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Effect of Fin Orientations in a Spherically Encapsulated Phase Change Materials for Effective Heat Transfer Enhancement

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In the recent years, phase change materials (PCM) are being used for various applications. Considering its potential in engineering sector, researchers are working in every aspect to overcome the inherent lower thermal properties of PCM. Though numerous techniques were reported in the past to augment the heat transfer in PCM based storage system, no attempt has been made on accounting the heat transfer enhancement in internally finned spherical capsule. In the present study, experiments were conducted to explore and report the effect of fin orientation (orthogonal and circumferential) on heat transfer enhancement of a PCM filled in a spherical capsule. The temperature profile of paraffin PCM filled in an orthogonal and circumferential internally finned spherical capsule of charging and discharging process of was compared respectively with no fin configuration. The inference from the results is that for the same surface area, orthogonally oriented fin resulted in appreciable reduction in total time taken for complete charging/discharging process than the circumferential fin and no fin configuration. The reduction in charging duration of 22 % and 42 % was observed in orthogonal fin orientation compared to circumferential fin and no fin configurations, respectively. Similarly, 15 % and 38 % reduction in discharging duration was observed in orthogonal fin compared to circumferential fin and no fin configurations, respectively.

1. Introduction

In a thermal energy storage (TES) system, the useful energy is transferred to the storage medium where it is transformed into internal energy and later it can be retrieved. The TES via a latent heat system using a Phase Change Material (PCM) is widely used in various low and high temperature applications because of its high latent heat storage capacity with small temperature swing, chemical properties, non-flammability and lower cost. However, one major drawback that requires greater attention in terms of the thermal performance is that most PCMs have higher internal resistance due to their low thermal conductivity. This limits the wider usage of PCMs as TES medium in versatile energy applications. Hence, heat transfer augmentation techniques are valuable for any Latent Heat Thermal Energy Storage (LHTES) applications. Many authors have studied the properties of PCM based LHTES system in heating/cooling applications, low/high temperature applications and industrial/residential applications. Gibbs and Hasnain (1995) reported that the paraffins have excellent thermal and chemical stability. The degradation probability of organic PCM is less compared to the inorganic PCM. This explains the reason behind choosing paraffin as PCM over the inorganic PCMs. Zalba et al., (2003) reported that the organic PCM (Paraffin) has poor heat transfer properties, low heat of fusion and lower density than inorganic PCM (Hydrated Salt). Farid et al., (2004) presented a review article on three aspects: PCM materials, encapsulation and applications. The authors reported that, paraffin waxes are cheap, available at different phase change temperatures and have moderate thermal energy storage density but low thermal conductivity and hence require larger surface area. Next to the selection of PCM, geometry and material of PCM encapsulation has a vital role in the heat transfer characteristics of a LHTES system. Salunkhe et al., (2012) reviewed the impact of PCM encapsulation geometry and material on the thermal

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performance of a PCM based storage system. The authors discussed the influence of PCM encapsulation geometry, thickness, material and size over the phase change process of the thermal system. Chen et al., (2000) experimentally investigated the thermal performance of a spherically encapsulated PCM during the charging process. Their results show that low inlet HTF temperature and high HTF flow rate resulted in higher storage tank efficiency.

Apart from the selection of encapsulation material, geometry, heat transfer fluid (HTF) temperature and flow rate, the thermal performance of PCM based storage system can be appreciably augmented by the introduction of fins in containers/PCMs. Several numerical studies were carried out in recent years to report the impact of adding the fins internally/externally in the thermal performance of the TES system. Ren and Chan (2016) numerically studied the impact of fin addition during the melting process of PCM by using the lattice Boltzmann method. Wang et al. (2016) investigated the PCM melting process in the sleeve tube with internal fins using FLUENT software and reported that, the most effective angle between the adjacent fins is 60 - 90°, when natural convection is considered. A few researchers have also studied the effect of fins in a TES system experimentally. Baby and Balaji (2012) experimentally studied the thermal performance of finned heat sinks filled with PCM for thermal management of portable electronic devices. Their results showed that incorporation of fins with the PCM filled heat sinks appreciably enhanced the operational performance of portable electronic device. Rathod and Banerjee (2015) reported that the heat transfer rate of a PCM can be augmented by the use of longitudinal fins. It is understood from their results that incorporation of three longitudinal fins reduced the time take for complete solidification of PCM by 43.6 %. Solomon and Velraj experimentally studied the reduction in solidification time of PCM filled in a vertical finned cylindrical unit. It is also reported in the literature that, the enhancement in the thermal performance of the TES system can be achieved by the usage of lessing rings (Velraj et al., 1998), metal matrices (Ettouney et al., 2006) and through addition of nanoparticles (Kumaresan et al., 2012).

The inference from the literature survey is that several techniques have been adopted to improve the heat transfer in PCM based storage system. Further, it is understood that spherical container possesses better ratio of heat transfer surface area to volume compared to other encapsulation geometries. To the best of authors knowledge, no attempts have been conducted yet to investigate the effect of orientation of fins placed in a spherical capsule. The main objective of the present work is to report the effect of incorporating the internal fins having different orientations (orthogonal and circumferential) on augmenting the heat transfer in spherically encapsulated PCM. The PCM temperature time history obtained from the experiments carried out with and without fin are compared and reported.

2. Experimental investigation

In the present work, charging/discharging study of three different fin configurations such as spherical container without fin, circumferentially finned spherical container and orthogonally finned spherical container are analysed and reported. Figure 1 (i), (ii) and (iii) shows the hemisphere of the without fin spherical container, circumferential finned spherical container, and orthogonal finned spherical container respectively.

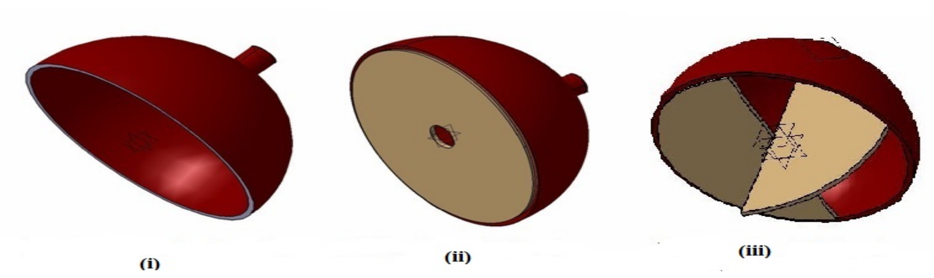

Figure 1: Cross section of Spherical container with different fin configurations i) without fin, ii) Circumferentially finned spherical container, iii) Orthogonally finned spherical container

In each capsule, the opening provided at the top is used for the filling of PCM and for inserting the vertical thermocouples. Horizontal thermocouples are inserted after drilling a hole and slightly offsetting it from the center. All these spherical capsules are made up of stainless steel and has the internal diameter of 88 mm and wall thickness of 1 mm. The finned spherical capsules have a fin surface area of 5976 mm2. The J-type thermocouple (accuracy ± 2.2 °C) is used for temperature measurement and each spherical capsule has six thermocouples and their locations are shown in Figure 2. In the figure, thermocouples T1, T2, T3 are located in radial direction from top to bottom and thermocouples T4, T5, T6 are located in axial direction from right to left.

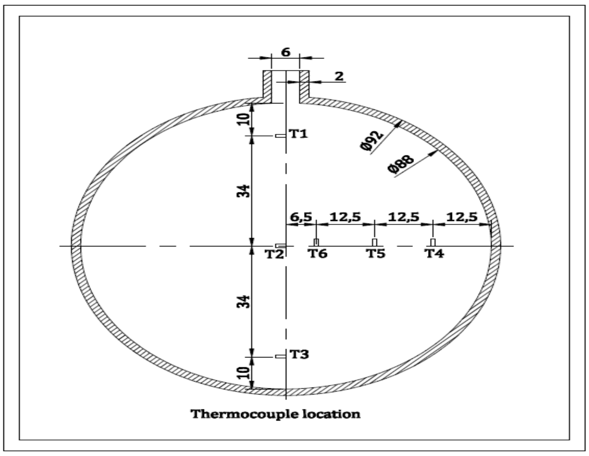

Figure 2: Positions of Thermocouples inside the spherical capsule

2.1 Experimental setup description

The experimental setup consists of a cylindrical tank, PCM encapsulated spherical capsule, stagnant Therminol 55 oil bath, electric heater (2.0 kW) controlled by thermostat and thermocouples. The PCM considered in the present study is the commercially available paraffin wax with the phase change temperature of 50~60°C. A quantity of 292 g of paraffin was filled inside the spherical capsule with the fill volume of 90%. The cylindrical tank is made up of mild steel filled with 0.053 m^3 of oil, contains a removable lid of 340x100mm dimension which is fastened with 3x8 mm bolts. Inlet and outlet valves are provided to fill and drain the HTF. A stirrer driven by a DC motor is inserted through a 4-mm drilled hole on the lid. The PCM filled spherical capsule was placed at 150 mm height from the bottom by using a 'O' ring shaped fixture. An electric coil heater of 2.0 kW was fitted at the bottom of the tank and a thermostat is fitted to control the bath temperature. The cylindrical tank was insulated by glass wool for a thickness of 50 mm and further insulation is provided by the presence of air entrapped in the gap between two concentric cylinders of dimension 260 mm x 300 mm for the inner cylinder and 340 mm x 400 mm for the outer cylinder. The thermo-physical properties of the chosen organic PCM was determined using the Mettler Toledo Differential Scanning Calorimetry (DSC) instrument at a scanning rate of 5°C/min. The various properties of selected paraffin PCM are given in Table 1.

Table 1: Thermo-physical properties of the chosen PCM

Properties	Values
Solid-Solid phase change temperature	37~50.5°C
Solid-liquid phase change temperature	50.5~63°C
Specific heat capacity (solid)	2.4 kJ/kg K
Specific heat capacity (liquid)	1.8 kJ/kg K
Latent heat (Solid)	38 kJ/kg
Latent heat (Liquid)	104.2 kJ/kg
Thermal conductivity	0.24 W/m K
Density of solid (at 15℃)	910 kg/m^3
Density of liquid (at 70℃)	790 kg/m^3

2.2 Experimental procedure

The experimentation involves two processes, melting/charging and solidification/discharging processes of the chosen PCM encapsulated in the spherical capsule. Initially, HTF at room temperature is filled inside the vessel using the provision made in the setup. The lid of the vessel is closed with help of a hinged arrangement. Initial readings of all the thermocouples are recorded in the data acquisition system. The heater is switched on and the temperature of the heater is adjusted analog controller of the heater is set to the required temperature. The melting process was carried out by maintaining a constant HTF temperature of 70℃. The heat energy from HTF is transferred to the PCM and hence the PCM temperature increases from ambient temperature of 34°C. The temperature readings are recorded until the phase change material gets completely melted. Subsequently, the discharging process was proceeded with a constant HTF temperature of 36℃ by maintaining heater under off mode condition. During the start of each solidification experimental process, the PCM in the spherical container was ensured to be in a totally melted condition at 70°C. The solidification and melting experiments were done individually for all three spherical encapsulations. The temperature data of PCM recorded during the course of phase change process at various locations along the horizontal diameter of the spherical encapsulation is presented in this paper.

3. Results & Discussion

3.1 Charging/Melting Process

The temperature history of PCM encapsulated in spherical container with no fin configuration, circumferentially finned configuration and orthogonally finned configuration during charging/melting process at the specified locations of the thermocouples is shown in Figure 3. It is seen from the Figure 3(a) that during the initial 40 minutes, the PCM temperature at all locations increases gradually (up to 50℃). During this duration, sensible heat transfer between the PCM and HTF took place. Once the latent heat process was initiated, i.e. after the 50°C, temperature of the PCM remained constant. During melting the energy is stored in the form of latent heat in PCM and it is ensured that the temperature of PCM at all locations exceeds the phase change temperature of paraffin. As expected, the rise in PCM temperature with respect to time is greater near the surface of the metallic capsule (T4) than near the centre (T2). The results show that the time taken for complete charging of PCM encapsulated with no fin configuration is 120 minutes. Figure 3(b) depicts that the temperature of PCM at all locations increases gradually for around 20 minutes and the temperature thereafter remain fairly constant after reaching the melting point of PCM. The thermocouples at the points that are in proximity to the metallic capsule (T4) record a greater increase in temperature than near the centre (T2) at each time. But the presence of fins at the horizontal axis aids the heat transfer and the temperature gradient across the peripheral and centre is small compared to without fin configuration.

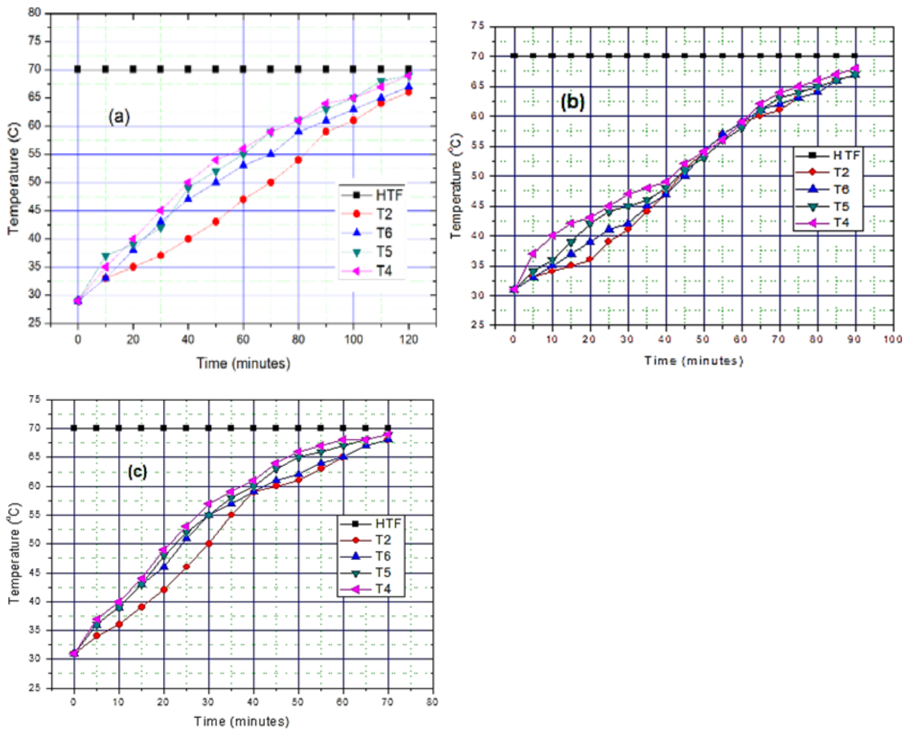

Figure 3: Temperature–time history of PCM encapsulated in (a) without fin spherical container, (b) Circumferentially finned spherical container, (c) Orthogonally finned spherical container during charging process

As time progresses, majority of the heat transfer occurs due to free convection and hence the dependence on the surface area of the spherical capsule with fin. Further, it is observed from Figure 3 (b) that the total time taken to charge the PCM encapsulated in a spherical capsule having a circumferential fin is 90 minutes. Figure 3 (c) illustrates that the PCM temperature at all locations increases gradually for around 15 minutes and the temperature thereafter remain fairly constant after reaching the melting point of PCM. It is seen from Figure 3 (c) that the slopes of the curves decrease as time increases. The rationale being the accumulation of energy changes from sensible energy initially to latent heat energy as time progresses. During this period, conduction heat transfer is predominant and once the PCM begins to melt, convection becomes the dominant mode of heat transfer. Also, it can be observed that total mass of the PCM contained in the spherical capsule melts within 70 minutes.

3.2 Discharging/Solidification Process

It is seen from Figure 4 (a) that the PCM temperature at all location decreases gradually and the PCM temperature remained constant once the latent heat is released. It can also be seen that the fall in temperature of the PCM with time is greater near the capsule wall (T4) than at the centre (T2) of the capsule. This is due to the conductive resistance of the PCM.

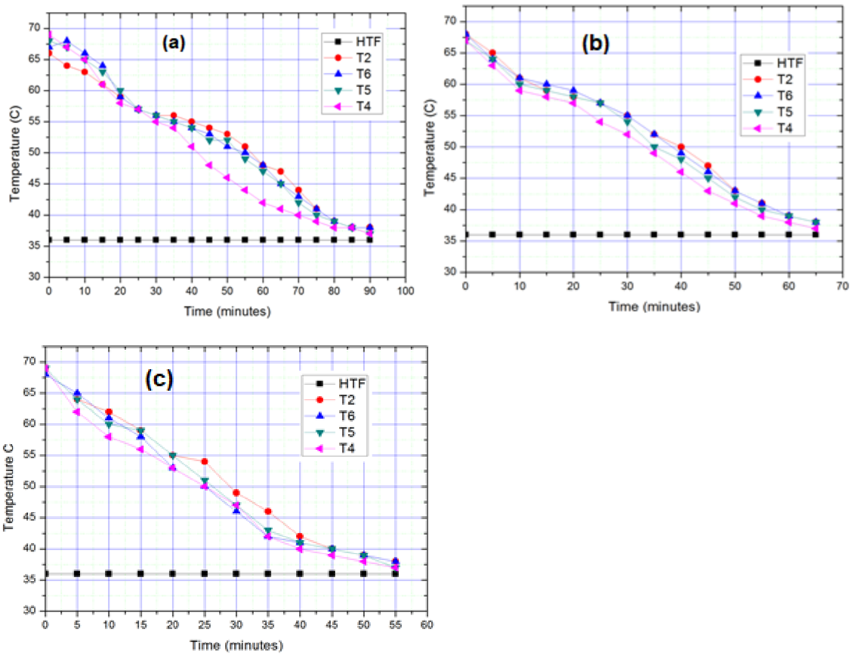

Figure 4: Temperature–time history of PCM encapsulated in (a) without fin spherical container, (b) Circumferentially finned spherical container, (c) Orthogonally finned spherical container during discharging process

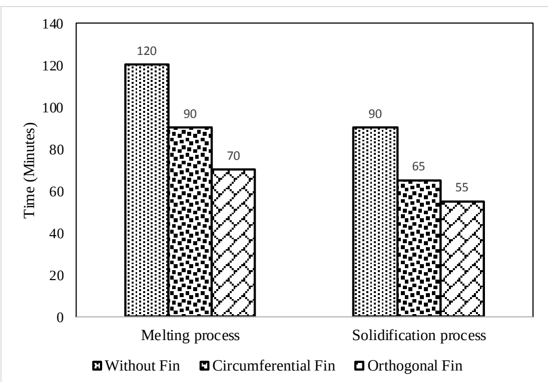

Figure 5: Comparison of melting and solidification duration of different finned spherical capsules

It is also seen from Figure 4 (a) that the total duration period taken for the discharging of PCM in the spherical capsule having no fin is 90 minutes. Figure 4 (b) shows that the time taken for the complete discharging of

PCM encapsulated in the spherical capsule with circumferential fin configuration is 65 minutes. The inference from Figure 4 (b) that the curves make sense because initially the slope is high, but then it levels off due to phase change process around 57°C. The fall in PCM temperature with respect to time is greater near the surface of the wall capsule (T4) than near the centre (T2) of the capsule similar to without fin configurations. In the case of orthogonally finned spherical container, the PCM got completely in a time duration of 55 minutes. Figure 4 (c) shows that slope of the graph in the initial stages is high then very less during phase change process and further slowly increases as time progresses. As convection is the mode of heat transfer, the pattern of solidification depends on the surface area of contact. Figure 5 compares the total time taken for charging and discharging process of PCM encapsulated in spherical container with different orientation. The inference from Figure 5 is that the time duration taken for complete charging of PCM was higher compared to discharging process. The prolonged duration during the charging process is due to the inclusion of sensible heat energy.

4. Conclusion

The present work compares the phase change behavior of a paraffin PCM encapsulated in a spherical capsule with different fin configurations. The time taken by the chosen PCM for complete charging and discharging process with no fin, circumferential fin and orthogonal fin configuration were recorded and analyzed. The main inference from the results is that the incorporation of fin augments the heat transfer between the HTF and PCM. The total time duration for complete charging/melting of the PCM in the orthogonal fin configuration was 22 % and 42 % lesser when compared to circumferential fin and no fin configurations, respectively. Similarly, the time taken for complete discharging of PCM in orthogonal fin configuration reduced up to 15 % and 38 % when compared to circumferential fin and no fin configurations, respectively. Further, it is construed from the experiments that for the design of effective latent heat thermal energy storage system, internal fin with orthogonal orientation is recommended over circumferential fin configuration.

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