International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0738

EXPERIMENTAL STUDY OF A LATENT HEAT THERMAL ENERGY STORAGE UNIT ENCAPSULATED WITH MOLTEN SALT/COPPER FOAM COMPOSITE SEEDED WITH NANOPARTICLES

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ABSTRACT

Solar energy storage has vast applications in a wide range, and nanoparticles and metal foam can be used to improve energy storage density and heat transfer rate in a storage system. In this study, solar salt, nano-salt (solar salt seeded with 2 wt. % aluminium oxide (Al_2O_3) nanopowder) and nano-salt/copper foam composite were used as storage media, and the thermal performances during heat storage/retrieval processes were investigated with a pilot experimental rig. The temperature distributions of the PCMs at radial, theta, and axial locations were measured. The results show that Al_2O_3 nanopowder can slightly improve the heat transfer of the nano-salt, while the system encapsulated with the nano-salt/copper foam composite can be significantly enhanced, e.g. the time-duration of the charging process can be reduced by about 74.5%, compared to that of pure salt. Theoretical analysis also revealed the heat transfer domination by temperature distribution. The heat storage power can reach 200.27 kW/m^3 when nano-salt/copper foam composite was used.

Keywords: solar salt, aluminium oxide nanopowder, copper foam, latent thermal energy storage

1. INTRODUCTION

Solar energy as the renewable energy can be used in multiple application. Phase change materials (PCMs) are proposed as a good solution to store the thermal energy regarding the time dependent of solar energy [1]. Nitrate salts as PCMs have been widely used in the middle-temperature range of solar energy application. Many techniques are addressed the issues of low thermal conductivity and specific heat capacity of pure salt, including extended fins, macro- and micro-encapsulation of the PCMs, addition of high conductive materials, and impregnating the PCMs into highly conductive porous structures.

Metal foam with good mechanical and thermal properties can be used to form the composite PCMs, which shows attractive thermal conductivity. Several researchers investigated the thermo-physical properties and system performances relating to metal foam composites extensively [2-5]. Dispersing nanoparticles into PCMs can keep and increase the specific heat capacity [6-9]. Navarrete et al. [9] characterized a composite formed by solar salt and Al-Cu alloy nano-encapsulated layer. It pointed out that the total energy storage can be increased owing to contribution of the latent heat storage of the nano-encapsulated PCM. Meanwhile, it has been proven that the combination of metal foam and nanoparticles is a promising solution to enhance the thermo-physical properties of pure salt or other [10-11].

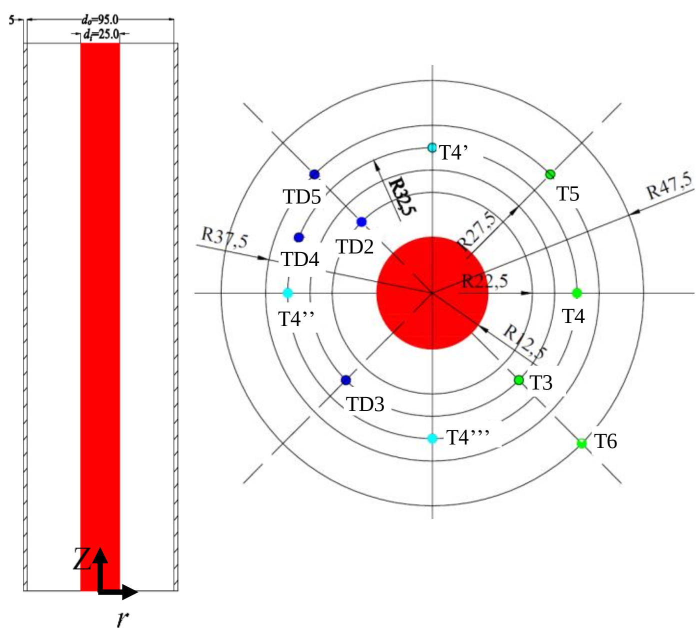
Besides the thermo-physical properties in a small scale, it is indispensable to investigate the thermal response of the composite PCMs in an energy storage unit. In the present study, solar salt ($NaNO_3$:KNO_3=6:4), nano-salt ($NaNO_3$:KNO_3=6:4 seeded with 2 wt.% aluminium oxide nanopowder (Al_2O_3)) and nano-salt/copper foam composite were considered as storage media and tested with a pilot experimental rig, which was built to study the performance of sodium nitrate

($NaNO_3$) and nano-salt ($NaNO_3$ seeded with 0.5 wt. % Fe_2O_3) preliminarily [12]. Heat storage and retrieval tests were conducted at various heating temperatures. The temperature distributions of the PCMs at different locations were measured, including radial, theta, and axial locations, while the heat transfer characteristics together with the energy power of the latent thermal energy storage (LTES) unit were revealed extensively.

2. EXPERIMENTAL RIG AND PROCEDURE

2.1 Experimental test rig

Fig. 1 shows the sections of the cylindral LTES unit. It can be seen that a cartridge heater worked as heat source was located in the inner pipe made of the stainless steel, which was supplied with a constant input power of 380 W, while the surroundings were encapsulated with PCMs. The power supplied to the heater was by a Varaic connected to the PC, which was via control system using LabVIEW software. Various thermocouples (type K with the diameter of 3 mm) were inserted at different locations inside the unit as shown in Fig. 1 (b), including radial, theta, and axial locations, and from the nearest to the farthest thermocouple of the heating element. The thermocouples labelled with *T*D2, *T*D3, *T*D4 and *T*D5 were located in the middle axial positions, that is, *Z*=150 mm, and others labelled with *T*3, *T*4 and *T*5 were located at *Z*=125 mm. During the tests, *T*4, *T*4', *T*4'' and *T*4''' located in four theta directions were used to check the homogenous heat transfer of the PCMs. In addition, *T*6 in the farthest radial direction were at the deepest point (*Z*=25 mm). A LabVIEW code was designed to record the temperature measured values, which were transferred into the computer with the time interval of 1.4 s. In addition, in order to keep the safety requirement during melting of salt, a safety pressure relief valve was added to ensure that no pressure was built up inside annulus cylinder.



(a) (b)

Fig 1 Experimental test rig and layout of thermocouples.

2.2 Experimental procedure

The LTES unit was filled with three types of PCMs, each with pure solar salt 2500 g, and 2250g and 2000 g, respectively. Al_2O_3 nanopowder with the mass fraction of 2%, and copper foam with the porosity of 95% were used to form the composite PCMs. As a result, nano-salt encapsulated in the unit is 2295 g, while nano-salt/copper foam composite is 2676g.

The heat storage experiments were initially conducted when the entire LTES unit was at a room temperature of 10~30 °C. The heating temperatures were set as 240 °C, 260 °C and 280 °C for solar salt and its composites, respectively. The heat retrieval experiments were started after the unit mainly reached the heating temperatures. During heat retrieval process, the whole unit was cooled down naturally at the room temperature of about 10~20 °C. In the present study, the time-durations of heat storage were considered from 30 °C to the heating temperatures, while those of heat retrieval were from the starting temperature to temperature of 50 °C.

3. RESULTS AND DISCUSSION

3.1 Different heating temperatures

Fig. 2 shows the temperature evolutions for solar salt at different heating temperatures. The higher heating temperature controlled can accelerate the melting process, e.g., the charging times are 20900 s and 9002 s at the heating temperatures of 240 °C and 280 °C, respectively. This is due to large temperature difference between the heater and PCMs leads to the enhanced heat transfer.

The low temperature of point T6 is due to the contact with the lateral surface of the unit, which causes heat loss from the lateral surface accordingly. It can be seen from Fig. 2 that thermocouples at *Z*=150 mm show a higher melting characteristics than *Z*=125 mm, which is due to the buoyancy effect as the melting starts from the top to the bottom of the PCM. The heat transfer depends on the conduction at the beginning period, then a natural convection happens as soon as the phase change starts.

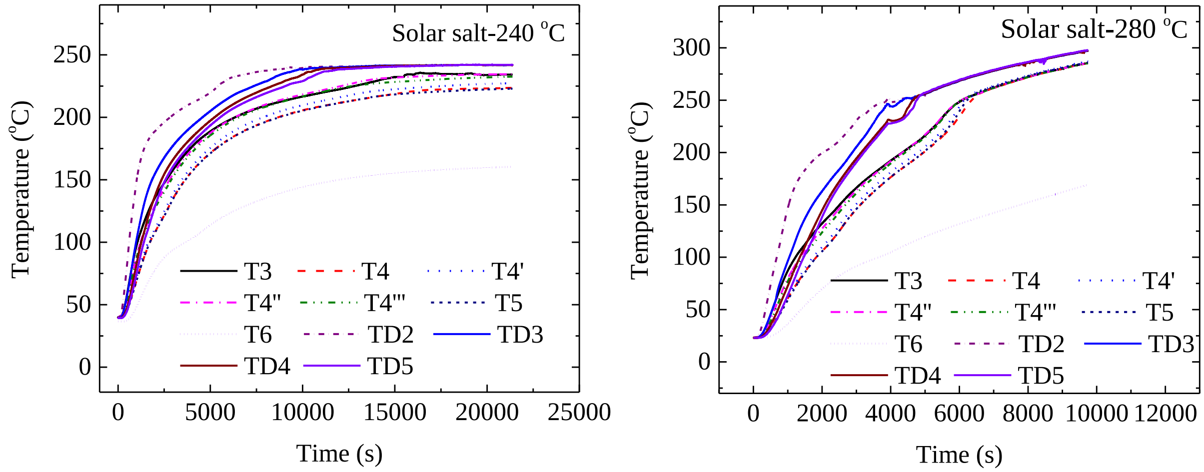


Fig 2 Temperature evolutions and distributions for solar salt at different heating temperatures for heat storage.

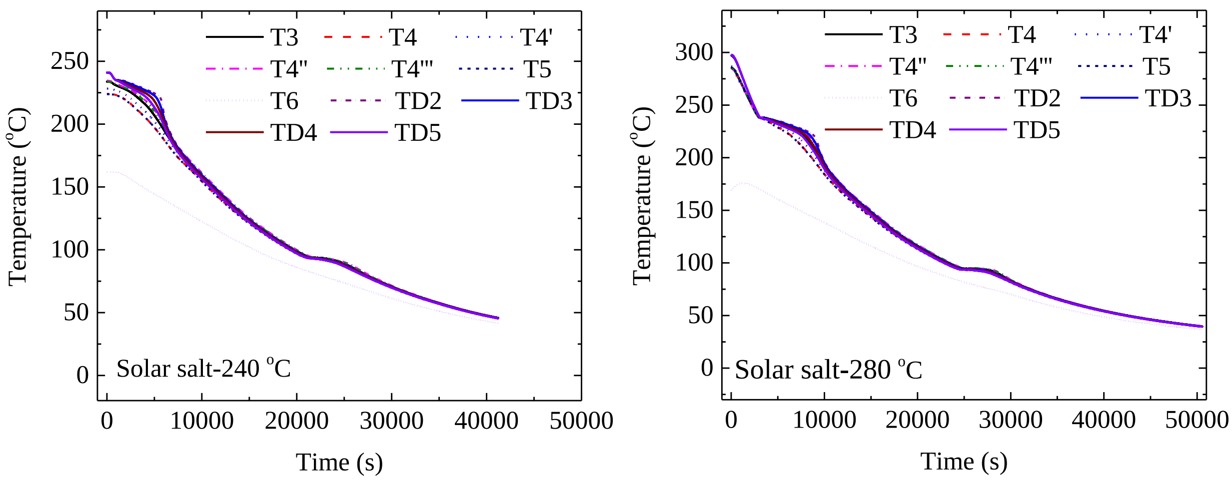


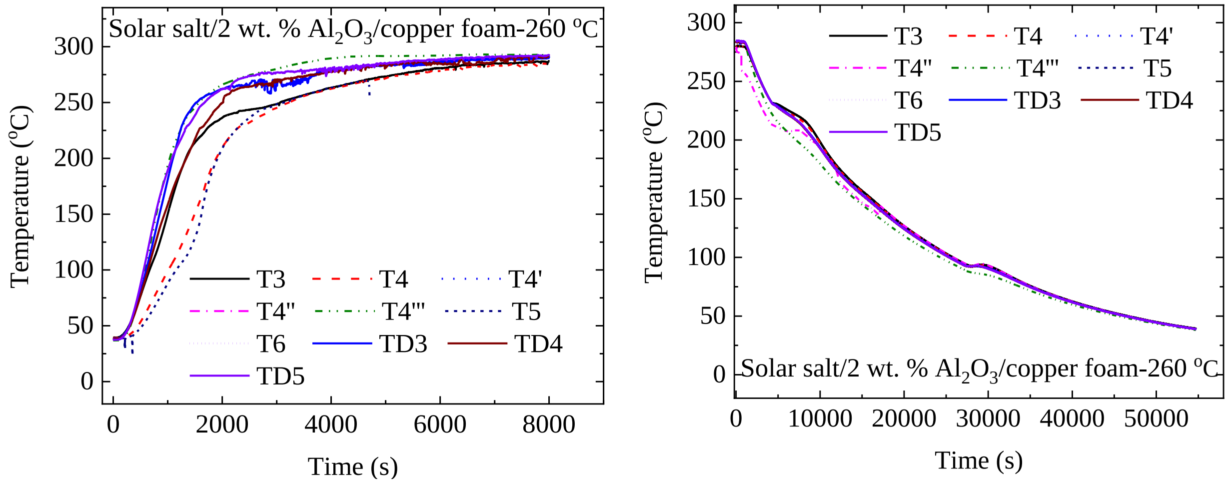
Fig 3 Temperature evolutions and distributions for solar salt at different starting temperatures for heat retrieval.

Fig.3 shows the temperature evolutions during heat retrieval process. The discharging times are about 38696 s and 42553 s when the starting temperatures are 240 °C and 280 °C, respectively. More energy can be stored with the higher heating temperature, which induces larger time-duration of heat retrieval subsequently.

3.2 Pure salt and composite PCMs

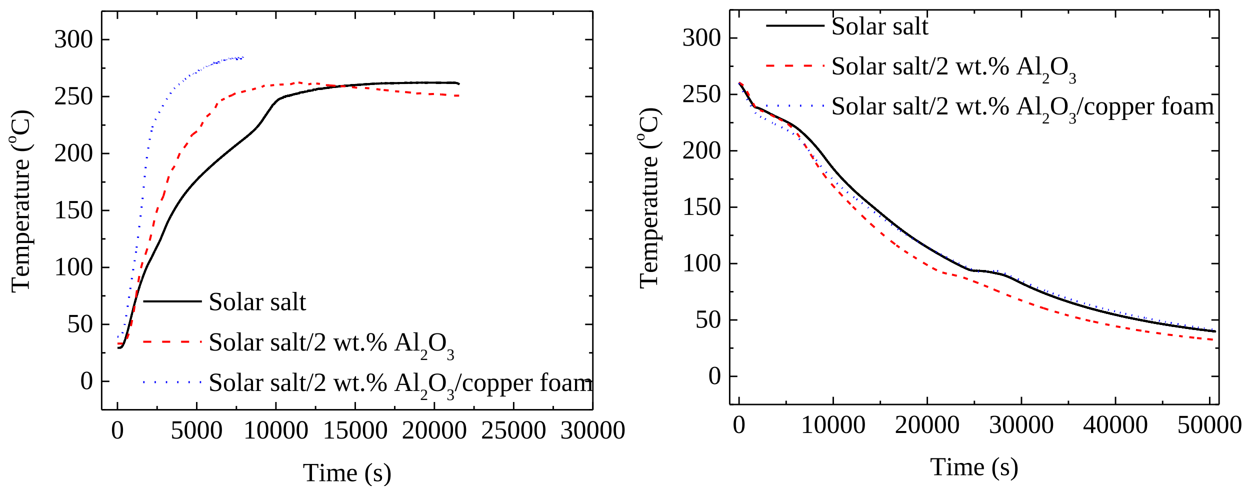
Fig. 4 shows the temperature evolutions and distributions of nano-salt/copper foam composite both for heat storage and retrieval processes. There are slightly difference among *T4*, T4', T4'' and T4''', indicating that the heat transfer seems homogenous at the same radial and axis positions. The heat retrieval process shown in Fig. 4(b) seems very slow, which is due to air cooling domination inducing large thermal resistance.

Point T4 is selected as the representative thermocouple, and the comparisons of temperature evolutions for solar salt and composite PCMs are shown in Fig. 5. It can be seen from Fig. 5(a) that the time-durations of the nano-salt and nano-salt/copper foam composite for heat storage are considerably reduced, e.g., the charging times are 14938 s, 10276 s and 3815 s for solar salt, nano-salt, nano-salt/copper foam composite, indicating a reduction of the time-duration by 31.2% and 74.5%, respectively. However, the discharging times are 42896 s, 38290 s and 45430 s for solar salt, nano-salt, nano-salt/copper foam composite, respectively. The phenomenon of slight improvement can be attributed to air cooling with large thermal resistance outside the test rig dominated the whole process, although the enhancement of the thermo-properties of the nano-salt and nano-salt/copper foam composite. In addition, because of the increase heat transfer, the unit with nano-salt/copper foam composite can reach to the higher temperature after heat storage, inducing the larger time-duration of heat retrieval.



(a) (b)

Fig 4 Temperature evolutions and distributions for nano-salt/copper foam composite. (a) heat storage (b) heat retrieval.



(a) (b)

Fig 5 Comparisons of temperature evolutions for solar salt and composite PCMs (Point *T4*). (a) heat storage (b) heat retrieval.

3.3 Energy power during heat storage/retrieval

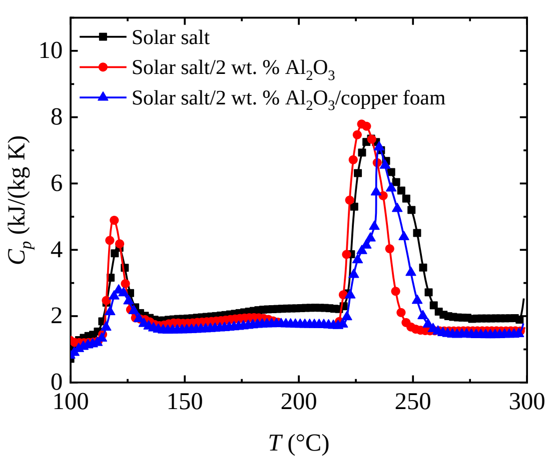


Fig 6 Apparent specific heat capacities of solar salt and composite PCMs.

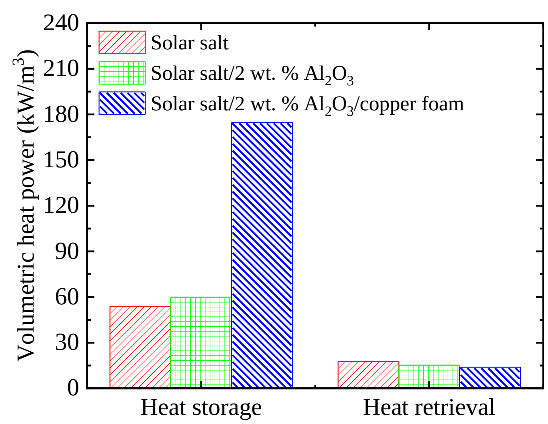


Fig 7 Heat storage and retrieval powers of the unit under the heating temperature of 260 °C.

Latent and sensible enthalpy change were estimated according to the mass of the salt filled in the LTES unit. Then the heat storage and retrieval powers were approximately estimated accordingly, which was based on the apparent specific heat capacities shown in Fig. 6. The latent heat is incorporated into the specific heat of PCM, which is named apparent specific heat accounting for the phase change process [13]. The volumetric heat storage powers in the LTES unit are in the range of 32.39~200.27 kW/m^3, whereas the volumetric heat retrieval power from the LTES unit ranged from 13.12 kW/m^3 to 19.27 kW/m^3, as shown in Fig. 7.

4. CONCLUSIONS

Heat storage and retrieval characteristics of a pilot test rig were experimentally investigated, which was encapsulated with solar salt, salt/2 wt. % Al_2O_3 nanopowder (nano-salt) and salt/copper foam composite seeded with 2 wt. % Al_2O_3, respectively. The following conclusions can be drawn:

1) The heat transfer seems homogenous at the same radial and axis positions of the LTES unit. The higher heating temperature can accelerate the melting process, but the time-durations of heat retrieval will be larger after stored at higher heating temperature.
2) Both Al_2O_3 nanopowder and copper foam can significantly improve the heat transfer of pure solar salt, e.g., the time-duration of heat storage can be reduced by 31.2% and 74.5% for nano-salt and nano-salt/copper foam composite, respectively. The additives can slightly decrease the time-duration of heat retrieval because air cooling dominates the process.
3) The volumetric heat storage powers in the LTES unit are in the range of 32.39~200.27 kW/m^3, whereas the volumetric heat retrieval power from the LTES unit ranged from 13.12 kW/m^3 to 19.27 kW/m^3, which indicates the heat storage power can be significantly improved.

ACKNOWLEDGEMENT

This research has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 706788.

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