Performance comparison of two eutectic solder based latent heat storage systems during discharging

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Abstract. Latent heat storage systems consisting of phase change materials (PCMs) offer the advantage of a large thermal energy storage density as compared to sensible heat storage systems. Most recent work has focussed on organic and inorganic PCMs which have problems of subcooling and phase segregation. Metallic PCMs are a recent innovation for medium to high temperature applications due to their high thermal conductivities, high volumetric storage capacities and their low degrees of sub-cooling during the release of latent heat. For medium temperature applications like cooking of food, very limited work has been done on metallic PCMs for energy storage. Solder based PCMs have rarely been investigated for medium temperature applications thus it is necessary to carry out an experimental study on the use of a solder as PCM candidate. No work has ever been reported using the eutectic solder (Sn63/Pb37) as a PCM. Its use is justified since it is low cost and locally manufactured solder worldwide. Another recent innovation is cascaded thermal energy storage (TES), whereby two PCMs with different melting temperatures are used in a single storage tank to improve the efficiency of energy storage. No work has also appeared in recent literature involving metallic solders in cascaded systems. In a bid to investigate the suitability of the eutectic solder as a PCM for medium temperature applications, two eutectic solder (Sn63/Pb37) based systems are experimentally evaluated during discharging cycles. The first system is a single PCM system composed of a packed bed of spherically encapsulated eutectic solder capsules. The other system is a two PCM cascaded system comprising of eutectic solder spherical capsules at the top and erythritol spherical capsules at the bottom in a storage ratio of 50 %: 50 %. Discharging experiments are carried with three different discharging flow-rates to investigate the effect of the flow-rate on the thermal performance. The three discharging flow-rates used are 4 ml/s, 6 ml/s and 8 ml/s. For both storage systems, an increase in the discharging flow-rate increases the peak discharging energy and exergy rates. For both storage systems, an increase in the discharging flow-rate increases the peak discharging energy and exergy rates. The single PCM system shows higher energy and exergy rates for most of the discharging duration compared to the cascaded system. An increase in the flow-rate increases the peak energy and exergy discharging rates for the single PCM and the cascaded PCM storage systems. The single PCM system out-performed the cascaded system during the discharging tests possibly due to the lower melting temperature and lower thermal conductivity of the bottom PCM (erythritol) in the cascaded system. However, for the higher flow-rates (6 ml/s, 8 ml/s), the cascaded system shows a slightly better or comparable performance at the start and at end of discharging.
Keywords: Erythritol, Eutectic solder (Sn63/Pb37), Phase Change Material (PCM), Thermal Energy Storage (TES).

1. Introduction

In order to utilize effectively intermittent renewable energy resources like solar thermal energy, thermal energy storage (TES) systems can be used to cater for intermittent periods as well as periods without no solar thermal energy resources for example at night. Latent heat TES storage (LHTES) systems consisting of phase change materials (PCMs) offer the advantage of a large thermal energy storage density as compared to sensible heat TES (SHTES) systems. Most recent work has focussed on organic and inorganic PCMs which have problems of subcooling and phase segregation [1-4]. Metallic PCMs are a recent innovation for medium to high temperature applications due to their high thermal conductivities, high volumetric storage capacities and their low degrees of sub-cooling during the release of latent heat [5-9]. For medium temperature applications like cooking of food and process heating, very limited work has been done on solder based metallic PCMs for energy storage [10-12]. Solder based PCMs have are particularly attractive because of their high thermal conductivity, good nucleation characteristics and high volumetric storage density. Limited recent work has been reported using the eutectic solder (Sn63/Pb37) as a PCM [13-14]. Its use is justified since it is low cost and locally manufactured solder worldwide. Another recent innovation is cascaded thermal energy storage (TES), whereby two PCMs with different melting temperatures are used in a single storage tank to improve the efficiency of energy storage [15-16]. No work has also appeared in recent literature involving metallic solders in cascaded systems. In a bid to investigate the suitability of the eutectic solder as a PCM for medium temperature applications, two eutectic solder (Sn63/Pb37) based systems are experimentally evaluated during discharging cycles in this paper. The objective of the study is to compare two eutectic solder based packed bed latent heat TES systems during discharging to find out whether a cascaded system performs better than a single PCM system. Work related to medium packed bed latent heat storage systems using metallic PCMs is rather limited, and investigations need to be done since metallic PCMs have high thermal conductivities and very low degrees of super-cooling. The results presented here will provide invaluable information of these mentioned medium temperature LHTES and provide a platform for using them for validating models for parametric studies and performance optimization.

2. Experimental method and thermal analysis

2.1. Experimental method

The main components of the experimental setup are shown in the schematic diagram of Fig. 1 and it has been presented elsewhere in more detail [17, 18]. For the single PCM based system, forty (40) spherical eutectic solder PCM capsules were inserted into the storage tank and the top level capsules were at Level A below the tank’s inlet port. Sunflower Oil filled up the void between the capsules up to Level A and the storage tank void fraction was estimated to be around 0.49. For the two PCM cascaded system, twenty erythritol capsules were carefully placed into the bottom of storage tank. After this, twenty eutectic solder were also carefully placed above the erythritol capsules to cover the top part of the storage tank ensuring that all eutectic solder capsules were above the erythritol capsules. The storage ratio of the two PCM cascaded system was 50 %: 50 % (1:1). Sunflower Oil was also used to fill up the void between the capsules up Level A. The properties of the two PCMs are shown in Table 1. Erythritol is seen to melt at around 120 °C, while eutectic solder melts at 183 °C. Eutectic solder has a higher thermal conductivity and density as compared to erythritol, whereas erythritol has a higher phase change enthalpy.
Table 1. Thermo-physical properties of the two PCMs.

| Property                        | Erythritol                | Eutectic Solder (Sn63/Pb37) |
|--------------------------------|---------------------------|----------------------------|
| Melting Temperature (°C)       | 118.4 - 122.0 [11]        | 183 [19, 21]                |
| Specific Heat Capacity (kJ/kgK)| 1.38 (20 °C), 2.76 (140 °C) [11] | 0.21 (30 °C) ( [19]        |
| Phase change enthalpy (kJ/kg)  | 310.6 [11]                | 52.1 [20]                  |
| Density (kg/m³)                | 1480 (20 °C), 1300 (140 °C) [11] | 8400 [21]              |
| Thermal conductivity (W/mK)    | 2.64 (20 °C), 1.17 (140 °C) [11] | 50 [21]                   |
| Average mass of PCM in the capsule (g) | 44                      | 164                      |

Figure 1: Schematic diagram of experimental setup [17, 18].

During the charging cycles valves (1), (2), (4) and (7) were closed while valves (3), (5), (6) and (8) were opened. Charging of the storage system storage was terminated when the bottom temperatures of the storages (T_D) were around 190 °C to ensure melting of the PCM at the bottom for the single PCM base system. The PCM had a melting temperature of around 183 °C and this ensured melting at the bottom. For the cascaded storage system, charging was terminated when the temperatures of the bottom storage temperature (T_D) was around 180 °C to ensure that the flash point temperature of erythritol was not exceeded. The flash point temperature of erythritol is around 190 °C and as a safety precaution the lower bottom temperature of the cascaded system was limited to 180 °C.

For the discharging experiments, valves (2), (4) and (7) were opened while valves (1), (3), (5), (6) and (8) were kept closed. Discharging was terminated when the inlet and outlet temperatures of the discharging unit (d) were equal indicating that no energy could be further extracted from the storage tank. The discharging unit (d) was an insulated 5 litre stainless steel water pot with a copper spiral coil immersed in it so that it transfers heat from the storage tank to the water. Discharging experiments were
carried out immediately after charging experiments with flow-rates of 4 ml/s (low), 6 ml/s (medium) and 8 ml/s (high) respectively to investigate the effect of the flow-rate on the discharging performance after charging with the same flow-rates.

2.2. Thermal analysis

The discharging energy rate (power) depends on inlet and outlet coil discharging temperatures and it is expressed as;

$$\dot{E}_{\text{d}} = \rho_{av} c_{av} \dot{V}_{\text{d}} (T_{\text{d,in}} - T_{\text{d,out}})$$  \hspace{1cm} (1)

where $\rho_{av}$ is the temperature dependent average density of the oil at the start and end of charging, $c_{av}$ is the temperature dependent average density of the oil, $\dot{V}_{\text{d}}$ is the volumetric discharging flow-rate, $T_{\text{d,in}}$ is the inlet discharging temperature of the discharging coil and $T_{\text{d,out}}$ is the outlet discharging temperature of the coil. The discharging exergy rate is given as;

$$\dot{E}_{\text{x}} = \rho_{av} c_{av} \dot{V}_{\text{d}} \left[(T_{\text{d,in}} - T_{\text{d,out}}) - (T_{\text{amb}} \ln \frac{T_{\text{d,in}}}{T_{\text{d,out}}}) \right]$$  \hspace{1cm} (2)

where $T_{\text{amb}}$ is the ambient temperature. Density and the specific heat capacity of Sunflower Oil varied with the temperature and these variations are expressed as [20]

$$\rho_s = 930.62 - 0.65T$$  \hspace{1cm} (3)

$$c_s = 2115.0 + 3.13T.$$  \hspace{1cm} (4)

3. Results and discussion

To evaluate the quantity of the discharged energy, energy rate profiles are presented for the two storage systems in Figure 2. The energy rate profiles for the two systems are seen to peak rapidly as discharging commences and fall gradually from the peak values as thermal energy from the storage tanks is used up to heat up water. The peak values of the energy rates for the lowest flow-rate occur almost the time and the eutectic solder single PCM system shows higher values for the duration of discharging possibly to the higher initial TES temperatures. The energy rate values, however, become comparable as discharging progresses. For example from around 55 mins, the difference becomes almost insignificant. Increasing the discharging flow-rate from 4 ml/s to 6 ml/s, increases the heat transfer rate such that greater peak energy rates are obtained. The peak energy rate for the single PCM is around 1000 W, whereas for the cascaded system it is around 950 W. These peak discharging energy rate values also occur earlier when compared to the flow-rate of 4 ml/s. Due to the greater initial heat transfer rate for the cascaded system with two phase change transitions, the peak energy rate value occurs slightly earlier and marginally higher energy rate values for the cascaded system are seen between 0 and 5 mins. The single PCM system shows significantly higher energy rate values from 5 mins to around 50 mins during discharging with a flow-rate of 6 ml/s.

Using the highest discharging flow-rate of 8 ml/s, the highest peak values are obtained and these occur earlier due to the increased heat transfer rate. The peak energy rate value occurs slightly earlier for the cascaded system and the period where the significant difference between the energy rate profiles is between 5 mins and 35 mins. During this period, the single PCM system shows greater values but the period is shorter as compared to flow-rate of 6 ml/s suggesting more thermal performance degradation in the single PCM eutectic solder based system with the higher flow-rate of 8 ml/s. In fact, the period of the significant difference reduces with an increase in the flow-rate from 4 ml/s to 6 ml/s.
Figure 2. Discharging energy rates for the two storage systems using different flow-rates.

The energy rate values only evaluate the quantity of energy discharged, the quality of the energy discharged is shown by the exergy rate profiles shown in Figure 3. Exergy rate profiles follow more or less the same trends as the energy rate profiles but with lower values since heat losses are catered for by the exergy rate evaluations. The slightly higher initial heat transfer rates for the 6 ml/s and 8 ml/s cases is well depicted by the cascaded system’s exergy rate profiles which show exergy rate peak values earlier suggesting better initial heat transfer. The period of the significant difference between the exergy rate profiles of the two storage systems is reduced with an increase in the discharging flow-rate in a manner similar to the energy rate profiles. An increase in the flow-rate also causes an increase in the peak exergy rate values.
4. Conclusion  
Two eutectic solder (Sn63/Pb37) based systems were evaluated experimentally during discharging cycles. The two systems were a single PCM system composed of a packed bed of spherically encapsulated eutectic solder capsules, and a two PCM cascaded system comprising of eutectic solder spherical capsules at the top and erythritol spherical capsules at the bottom in a storage ratio of 50\%:50\%. Discharging experiments were carried with three different discharging flow-rates to investigate the effect of the flow-rate on the thermal performance of these systems. Three discharging flow-rates of 4 ml/s, 6 ml/s and 8 ml/s, respectively were used in the experimental tests. For both storage systems, an increase in the discharging flow-rate increased the peak discharging energy and exergy rates. The single PCM system showed higher energy and exergy rates for most of the discharging duration compared to the cascaded system. An increase in the flow-rate increased the peak energy and exergy discharging rates for the single PCM and the cascaded PCM storage systems. The single PCM system outperformed the cascaded system during the discharging tests possibly due to the lower melting temperature and lower thermal conductivity of the bottom PCM (erythritol) in the cascaded system.

References
[1] Mussard M, Nydal O. Comparison of oil and aluminum-based heat storage charged with a small-scale solar parabolic trough. Applied Thermal Engineering 2013; 58:146–54.
[2] Sharma SD, Buddhi D, Sawhney RL, Sharma A. Design, development and performance evaluation of a latent heat storage unit for evening cooking in a solar cooker. Energy Conversion and Management 2000; 41:1497–508.
[3] Sharma SD, Iwata T, Kitano H, Sagara K. Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit. Solar Energy 2005; 78:416–26.
[4] Hussein HMS, El-Ghetany HH, Nada SA. Experimental investigation of novel indirect solar
cooker with indoor PCM thermal storage and cooking unit. Energy Conversion and Management 2008; 49: 2237–46.

[5] Fernández AI, Barreneche C, Belusko M, Segarra M, Bruno F, Cabeza LF. Considerations for the use of metal alloys as phase change materials for high temperature applications. Solar Energy Materials and Solar Cells 2017; 171: 275–81.

[6] Ma F, Zheng P. Investigation on the performance of a high-temperature packed bed latent heat thermal energy storage system using Al-Si alloy. Energy Conversion and Management 2017; 150:500–14.

[7] Andráka CE, Kruizenga AM, Hernandez-Sanchez BA, Coker EN. Metallic phase change material thermal storage for dish Stirling. Energy Procedia 2015; 69: 726 –36.

[8] Fukuhori R, Nomura T, Zhu C, Sheng N, Okinaka N, Akiyama T. Macro-encapsulation of metallic phase change material using cylindrical-type ceramic containers for high-temperature thermal energy storage. Applied Energy 2016; 170: 324–28.

[9] Becattinia V, Geissbü hler L, Zanganeh G, Haselbacher A, Steinfeld A. Pilot-scale demonstration of advanced adiabatic compressed air energy storage, Part 2: Tests with combined sensible/lateral thermal-energy storage. Journal of Energy Storage 2018; 17: 140-152.

[10] Mawire A, Shobo AB. Investigation of In–48Sn as a phase change material candidate for thermal storage applications. Renewable Energy and Environmental Sustainability 2017; 2: 20.

[11] Shobo AB, Mawire A. Experimental comparison of the thermal performances of acetanilide, meso-erythritol and an In-Sn alloy in similar spherical capsules. Applied Thermal Engineering 2017; 124:871–82.

[12] Shobo AB, Mawire A, Aucamp M. Rapid thermal cycling of three phase change materials (PCMs) for cooking applications. Journal of the Brazilian Society of Mechanical Sciences and Engineering 2018; 40:329.

[13] Mawire A, Lentswe KA, Shobo A. Performance comparison of four spherically encapsulated phase change materials for medium temperature domestic applications. Journal of Energy Storage 2019; 23: 469–79.

[14] Mawire A, Lefenya TM, Ekwomadu CS, Lentswe KA, Shobo AB. Performance comparison of medium temperature domestic packed bed latent heat storage systems. Renewable Energy 2020; 23: 1897–1906.

[15] Lakshmi Narasimhan N. Assessment of latent heat thermal storage systems operating with multiple phase change materials. Journal of Energy Storage 2019; 23:442–55.

[16] Yang L, Zhang XS. Performance of a new packed bed using stratified phase change capsules. International Journal of Low-Carbon Technologies 2012; 7: 208–14.

[17] Shobo AB, Mawire A, Okello D. Experimental thermal stratification comparison of two storage systems. Energy Procedia 2017; 142: 3295–3300.

[18] Lugolole R, Mawire A, Lentswe KA, Okello D, Nyeinga K. Thermal performance comparison of three sensible heat thermal energy storage systems during charging cycles. Sustainable Energy Technologies and Assessments 2018; 30: 37–51.

[19] Wu YK, Lin KL, Salam B. Specific heat capacities of Sn-Zn-Based solders measured using differential scanning calorimetry. Journal of Electronic Materials 2009; 38: 227–30.

[20] Morando C, Formaro O, Garbellini O, Palacio H. Thermal properties of Sn-based solder alloys. Journal of Materials Science: Materials in Electronics 2014; 25:3440–47.

[21] Sn63Pb37 RA Solder Wire4880–4888 Technical Data Sheet 2018: https://images-na.ssl-images-amazon.com/images/I/81h+ZhgF19L.pdf, website accessed January 2018.