Solidification characteristics of deionized water in a spherical capsule using bio-additives: An experimental study

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Abstract. The present work investigates the solidification activity of deionized water as phase change material dispersed with various bio-additives such as gelatin and corn starch in a spherical capsule immersed in a constant temperature bath. Tests are carried out at two different bath temperatures (-6°C and -9°C) and it was noted that deionized water undergoes a subcooling of -3.8°C at a bath temperature of -6°C. However, no subcooling is reported for the deionized water with a concentration of 0.1wt.% for both the additives. A maximum reduction of 51% and 45% in total solidification time is observed for gelatin solution at bath temperatures of -6°C and -9°C respectively. A significant reduction of 82% is observed while considering 50% of phase change material(PCM) mass at a bath temperature of -6°C. Hence, it is concluded that reducing subcooling and partial charging of water-based PCMs would help to increase the Cool Thermal Energy Storage (CTES) system's energy efficiency.

Keywords: Phase change material, deionized water, solidification, spherical capsule, bio-additives, partial charging and discharging

1. Introduction
In various industries such as building air conditioning, pharmaceuticals, process industries, industrial establishments, etc., CTES (cold thermal energy storage) systems are commonly used where growing demands exist for a shorter period. Systems based on phase change material (PCM) find a desire in researchers because of their higher storage capacity to stay warm or cool at room temperature and their isothermal features[1-3]. Researchers have shown a great deal of interest in the various thermal parameters related to material encapsulation size[4], geometry, application-based PCMs, dispersion of nucleating agents[5], nano particles[6], and integration of fins[7] in the containers. Spherical geometry produces the highest heat transfer surface area to volume ratio[8]. For cold storage applications, water is the most reliable choice because of its high latent heat, availability, high thermal conductivity, etc. The supercooling problem is experienced with water despite its benefits. The presence of subcooling in water, on the other side, slows the onset of solidification and necessitates a lower evaporator operating temperature in the chiller system, resulting in a 3 to 4% rise in specific energy usage[9]. The performance of the cooling systems used in CTES systems is seriously impaired by this supercooling. Various techniques, such as the incorporation of nucleating agents, nanoparticles, micro/nanoencapsulation, and the insertion of fins, have been attempted by researchers with the goal of removing PCM subcooling. The usage of a nucleating agent in combination with the PCM is a
popular way to minimize subcooling, and these may be solid particles or crystals that allow the PCMs to crystallize. Chen et al. [10] research shows the function of various nucleating agents in enhancing the likelihood of water nucleation and documented the effects of mass of the various nucleating agents (e.g. iron ore, iron chip, sandy river, and silvers) on the onset of nucleation. Milon and Braga[11] reported that there was no noticeable sub-cooling of water at lower bath temperatures. They highlighted the major role of the temperature difference between the heat transfer fluid and the PCM to trigger the nucleation. The solidification of water have been studied with the dispersal of different nanoparticles such as alumina [12], silicon dioxide [13], titanium oxide [14], graphene nanoplatelets (GNP) [15], and multiwall carbon nanotubes [16]. It is concluded from the literature review that the addition of nucleating agents is found to be more helpful towards the mitigation of subcooling in water PCM. Thus, this study attempts to see the effect of additives dispersed with deionized water on solidification characteristics.

2. Experimentation

The experimental setup details and experimentation are similar to those explained in the author’s previously published article [7].

![Figure 1. Experimental setup](image)

The Phase Change Material solution is prepared by adding the specified additive compounds to deionized water. The additives used in the given study were Gelatine and corn starch. The additive solutions are prepared are explained in the following way. The additive is taken using a spatula and is weighed on a weighing scale. One gram of each of gelatine and corn starch is added to one liter (1000 ml) of water. The additive solution is homogenized by stirring for about ten minutes for gelatine and corn starch. Further, the additive solutions were subjected to autoclaving to prevent the growth of bacteria. Autoclaving is the process of heating a solution at 121 °C for 25 minutes. This process furthers the homogenizing of the solutions and kills any residual bacteria.
The 0.1 \% weight solution of Gelatine mixed with deionized water was taken in an LDPE capsule of 74mm Outer Diameter filled up to 95 \% of its volume. Three two-wire RTDs of the type PT 100 were taken and placed radially inside the capsule. The RTDs were placed so that the solidification could be observed in three zones, viz. 50 \%, 75 \%, and 100 \% of the PCM mass inside the capsule. The experiments were conducted at bath temperatures of -6°C and -9°C. The experiments were started at room temperature and the experiment was stopped after total solidification was achieved or when the PCM at the center of the capsule had attained the steady temperature state with the bath temperature.

3. Results and Discussion

3.1. Temperature –time record of the PCM

Fig.2(a-b) refers to the PCM's temperature history at the centre of the capsule with and without additives at bath temperatures of -6°C and -9°C. The capsules filled with deionized water without additives showed a subcooling of -3.8 °C at a bath temperature of -6°C. However, the capsules filled with bio additive solution of gelatin and corn starch did not yield subcooling phenomenon at the same bath temperature. Similarly, at a bath temperature of -9°C, no subcooling is reported by the capsules filled with and without bio additive PCM.

![Figure 2(a). Temperature -time record of the PCM at -6°C](image)

The subcooling phenomenon is not reported in the capsules filled with bio-additives. This may be because the gelatin and corn starch solution's increased thermophysical properties mixed with the base PCM paved the way for the release of subcooled energy at a bath temperature of -6°C. The onset of solidification is found to be advanced with both additives. The onset is improved by 14\% and 38\% with gelatin solution and corn starch solution compared to the base PCM at -6°C. Further, the onset is improved by 15\% and 42\% for both the solutions at a bath temperature of -9°C. The time taken for complete solidification is decreased by 51\% for both the additives compared to the base PCM at the surrounding temperature of -6°C. However, at a temperature of -9°C the % reduction in solidification time is found to be 45\% and 29\% for gelatin and corn starch solution. Thus with the addition of bio-
additives to the base PCM, the total solidification time is reduced considerably for both the additives with gelatin solution found to be more effective among the additives. Thus with the addition of bio additive to the base PCM, the subcooling is eliminated and a substantial reduction in solidification time is achieved[17].

![Figure 2(b). Temperature-time record of the PCM at -9°C](image)

### 3.2 Solidified mass fraction

![Figure 3(a). Solidification duration vs. Frozen mass(%) at -6°C](image)

Figures 3(a-b) reveals the time taken by the solidified mass at various bath temperatures. The time taken by the deionized water to freeze 50%, 75%, and 100% PCM mass is 47.5, 87, and 181 minutes at a bath temperature of -6°C. Similarly, at -9°C, the deionized water's time to freeze respective mass fractions are 24, 56 and 105 minutes. Likewise the gelatin and corn starch of 0.1wt.% concentration
dispersed in base PCM filled in spherical capsule took 15.5, 50, and 88 minutes and 21.5, 67.5 and 98 minutes respectively at a bath temperature of -6°C. Similarly, the gelatin and corn starch solution took 13.42 and 57.5 minutes 17,51.5 and 74 minutes respectively at a bath temperature of -9°C. Considering 50% PCM mass, the time taken by the gelation solution took only 18% to solidify whereas the cornstarch solution took 22% to solidify for the same PCM mass. A significant reduction of 82% is observed while considering 50% of phase change material(PCM) mass at a bath temperature of -6°C. Hence, it is concluded that reducing subcooling and partial charging of water-based PCMs would help to increase the Cool Thermal Energy Storage (CTES) system's energy efficiency[5,17].

![Figure 3(b). Solidification duration vs. Frozen mass(%) at -9°C](image)

The plots show that enhanced heat transfer rate persists till 50% of PCM mass and thereafter the heat transfer rate decreases beyond 50% PCM mass. The observation of enhanced heat transfer rate is due to the increase in the additives’ thermophysical properties mixed with the base PCM.

### 3.3 Surface Heat Flux:

The time-averaged surface heat flux is calculated by using the relation employed by the author in the previously published article[18].

The surface heat flux plots for the various mass fraction is shown in figures 5(a-b). The graphs show that the surface heat flux varies from 684 to 360 W/m² for deionized water at a bath temperature of -6°C. At the same bath temperature, the heat flux reported for gelatin solution is 2095 to 742 W/m² and for corn starch solution, it varies between 1510 to 666 W/m². At the surrounding bath temperature of -9°C, the heat flux values reported for deionized water are 1353 to 637 W/m². Likewise, the values derived for gelatin solution varied between 2706 to 1145 W/m², and for corn starch solution it ranged from 1910 to 870 W/m2. Thus from the above values, it is understood that there is a considerable increase in heat flux with the addition of bioadditives to the base PCM. The increase in heat flux is found to be remarkable up to 50% PCM. The increase in heat flux for gelatin solution is found to be 3.1 times higher than the deionized water at -6°C. Similarly, the increase in heat flux is found to be 2.2 times higher than the deionized water at the same bath temperature for corn starch solution. Thus,
with the gelatin solution's employment to the base PCM, enhanced heat flux is attained at \(-6^\circ C\) for 50\% PCM mass. Thus when operating at partial charging mode and considering 50\%PCM mass, a possible energy savings of 82\% is achieved.

\[\text{Figure 4(a) Heat flux vs Frozen mass(\%) at } -6^\circ\text{C}\]

\[\text{Figure 4(b). Heat flux vs Frozen mass(\%) at } -9^\circ\text{C}\]
4. Conclusion

The salient finding of the present investigation is highlighted below:

The onset of solidification is improved by 15% and 42% for gelatin and corn starch solutions at a bath temperature of -9°C compared to the deionized water. No subcooling phenomenon is reported with the addition of bio-additives at different bath temperatures.

The total solidification time is decreased by a value of 51% for both the additives compared to the base PCM at a surrounding temperature of -6°C. At a bath temperature of -6°C, a substantial reduction of 82% is observed while considering 50 %t of PCM mass.

References

[1] Regin, A.F., Solanki, S.C. and Saini, J.S., 2008 Heat transfer characteristics of thermal energy storage system using PCM capsules: a review. Renewable and Sustainable Energy Reviews, 12(9), pp.2438-2458.
[2] Oró E, de Gracia A, Castell A, Farid MM, Cabeza LF. 2012 Review on phase change materials (PCMs) for cold thermal energy storage applications. Applied Energy, 99:513–533.
[3] Tao YB, He YL. 2018 A review of phase change material and performance enhancement method for latent heat storage system. Renewable and Sustainable Energy Reviews, 93:245–259.
[4] Ismail KAR, Moraes RIR. 2009 A numerical and experimental investigation of different containers and PCM options for cold storage modular units for domestic applications. Int J Heat Mass Transf., 52:4195–202.
[5] Chandrasekaran, P., Cheralathan, M., Kumaresan, V. and Velraj, R., 2014. Enhanced heat transfer characteristics of water based copper oxide nanofluid PCM (phase change material) in a spherical capsule during solidification for energy efficient cool thermal storage system. Energy, 72, pp.636-642.
[6] Altohamy, A.A., Abd Rabbo, M.F., Sakr, R.Y. and Attia, A.A., 2015. Effect of water based Al2O3 nanoparticle PCM on cool storage performance. Applied Thermal Engineering, 84, pp.331-338.
[7] D Premnath et al., 2020 Solidification characteristics of phase change material in a rectangular finned spherical capsule. IOP Conf. Ser.: Mater. Sci. Eng. 912 042012.
[8] Saitoh T 1983 On the optimum design for latent heat thermal energy storage reservoir. Refrigeration, 58:749-756.
[9] Cheralathan M, Velraj R, Renganarayanan S 2007 Performance analysis on refrigeration system integrated with encapsulated PCM based cool thermal energy storage system. International Journal of Energy Research, 31:1-16
[10] Chen, S., Chen, C., Tin, C., Lee, T., Ke, M., 2000. An experimental investigation of cold storage in an encapsulated thermal storage tank. Exp. Thermal Fluid Sci. 23, 133–144.
[11] Milon, J.J., Braga, S.L., 2005. Supercooling water in cylindrical capsules. Int. J. Thermo Phys. 26, 1781–1802.
[12] Colla, L., Fedele, L., Mancin, S., Danza, L., Manca, O., 2017. Nano-PCMs for enhanced energy storage and passive cooling applications. Appl. Therm. Eng. 110, 584–589.
[13] Zhang, X.J., Wu, P., Qiu, L.M., Zhang, X.B., Tian, X.J., 2010. Analysis of the nucleation of nanofluids in the ice formation process. Energy Convers. Manag. 51, 130–134.
[14] Motahar, S., Alemrajabi, A., Khodabandeh, R., 2017. Experimental study on solidification process of a phase change material containing TiO2 nanoparticles for thermal energy storage. *Energy Cons. Manag.* 138, 162–170.

[15] Liu, Y., Li, X., Hu, P., Hu, G., 2014. Study on the supercooling degree and nucleation behavior of water-based graphene oxide nanofluids PCM. *Int. J. Refrig.* 50, 80–86.

[16] Temel, U.M., Kurtulus, S., Parlak, M., Yapici, K., 2018. Size-dependent thermal properties of multi-walled carbon nanotubes embedded in phase change materials. *J. Therm. Anal. Calorim.* 132, 631–641.

[17] Kumaresan V, Chandrasekaran P, Nanda M, Maini AK, Velraj R. 2013 Role of PCM based nanofluids for energy-efficient cool thermal storage system. *International Journal of Refrigeration*, 36:1641–1647.

[18] Premnath Doss, Chandrasekaran Ponnusamy & Ganapathy Subramanian Laligudi Ramachandran (2020) Predictive modeling of solidification characteristics of a phase change material in a metallic spherical capsule fitted with fins of different lengths, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, DOI: 10.1080/15567036.2020.1817192.