems

With the medium flowrate, cascaded TES 2 shows the higher initial exergy rate values as compared to the other TES systems possibly due to the lower thermal conductivity and slightly larger thermal mass effect. However, after about 20 mins, the rate of exergy accumulation of cascaded TES 3 increases to be similar to that of cascaded TES 2. About the same time, the exergy rate of the single PCM system also overshoots that of cascaded TES 1. Cascaded system 1 shows the worst thermal performance in terms of the exergy rates at this flowrate.

At the highest flowrate, cascaded TES 3 and cascaded TES 2 show similar exergy rates until about 25 mins when the former can be seen to accumulate exergy at greater rates than the latter. After about 100 mins, the exergy accumulation rate for cascaded TES 2 begins to degrade. The single PCM system can be observed to steadily increase in its exergy accumulation rate, and it eventually becomes the best from about 120 mins until the end of charging. Cascaded TES 1 can be observed to be the poorest performer in terms of exergy accumulation rate at the high flowrate. The peak exergy accumulation rates of cascaded systems 1 - 3 can be seen to generally reduce as the HTF's flowrate is increased, whereas those of the single PCM system increase suggesting an exergy accumulation rate improvement with an increase in the flowrate.

5. Conclusion

Experimental exergy charging characteristics of four medium temperature packed bed latent heat thermal energy storage systems using Sunflower Oil as the heat transfer fluid have been compared and presented. Cascaded TES 3, the 3 PCM cascaded system showed higher exergy charging rates because of the release of latent heat in 3 phase change transitions. Its thermal performance was comparable to cascaded TES 2 with adipic acid at the bottom of the storage tank. The charging times for cascaded TES 2 and cascaded TES 3 are also shorter when compared to the other storage systems suggesting a better charging performance. The single PCM showed the lowest exergy charging rate at the lowest flowrate but its performance improved to better than that of cascaded TES 1 with an increase in the flowrate. This suggests that performance improvement in cascaded TES systems depends on the melting temperature of PCM since the lower melting temperature PCM in cascaded TES 1 showed poorer exergetic performance in some instances compared to the single PCM system.

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