HEAT TRANSFER ENHANCEMENT OF A CASCADED THERMAL ENERGY STORAGE SYSTEM WITH VARIOUS ENCAPSULATION ARRANGEMENTS

by

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Ever increasing energy demand ever encourage for new energy production and conservation. In the present work, the cascaded latent heat solar thermal energy storage system has been developed to deliver the heat at different temperature limits and its performance on the improvement of heat transfer characteristics are studied with the use of multiple phase change material (PCM) with various encapsulation arrangements. The storage system consists of three different PCM which have different melting temperatures such as D-mannitol, D-sorbitol, and paraffin wax. Each PCM is encapsulated in different materials of spherical balls like copper, aluminum, and brass. Permanent welding of fins, inside the encapsulated balls of type rectangular, annular and pin is done for enhanced heat transfer. This work investigates for the best combination of fins which may allow the highest heat transfer rate for the least cost. It has been concluded that the transfer of energy is the highest in the use of copper balls for encapsulation of PCM with the attachment of annular fin inside the balls. With respect to energy cost per kJ of heat transfer, the PCM encapsulated in aluminum balls with annular fins may be preferred. However, in all the combinations, to gain higher efficiency of the system proper arrangements of all system components very close to each other is essential to the provision of perfect insulated storage tanks and the components of the piping circuit.

Key words: cascaded thermal energy storage system, multiple PCM, encapsulation materials

Introduction

Among the various sources of renewable energy, never depleting solar energy has gained importance in current global discussions on energy and safe environment. In industrial processing, a huge amount of petroleum fuel energy (41%) and natural gas energy (40%) is spent for heating, drying, and other processing at different temperature levels which provide a huge potential for the use of solar thermal heat in the industrial sector. Available energy sources and the demands, in general, do not match each other. The main problems associated with the

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use of solar energy are intermittent solar radiation is by its nature, its time factor of availability, weather condition, latitude and more importantly the solar energy storage.

The energy storage device is one of the possible solutions for energy conservation and leveling of energy demand patterns. Thermal energy storage (TES) is considered by many to be one of the energy storage technologies. Thermal energy can be stored temporarily either at lower or at higher temperatures [1]. Among the various TES methods, the latent TES employing a PCM, has been widely reported as an effective way due to its advantages of high energy storage density and its isothermal operating characteristics [2]. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. The PCM gets solidified when the temperature of surroundings falls down, by releasing the stored latent heat to the heat transfer fluid (HTF). A PCM melts and solidifies at a certain temperature and is capable of storing and releasing a large amount of energy. Heat is absorbed or released when the PCM changes its phase from solid to liquid and vs. [3]. The performance of the TES system can be improved by increasing the thermal conductivity of the PCM by encapsulating PCM in high conductivity materials [4]. Velraj et al. [5] developed many techniques to increase the efficiency of TES system among which the use of fins are most economical and effective method. The use of encapsulated PCM with the attachment of fins in TES system have a great impact on the time required for charging of PCM (i. e., PCM absorb heat from surrounding fluid and undergoes a phase change from solid state to liquid state) [6]. The variations of fin geometry also affect the charging and discharging time of PCM, the charging time is reduced about 43% with the use of fins [7, 8]. Also, the use of different profiles and materials of fin inside the encapsulation ball in TES system results in maximum heat transfer and high effectiveness [9]. The TES tank dimensions greatly influence the heat transfer rate between the HTF and PCM [10]. The time required for charging of PCM is decreased with the use of increased number of fins in encapsulation ball and also increases the overall heat transfer rate [11]. The heat transfer rate from HTF to PCM is directly proportional to the difference in temperature between the walls of encapsulation materials and the HTF and also condition of PCM present in the encapsulated ball [12]. The heat absorbing rate of HTF from the parabolic trough collector (PTC) is directly relative to the mass-flow rate of HTF [13]. For high heat gain rate in the solar collector, the high mass-flow rate of the HTF is recommended [14].

Heat energy storage using thermal system is a common one and a good amount of literature exist. In the extensive survey, very minimal or no literatures were found on the analysis of cascaded latent heat thermal storage systems with multiple PCM and fins. In the present work, a comparative study has been made on the improvement of heat transfer in a cascaded latent heat solar TES system with the use three different PCM (D-mannitol, D-sorbitol, and paraffin wax) and also with the use of high thermal conductivity encapsulation materials (copper, aluminum, and brass) with the attachment of different profiles fins (pin fin, rectangular fin, and annular fin).

Materials and methods

This experimental set-up includes a PTC, Therminol-66 as HTF, storage tanks containing encapsulated internally fins welded balls filled with three types of PCM, thirteen thermocouples to measure the temperature at various points and a circulating pump to circulate and maintain a continuous flow of HTF. An auxiliary heater is augmented for performing the experiment, during the absence of sunlight. The PTC, made of highly reflective stainless steel sheet, 6 m length and with 9 m² aperture area, is used to heat up the HTF that enters the absorber tube. The specifications of the fabricated PTC are shown in tab. 1. The photographic view of PTC and cascaded thermal energy storage (CTES) system is shown in fig. 1. Nagappan, B., *et al.*: Heat Transfer Enhancement of a Cascaded Thermal Energy ... THERMAL SCIENCE: Year 2019, Vol. 23, No. 2A, pp. 823-833

Table 1. Specifications of PTC

| Concentration ratio | 16.21 | Absorber tube length | 6 [m] |
|----------------------|-----------------------------------|-------------------------------------|---------------------|
| Collector width | 1.5 [m] | Outer diameter of the vacuum tube | 0.10 [m] |
| Supporting structure | Mild steel | Inner diameter of the absorber tube | 0.0254 [m] |
| Collector length | 6 [m] | Outer diameter of the absorber tube | 0.0374 [m] |
| Reflective material | High reflectivity stainless steel | Aperture area | 9 [m ²] |



Figure 1. Photographic view of PTC and CTES system

The higher mass-flow of HTF makes more absorption of the heat from the collector and hence recommended for effective mass-flow rate [15]. The PTC supplies heated HTF to the PCM storage tanks. Basically, there are four insulated mild steel PCM storage tanks used in the experiment each of length 0.5 m, diameter 0.4 m, and thickness 6 mm. The insulation by 10 cm glass wool is done on the tanks and the pipelines have 7 mm insulation to avoid loss of heat. The latent heat thermal energy storage (LHTES) system and the circuit of pipes are fully filled up with 50 liters of HTF therminol-66 and leak check is made to avoid any leaks in any part of the system. The encapsulation sphere materials chosen for the experiment is copper, aluminum, and brass. The tank named as 0 is the oil tank. The rest three tanks numbered as 1, 2, and 3 tanks contain encapsulated balls of D-mannitol, D-sorbitol, and paraffin wax, respectively. Also, these encapsulations contain welded fins at the inner surface of spheres so as to enhance the heat transfer between HTF and PCM and the heat is stored is in PCM as a latent heat form [16]. The temperature range calculated with respect to the heat absorbed by the PTC plays a vital role in the selection of PCM. Energy collected in the HTF is captivated by the PCM and stores in the PCM during charging and the reverse happen during discharging.

The experimental layout is shown in fig. 2. The working of the developed system is explained below. The energy from Sun is received by the HTF goes through all tanks and losing heat on a continuous basis to the PCM available in tanks numbered as 1, 2, and 3 of D-mannitol, D-sorbitol, and paraffin wax. The arrangements of different PCM are



Figure 2. Experimental layout

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arranged in the order from highest to lowest melting points. The copper, aluminum, and brass encapsulated ball materials welded at the inner surface of balls with different fins of profiles pin, annular, and rectangular types are used to contain PCM. Finally, the HTF after losing possible heat energy at different PCM enters to the processing unit in which the oil losses all its residual energy and then further enters the absorber tube of the collector to get further heated up. The properties of selected PCM and HTF are shown in tab. 2. A gear pump is employed for effective circulation of the HTF for the expected mass-flow rate. During charging the energy is derived from Sun by PCM through HTF and during discharging with disconnection of the collector, energy is given out by the PCM to HTF and further, it is used for some heating applications. The temperature of HTF in the inlet and outlet of PTC, at three different locations of each tank is recorded for calculating the thermal energy lost or gained by the HTF for every 10 minutes of the time interval.

| Therminol-66 | | PCM | | | | |
|--------------------------|--|---|--------------|------------|------------|--|
| Oil density | 1005 [kgm ⁻³] | Criteria | Paraffin wax | D-sorbitol | D-mannitol | |
| Specific heat capacity | 1.495 [kJkg ⁻¹ K ⁻¹] | Melting point of PCM [°C] | 50-59 | 90-102 | 160-166 | |
| Oil thermal conductivity | 0.12 [Wm ⁻¹ K ⁻¹] | Melting enthalpy [kJkg ⁻¹] | 212 | 187 | 318 | |
| Kinematic viscosity | 29.64·10 ⁻⁶ [m ² s ⁻¹] | Density of PCM [kgm ⁻³] | 1500 | 1524 | 1490 | |
| Range of use | 0-345 [°C] | Specific heat capacity [kJkg ⁻¹ K ⁻¹] | 2.38 | 2.49 | 2.5 | |

Table 2. Properties of PCM and HTF

Instrumentation error analysis

Instrumentation and its uncertainties are to be accounted. For the analysis, there are K-type thermocouples used at thirteen different locations to sense the temperature values in the cascaded system and the absorber tube of the collector. Of the 13 thermocouples, two at inlet and outlet of PTC and three per storage tank in the top, middle and bottom positions and two more are used in the process heater. The K-type thermocouple has the accuracy of 1 °C with the digital temperature indicator resolution of 0.1 °C which is used to measure the temperature. The instrumentation error allied within the calculated temperature range is calculated as 0.328%. A flow meter is used to adjust the flow rate of HTF in the circuit with an error of 2.59%. The errors involved in energy stored/released from HTF and PCM is about 2.61% and 0.728%, respectively. The maximum heat transfer error is about 3.34%.



Figure 3. Finned encapsulated balls

Heat transfer calculations

The enhanced heat transfer can be obtained by encapsulating PCM in a spherical ball with the attachment of different profiles of fins in each encapsulation ball. The attachment of different profiles (pin, rectangular, and annular) of the fin is shown in fig. 3. The PCM storage tank stores the heat in the form of latent heat. The amount energy stored depends on the mass of PCM used in each tank. Amount of PCM required is calculated with the use of eq. (1) where m_p is a mass of PCM in each encapsulated ball and N_p is a number of encapsulated balls used in each storage tank. The mass of PCM required in each encapsulated ball is calculated by eq. (2) where ρ is the density of PCM and V_p is the volume of each spherical ball. The amount of heat transfer from HTF, Q_{HTF} , is equal to the amount heat gain to PCM, Q_{PCM} , in each storage tank and vice versa which is calculated by eq. (3) where m is mass of PCM in each storage tank, C_p - the specific heat of PCM, m_o - the mass of HTF, $C_{p,o}$ - the specific heat of HTF, T_{o} – the outlet temperature of HTF from each storage tank, T_{i} – the inlet temperature of HTF to the storage tank, ti – the total time taken for charging or discharging, and L.H – the latent heat of PCM. The rectangular fins of length 2 cm and width 2 cm are attached inside the spherical ball and experiments are conducted with encapsulation of PCM in each ball. Same way the experiments are followed for annular fins (2 cm radial difference) and pin fins (diameter 1 cm and length 2 cm). The overall fin effectiveness, ε , is the ratio of heat transfer with use of fin Q_{fin} to the heat transfer without the use of fin $Q_{\text{no fin}}$ which is calculated by eq. (4) where h is the heat transfer coefficient, $A_{\rm w}$ is the total wall surface area of the encapsulated ball, $T_{\rm w}$ – the wall surface temperature of the ball, and T_{∞} – the surrounding temperature of fin *i. e.* PCM.

$$m = m_p N_p \tag{1}$$

$$m_p = \rho V_p(0.8) \tag{2}$$

$$Q_{\rm PCM} = \int_{t_i}^{t_m} m C_p \,\Delta T + m (L.H) + \int_{t_m}^{t_f} m C_p \,\Delta T = Q_{\rm HTF} = \frac{m_o C_{p,o} \left(T_o - T_i\right)}{ti}$$
(3)

$$\varepsilon = \frac{Q_{\rm fin}}{Q_{\rm no\,fin}} = \frac{Q_{\rm fin}}{h\,A_{\rm w}(T_{\rm w} - T_{\infty})} \tag{4}$$

Results and discussion

There should be consistency in recording heat transfer features of the cascaded LHTES system readings and for that, the experiments have been performed for 50 times during charging and discharging states. Of the experimental data obtained for different encapsulation materials (*i. e.*, copper, aluminum, and brass) with different fins, due to the higher surface area available, annular fins welded onto the encapsulations of different materials has the highest heat transfer in comparison with the pins fins and rectangular fins arranged with different encapsulation materials. A detailed presentation of data with annular fins is discussed in detail. The charging time and temperature values are noted for every 10 minutes and as the same way, it is done for discharging too. Copper material encapsulation with annular fin has shown better charging rate and hence excellent heat transfer rate in comparison with other materials and fin types.

This experiment has been carried out, as previously discussed for three materials of encapsulation balls of copper, aluminum, and brass with three types of fins pin, annular, and rectangular fins. The very interesting point is to have a low melting time and this is achieved by use of fins with the melting time reduction of 40.3% [17]. Of these, the annular, fins have higher efficiency with different encapsulations accompanied with PCM. Figures 4 and 5 represent the time taken for charging and discharging process of PCM D-mannitol with aluminum, copper, and brass encapsulations with annular fins. The charging temperature initially increased gradually for 160 minutes and tends to be constant after the PCM has reached the melting point at 165 °C,

during this stage the PCM changes its phase from a solid-state to liquid-state. The copper encapsulation with annular fins during charging reached a temperature of 300 °C in 170 minutes whereas for other encapsulations of aluminum at 320 minutes (obtained 265 °C) and brass at 300 minutes (absorbed 240 °C) are noted. During discharging mode the brass happens to be steady for 90 minutes and finally has reached 64 °C whereas the copper and aluminum reached 60 °C and 97 °C, respectively, at 400 minutes. As expected, it is lesser time taking for charging process than that of discharging process.



Figure 6 represents the encapsulations spheres made of copper, brass, and aluminum with annular fin arrangement for energy adding charging of D-sorbitol PCM. The steady increase in temperature till 93 °C and finally crops up a temperature of 153 °C in 2 hours. The aluminum and brass have raised the temperature with fewer slopes, arrived 129 °C and 110 °C in 3.6 hours of time. The lower thermal conductivity of brass has resulted in the least heat gained with respect to other materials [18]. Also, fig. 7 represents the discharging for D-sorbitol. Brass encapsulation with annular fins is noticed at a stable rate of decrease in temperature for an hour, finally, has dropped to 70 °C in 260 minutes. The aluminum and copper have dropped to 65 °C and 51 °C in a spell of 5 hours.



Figures 8 and 9 show the charging and discharging process of paraffin wax which has a melting point around 50 °C. With paraffin wax, the three encapsulation materials copper has absorbed a temperature of 119 °C at 170 minutes and brass, and aluminum with annular fins



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have absorbed 102 °C and 106 °C, respectively, at 170 minutes each. During discharging where the copper has transferred maximum heat to the HTF and ended up at 44 °C in 190 minutes and the similar data for brass and aluminum are 70 °C in 150 minutes and 65 °C in 190 minutes, respectively. Obviously, the charging is earlier than the discharging because of solid boundary formation during solidification of PCM during discharging which prevents heat transfer in the storage system [19, 20].

Heat transfer of D-mannitol PCM

The heat transfer data has been obtained from the different encapsulations (copper, aluminum, and brass) each with different types of fins (annular, pin, and rectangular). It can be inferred from fig. 10 that the heat energy gained by D-mannitol in CTES system during charging has attained a maximum heat transfer of 4146.3 kJ with the combination of copper encapsulations and annular fins. The lowest is noticed for the pair of brass encapsulation and rectangular

fins have attained a heat transfer of 2897.55 kJ because of lower thermal conductivity. Copper that has a higher thermal conductivity when compared to the other encapsulations absorbs the heat at a faster rate when compared to the aluminum and brass. The annular fin possesses a higher heat transfer rate for the reason that it has a higher surface area for transfer of heat as compared with pin fin and rectangular fins. On the consideration of cost, the aluminum encapsulation has been concluded to be economical, whereas on considering high heat transfer rate the copper encapsulation is found to be the most efficient. By the usage of rectangular finsthe solidification time is reduced by 43.6%.



Figure 11 shows the discharging of D-mannitol. It is observed that the least heat transfer has been for the brass encapsulations with rectangular fins as 2457.1 kJ and the same is noticed as 500 kJ lesser than that for charging because of heat loss in the storage system, whereas copper encapsulations with annular fin have a higher heat transfer during the discharge of 3991.4 kJ. The similar trend is witnessed for other encapsulations with dif-



ferent fins. Due to the higher thermal conductivity of copper, it allows the PCM inside to allow heat at a faster rate which hence makes the copper as most efficient. The cost analysis has been made by considering material cost, fabrication cost for welding of fins in each encapsulation ball and the heat transfer from HTF to PCM through each encapsulation. According to the cost of energy, the less cost encapsulation is annular finned aluminum balls with the price of INR 0.306/kJ in discharging process and INR 0.25/kJ in charging process.

Heat transfer of D-sorbitol PCM

The charging rate of D-sorbitol PCM in CTES system as shown in fig. 12. During charging, copper encapsulation with annular fins has been found to have the highest heat transfer of 2324.24 kJ. The least has been recorded with the brass encapsulation with rectangular fins 1572.03 kJ because of the reason of lowest thermal conductivity. The same trend has been observed in aluminum encapsulation which has shown higher heat transfer rate with annular fins as 2098.5 kJ when compared with other types of fins. Figure 13 represents discharging of D-sorbitol in CTES system. Brass encapsulations with rectangular fins are recorded the least value of heat transfer with 1227.6 kJ due to its lower value of thermal conductivity. Whereas the copper with annular fins has a heat transfer of 2214.4 kJ and the same during discharging is nearly 110 kJ lower than charging. As per energy cost, the least expensive encapsulation is annular finned aluminum balls with the price of INR^{**} 0.65/kJ & INR 0.53/kJ during discharging and charging process, respectively.



Heat transfer of paraffin wax PCM

The charging rate of paraffin wax in CTES system is shown in fig. 14. During charging the copper encapsulated with annular finned balls has a maximum heat transfer of 2004.12 kJ

** 100 INR = 1.4 \$ US

and the least is for rectangular finned brass encapsulated balls with 1309.14 kJ of heat transfer. Figure 15 shows discharging of paraffin wax in CTES system. The 1002.1 kJ of heat transfer is obtained in rectangular finned brass encapsulated balls, which is the lowest heat energy transfer compared to all finned balls. However, the annular finned aluminum encapsulated balls have the heat transfer of 1366.1 kJ is concluded to be the most economical encapsulation the cost of INR 1.59/kJ and INR 1.70/kJ during discharging and charging, respectively.



Fin effectiveness

The efficiency of a fin is defined as the ratio of the actual heat transfers from the fin to that the heat that would be dissipated if the whole surface of the fin is maintained at base temperature. Whereas fin effectiveness is defined as the ratio of the actual heat transfer that takes place from the fin to the heat that would be dissipated from the same surface area without a fin. From efficiency, effectiveness can be analyzed and *vice versa*. Higher the thermal conductivity of a fin material will be highly effective for heat transfer. In this section, fin effectiveness is presented in detail and has been calculated using eq. (4). The heat transfer rate, of all encapsulated balls with and without fins, is calculated. Based on these values the effectiveness of each fin namely annular fin, pin fin, and rectangular fin has been estimated and are shown in tab. 3. In the conducted experiment, the fin effectiveness has shown significant variations for different PCM and encapsulations. Fin effectiveness is calculated to be the higher of 1.43 for annular fin type joined permanently inside copper encapsulation having higher thermal conductivity with paraffin wax combination as the PCM.

| D-Mannitol | | D-sorbitol | | Paraffin wax | | | | | |
|-------------|--------|------------|-------|--------------|----------|-------|--------|----------|-------|
| FIIIS | Copper | Aluminum | Brass | Copper | Aluminum | Brass | Copper | Aluminum | Brass |
| Pin | 1.28 | 1.10 | 1.34 | 1.16 | 1.13 | 1.09 | 1.31 | 1.22 | 1.22 |
| Rectangular | 1.08 | 1.07 | 1.16 | 1.09 | 1.11 | 1.05 | 1.21 | 1.09 | 1.16 |
| Annular | 1.31 | 1.25 | 1.41 | 1.34 | 1.30 | 1.24 | 1.43 | 1.31 | 1.30 |

| Table | 3. | Fin | effectiveness |
|-------|-----|-----|------------------|
| Invit | ••• | | chiecen (chiebb |

Conclusion

The heat transfer study on cascaded solar TES system, with different PCM (D-mannitol, D-sorbitol, and paraffin wax) and encapsulation arrangements (by using different encapsulation materials and the attachment of different profile of fins in each encapsulation ball), it has been concluded that the transfer of energy is the highest in the use of copper balls for encapsulation of PCM with attachment of annular fin inside the balls. The use of copper material, annular finned balls, has shown more efficient energy transfer rate about 4147 kJ during the charging process and 3992 kJ during the discharging process in D-mannitol PCM tank. The most economical encapsulation material is aluminum with annular fin attachment during the charging and the discharging process.

Nomenclature

- $A_{\rm w}$ wall surface area of encapsulation ball, [m²]
- C_p specific heat capacity, [kJkg⁻¹K⁻¹]
- $C_{p,o}$ specific heat of HTF [kJkg⁻¹K⁻¹]
- h heat transfer coefficient [Wm⁻²K]
- L.H melting enthalpy of PCM, [kJkg⁻¹]
- m total mass of the PCM, [kg]
- m_o total mass of HTF, [kg]
- m_p mass of PCM in each encapsulation, [kg]
- N_p number of encapsulated balls in each storage tank
- Q heat transfer by PCM or HTF during charging and discharging, [kJ]
- t temperature [°C]
- T_{∞} surrounding temperature [°C]
- T_i temperature of HTF at inlet [°C]
- *ti* time [s]
- $T_{\rm o}$ temperature of HTF at outlet [°C]
- $T_{\rm w}$ wall surface temperature [°C]
- V_p volume of spherical ball, $[m^3]$

References

 ΔT – difference in temperature, [°C]

Greek symbol

 ρ – density of PCM, [kgm⁻³]

Acronyms

- CTES cascaded thermal energy storage
- HTF heat transfer fluid
- LHTES latent heat thermal energy storage
- PCM phase change material
- PTC parabolic trough collector
- TES thermal energy storage

Subscripts

- f final
- i initial/inlet
- m melting
- o outlet
- w wall surface of encapsulation
- Karthikeyan, S., Velraj, R., Numerical Investigation of Packed Bed Storage Unit Filled with PCM Encapsulated Spherical Containers – A Comparison between Various Mathematical Models, *International Journal of Thermal Sciences*, 60 (2012), Oct., pp.153-160
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