Solidification characteristics of phase change material in a rectangular finned spherical capsule

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Abstract. This work investigates the solidification characteristics of deionized water in a stainless steel spherical capsule fitted with rectangular fins immersed in a constant temperature bath. Experiments are carried at three different bath temperatures (-6, -9, and -12°C). Four rectangular fins of size 20.6mm length, width 10.6 mm, and 1mm thick made of copper are fixed on the inner surface of the spherical capsule. Results indicated that fin had a significant reduction in total solidification time. A reduction of 13% in total solidification duration is achieved at -9 and -12°C. However a decrease of 87-90% in freezing duration is observed while considering 50% of PCM mass at bath temperatures of -6°C, -9°C, and -12°C. It is concluded that fins can be employed in CTES systems at lower bath temperatures to achieve expected energy savings of 9-12% under the partial charging method.

1. Introduction

CTES (cold thermal energy storage) systems are widely used in various sectors like building air conditioning, pharma, process industries, commercial establishments, etc where the high demand occurs for a shorter time frame. CTES systems based on phase change material (PCM) find a broader interest among researchers because of their higher storage capacity and isothermal behavior [1-3]. Investigators have shown much interest in the various thermal parameters related to material encapsulation size, geometry, PCM used based on application, the inclusion of high conductivity material in the PCM, inclusion of extended surfaces, etc. Among the encapsulation, spherical geometry is preferred over the other geometries due to its high heat transfer surface area to volume ratio [4]. Water is the most reliable option for cold storage applications due to its high latent heat, availability, high thermal conductivity, etc. Despite its advantages, the supercooling problem is encountered with water. This supercooling severely affects the performance of refrigeration systems employed in CTES systems. Cheralathan et al [5] observed a 1°C reduction in the temperature of the evaporator resulting in a 3-4% increase in specific energy consumption (SEC) and a 1 °C reduction in the temperature of the condenser resulting in a 2-3% reduction in SEC while investigating the PCM based CTES systems. Chandrasekaran et al [6] analyzed the freezing characteristics of water used as PCM in spherical capsules of different sizes and reported that with the right temperature difference larger capsules can be employed for the efficient design of CTES systems while considering 75% of
of CTES systems, researchers had tried experimental trials with pin fins using water as PCM. Jia et al. [10] studied the freezing characteristics of water in a spherical capsule by brazing process. The fins are uniformly fixed to the capsule. The stability of nanoparticles is a major concern that settles down on a longer run. However, the use of fins avoids the settlement issues. It has been observed from the literature that the usage of fins in a spherical capsule improved the solidification rate and also it was found that few researchers had tried experimental trials with pin fins using water as PCM. Hence for the development of energy efficient CTES systems, an attempt has been made to investigate the solidification characteristics of water PCM in a rectangular finned capsule at various bath temperatures.

2. Experimentation

Figure 1 shows the outline representation of the experimental setup. The setup includes a vapor-compression refrigeration unit, a constant temperature bath with proper insulation, a PDTC (proportionate differential temperature controller), and a data acquisition system (Keysight 34972A) with sensors for temperature measurement. The cylindrical constant temperature bath consists of stainless steel material (volume 0.05m³) and is propped with 50 mm thick polyurethane foam. The bath is filled with a mixture of 70% water and 30% ethylene glycol by weight. The required bath temperature is maintained by employing a refrigeration unit and a 3kW heater each. The bath temperature in the tank is kept constant utilizing a mechanical stirrer powered by a 9W electric motor mounted on top of the tank and an 18W submersible pump at the bottom of the tank. For the current research the spherical capsule made of stainless material (73mm ID, 75mm OD) is selected. Rectangular fin of size 20.6mm x10.6mm x1mm and two spherical balls of the same size are used for the current work. One capsule is fitted with four fins and the other without a fin. Fins are fixed to the spherical capsule by brazing process. The fins are uniformly located in the radial direction with an inclusive angle of 90° between them. Fins placement and dimensions are shown in Figure 2. The capsules are filled up to 90% volume using standard 5ml and 100ml volumetric flasks (Class B). The temperature variation of PCM is measured using four RTDs (PT 100). One RTD is positioned at the center of the capsule and the other RTDs are placed at radial distances of 17mm, 23mm, and 29mm from the center of the capsule (Refer fig.2). These four positions, estimated from the capsule top, relate
to 100 %, 90 %, 75 %, and 50 % of the annulus volume of the sphere. Therefore, the associated mass is claimed to be solidified when the freezing front arrives at those locations.

All tests are performed at three separate bath temperatures of -6°C, -9°C, and -12°C for both the capsules. Initially, the appropriate bath temperature is achieved via a refrigeration device. The spherical balls are submerged in the bath at a fixed depth to reach the desired temperature. The temperature changes in the PCM are constantly recorded using a data acquisition system. The tests are persisted until the PCM temperature hits the bath temperature at the capsule core. The uncertainties associated with the quantities measured and derived during the experiment are shown in Table 1 using Moffat’s method [15].

Figure 1. Experimental Setup.

Figure 2. Fin dimensions and locations of RTDs in spherical capsule.
Table 1. Uncertainty analysis.

| Type      | Quantities       | Uncertainties |
|-----------|------------------|---------------|
| Measured  | Diameter         | ± 0.02mm      |
|           | Latent heat      | ± 6 kJ/kg     |
|           | Temperature      | ±0.1°C        |
|           | Mass             | ± 0.002g      |
|           | Volume (100ml)   | ± 0.002ml     |
| Derived   | Average Heat flux| ± 1.9%        |

3. Results and Discussion

3.1 Temperature vs time at the center of the capsule

Figure 3 (a to c) represents the temperature vs time plot at the center of the capsule maintained at bath temperatures of -6°C, -9°C, and -12°C respectively.

![Figure 3](image)

Figure 3. Temperature vs time plot of the PCM at the capsule’s center with and without fins at (a) -6°C, (b) -9°C and (c) -12°C.
From Figure 3(a to c) it is observed that the capsule without fins showed a maximum subcooling of 3.86°C and the subcooling duration was 6.5 minutes. Similarly, at -9°C, the capsule without fin showed a maximum subcooling of 2.1°C. The capsule with fin (finned capsule) eliminated the subcooling at both the bath temperatures of -6°C and -9°C. The onset of solidification for spherical capsule without fin is found to be 15 min and for finned capsules, it was found to be 8 minutes at -6°C. Similarly, at -9°C and -12°C bath temperature, the onset of solidification for the capsule without fin was found to be 8.5 and 7.5 minutes respectively. For the finned capsule, it was found to be 7 and 6 minutes respectively. The above results imply that the fin has a significant effect in advancing the onset of solidification.

Solidification time for the capsule without fin is found to be 101.5, 70, and 53 minutes at -6°C, -9°C, and -12°C respectively. For the finned capsule, the solidification time is observed to be 92, 60.5, and 46 minutes at -6°C, -9°C, and -12°C respectively. Hence, with the addition of fins, the total solidification time is reduced considerably at all bath temperatures. However, the maximum reduction in total solidification time of 13% is achieved at a bath temperature of -9°C and -12°C. Jia et al.[10] have found a related trend in a capsule of stainless steel for PCM composite material.

### 3.2 Solidified Mass Fraction

Figure 4 shows the freezing duration versus frozen fraction for different HTF temperatures (-6°C, -9°C and -12°C).

![Graph](https://via.placeholder.com/150)

**Figure 4.** Freezing duration vs solidified mass at HTF temperatures of (a) -6°C, (b) -9°C and (c) -12°C.

The time taken by the freeze front to stretch 50% of PCM mass in a spherical capsule without fins is 32.5, 21.5 and 10 minutes at -6°C, -9°C and -12°C respectively. Similarly, for the capsule with fin the
time taken by the freeze front to attain 50% of PCM mass is 11.5, 8 and 4.5 minutes at -6°C, -9°C, and -12°C respectively. The time taken by the freeze front to attain 75% of PCM mass in a spherical capsule without fin is 54.5, 37 and 23 minutes and for the capsule with fins it is 30, 19, 5 and 13.5 minutes at -6°C, -9°C and -12°C respectively. Similarly for the freeze front to attain 90% of PCM mass the time taken by the capsule without fins and with fins is 77, 55.5 and 37 and 55.5, 36.5, and 26 minutes at -6°C, -9°C and -12°C respectively.

![Graph](image1)

**Figure 5.** Heat flux vs solidified mass at HTF temperatures of (a) -6°C, (b) -9°C and (c) -12°C.

From the Fig.4 (a to c) it is noticed that accelerated charging prevailed till 50% of PCM mass and subsequently drop in solidification rate is observed at all bath temperatures. Chandrasekaran et al [16, 17] reported that 50% of PCM mass in an LDPE capsule is solidified at 25% of the total duration using water as PCM and NFPCM (Nanofluid PCM - copper oxide and multiwall carbon tube). Comparing with the present work, 50% of cold energy is stored within 10-13% of the overall charging period at -6°C to -12°C. This result clearly indicates that by incorporating fins in the capsule cold energy (50% PCM mass) can be stored at a quicker time. At -9°C bath temperature, the time taken for the 90% of PCM mass to be solidified was 55.5 minutes for the capsule without fin. This same time of 55.5 min was achieved by the finned capsule for the 90% of the PCM mass to be solidified at a bath temperature of -6°C. Similarly at -12°C bath temperature, the time taken for the 90% of PCM mass solidified was 37 minutes for the capsule
without fin. This same time of 37 minutes was observed by the finned capsule at -9°C. Thus at a bath temperature of -6°C and -9°C augmented solidification rate was achieved by the finned capsule.

It was therefore concluded that, by adding fins the evaporator temperature can be operated at higher evaporator temperature. This increase in the evaporator temperature decreases the specific power consumption in the range of 3- 4% [5]. Thus it can be concluded that energy savings of approximately 9- 12% would be possible for the efficient operation of CTES chiller systems under partial charging mode.

3.3 Time-averaged heat flux
The time-averaged heat flux ($\overline{q}$) is evaluated using the following Equation

$$\overline{q} = \frac{m_i \times \lambda}{A_i \times \Delta t}$$

where, $m_i$ represents the mass of solidified PCM (kg), $i$ represents the radial positions (whose values of 1,2,3 and 4 corresponds to the 100%, 90%, 75% and 50% of solidified mass), $A_i$ is the surface area of the capsule, $\Delta t$ is the time taken for the freeze front to arrive at the $i^{th}$ location and $\lambda$-latent heat of PCM used(for water it is $\approx$333 kJ/kg).

From the Fig.5(a to c) it is noticed that the surface heat flux varies from 976 W/m$^2$ to 625 W/m$^2$ for the un-finned capsule when the bath temperature is kept at -6°C and for finned capsule, the heat flux fluctuated from 2667 W/m$^2$ to 667 W/m$^2$ at the same bath temperature. At bath temperature of -9°C, the heat flux varied from 1427 to 876 W/m$^2$ for un-finned capsule, and for finned capsule, the heat flux fluctuated from 3834 to 1014 W/m$^2$. Similarly at -12°C the heat flux varied from 3171 to 1197 W/m$^2$ for un-finned capsule and for finned capsule the heat flux fluctuated from 6816 to 1410 W/m$^2$. Thus it is found from the above findings that the heat flux for the finned capsule is higher than the unfinned capsule.

4. Conclusions
The following conclusion was drawn from the experimental results.

1. The addition of fins to the surface has advanced the onset of solidification.
2. A maximum reduction of 13% in total solidification duration is achieved at a bath temperature of -9°C and -12°C.
3. By adding fins the evaporator temperature can be operated at lower temperature potential which in turn reduces the specific power consumption. Thus a probable energy savings of 9-12% would be possible for the CTES chiller systems operated under partial charging mode.

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