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

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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 PCMs with various encapsulation arrangements. The storage system consists of three different PCMs 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, Aluminium, 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 PCMs with the attachment of annular fin inside the balls. With respect to Energy cost per kJ of heat transfer, the PCMs encapsulated in Aluminium 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.

Keywords*: cascaded thermal energy storage system, multiple phase change materials, encapsulation materials*

1. 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 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 thermal energy storage methods, the latent thermal energy storage employing a phase change material (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 vice versa [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 phase change materials (PCMs) and fins. In the present work, a comparative study has been made on the improvement of heat transfer in a cascaded latent heat solar thermal energy storage system with the use three different PCMs (D-mannitol, D-sorbitol, and Paraffin wax) and also with the use of high thermal conductivity encapsulation materials (Copper, Aluminium, and Brass) with the attachment of different profiles fins (pin fin, rectangular fin, and annular fin).

2. Materials and methods

This experimental setup 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 m^2 aperture area, is used to heat up the HTF that enters the absorber tube. The specifications of the fabricated PTC are shown in Table 1. The photographic view of PTC and cascaded thermal energy storage (CTES) system is shown in fig. 1.

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, Aluminium, 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 PCMs and the heat is stored is in PCMs 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 PCMs 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 PCMs available in tanks numbered as 1, 2 and 3 of D-Mannitol, D-Sorbitol, and Paraffin wax. The arrangements of different PCMs are arranged in the order from highest to lowest melting points. The Copper, Aluminium, 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 PCMs. Finally, the HTF after losing possible heat energy at different PCMs 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 PCMs and HTF are shown in Table 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 PCMs 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.

Figure 1. Photographic view of PTC and Cascaded TES system

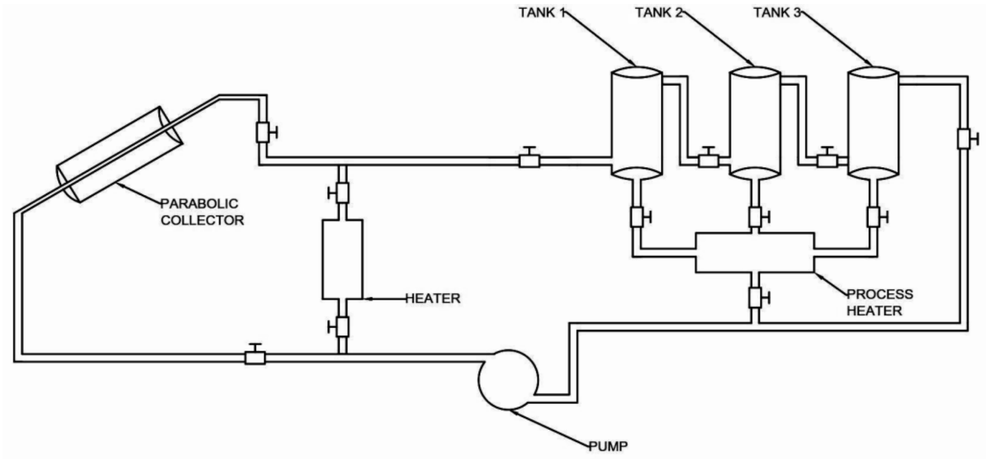


Figure 2. Experimental layout

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]

Table 2. Properties of PCMs & HTF

Therminol - 66		**Phase change materials**			
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^2s^{-1}]	Density of PCM [kgm^{-3}]	1500	1524	1490
Range of use	0 – 345 [^oC]	Specific heat capacity [$kJkg^{-1}K^{-1}$]	2.38	2.49	2.5

2.1. 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^oC with the digital temperature indicator resolution of 0.1^oC 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%.

3. Heat transfer calculations

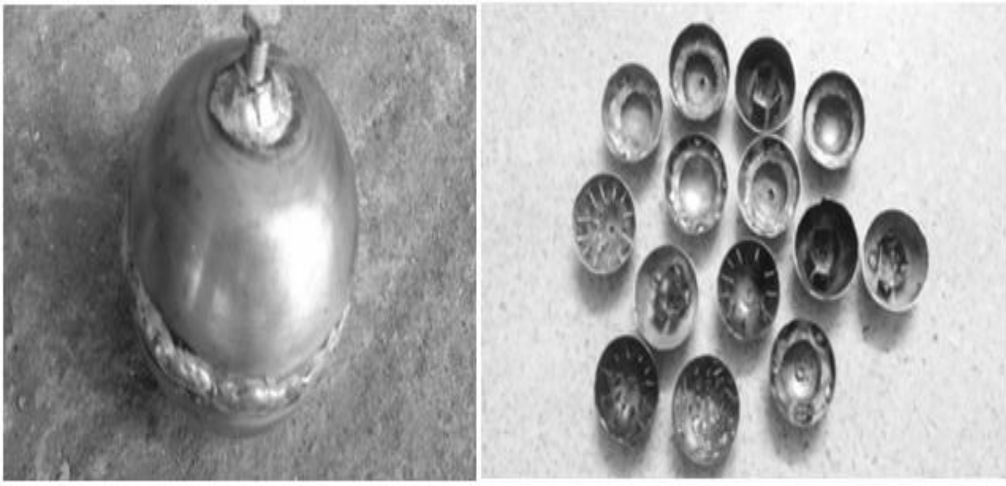


Figure 3. Finned encapsulated balls

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 is the specific heat of PCM, m_o is the mass of HTF, $C_{p,o}$ is the specific heat of HTF, T_o is the outlet temperature of HTF from each storage tank, T_i is the inlet temperature of HTF to the storage tank, *ti* is the total time taken for charging or discharging and *L.H* is 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 $Q_{no\ fin}$ which is calculated by eq. (4) where h is the heat transfer coefficient, A_w is the total wall surface area of the encapsulated ball, T_w is the wall surface temperature of the ball, and T_∞ is the surrounding temperature of fin i.e. PCM.

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

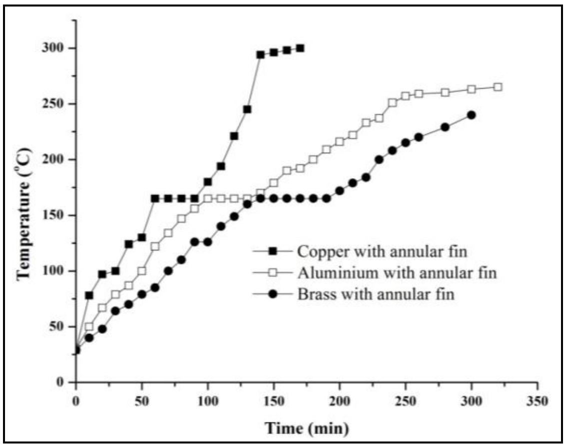
$$m_p = \rho . V_p . (0.8) \tag{2}$$

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

$$\varepsilon = \frac{Q_{fin}}{Q_{no\ fin}} = \frac{Q_{fin}}{h A_w (T_w - T_\infty)} \tag{4}$$

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, Aluminium, 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.



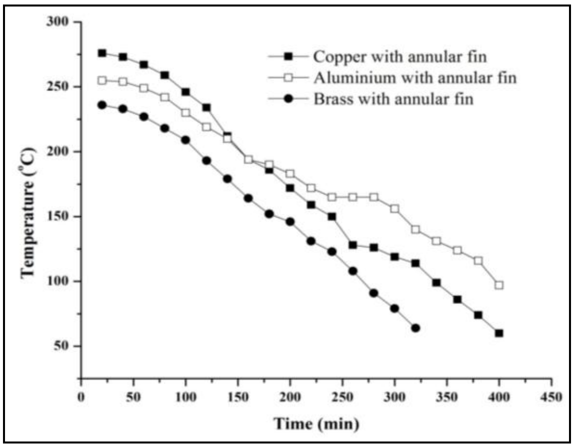


Figure 4. Charging of D-mannitol

Figure 5. Discharging of D-mannitol

This experiment has been carried out, as discussed above for three materials of encapsulation balls of Copper, Aluminium, 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 PCMs. Figs. 4 and 5 represent the time taken for charging and discharging process of PCM D-mannitol with Aluminium, 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 Aluminium 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 Aluminium 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.

Fig. 6 represents the encapsulations spheres made of Copper, Brass, and Aluminium 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 Aluminium 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 Aluminium and Copper have dropped to 65°C and 51°C in a spell of 5 hours.

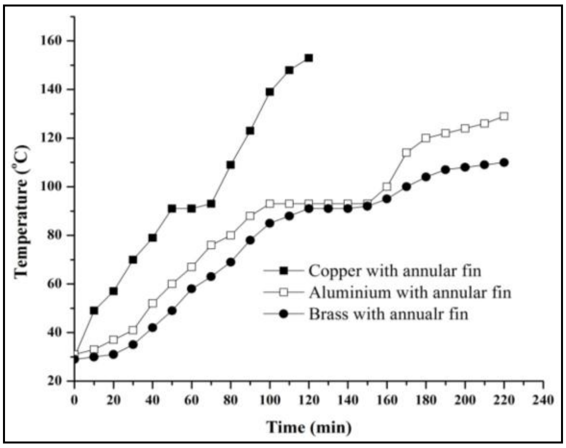


Figure 6. Charging of D-Sorbitol

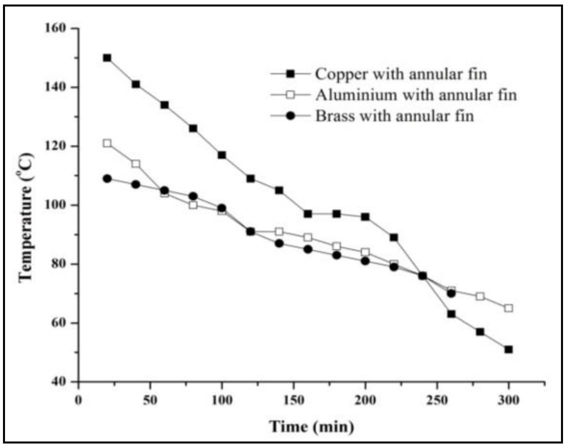


Figure 7. Discharging of D-Sorbitol

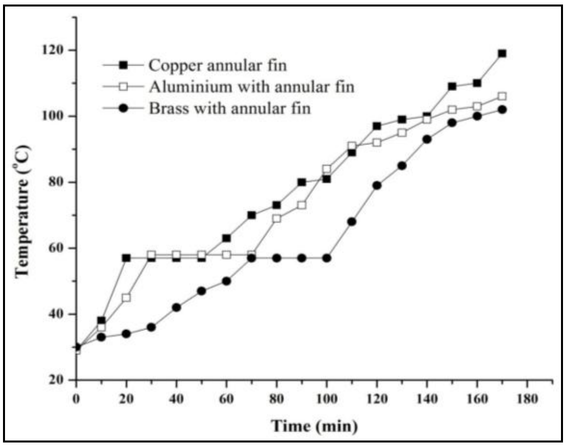


Figure 8. Charging of Paraffin wax

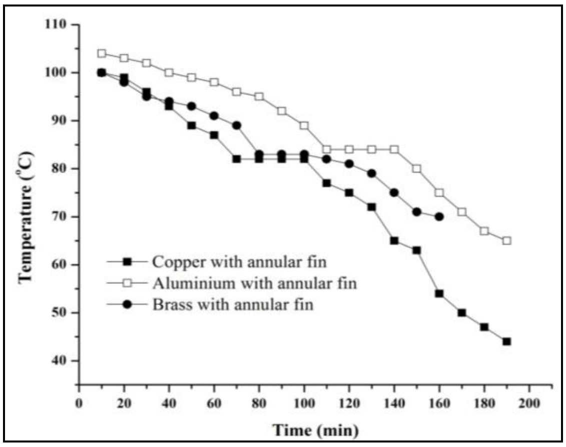


Figure 9. Discharging of Paraffin wax

Figs. 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 Aluminium with annular fins 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 Aluminium 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].

4.1. Heat transfer of D-mannitol PCM

The heat transfer data has been obtained from the different encapsulations (Copper, Aluminium, 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 Aluminium 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 Aluminium 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 fins, the solidification time is reduced by 43.6%.

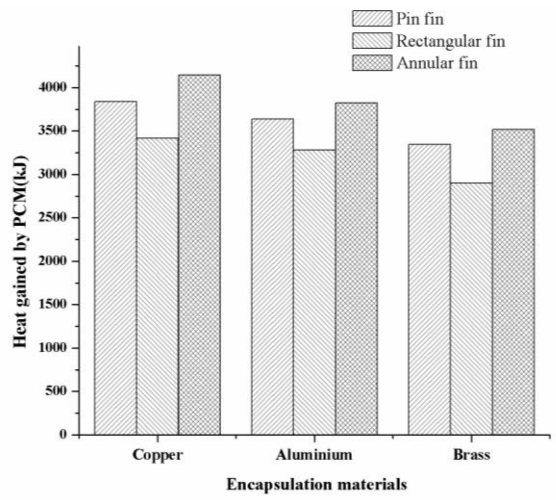


Figure 10. Heat gained by D-mannitol

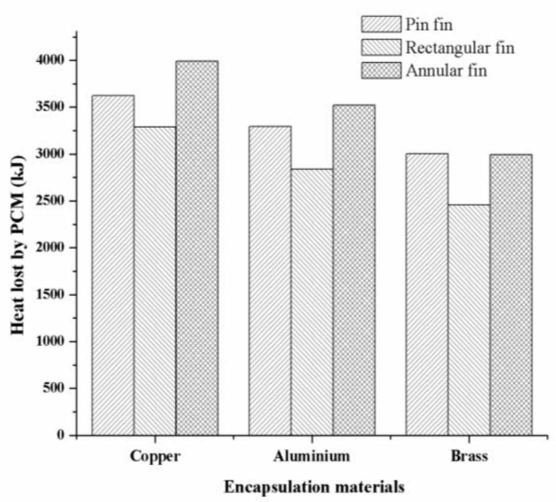
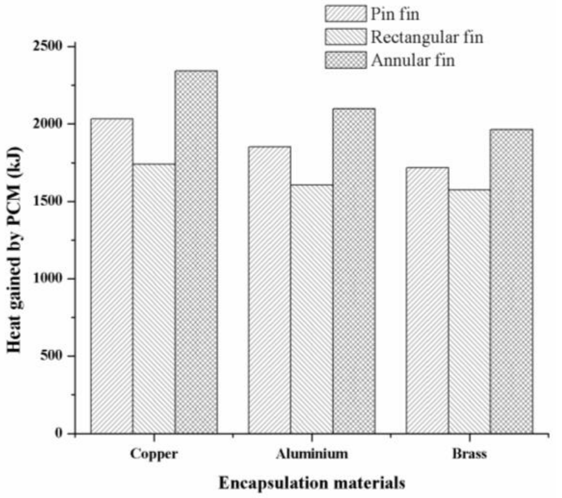


Figure 11. Heat lost by D-mannitol

Fig. 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 different 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 Aluminium balls with the price of INR 0.306/kJ in discharging process and INR 0.25/kJ in charging process.

4.2. 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 Aluminium encapsulation which has shown higher heat transfer rate with annular fins as 2098.5 kJ when compared with other types of fins. Fig. 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 Aluminium balls with the price of INR 0.65/kJ & INR 0.53/kJ during discharging and charging process respectively.



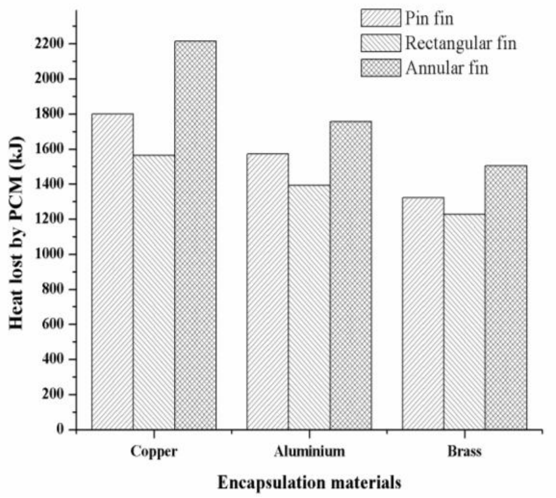
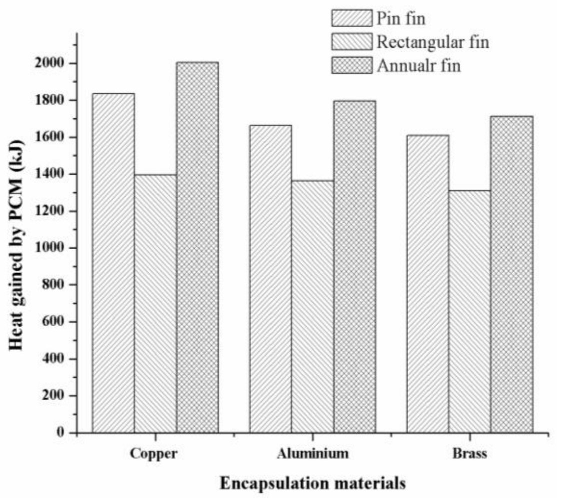


Figure 12. Heat gained by D-sorbitol **Figure 13. Heat lost by D-sorbitol**

4.3. Heat transfer of paraffin wax PCM



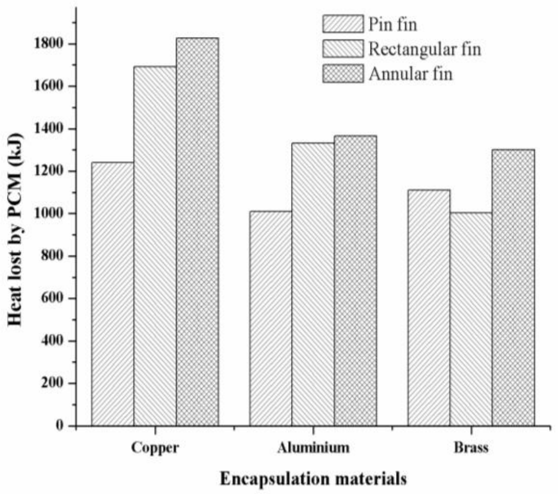


Figure 14. Heat gained by paraffin wax **Figure 15. Heat lost by paraffin wax**

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 and the least is for rectangular finned Brass encapsulated balls with 1309.14 kJ of heat transfer. Fig. 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 Aluminium 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 & INR 1.70/kJ during discharging and charging respectively.

4.4. 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 Table 3. In the conducted experiment, the fin effectiveness has shown significant variations for different PCMs 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.

Table 3. Fin effectiveness

Fins	D-Mannitol			D-Sorbitol			Paraffin wax		
	Copper	Aluminium	Brass	Copper	Aluminium	Brass	Copper	Aluminium	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

5. Conclusions

The heat transfer study on cascaded solar thermal energy storage system, with different PCMs (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 PCMs 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 Aluminium with annular fin attachment during the charging and the discharging process.

Nomenclature

A_w	- wall surface area of encapsulation ball [m^2]
C_p	- specific heat capacity, [$kJkg^{-1}K^{-1}$]
$C_{p,o}$	- specific heat of HTF [$kJkg^{-1}K^{-1}$]
h	- heat transfer coefficient [$Wm^{-2}K$]
L.H	- melting enthalpy of PCM, [$kJkg^{-1}$]
m	- total mass of the PCM, [kg]

m_o - mass flow rate HTF [kgs^{-1}]
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 [^oC]
T_∞ - surrounding temperature [^oC]
T_i - temperature of HTF at inlet [^oC]
ti - time [s]
T_o - temperature of HTF at outlet [^oC]
T_w - wall surface temperature [^oC]
V_p - volume of spherical ball, [m^3]
ΔT - difference in temperature, [°C]
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
p - phase change material
w - wall surface of encapsulation

References

[1] 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), pp.153-160

[2] Ranjbar, Ali, Akbar., *et al.*, Numerical Heat Transfer Studies of a Latent Heat Storage System Containing Nano-Enhanced Phase Change Material, *Thermal Science, 15* (2011), 1, pp. 169 - 181

[3] Nallusamy,N., *et al*., Experimental Investigation on a Combined Sensible and Latent Heat Storage System Integrated with Constant/Varying (Solar) Heat Sources, *Renewable Energy, 32* (2007), pp. 1206-1277.

[4] Liwu, Fan., J, M, Khodadadi., Thermal Conductivity Enhancement of Phase Change Materials for Thermal Energy Storage: A Review, *Renewable and Sustainable Energy Reviews*, 15 (2011), pp. 24-46

[5] Velraj, R., *et al.*, Heat Transfer Enhancement in a Latent Heat Storage System, *Solar Energy, 65* (1999), 3, pp. 171-180

[6] H. J. Xu., C. Y. Zhao., Thermodynamic Analysis and Optimization of Cascaded Latent Heat Storage System for Energy Efficient Utilization, *Energy*, *90* (2015), 2, pp. 1662-1673

[7] Peleg, P., *et al*., Numerical optimization of a PCM-based heat sink with internal fins, *International Journal of Heat and Mass Transfer*, 61 (2013), pp. 638–645

[8] Mat, S., *et al*., Enhance Heat Transfer for PCM Melting in Triplex Tube with Internal-External Fins, *Energy Conversion and Management, 74* (2013), pp. 223-236

[9] Babak, Kamkari., Hossein, Shokouhmand., Experimental Investigation of Phase Change Material Melting in Rectangular Enclosures with Horizontal Partial Fins, *International Journal of Heat and Mass Transfer, 78* (2014), pp. 839-851

[10] Piia, Lamberg., Kai, Sir., Approximate Analytical Model for Solidification in a Finite PCM Storage with Internal Fins, *Applied Mathematical Modelling, 27* (2003), pp. 491–513

[11] Li-Wu, Fan., *et al*., Effects of Melting Temperature and the Presence of Internal Fins on the Performance of a Phase Change Material (PCM)-based Heat Sink, *International Journal of Thermal Sciences*, *70* (2013), pp. 114-126

[12] Cheralathan, M., *et al*., Performance Analysis on Industrial Refrigeration System Integrated with Encapsulated PCM-Based Cool Thermal Energy Storage System, *International Journal of Energy Research, 31* (2007), 14, pp. 1398–1413

[13] Senthil, Ramalingam., Marimuthu, Cheralathan., Effect of the PCM in a Solar Receiver on Thermal Performance of Parabolic Dish Collector, *Thermal Science*, doi:10.2298/TSCI150730007S

[14] Madadi, V., *et al.*, First and Second Thermodynamic Law Analyses Applied to a Solar Dish Collector, *Journal of Non-Equilibrium Thermodynamics, 39* (2014), 4, pp. 183-197

[15] Abdulgalil, Mohamed, M., *et al.*, Effect of Thermal Energy Storage in Energy Consumption Required for Air Conditioning System in Office Building under the African Mediterranean Climate, *Thermal Science*, *18* (2014), 1, pp. S201-S212

[16] Rudonja, Nedzad, R., *et al.*, Heat Transfer Enhancement Through PCM Thermal Storage by use of Copper Fins, *Thermal Science*, *20* (2016), 1, pp. S251-S259

[17] Manish, K, Rathod., Jyotirmay, Banerjee., Thermal Performance Enhancement of Shell and Tube Latent Heat Storage Unit using Longitudinal Fins, *Applied Thermal Engineering, 75* (2015), pp. 1084-1092

[18] Ozturk, H., Comparison of Energy and Exergy Efficiency for Solar Box and Parabolic Cookers, *Journal of Energy Engineering, 133* (2007), 1, pp. 53-62

[19] Amirhossein, Mosaffa., *et al.*, Phase Change Material Solidification in a Finned Cylindrical Shell Thermal Energy Storage: An Approximate Analytical Approach, *Thermal Science*, *17* (2013), 2, pp. 407 – 418

[20] Sina, Kashani., *et al.*, Numerical Analysis of Melting of Nano-Enhanced Phase Change Material in Latent Heat Thermal Energy Storage System, *Thermal Science*, *18* (2014), 2, S335-S345