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RESEARCH ARTICLE - MECHANICAL ENGINEERING

Experimental Investigation on Improving the Heat Transfer of Cascaded Thermal Storage System Using Different Fins

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Abstract The ever-increasing energy demand is the source of experimentation to explore different possibilities of producing higher energy and storing it for various needs. An experimental setup has been developed to study the heat transfer of cascaded thermal energy storage system using fins. Three different encapsulation materials copper, brass, and stainless steel are tried, and inside these encapsulations rectangular, annular, and pin fins are welded to increase the heat transfer area. Three different phase change materials namely D-mannitol, D-sorbitol, and paraffin wax are arranged inside the finned encapsulations. In this paper a detailed analysis is made with different encapsulations with rectangular, annular and pin fin, and is found to have the heat transfer as 4146.3 and 3991.4 kJ during charging and discharging conditions respectively for annular fin. The heat transfer rate is the highest one for annular fin in comparison to other types of pin and rectangular fins. Further, the efficiency of annular fins with copper encapsulation is found to be about 90% and while that of brass and stainless steel encapsulation are 88 and 85%, respectively. The results with annular fin analysis are completely presented in this research work.

Keywords Fins · Heat transfer · Phase change material · Fin effectiveness

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List of Symbols

m_p	Mass of PCM in each encapsulation (kg)
N_P	Number of encapsulated balls in each storage tank
v_p	Volume of spherical ball (m^3)
ρ	Density of PCM (kg m^{-3})
m	Total mass of the PCM (kg)
C_p	Specific heat capacity (J kg^{-1} K^{-1})
ΔT	Difference in temperature (°C)
L.H	Melting enthalpy of PCM (kJ kg^{-1})
Q	Heat transfer by PCM during charging and discharging (kJ)
Q_{RF}	Heat transfer through rectangular fin (kJ)
Q_{PF}	Heat transfer through pin fin (kJ)
Q_{AF}	Heat transfer through annular fin (kJ)
h	Heat transfer coefficient (W/m^2 °C)
k	Thermal conductivity of material (W/m °C)
p	Perimeter of fin (m)
w	Width of fin (m)
L	Length of fin (m)
T_b	Surface temperature at base (°C)
T_∞	Surrounding temperature (°C)
m_f	Fin constant
D	Diameter of pin fin (m)
r_1	Encapsulation ball surface radius (m)
r_2	Annular fin radius (m)
A_c	Cross-sectional area of fin (m^2)
A_b	Surface area (m^2)
t	Thickness of fin (m)

Abbreviations

HTF	Heat transfer fluid
INR	Indian national rupee
LHTES	Latent heat thermal energy storage

PCM	Phase change material
PTC	Parabolic trough collector
TES	Thermal energy storage

Subscripts

i	Initial
m	Melting
f	Final
p	Phase change material

1 Introduction

Energy is an important one to produce at the highest for various uses of daily needs. Implementation of proper energy storage device helps in improving the management of energy efficiently to match the supply and needs. Basically there are two types of heat energy namely sensible and latent heat, and because of high storage density during latent heat, it has more importance. In comparison with conventional heating with latent heat transfer process, the PCM liberates more energy thus bringing higher use efficiency [1]. Higher energy storage was noticed with improved characteristics to store the absorbed heat at isothermal conditions [2]. The pressure required for converting PCM from liquid to solid phase change or vice versa is comparatively lower than liquid to gas phase change. Hence liquid-to-solid state PCM has been preferred as a latent heat storage system. Nallusamy et al. [3] investigated conventional heat storage system of lower efficiency with lower heat transfer, and the drawbacks were overcome by combined latent and sensible heat storage system. High latent heat energy storing PCM was filled inside different encapsulating materials of higher thermal conductivity played an important role [4]. Efficiency of heat storage system depends on heat storage and extraction. Velraj et al. [5] had explained many techniques to increase the efficiency of heat storage systems among which utilization of fins were the most economical and effective method. Encapsulated D-mannitol offered larger heat transfer area and also improved the rate of heat transfer [6]. The various fin geometry with different encapsulation influenced the charging and discharging time [7]. Mat et al. [8] investigated that the charging time of PCM was reduced by 43.3% using fins. The maximum energy transfer and effectiveness could be obtained using different fin materials with varied geometry [9]. Pia Lambert et al. [10] explained that the width to height ratio of the storage tank dimensions strongly had influenced the heat transfer rate. Li-wu fan et al. [11] proved that the increase in the number of fins decreased the melting time of PCM and increased the total heat transfer rate, melting enhancement ratio and overall fin effectiveness. Energy transfer to the PCM is directly proportional to difference in temperature between heat transfer fluid (HTF) and the walls of the encapsulating materials. Also the heat transfer rate depends on the state of PCM being in the state of solid or liquid or both [12,13]. Mass of HTF is the important factor to absorb the heat from the collector and higher HTF mass flow rate is recommended for higher energy transfer [14].

Many studies have been done on storage of heat energy in a thermal storage system. But the improvement for the heat storage system can be made better by using different fins welded with different encapsulations in a cascaded system. From the detailed literature survey, it is concluded to analyze three different encapsulated materials with copper, brass, and stainless steel with fins of types rectangular, annular and pin that are welded inside the encapsulations. The welded and encapsulated balls is arranged in the three tanks for storing different PCM's. D-mannitol, D-sorbitol, and paraffin wax are arranged in first, second, and third tanks, respectively. During charging mode, Therminol-66, the heat transfer fluid, is made to pass by the tanks which in turn gives its sensible heat observed from parabolic trough collector (PTC). During the off-sunshine hours, the accumulated heat by PCMs is given back to the Therminol-66 which is called as discharging mode. There are 13 thermocouples employed to measure the temperatures at various positions.

Hence the work focuses on the heat transfer of cascaded thermal energy storage system with three different PCMs namely D-mannitol, D-sorbitol and paraffin wax. The analysis has been carried out with three different encapsulated materials namely copper, brass and stainless steel. Encapsulation materials are welded inside with three different types of fins namely rectangular, annular, and pin. Encapsulated balls contain three PCMs and are arranged in the three different tanks independently. This work is intended to investigate the best combination of fins which could provide the maximum possible heat transfer economically.

2 Materials and Methods

The experimental layout is shown in Fig. 1. This experimental setup includes a PTC, Therminol-66 as HTF, storage tanks containing encapsulated internally fins welded balls filled with three types of PCM, 13 thermocouples to measure temperature at various points and a circulating pump to circulate and maintain continuous flow of HTF. An auxiliary heater is provided to perform the experiment, if required, during the time when natural light is not available. The storage tank of diameter 0.3 m, length 0.4 m, and thickness 0.006 m is made by mild steel plate. The PCM storage tanks are insulated with glass wool of thickness 0.12 m and the pipe lines are insulated with cotton rope of thickness 0.07 m. The setup is completely

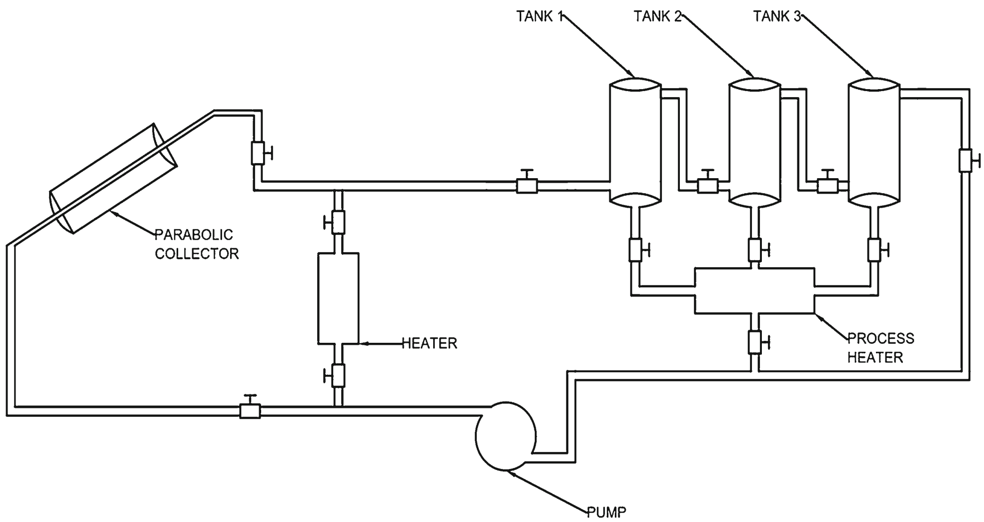

Fig. 1 Experimental layout

Fig. 2 Photographic view of PTC and Cascaded TES system

insulated to prevent the heat escaping out of the storage tank. The latent heat thermal energy storage (LHTES) system and the circuit of pipes are fully filled up with 50 l of Therminol-66 as HTF, and a careful examination has been carried out for the leaks in the oil passage way. The encapsulation sphere materials selected for the experiment is copper, brass, and stainless steel. The encapsulation spherical balls of 100 mm diameter with 2 mm thickness are welded internally with pin fins, annular fins, and rectangular fins are the major division in this study to enhance the heat energy transfer rate. D-mannitol, D-sorbitol, and paraffin wax are the PCMs to be kept inside the encapsulated spheres. The first tank has D-mannitol encapsulated balls, the second tank has D-sorbitol encapsulated balls, and the third tank contains paraffin wax encapsulated balls. Experimental data have been related with the three PCMs are kept inside the encapsulated spheres and arranged in the successive three tanks with a particular encapsulation materials. The different types of fins that are welded to the different encapsulating materials are placed in storage tank, and heat is being absorbed from the HTF and stored in PCM filled in the encapsulations.

PCM that absorbs heat from HTF and stores in the form of hidden heat (i.e., latent heat) [15]. The selection of PCM is dependent basically on the required range of temperature. The temperature range is calculated with respect to the heat absorbed by the PTC. The PTC that consists of highly reflective stainless sheet of 9 m^2 aperture area and in 6 m in length heats up the HTF that flows in the glass tube. The actual photograph of PTC and cascaded thermal energy storage (TES) system is shown in Fig. 2. Higher mass flow of HTF enhances the absorption of the heat from the collector, and hence higher HTF mass flow rate is recommended. The PTC supplies heated HTF to the PCM storage tanks.

The PTC, HTF, and PCM properties are shown in Tables 1 and 2. Energy collected in the HTF is captivated by the PCM and stores in it. The HTF gets heated up by the radiations of the sun, go into the first PCM tank containing D-mannitol stated to have the highest melting point of the three. Hence the

Table 1 Specifications of PTC

Concentration ratio	15	Length of Absorber tube	600 cm
Width of the collector	150 cm	OD of vacuum glass tube	10 cm
Supporting structure material	Mild steel	ID of absorber tube	2.54 cm
Length of the collector	600 cm	OD of the absorber tube	3.74 cm
Material of the absorber tube	High reflectivity stainless steel	Aperture area of the collector	9 m^2

Table 2 Properties of PCM and HTF

Therminol-66		Phase change materials			
		Criteria	Paraffin wax	D-sorbitol	D-mannitol
Oil density	1005 $kg\,m^{-3}$				
Specific heat capacity	1495 $J\,kg^{-1}\,°C^{-1}$	Melting point of PCM °C	51–58	91–101	157–170
Oil thermal conductivity	0.12 $W\,m^{-1}\,°C^{-1}$	Melting enthalpy $J\,g^{-1}$	212	187	318
Kinematic viscosity	$29.64 \times 10^{-6}\,m^2s^{-1}$	Density of PCM $g\,m^{-3}$	1500×10^3	1524×10^3	1490×10^3
Range of use	0–345 °C	Specific heat capacity $J\,kg^{-1}\,°C^{-1}$	2380	2490	2500

heat transfer takes place between the HTF and PCM in first tank and HTF enters the second tank containing D-sorbitol as PCM and the heat transfer takes place. Finally the HTF enter the third tank contains paraffin wax which has the least melting point of the three. Finally the HTF exits the third tank entering to process unit in which the oil losses its energy and then enters to the absorber tube of collector to get heated up. Circulation of the HTF is maintained by a gear pump with the control of mass flow rate. The copper, brass, and stainless steel encapsulated materials are used in this work, and the experimentation has been done with change of various encapsulated materials. This activity is called as charging process. During off-sunshine hours, the collector is disconnected from the circuit, and on the HTF entering the PCM storage tank, it gains the heat from PCM. This activity is called discharging process. The temperature of HTF in the inlet and outlet of PTC is noted for calculating the thermal energy gain by the HTF. The HTF temperature in the PCM tank is observed at three different locations in each tank, and the mean temperature is considered to estimate the transfer of energy rate between HTF and PCM for every 10 min of time interval.

A fin is an extended surface of an object used to increase the rate of heat energy transfer to the environment or from the environment by steadily increasing the amount of convection. The heat transfer efficiency of using fin is higher than that of an un-finned system [16]. The amount of conduction, convection, or radiation of an object shows the amount of heat it transfers. The most common way is to increase the heat energy transfer rate by rising the difference in temperature between the object and the environment or by increasing the surface area of the particular object. This study deals with increase in the surface area of the object by using the fins that are welded inside the encapsulations. Even though many fin types exist, this study focuses three types of fins namely annular fins, pin fins that are to be welded inside the different encapsulated balls. The selection of fin material is dependent on the encapsulating material for quality weldments. Figure 3 represents the photographic view of annular, rectangular, and pin fins which are welded inside the spherical encapsulation balls ensuring better heat transfer area and thus improves heat transfer from HTF to PCM and vice versa during charging and discharging modes [17].

After welding of fins, the two halves of the balls are welded together and the different PCM is filled through openings on the spheres and the openings be closed. The PCM-filled encapsulation spheres are finally kept in storage tank to measure heat energy transfer rate. Every tank is equipped with thermocouples arranged in different levels of tank to measure the temperatures for every 10 min during the flow of HTF.

2.1 Instrumentation and Uncertainties

There are thirteen numbers of K-type thermocouples used to sense the temperature values in the cascaded system and the absorber tube of the collector. Two thermocouples are at inlet and outlet of PTC and three thermocouples per storage tank are arranged in top, middle and bottom. Also two more thermocouples are used in process heater. The K-type thermocouple accuracy of 0.15 °C with the digital temperature indicator resolution of 0.1 °C is used to measure the temperature. The instrumentation error allied within the calculated temperature range is 0.62%. A flow meter is used to adjust the flow rate of HTF in the circuit with an error of 2.05%. A circulating pump is used for circulating the HTF in closed circuits with specification as 0.5 HP, 28 A of current

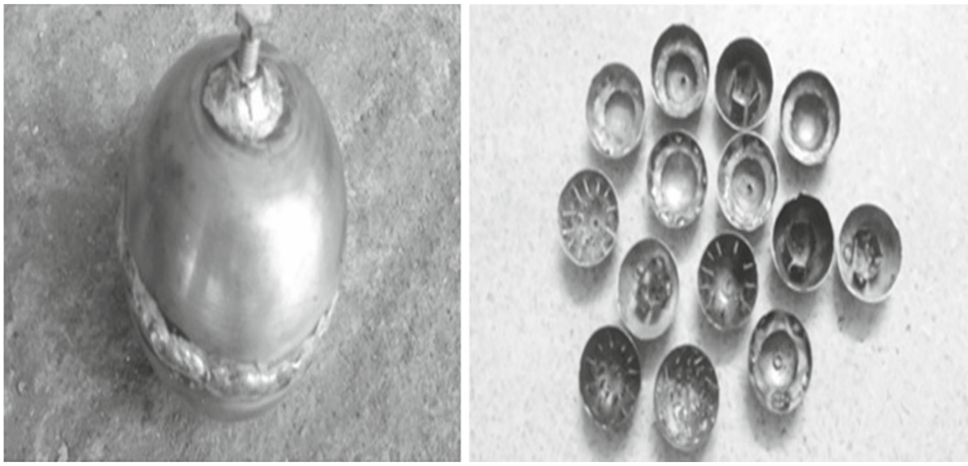

Fig. 3 Finned encapsulated balls

Fig. 4 Storage tank

and a speed of 2800 rev/min. The error of instantaneous heat transfer is 1.50% and cumulative heat transferred is 1.52%.

3 Heat Transfer Calculations

PCM-filled fin-welded encapsulations are placed on the storage tank as shown in Fig. 4. A total of nine balls each with same PCM are arranged per tank such that the first tank with D-mannitol encapsulation spheres, the second tank with D-sorbitol encapsulation spheres, and the last tank with paraffin-wax-encapsulated spheres and the energy from the HTF is absorbed by the different PCM's. The PCM storage tank stores the latent heat in the PCM, and the energy stored depends on the quantity of PCM used in each tank.

Amount of PCM required is calculated with the use of Eq. (1), where m_p is PCM mass in *kg* per encapsulation ball and N_p is number of encapsulations used in each storage tank. The mass of PCM encapsulated in each ball is about 80% of its volume, and this can be calculated by Eq. (2) where ρ is the mass density in kg m^{-3} of each PCM and v_p is the volume of spherical ball in m^3. Total heat energy transfer between HTF and PCM during charging and discharging process is calculated using Eq. (3), where C_p is specific heat capacity at constant pressure of PCM in kJ kg^{-1} K^{-1}, L.H is the latent heat capacity of each PCM in kJ kg^{-1} and ΔT is the temperature difference between HTF and PCM in K.The different profiles of fins are shown in Fig. 5.

Cengel [18] has suggested heat transfer equations for rectangular fin, pin fin and annular fin and are listed in Eqs. (4), (6) and (7), in which m_f is the fin constant can be calculated using Eq. (5) where h is the heat transfer coefficient in W m^{-2} K^{-1}, p is the perimeter of each fin in m, k is the thermal conductivity of fin material in W m K^{-1} and A_c is the cross-sectional area of each fin in m^2. The heat transfer through rectangular fin is calculated using Eq. (4) where L is the length of rectangular straight fin and it is about 0.02 m, w is the width of fin approximately 0.02 m, t is the thickness of

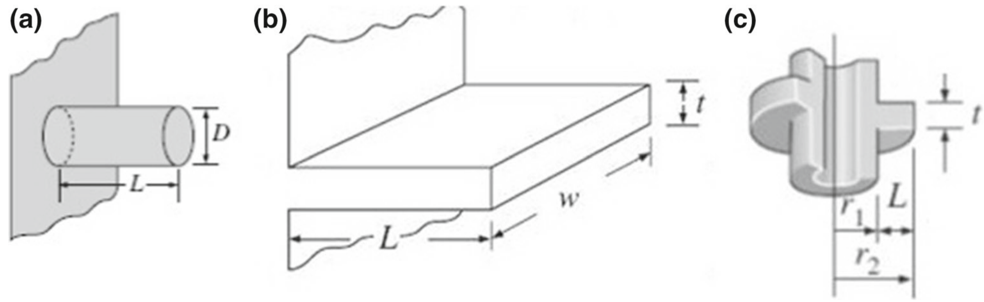

Fig. 5 fin profiles **a** pin fin, **b** rectangular fin, **c** annular fin

each rectangular fin measuring 0.002 m, T_b is encapsulated ball surface temperature, and T_∞ is PCM temperature. The heat transfer by pin fin is computed using Eq. (6) in which D refers to diameter of pin fin in m and that of by annular fin is calculated using Eq. (7) in which r_1 is the wall radius to be kept as *zero* in calculation and r_2 is the annular fin radius of 0.02 m measured from the wall surface. The effectiveness of fin is the ratio of heat transfer with using fin and heat transfer without fin is presented in Eq. (8) where A_b is the wall surface area at the base in m^2. The numerator Q_{fin} used in Eq. (8) is calculated using different Eqs. (4), (6) and (7) independently for effectiveness calculations and the terms used and its meaning in various equations remain the same. The energy cost, measured in INR per kJ, given in Eq. (9) is the ratio between INR and Q_{avg}. Average heat transfer generated for various encapsulations is indicated as Q_{avg}. INR refers to one-time capital cost of PCM with manufacture of different encapsulation materials and its fabrication.

$$m = m_p N_p \quad (1)$$

$$m_p = \rho v_p \,(0.8) \quad (2)$$

$$Q = \int_{t_i}^{t_m} m\, C_p \Delta T + m(\text{L.H}) + \int_{t_m}^{t_f} m\, C_p \Delta T \quad (3)$$

$$Q_{RF} = [hpk2w\,(L + t/2)]^{1/2} \times (T_b - T_\infty)\tanh(m_f L) \quad (4)$$

$$m_f = \sqrt{\frac{hp}{kA_c}} \quad (5)$$

$$Q_{PF} = [hpk\pi D\,(L + D/4)]^{1/2} \times (T_b - T_\infty)\tanh(m_f L) \quad (6)$$

$$Q_{AF} = \left[hpk2\pi\left((r_2 + t/2)^2 - r_1^2\right)\right]^{1/2} \times (T_b - T_\infty)\tanh(m_f L) \quad (7)$$

$$\varepsilon_{fin} = \frac{Q_{fin}}{Q_{no\,fin}} = \frac{Q_{fin}}{hA_b\,(T_b - T_\infty)} \quad (8)$$

$$\text{Energy cost} = \frac{\text{INR}}{Q_{avg}} \quad (9)$$

4 Results and Discussion

The outcome are acquired from the examination of heat transfer features of the cascaded LHTES system has been recorded during the process of charging and discharging of PCM by probating the system for more than 50 times. Though the experiment deals with different encapsulation materials (i.e., copper, brass, and stainless steel) with different fins, the optimized result states that the annular fins welded on to the encapsulations of different materials has shown highest heat transfer than with the pins fins and rectangular fins due to the higher surface area, and hence different encapsulations of different materials with annular fins are discussed in detail. The charging time and temperature values are noted with a time gap of 10 min and as the same way the discharging time with temperature are noted. During experimentation, it has been noticed that the annular finned copper-encapsulated PCM have quicker rate of heat absorption from the HTF than the charging rate with other type of fins/materials.

This experiment has been carried out with copper, brass, and stainless steel encapsulations with pin fin, annular fin, and rectangular fin. By the use of fins, melting time has been reduced by 40.3%. But among these, the annular fins are found to have higher efficiency with different encapsulations and PCM that is represented. Figures 6 and 7 represent the time taken for charging and the time taken for discharging process of D-mannitol with brass, copper, and stainless steel encapsulations with annular fins. The charging temperature initially increased gradually for 160 min and tends to be constant after the PCM has reached the melting point of 165 °C. The copper encapsulation with annular fins during charging reached a temperature of 300 °C at 170 min which happened to be faster than that of stainless steel at 320 min (obtained 265 °C) and brass at 300 min (absorbed 240 °C). During discharging, the brass to be found steady for 90 min and finally has reached 64 °C whereas the copper and stainless steel reached 60 and 97 °C, respectively at 400 min. It is found that time taken for charging is lesser than that of discharging.

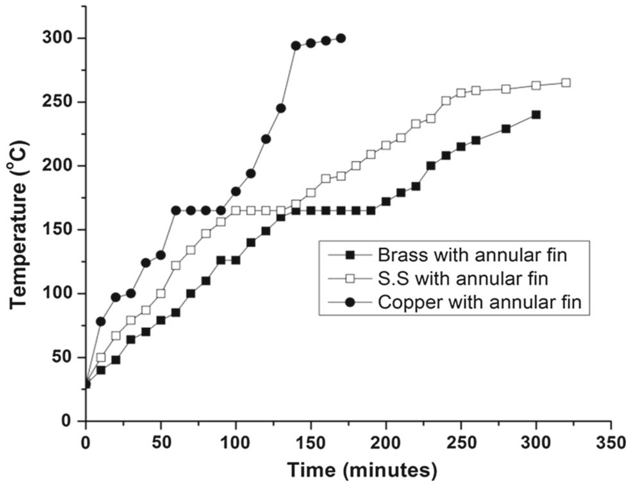

Fig. 6 Charging of D-mannitol

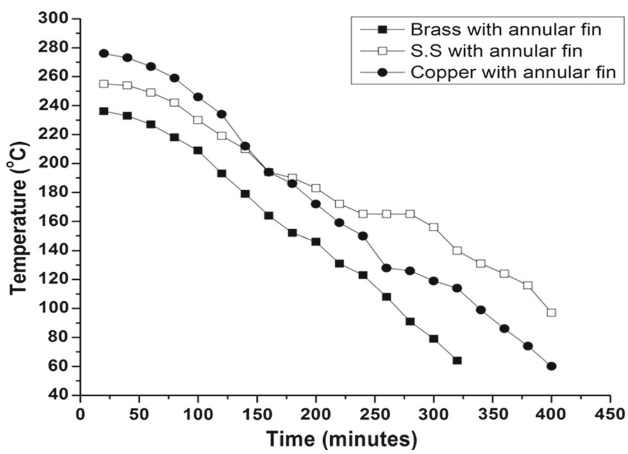

Fig. 7 Discharging of D-mannitol

Figure 8 represents the charging of D-sorbitol PCM with annular fins in copper, stainless steel, and brass encapsulations. It is found that the copper encapsulation during charging increased gradually till the PCM melting temperature of 89 °C, and finally crop up a temperature of 153 °C in 2 h. The stainless steel has arrived 129 °C in 3.6 h of time. Brass attained a temperature of 110 °C in 3.6 h. The heat gained by the brass is lesser when compared with other encapsulations as it has lower thermal conductivity [19]. Figure 9 represents the D-sorbitol during discharging. 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 min. The stainless steel has dropped to 65 °C in a time of 5 h and the copper dropped to 51 °C in a spell of 5 h.

Figure 10 represents the charging process of paraffin wax that has a melting point of 50 °C. Copper encapsulation with paraffin wax has absorbed a temperature of 119 °C at 170 min. Brass and stainless steel with annular fins had absorbed 102 and 106 °C, respectively, at 170 min each. Figure 11

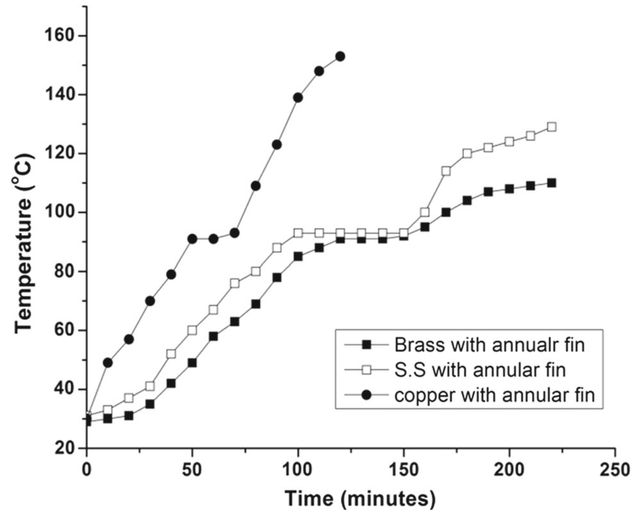

Fig. 8 Charging of D-sorbitol

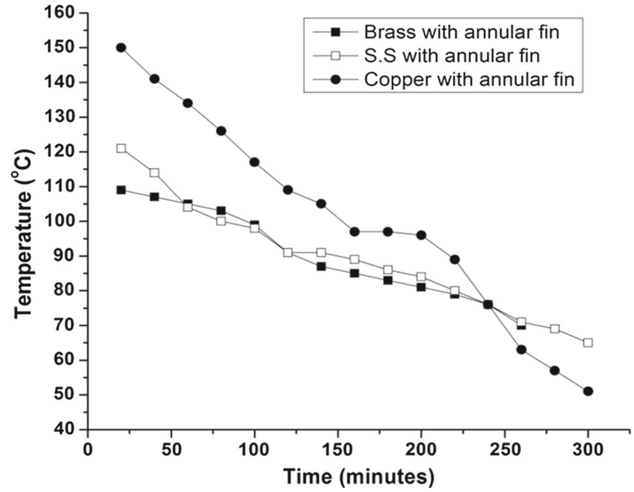

Fig. 9 Discharging of D-sorbitol

shows the discharging of paraffin wax where the copper has transferred maximum heat to the HTF and ended up at 44 °C in 190 min. Brass and stainless steel have reached at 70 °C in 150 min and 65 °C in 190 min, respectively. It is clear that the charging is earlier than the discharging due a solid boundary that is formed during solidification of PCM during discharging that prevents heat transfer in the storage system [20,21].

4.1 Heat Transfer of D-mannitol PCM

The heat transfer data have been obtained from the different encapsulations (copper, brass, and stainless steel) each with different types of fins (annular, pin, and rectangular). Figure 12 shows that the heat energy gained by D-mannitol during charging has attained a maximum heat transfer of 4146.3 kJ with the combination of copper encapsulations

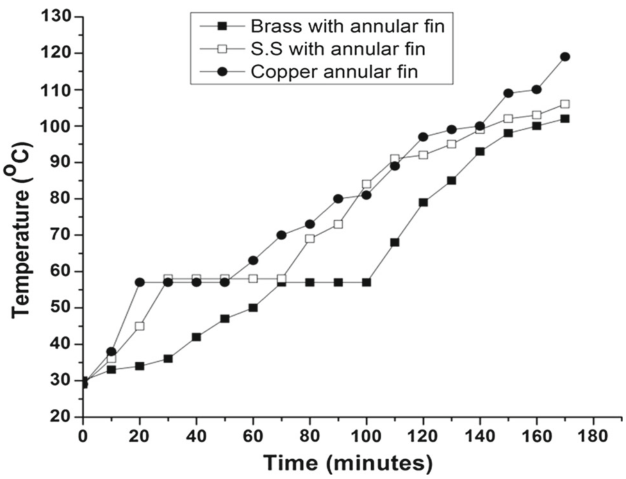

Fig. 10 Charging of paraffin wax

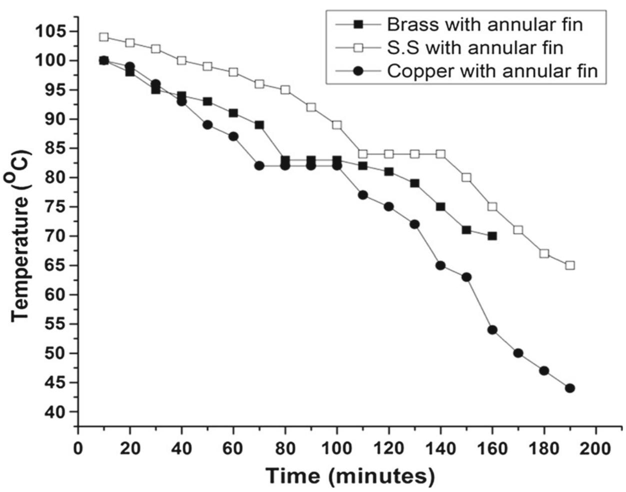

Fig. 11 Discharging of paraffin wax

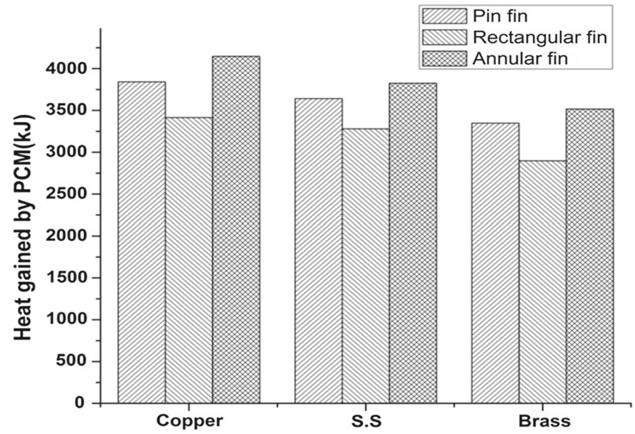

Fig. 12 Heat gained by D-mannitol

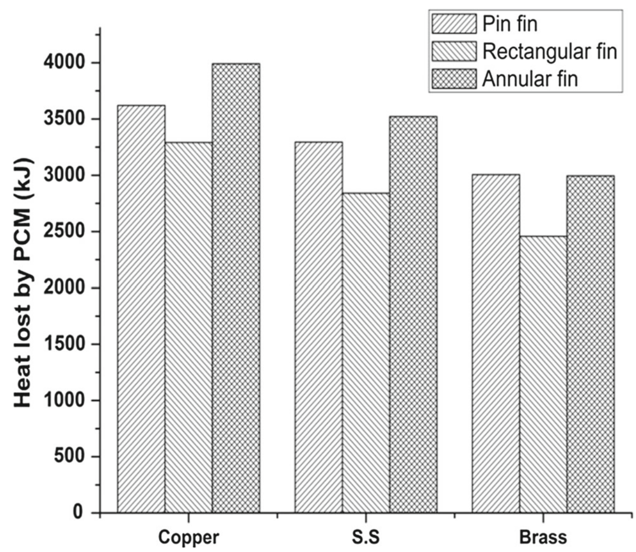

Fig. 13 Heat lost by D-mannitol

and annular fins. The lowest is noticed for the pair of brass encapsulation and rectangular fins has 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 faster rate when compared to the stainless steel and brass. The annular fin possesses a higher heat transfer rate for the reason that it has higher surface area for transfer of heat as compared with pin fin and rectangular fins. On the consideration of cost, the stainless steel 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, solidification time is reduced by 43.6%.

Figure 13 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 has a higher heat transfer during the discharge of 3991.4 kJ. The similar trend is witnessed for other encapsulations with different fins. Due to 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 [22]. 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 cost of energy, the less cost encapsulation is annular finned stainless steel balls with the price of Rs. 0.308/kJ in discharging process and Rs. 0.27/kJ in charging process.

4.2 Heat Transfer of D-sorbitol PCM

The charging rate of D-sorbitol PCM is shown in Fig. 14. During charging, copper encapsulation with annular fins has

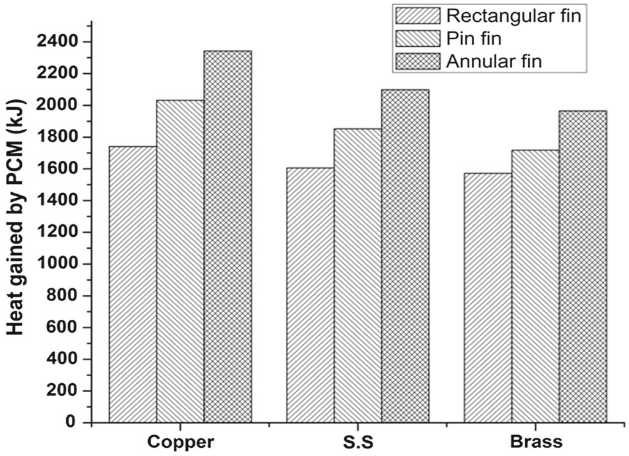

Fig. 14 Heat gained by D-sorbitol

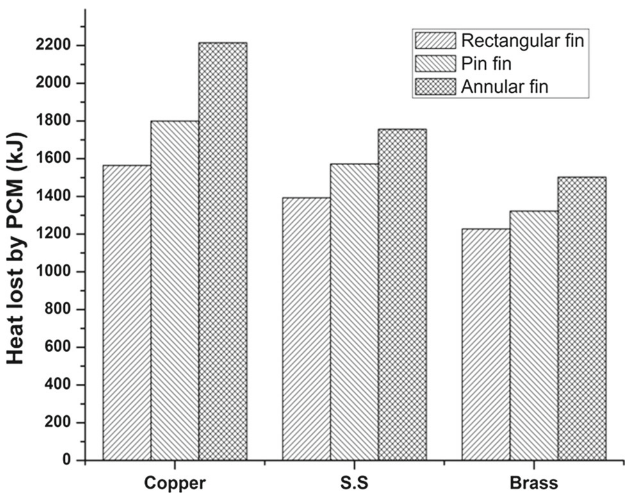

Fig. 15 Heat lost by D-sorbitol

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. Same trend has been observed in stainless steel encapsulation which has shown higher heat transfer rate with annular fins as 2098.5 kJ when compared with other types of fins.

Figure 15 represents discharging of D-sorbitol. Brass encapsulations with rectangular fins is recorded the least value of heat transfer with 1227.6 kJ due to its lower value of thermal conductivity, whereas the stainless steel with annular fins has a heat transfer of 2098.5 kJ, and the same during discharging is nearly 300 kJ lower than charging. As per energy cost, the least expensive encapsulation is annular finned stainless steel balls with the price of Rs. 0.67/kJ and Rs. 0.55/kJ during discharging and charging process, respectively.

4.3 Heat Transfer of Paraffin Wax PCM

The charging rate of paraffin wax is shown in Fig. 16. During charging, the copper-encapsulated annular finned balls have a maximum heat transfer of 2004.12 kJ, and the least is for rectangular finned brass encapsulated balls with 1309 kJ of heat transfer. The copper-encapsulated annular finned balls have the highest heat takeout of 1759 kJ during discharging process.

Figure 17 shows discharging of paraffin wax. The 1009 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 stainless steel encapsulated balls have the heat transfer of

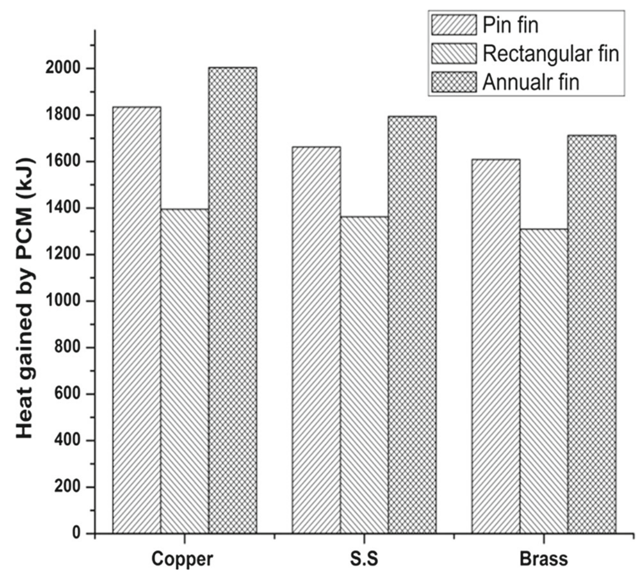

Fig. 16 Heat gained by paraffin wax

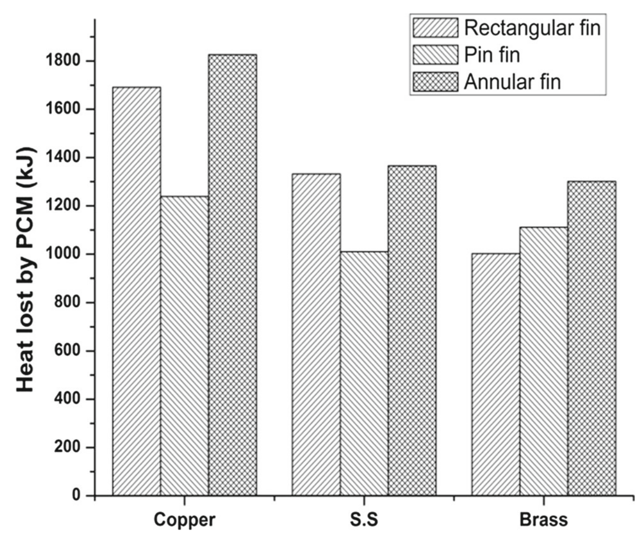

Fig. 17 Heat lost by paraffin wax

Table 3 Fin effectiveness

Fins	D-sorbitol			D-mannitol			Paraffin wax		
	Copper	Stainless steel	Brass	Copper	Stainless steel	Brass	Copper	Stainless steel	Brass
Rectangular	1.09	1.11	1.05	1.08	1.07	1.16	1.21	1.09	1.16
Pin	1.16	1.13	1.09	1.28	1.10	1.34	1.31	1.22	1.22
Annular	1.34	1.30	1.24	1.31	1.25	1.41	1.43	1.31	1.30

1794 kJ is concluded to be the most economical encapsulation the cost of Rs. 1.61/kJ and Rs. 1.72/kJ during discharging and charging, respectively.

4.4 Fin Effectiveness

Fin effectiveness has been calculated based on Eq. (8). The heat transfer rate of all encapsulated balls is calculated with and without fins. Based on the values the effectiveness of each fin namely annular fin, pin fin and rectangular fin are calculated and shown in Table 3. In the experiment, the fin effectiveness has shown variation according to the PCM and encapsulations. Fin effectiveness is calculated to be the highest of 1.43 for annular fins welded inside copper encapsulation and paraffin wax as the PCM.

5 Conclusions

The analysis of cascaded thermal energy storage system has been done with the heat transfer effect. A schematic has been developed to perform the experiment. There are three materials namely copper, brass, and stainless steel are chosen as encapsulation sphere materials. For making the heat transfer area to be increased in the three encapsulated materials three types of fins namely rectangular fins, pin fins and annular fins are welded inside the spherical balls. The welded encapsulated balls are filled with three PCM's as D-mannitol, D-sorbitol and paraffin wax and are arranged in the three tanks. During charging state, the PTC heats the fluid Therminol-66 (HTF) and is made to flow for a specific encapsulated material and for a particular type of fin keeping the PCM as D-mannitol, D-sorbitol, and paraffin wax in the three tanks. The same set up is tried for other two materials with same fin type. Also different fin combination has been tried. The above-mentioned experiments have been performed for discharging state too during the off-sunshine hours.

The results have proven that the PCM with annular finned encapsulated balls acquired higher heat transfer rate from the HTF compared with other finned balls due to higher surface area than the rectangular or pin fins. It has also been concluded that the transfer of energy is highest in copper with annular finned balls and followed by stainless steel with annular fins. However, the heat transfer rate for other types of finned encapsulated balls expose variations with change in the use of PCM. The copper-encapsulated annular finned balls have more efficient energy transfer rate of 4146.3 kJ during charging and 3991.4 kJ during discharging with D-mannitol as PCM. The most economical encapsulation is the stainless steel with annular fins during charging and discharging.

In the natural energy depleting scenario, it is always preferable to identify the system which uses the never decreasing solar energy for cooking, etc. The heat gained from solar by HTF is used in a cooking system of a school which replaced the conventional liquefied petroleum successfully.

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