Comparison of freezing characteristics of phasechange material in metallic and low density polyethylene spherical capsules

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Abstract. The purpose of this study is to analyze the impact of the material of the spherical capsule on the solidification characteristics of deionized water as the phase change material (PCM) filled with 90% of its fill volume. The experiment was performed with two same sized balls measuring 86mm diameter made of LDPE (Low density polyethylene) and Stainless Steel kept at distinct bath temperatures (-6, -9 and -12°C). It was noticed that the material of the spherical capsule had an influence on the solidification characteristics of the PCM. The Stainless Steel capsule froze significantly faster than the LDPE capsule for all the mass fractions. This effect was prominent in the lower mass fraction of 50%. It was also inferred that the percentage by which the Stainless Steel capsule froze faster than the LDPE capsule escalated by 32.63%, 40.90% and 43.18% at higher potential temperatures for 50% mass fraction.

1. Introduction
The peak demand of HVAC (Heat ventilation and air conditioning) and refrigeration systems for various industrial applications where large amounts of short duration loads are frequently required, such as building cooling, food processing, and industrial process cooling can be effectively reduced by the introduction of an energy reservoir. Here the potential heat is stored in the reservoir, which is then converted to useful energy in the future. Amongst the existing cold storage systems, the phase change material (PCM) based systems is widely popular due to its exponentially increased energy consumption. The PCM possesses high storage density, isothermal conditions and making it preferential for the storage of cool energy. The PCM is encapsulated in order to increase the heat transfer area, reduce the PCM reactivity towards the outside environment, and control the changes in the storage material volumes. Among all the available geometries, spherical capsules are employed in the experiment as it possesses least surface area for a given volume, thus boosting its heat containing capacity. Referring to previous literature survey by Chandrasekaran et al.[1] it was noted that at lower temperature driving potential, the capsule size had a significant impact on subcooling and was completely eliminated for all capsule sizes at higher temperature potential. Chandrasekaran et al.[2] reported that increase in fill volume had a significant effect in reducing the subcooling and at higher temperature potential the heat flux increased in multifolds during solidification of 50% of the PCM mass. It was also reported by Cheralathan et al.[3] that increase in porosity leads to an enhanced rate of energy storage.
The unsteady behavior of a phase change material based cool thermal energy storage had been investigated by Liwu Fan et al [4]. Different methods of heat transfer enhancement techniques, encapsulation of phase change materials in Thermal Energy Storage System and solar system were covered by Kanimozhi et al [5]. The work carried out by different researchers in the heat transfer enhancement techniques in thermal energy storage system and solidification of PCM were reviewed by Aneesh et al [6]. Ismail et al [7] also observed that increasing the size of the spherical capsule leads to a delay in time for full capsule solidification. The effect of the geometry and the Jacob number on the solidification end-time was examined by Barba et al [8]. Between different geometrical configurations of the PCM, it is observed that for small spherical capsules with high Jacob numbers and thermal conductivity the shortest duration for total solidification is matched. Vikram et al[9] concluded that the accelerated charging mode prevails in all PCM tests, but in decelerated mode, approximately 6% of the volume is solidified. Zou et al. [10] concluded that CaCl₂•6H₂O composite PCM comprising 15 wt. % urea and 5.0 w.% ethanol had appreciable performance in air conditioning applications with a temperature drop of 11.62 °C and an enthalpy of 127.2 J / g for phase transition. The enhancement of heat transfer rate due to addition of surfactant in corresponding oil based PCMs were discussed by Irsyd M et al [11]. Azzouz K et al [12] summarized that PCM method also demonstrated that the introduction of thermal inertia globally improves the flow of heat from the evaporator and enables a higher evaporation rate, which enhances the device's energy performance. Thus from the literature review it is noticed that very few work has been reported on comparison of solidification characteristics between LDPE and stainless steel capsules of higher diameters. Therefore an attempt has been made to compare the solidification characteristics between two capsules.

2. Experimentation

![Figure 1. Schematic diagram of the experimental setup.](image)

The figure 1 depicts an outline representation of the experimental setup. Two Spherical capsules of 86mm inner diameter and 1mm thickness made of stainless steel and LDPE (figure.2) are immersed in a steel bath holding a capacity of 0.015 m³ filled with secondary coolant (ethylene glycol + water...
The experiment is conducted at various bath temperatures of -6°C, -9°C and -12°C. The capsules are filled with deionized water as PCM upto 90% of their fill volume. One RTD (Resistance temperature detector) is placed at the centre and the other RTDs are placed radially at a distance of 19.6mm, 26.7mm and 33.7mm from the centre of the capsule (figure 3). These distances correspond to the radii of 50%, 75%, 90% and 100% of the mass fraction frozen from the surface of the capsule. Primitively the ice formation initiates over the inner surface of the capsule and gradually tends to freeze towards the centre of the capsule. The solidification time is then studied with the help of the data transmitted by the RTD to the data logger. Further, various studies and comparisons were made on the effect on the frozen mass fraction with respect to time as well as the heat flux through the capsule with respect to time.

**Figure 2.** Image of 88mm LDPE and Stainless steel capsules.

**Figure 3.** Various RTD positions in the capsule.
3. Results and Discussion

3.1. Temperature–time record of the PCM

From figure 4 (a-c) it is noticed that both LDPE and metallic capsules drop temperature faster for the initial 30 degrees than the latter at all three operating bath temperatures. The following graphs report that the onset of cooling for both LDPE and Stainless steel capsule occur at around 24 minutes for -6°C, 21 minutes for -9°C and 18.5 minutes for -12°C surrounding bath temperature. Sub-cooling which considered to be a major problem with deionized water as PCM is reported to be eliminated with employment of larger size capsules. However the offset curve dipped faster for the stainless steel capsule than the LDPE capsule. This can be attributed to stainless steels relatively immense thermal conductivity. Chen et al.[14] reported a higher likelihood of nucleation with an increase in capsule diameter (contains greater PCM volume). This raises the nucleation temperature as the capsule diameter increases, which in effect contributes to a decrease of the sub cooling phenomenon. The metallic capsule had attained double the potential temperature of the LDPE capsule after 2 hours of the commencement of the solidification process but completely solidified only 15 minutes before the LDPE capsule. The complete solidification time for LDPE and stainless steel capsule were found to be 172, 169.5 minutes for -6°C; 112.5, 109 minutes for -9°C and 85, 85.5 minutes for -12°C. This shows us that the stainless steel capsule is optimum in applications of partial-charging/discharging in cool thermal energy storage (CTES) systems.

![Temperature-time record of the PCM](image)

**Figure 4(a).** Freezing time vs temperature at -6°C.
3.2. Solidified mass fraction

The study on the mass fraction of the capsules with respect to time as depicted graphically in figure 5 (a-c) yielded interesting results. The Stainless Steel capsule froze significantly faster than the LDPE capsule for all the mass fractions. This effect was prominent in the lower mass fractions and diminished at the higher mass fractions due to the thermal insulation of densely formed ice. However, 50% solidification time for LDPE and stainless steel capsule were found to be 47.5, 32 minutes for -6°C; 33, 19.5 minutes for -9°C and 22, 12.5 minutes for -12°C respectively. Similarly, 75% solidification time for LDPE and stainless steel capsule were found to be 85.5, 63 minutes for -6°C; 56, 41 minutes for -9°C and 43, 31.5 minutes for 12°C respectively. And 90% solidification time for LDPE and stainless steel capsule were found to be 130, 98.5 minutes for -6°C; 83.5, 63 minutes for -
9°C and 65.5, 49 minutes for -12°C respectively. It was also inferred that the percentage by which the Stainless Steel capsule froze faster than the LDPE capsule escalated by 32.63%, 40.90% and 43.18% at -6°C, -9°C and -12°C respectively for 50% mass fraction. While it was noteworthy for the remaining mass fractions. From this we can draw a conclusion that the initial 50% of the PCM is frozen much faster than the latter 50% for the both the capsules. The stainless steel capsule specifically, among the two, froze at an appreciably higher rate for the former 50% of the mass fraction while being almost equal for the latter. Ismail et al.[13] stated that capsules made of materials of higher conductivity freeze faster than those made of materials of lower thermal conductivity.

![Figure 5(a). Freezing time vs. Frozen fraction at -6°C.](image1)

![Figure 5(b). Freezing time vs. Frozen fraction at -9°C.](image2)
3.3. Heat flux

The averaged surface heat flux with respect to time for various RTD positions was determined using the relation discussed in [1];

\[ \overline{q} = \frac{m_i \times \lambda}{A_s \times \Delta t} \]  

(1)

Where, ‘m’ represents mass of the PCM frozen (kg). The values of ‘i’ referring to 1, 2, 3, 4 are 50%, 75%, 90% and 100% of the frozen mass. \( \lambda \) - latent heat of PCM (333 ± 6 kJ/kg); ‘A_s’ - surface area of the capsule (m²), ‘\( \Delta t \)’ is the freezing front time needed to reach the ‘i’th position.

Figure 6(a-c) depicts graphical representation of heat flux versus frozen fraction history of deionized water as PCM. At bath temperature of -6°C, the heat flux varied from 773 to 427 W/m² for LDPE and 1150 to 434 W/m² for stainless steel capsule. Similarly under -9°C operating bath temperature, the heat flux ranged from 1113 to 653 W/m² for LDPE and 1887 to 675 W/m² for stainless steel capsule. And under -12°C bath temperature the heat flux ranges from 1669 to 864 W/m² for LDPE and 2944 to 903 W/m² for stainless steel capsule. It it evident that the heat flux at 50% of the mass fraction is almost twice as much as the heat flux at 100% of the mass fraction (centre) for LDPE capsule. However, the heat flux of stainless steel capsule at 50% of the mass fraction is almost thrice as much as the heat flux at 100% of the mass fraction. It was also noted that the heat flux ratio for 50% of the mass fraction for stainless steel capsule was about 1.5 times that of LDPE capsule. This shows us that stainless steel capsule is most optimally preferred over LDPE capsule in applications where partial charging of 50% mass of the PCM is necessary in CTES systems.
Figure 6(a). Heat flux vs. Frozen fraction at -6°C.

Figure 6(b). Heat flux vs. Frozen fraction at -9°C.

Figure 6(c). Heat flux vs. Frozen fraction at -12°C.
4. Conclusions
The following conclusions were drawn from the experimental results. Collectively from the above results we can summarize that the PCM in stainless steel capsule freezes faster than that in LDPE capsule. This effect is more predominant in the initial 50% of the mass fraction than the latter 50% of the mass faction. Further it can be inferred that the stainless steel capsule is subjected to more heat flux than the LDPE capsule, especially for the initial 50% of the mass fraction. Thus it can be concluded that the employment of stainless steel capsule would rather be ideal than an LDPE capsule of the same size in applications of ‘partial charging/partial discharging’ in order to achieve optimum efficiency of CTES Systems.

5. References
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