Thermal Property Enhancement on Water based PCM in Spherical Container for Cold Storage Applications

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Abstract. The purpose of the present work is to study the solidification behaviour of a di-water based PCM for cold energy management applications. Thickening agents such as agar, gelatin and cornstarch are examined at various mass fractions. The experiment is carried out in a low temperature bath of -7°C inside which the PCM sample is kept spherically encapsulated for uniform distribution. The behaviour and effect of addition of the nucleating agents are compared. The analysis showed that the subcooling of di-water was substantially reduced and its crystallisation occurs at a faster rate. It is concluded that faster crystallisation and reduction in subcooling can help increase the efficiency of a cool thermal energy system and can be applied to any commercial system in the society to help alleviate the electrical load.

1. Introduction

India is the world’s third largest consumer of electricity. The energy consumption of an average household went from a low of 55% less than 2 decades ago to 80%. In the average household cooling and heating appliances take up to 52% of the energy use. This all the more amplifies the need for a sustainable development manner which does not affect the ecological system and prompts us to adopt ideal methods that are cost effective and environment friendly. One of these methods to meet the energy demands would be to supply the energy during peak hour by storing energy during the off peak hour. This kind of technique when integrated with cool thermal energy systems, can be applied to various applications such as cooling systems in buildings, refrigeration units, industrial process cooling, transportation units, food processing etc.

Chandrasekaran et al. [1] studied that the main obstacle of supercooling of a water based PCM can be eliminated by filling up to 95% volume of the spherical encapsulation. Thus solidification is accelerated and there’s a significant decrease in subcooling. Moreover, Barba et al. [2] studied that the geometry that gave a quicker response to a temperature variation in the tank was spherically encapsulated nodules. In a more recent study it was confirmed by Vikram st al. [3] that the cool thermal energy storage of a PCM in spherical encapsulation was accelerated till it reached the innermost 6% after which the charging rate was decelerated. This could be fixed by the addition of additives such as thickeners or nucleating agents. Zou et al. [4] made a composite PCM from CaCl₂.6(H₂O) along with nucleating agents and thickeners such as SrCl₂.6(H₂O) and methyl cellulose mixed with urea for the regulation of phase change behaviour of the PCM. The subcooling was substantially reduced and the rate of crystallization was enhanced. A model was proposed by Irsyad...
et al. [5] where a high density PCM was used to store latent heat energy for cooling applications of chillers in buildings. Thus ultimately alleviating the load on electricity. The preferred temperature of the PCM should be in 5-12°C. As described in many comprehensive reviews [3-6], it is evident that PCM has been widely used for thermal energy storage applications since it can store a large amount of energy within a small volume and a relatively low temperature variation. Azzou et al. designed a refrigerator where a PCM was attached to the back of its evaporator. It successfully provided a successful model allowing for several hours of refrigeration without any electricity supply, thus improving the efficiency of a household refrigerator. Moreover, Lu et al. [7] utilized a concept where a PCM was used to store cool thermal energy in a refrigeration equipment. Their result showed that the addition of paraffin waxes and nucleating agents lowered the supercooling significantly thus implying that water based PCM’s are suitable for cold storage in chilled food cabinets. Lingfei et al. [8] designed a solar powered air conditioner for vehicles, where the solar power is stored in a capacitor that is used to run the air pump and the water pump. The air pump drives the outside air into the water pump of the PCM module which provides for the cooling in the cabin. This can alleviate the load on fossil fuel if applied on a large scale. Arce et al. [9] did a rather interesting study on how PCM’s can ultimately be used to help store energy and help climate mitigation in Spain and Europe thus relieving the pressure from natural resources. It was found that CO2 emissions had substantially decreased and the load on electricity was reduced. Thus cool thermal energy systems bring with it environmental benefits as well. Xianogin et al. [10] proposed a system to incorporate a PCM technology in telecommunication bases(TBS) which ultimately resulted in energy and demand savings. They worked on the basis of Latent Heat Storage Units. These units were tested in 5 different cities in China. They were able to bring down the space cooling energy consumption by lowering the operational time of conventional air conditioning systems used. Oro et al. [11] discovered that PCM’s used for cold thermal energy applications require thickeners and nucleating agents to reduce the subcooling effects and phase segregation.

The purpose of this study is to alter the freezing point of deionised water using organic thickeners so that subcooling is reduced and the rate of crystallisation is increased enabling the spherically encapsulated PCM to store more energy in a relatively lower period of time. This energy is then used for cooling applications during the peak hour. Only organic thickeners are considered in this study on account of their low toxicity, easy availability and low cost. The main ingredients that are tested here are agar, gelatin and cornstarch. It is truly fascinating to learn that commercially available organic additives can change the thermal properties of water in such a way that it is suitable for higher energy storage. Thus this concept will go a long way in case of large scale applications and help fulfill the energy demand without the exhaustion of natural resources. Cold thermal energy storage has gained a lot of momentum these days owing to these reasons.

2. Experimentation
2.1. Materials
Agar, gelatin and cornstarch were purchased from Seaweed Solution Laboratories. All of them exhibit an excellent gel strength of approximately 900g/cm³. In this experiment, deionised water is selected as the base PCM and three various organic thickeners namely cornstarch, agar and gelatin were used. Each of the dispersants cornstarch and agar were dispersed in DI water with the mass concentration of 1% and 2%. Lower mass concentrations of 0.2%, 0.6% and 1% are measured for gelatin.

2.2. Preparation
For the preparation of the stable water based PCM the following procedure has been adopted. Initially different weight percentages of the organic thickeners were measured at a DSC lab. All other ingredients used for the preparation of the PCM were measured using the same balance. Each of these samples were mixed with 200ml of deionized water. Fig 1. shows the preparation of the composite PCM. The solution is made uniform using a magnetic stirrer for 20min.
2.3. Apparatus and procedure

The schematic diagram of the experimental setup needed to conduct the solidification process of the organic thickeners is shown in Fig.2. The apparatus consists of mainly 4 parts: (1) Spherical encapsulation (2) Low temperature bath (3) Data logger (4) Computer. Fig 2 shows the general view of the experimental design. It consists of a low temperature bath of capacity 30L made of stainless steel. The heat transfer fluid used in the experiment is a mixture of water and ethylene glycol mixed at the ratio of 3:1. This helps avoid possible freezing. The low temperature bath is kept at a constant temperature of $-7^\circ$C. The refrigeration unit is of 1ton capacity and is supplied with a heating coil of 1.5KW. Fig 3 shows the general view of the spherical encapsulation containing the PCM, inside which 3 thermocouples are fixed at different volumes (50%, 75%, 90%). The top of the spherical encapsulation is sealed with a cork to prevent leakage. Agilent Data Logger 34972a is used to collect and store the temperature measurements at every 10 seconds.

The process is started by turning on the refrigeration unit and bringing the water bath to $-7^\circ$C. The spherical encapsulation is kept inside the low temperature bath once the water bath attains the desired temperature. The 3 RTD’s are connected to the data logger. Using the Agilent Benchlink software the various temperature values at different volumes are obtained. This data is continuously scanned and logged into a computer. The experiment was carried out until the temperature of the PCM at the centre of the encapsulation reached $-7^\circ$C. Once all 3 thermocouples attain the temperature of the water bath, the refrigeration unit is turned off. The temperature reading with respect to time for each sample of the PCM is compared using a computer. Charts are plotted for DI water and each of the different thickeners. Conclusions are drawn from the values obtained. In this study, the tests were run 2 times for each sample of the PCM.
3. Results and discussion

Due to the implicit advantages of organic thickeners such as low cost, easy availability and low toxicity the additives considered in this study are agar, gelatin and cornstarch.

From figure 4 we can understand that the solidification behaviour of DI water can broadly be divided into 4 stages. Sensible heat was reduced till it reached a uniform temperature of 6°C throughout the encapsulation at 470 seconds. In the first stage it was observed that the temperature changes from the initial state to the subcooling state. This meant that DI water was well below the freezing point but still stayed in the liquid phase and was subcooled to a temperature of -4.8°C after
which nucleation starts. The second stage sees the occurrence of nucleation and the completion of dendritic ice formation. This can easily be detected using the thermocouples immersed in the encapsulation. From the nucleation site a thin layer of dendritic ice spreads rapidly. Stage 3 involves the phase change process from ice crystal formation to the complete solidification of water. The onset of solidification was observed at 1240 seconds and offset solidification was observed at 7470 seconds. This process is termed the latent heat thermal storage process. On completion of the phase change process, cooling of ice takes place till it reaches the same temperature as that of the coolant and is the final stage of the crystallisation process. In 8500 seconds, all three thermocouples showed the temperature of the water bath i.e., -7°C.

![Figure 5. T-t graph for 1wt. % agar.](image)

The transient temperature variation of deionised water mixed with different mass fractions of agar (1wt. %, 2wt. %) can be observed from fig. 5 and fig. 6. The onset of solidification is observed at a relatively low temperature of 0.004°C for the PCM sample containing 1wt. % agar. The degree of subcooling is reduced from -4.8°C of that of DI water to a mere -0.286°C. Whereas with the addition of 2wt. % agar, complete eradication of subcooling is observed. A very high crystallisation rate was observed as well, reducing the solidification time by 23.5mins for both the PCM samples. The maximum reduction in solidification time was noticed to be 22.6%. Thickening agents such as agar are utilised to change the properties of DI water such that the viscosity is increased. This prevents the problem of phase separation by ensuring that the precipitated crystals distribute uniformly throughout the solution without sinking to the bottom.
Figure 6. T-t graph for 2wt.% agar.

Figure 7. T-t graph for 0.2wt. % gelatin.
The results of similar experiments conducted with the water based PCM containing mass concentrations of 0.2%, 0.6% and 1% of gelatin is presented in fig. 7, 8 and 9. The subcooled temperatures were found to be -2.8°C, -3.9°C and -3.8°C respectively. Drastic reduction in subcooling is observed at lower concentration whereas, a reduction in subcooling of only 1°C was observed for the sample containing higher mass concentrations of gelatin. However, the degree of subcooling is noticed to be considerably small at lower mass concentrations. This is due to the nucleation action of gelatin in
deionised water. Also it is to be noted that the solidification time was reduced by 26.7 min, 14.7 min and 5 min compared to that of DI water. The maximum reduction in solidification time was observed to be 25.7% in the PCM sample containing 0.2wt. % of gelatin. It is surmised from the above results that the addition of gelatin is favourable to reduce the subcooling but the efficient storage of energy can only be attained at smaller mass concentrations. This happens due to the fact that, as the concentration of the thickening agents increase, so does the surface energy of nucleation. This will in turn obstruct the formation of nucleation sites, thus making the subcooling curve even more steep.

Figure 10. T-t graph for 1wt. % cornstarch.

Figure 10 shows the variation in solidification behaviour when 1wt% of cornstarch is mixed with DI water. A drastic change was observed in the subcooling as it reduced from -4.8°C to -2°C. Maximum reduction in solidification time of 14% was observed for 2wt. % of cornstarch. Maximum reduction in subcooling or no subcooling at all is observed at mass concentration of 2%. The most probable reason for this is the high density gel that is obtained when cornstarch is mixed with DI water. A high density PCM is preferred for the storage of thermal energy for cooling applications [5]. However the duration for solidification is decreased only by 4 min and 15 min. This extension in solidification time could be due to the high density of the gel leading to a decrease in thermal conductivity which ultimately suppresses the natural convection.
4. Conclusion
The study carried out was solely focused on cold thermal energy storage and its different applications. PCM’s containing only organic thickeners have been considered. The crystallisation behaviour of the water based PCM was examined experimentally at a bath temperature of \(-7^\circ C\) and a list of observations were made:

- Deionised water exhibits good thermal properties and stability. This enables us to easily alter its freezing point in such a way that it is favourable for storing a high amount of latent thermal energy. High density thickeners of excellent gel strength have been used for this purpose. A spherical encapsulation of PCM containing organic thickeners such as agar, gelatin and cornstarch were prepared using magnetic stirring method.
- The residence of high density organic thickeners with deionised water takes the role of nucleating agents to increase the rate of crystallisation to that of the base PCM with drastic reductions in the degrees of subcooling. Also, maximum reductions in solidification time observed were 22.6\% (2wt. \% of agar), 25.7\% (0.2wt. \% of gelatin) and 14.5\% (2wt. \% cornstarch).
- Most organic PCM are chemically stable and non-reactive. Thickening agents can be used to avoid reversibility problems. They can be easily applied to large scale commercial applications such as chillers in buildings, food processing units and food trucks as they are cheap and are locally available.
- An efficient CTES system can help reduce the load on electricity and pave the way to a sustainable manner of development in one of the key energy consuming sectors, i.e. air conditioning applications.

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