Effect on solidification of deionized water based PCM in a spherical encapsulation- An experimental study

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Abstract. An aim of project work is to investigate the effect on solidification of phase change material (PCM) in a spherical capsule for cool thermal storage applications. The PCM used as Deionized (DI) water and low-density polyethylene (LDPE) spherical capsule is used as an encapsulation material. It is filled with three different concentration of PCM with NaCl of 0.5, 1.0 and 1.5 wt., % of total volume of encapsulation. An experiments are conducted by immersing the spherical capsules in the constant temperature bath which is maintained at -7°C temperature for all samples. The solidification time is observed in each capsule at various radial locations which correspond to 50%, 75%, and 100% of the mass solidified. The results obtained reveal that the PCM of NaCl has a great influence in reducing the solidification duration. Further, the capsule with 0.5wt.%, shows better results till the solidification of 75% mass than all the other capsules and slows down thereafter. Hence it is concluded that the consideration of DI water with 0.5wt.%, mass of NaCl in the spherical capsule for the design of the energy storage would increase energy efficiency of the system and reduce the energy consumption the chiller.

1. Introduction

A many types of energy storage systems based on thermal, electrical, mechanical energy and electrochemical energy. A some of energy storage systems have unfavorable effects on the surroundings. This poses a task to investigators to invent an energy storage which does not produce harmful effects. A latent heat energy storage method is used widely, which phase change of the material is used to store an energy and also having its high latent heat i.e. huge amount of energy stored per unit mass. The CTES system is a method used to store energy during off-peak hours and utilize in peak-hours. So that it’s reduces energy and mismatch between energy supply and demand during peak hours. This method is commonly used for reducing the variations in electric power between peak and off- peak hours. There is a huge demand for air conditioning in buildings in the daytime and reaches a peak at noon where the temperature is at a maximum. The load tends to reduce during night times due to a decrease in the ambient temperature.

In this study, the reservoir used is a large tank which is used to convert phase change materials into the solid phase (ice) which stores the energy. Rami et al. (2019) [1] is analyzed the system under consideration at several conditions for various PCM module preparations. It is concluded that a TES unit 10-14% decrease in charging time while not affecting the discharge with narrow air flow.
channels. Vikram et al. (2019) [2] is investigated the solidification of Deionized water (DI) with mixture of NaCl and D-sorbitol in the capsule. A water is used as a base of PCM and solidification is performed at -7°C. The results is observed that the NaCl is considerably influencing the subcooling and mass of solidification of PCM. Chen et al. (2000) [3] is analyzed the working of a spherical capsule integrated with storage tank while energizing. The coolant effect of temperature, flow rate, nucleation of the capsule, tank pressure drop and heat transfer is evaluated. It is observed that a storage tank was additional efficient with low temperature of coolant and high volume flow rate. Cheng et al. (2017) [4] investigated the experimental and numerical analysis of 3 stage Cascaded Cold Storage Unit CCSU and SCSU. The result observed that the though the cold energy gained in SCSU is greater than which are stored in CCSU, the rate of charging is optimized in CCSU and the energy efficiency is enhanced in CCSU. Asgharian et al. (2018) [5] studied the act of ice-bank systems experimentally and numerically analyzed the effects of the various parameters. The charging and discharging process is conducted and a rate of heat transfer on the walls and amount of liquid fractions resulted Use of two inlets chiller fluid resulted in dropping of charging time to eleven min and increased in efficiency by 37%. YT Lee et al. (2014) [6] studied the convection and conduction effects of spherical ball on thermal storage performance. The different modules are used to examine the ball and the effects of convection and conduction resulted. Hence this was more important in actual conditions that is when the ball had lesser thermal conductivity. Chandrasekaran et al. (2015) [7-8] is performed experimentally with the effect of size of spherical capsules and fill volume on solidification process with DI water as phase change material. From the results concluded that in larger ball size the freeze faster at front and the higher temperature had negligible effect in the small ball. Finally concluded that the larger ball size which is give better performance in CTES unit. The different fill volume of spherical ball in its total volume is analyzed. Its is observed that the higher fill volume increases he advance solidification in the capsule. Asker et al. (2018) [9] studied the inward solidification of PCM with a spherical ball. It was reported that the time of solidification is improved as the radius of the ball increased and also resulted that an entropy generation increases as ball radius increased and then attains a lesser value after a maximum radius. Mikail et al. (2017) [10] observed the solidification characteristics of different types of phase changing material and studied the convective cooling in both water and air. A prototype is made to expect the cooling of phase changing materials in congruent boundaries. Liu et al. (2016) [11] investigated inward solidification for phase changing materials in spherical capsules by measuring PCM shrinkage volume as the capsule solidifies. The shrink volume is occupied by PCM in a tube that sloped down into the ball. To obtain volume shrinkage, the height of PCM column was experimentally observed to report the shrinkage volume. Ponrajan Vikram et al. (2019) [12] studied the solidification characteristics of phase change material, dispersed with varying mass percentage of d-sorbitol and sodium chloride in encapsulated spheres. The experiment showed that as the sub cooling increased the cooling rate also increased. The observations are carried out at a bath temperature of -7°C, and the sub cooling of deionized water was found as -5.4°C. How- ever, when 0.5% mass of sodium chloride and 1% mass of D-sorbitol is added the sub cooling obtained decline to -2.8°C. So, it is observed that the cooling rate deteriorated with increase concentration of D-sorbitol and sodium chloride, but at specific levels of dispersion, the rate of cooling was enhanced. Therefore, it is concluded that partial charging of water-based phase change materials and decrease in sub cooling would be significant for increasing cool thermal storage efficiency.

Thiago Santos et al. (2019) [13] evaluated the thermal characteristics of a new encapsulated panel model filled with phase change materials (PCM) and examine it with a previously present panel for an air heat exchanger system. The analysis was done on melting and solidification characteristics of phase change material within each model. It also converges on latent thermal energy storage (LTES) of a thermal battery module. The current battery module had 9 panels, while the new model comprised of 7 panels with phase changing materials. It was reported that the new prototype was able to withstand 17.5kgs more than the present module with 30% more material consumption than the existing
prototype. It is also reported that an increase in time for melting and solidification as additional materials are utilized in the new prototype.

Karthik Panchabikesan et al. (2018) [14] investigated the improvement in free cooling potential for an altered cooling system which is analyzed with conventional cooling systems. The altered system uses encapsulated phase changing materials immersed in a cylindrical tank with nozzles for spraying water. It was noted that decline in charging duration and proliferation in heat transfer rate was obtained in the altered system when compared to the conventionally used system. The reduction in charging duration reported were 28.7% 34.8% with heat transfer fluid (HTF) inlet velocities 2m/s 1.5m/s respectively. Also, in the conventional cooling system the PCMs arranged in last 2 rows of the tank didn’t reach freezing temperature even after 10 hours of cooling, while in the encapsulated prototype of PCM, the complete storage tank was charged at each and every values of heat transfer velocities. So, it is reported that the proposed new prototype aids help the PCM to solidify completely at a significant rate and it inflates the thermal performance of the storage model.

In the area of CTES has been done various studies, but limited work is done for solidification behaviour on encapsulated PCM with NaCl as nucleating agent. The aim of present work is to investigate solidification behaviour of Di-water with NaCl.

2. Methods and Methodology

2.1. Fabrication of experimental setup

The cool thermal energy storage system (CTES) is fabricated with constant bath chiller unit. The CTES system used a Vapor Compression Refrigeration (VCR) system with a R144A as refrigerant. The VCR arrangement consists of a compressor, expansion valve, condenser and evaporator which are responsible to maintain a constant temperature of chiller unit. The evaporator coil is placed inside the bath for this purpose. Aqueous ethylene glycol is used as the heat transfer fluid. Its composition is 70% :30% of water and ethylene glycol respectively. A mechanical stirrer powered by a motor is used to consistently maintain the HTF temperature throughout the unit. A K-type thermocouple is inserted the bath enables the user to know the temperature of the HTF. The schematic experimental layout of experimental setup as exposed in below figure 1.

![Figure 1. An experimental setup schematic layout.](image-url)
RTD temperature sensors are used to determine the solidification inside the spherical capsule at different locations. The specification of the RTDs are PT-100. PT stands for Platinum which is the material used in the tip of the RTD and 100 denotes that the re-istance of the RTD at 0 °C is 100 Ohms. The method employed for determining the temperature is 2-wire RTD. It makes use of 2 wires to determine the temperature. One wire is used to rectify the error in the other wire. One of the wires has a much higher resistance compared to the other.

A data logger is used to compile all the data that is collected by the RTD. The KEYSIGHT 34972A LXI model Data Acquisition system is connected and used to measure the temperature. The memory from the data logger can be transferred to the computer via a software known as Agilent Bench Link data logger 3. Using this software, the interval between which the temperatures must be determined can be set. Also, the configuration of the RTDs and the time interval for measuring the temperature can be done using this software.

This research aims to investigate the effect of PCM Nacl on different concentration the solidification of the capsule. This is done by capsules of different concentration on Nacl. The results are then compared to a without PCM and with PCM of Nacl. The spherical capsules are made of low-density poly-ethylene material. Due to high corrosion and other operation consideration of the materials such as metals, copper and aluminum makes Plastic capsule the first choice for this experiment. The diameter of the spherical capsule is 72mm and the thickness is 1.2mm. One capsule is left unaltered and the other three capsules are varied in Nacl of 0.5wt.%, 1.0wt.%, and 1.5wt.% with the help of digital weight measuring device.

The capsule and RTD thermocouples are inserted together by using Flexkwik, superglue but this does not prevent leakage. The leakage is prevented using M-seal. M-seal not only seals the leakage but also holds the halves together. The deionized water is filled through a hole which is drilled at the top of the capsule. The diameter of the hole is 6mm. Regular water cannot be used as Phase Change Material because of the impurities in it. For this purpose the water used must be deionized. Deionization is the process of removing the ions in the water which may interfere with the heat transfer process. The spherical capsule is filled with only 90% of the DI water. This is due to the fact that ice occupies more volume than water. So when the DI water solidifies, the ice formed inside may damage the capsule. Thus, the capsule is not filled fully with DI water. The RTDs are placed in positions corresponding to 50%, 75%, and 100% of the volume solidified.

![Figure 2. Locations of RTDs in a spherical capsule.](image)

### 2.2. Experimental trail

A stick is used to hold the RTDs in position. The RTD s are stuck to the tape using Teflon Tape. The stick is then inserted and the hole is sealed with the help of M-seal. PVC pipes are used to immerse the
capsules in to the bath. With the help of a glue gun, the Capsule is fastened rigidly to the PVC pipe. The capsule is immersed at a desired height by marking a height on the PVC pipe. A holder is used to hold the capsules at the desired depth and to prevent it from completely submerging. The RTDs are connected to the data logger. Four RTDs from each capsule are linked to the data logger. The board consists of 16 channels. Hence all four capsules can be linked at the same time. But due to the size constraints of the bath, only two capsules can be experimented at a time.

After the RTDs have been connected to the board, it is inserted into the data logger and the data logger is switched on. The computer interfaced with the data logger is also switched on. The software is then opened. A new configuration is opened and named accordingly. The channels in which the RTDs are connected are selected and the method is selected as 2 wire RTD method. The time interval is selected as 10 seconds. i.e. the data logger scans the temperature with the help of the RTD every 10 seconds.

The CTES setup is switched on. By using a Proportionate Digital Temperature Controller, the desired temperature is set by the turn of a knob. After the temperature has been set, the stirrer motor is switched on. The system takes some time reach the desired temperature. Now the spherical capsule can be immersed into the bath. It is immersed inside the bath at a predetermined depth only after the scanning has started. This way, the cooling curve is obtained for the capsule is obtained right from the room temperature. The holder holds the capsule in position. The bath is closed to avoid loss of heat. The set of temperatures are obtained every 10 seconds. The scanning is stopped when all the RTDs indicate complete solidification. This occurs when all the positions are at the same temperature which is closer to the bath temperature. The CTES and the stirrer is then switched off. The data from the Data logger can be saved in the computer. It is exported as Comma Separated Values (CSV) file. The CSV file contains temperatures at a 10-second interval. The values are separated and saved in an Excel Workbook and a graph between time and temperature is plotted. The bath is maintained at same temperatures of -7°C for the purpose of experimentation.

3. Results and Discussion
The repeated trial experimental work is done and the following observations are discussed during solidification process at constant HTF bath temperature of -7°C. The transient temperature difference of PCM at the different volume locations of the spherical encapsulation to evaluate the subcooling, commencement and completion of solidification. The transient temperature variation at various radial position to calculate the mass fraction solidified during solidification process and to evaluate the variation in heat flux during the solidification process.

3.1. Time Temperature History
Supercooling. The TT graphs represented above has shown presence of Supercooling in DI at the three thermocouple locations as -3.349°C, -3.664°C, -3.959°C radially inwards. For 0.5 wt% NaCl Supercooling is only detected by thermocouple at the surface as -0.092°C. 1.0 wt% NaCl has presence of Supercooling as 0.175°C only at center while 1.5 wt% NaCl has supercooling radially inwards as -4.4°C, -5.045°C, -5.551°C. 1.5 wt% remained ineffective in eliminating supercooling in any of the thermocouple locations. 0.5 wt% respectively reduced the presence of supercooling among all the concentrations.
Figure 3. Temperature-time of DI-water at $T_{\text{bath}}$ of -7°C.

Figure 4. Temperature-time of DI-water with 0.5 wt.% NaCl at $T_{\text{bath}}$ of -7°C.

Figure 5. Temperature-time of DI-water with 1.0 wt.% NaCl at $T_{\text{bath}}$ of -7°C.
3.2. Latent Heat Duration
From the Time Temperature relationships, reduction in latent heat duration has been observed at all the three thermocouple locations.

3.2.1. Percentage reduction in latent heat duration. As compared to the DI water, addition of 0.5 wt%, 1.0 wt% and 1.5 wt% has brought down latent heat duration by 21.24%, 13.47% and 2.93% at the center of the ball, 60.64%, 56.62% and 60.24% at the surface of the ball, followed by 47.61%, 75.73%, 51.47% respectively in between surface and center of the ball.

3.2.2. Temperature of Solidification. From the charging cycle depression in freezing point has been observed on addition of NaCl, DI water showed phase change temperature of 0.183_C, 1.003_C and 0.418_C at the Surface, Center and in between Surface and Center. Addition of NaCl by 0.5 wt% has reduced temperature to 0.04_C, 0.338_C at Surface and Center while increase in temperature in between to 0.446_C. 1.0 wt% NaCl has brought down temperature to -1.159_C, 0.331_C and -1.11_C at Surface, Center and in between Center and Surface. Finally on increasing NaCl to 1.5 wt% reduction has been noted as -1.092_C, -0.67_C, -1.164_C at Surface, Center and in between Center and Surface.

![Figure 6. Temperature-time of DI-water with 1.5 wt. % NaCl at T_bath of -7°C.](image6)

4. Mass Solidification of PCM
At 50% solidification, the capsule with 0.5wt.%, of PCM takes the least time followed by without PCM capsule with the capsule of 1.5wt.%, taking the most time. At 75% solidification, the capsule
with 0.5wt.%, of PCM takes the least time. The capsules with plain surface and without PCM capsule have similar times of solidification. The capsule with 1.5wt.%, of PCM takes the highest time. At 90% solidification, the capsule with without PCM capsule takes the least time while the other capsules have similar solidification times. At 100% solidification, the capsule with without PCM capsule again takes the lowest time followed by 1.0wt.%, 0.5wt.%, of PCM capsule. At -6°C, it can be concluded the roughness has a positive effect on the solidification i.e. the capsules included with PCM have better solidification times compared to the without PCM capsule.

![Figure 8](image1.png)

**Figure 8.** Mass fraction solidified at different radial Locations.

5. **Heat Flux**

The surface heat flux by different volume percentage in a spherical capsule is calculated by using formula as below

![Figure 9](image2.png)

**Figure 9.** Surface heat flux with different volume percentage in a capsule.
The heat flux $q$ is calculated as

$$q = \frac{m\lambda}{At}$$

where, $m$ is the mass of the Phase Change material in kg, $\lambda$ is the latent heat of fusion value = 333 kJ/kg, $A$ is the surface area of the spherical capsule in $m^2$. $t$ is the time taken for solidification in seconds and the unit of Heat flux is W/m²

Heat Flux increase has been observed on addition of NaCl. When surface of the ball is considered, the increase in heat flux can be observed as 154.082 %, 130.56%, 151.52% respectively for 0.5 wt%, 1.0 wt% & 1.5 wt% respectively.

6. Conclusion

The conclusions are made based on repeated experimental observations which is conducted with various concentration of PCM with NaCl at different weight percentage of total volume of capsule and at bath temperature of -7°C.

DI water with NaCl as PCM of the capsule has strong influence in reducing the subcooling and gives more latent heat.

PCM capsule with DI water with 0.5wt.% NaCl shows the better results of solidification till 75% mass of PCM.

It is concluded that considering 75% mass of PCM for the energy storage is the optimum way for designing energy efficient cool thermal energy storage.

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