Temperature profile of PCM and HTF in packed bed storage during the process of solidification in spherical capsules

P Chandrasekaran$^{1,*}$ and B Sivakumar$^2$

$^{1,2}$Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, India

*E-mail: chandrap4@srmist.edu.in

Abstract. Amassing of cold energy is a foremost area in the field of thermal energy storage. The storing of cold thermal energy in a phase shift material is an art of solidification. The following experimentation depends on the domain of packed bed storage in which the 74mm spherical nodules of HDPE material whose fill volumes is around 90% is been solidified in a packed bed. The solidification curves and the HTF temperature profile concerning various set conditions have been analysed. The results revealed that layer 1 takes a minimum time to attain a lower temperature when compared with other reference layers. The results reveal that when the HTF temperature is brought from -6 to -9°C this trend is also maintained in the HTF temperature profile and found to be rapidly decreasing. Hence it is concluded that the inlet temperature of HTF plays a significant role during the process of solidification.

1. Introduction

Cool thermal energy storage is a promising phenomenon to meet the needs of refrigeration and air-conditioning domain during the peak load period with the inclusion of phase shift material. This technology has an added power pack advantage in maintaining the temperature of the application even though in the case of any interruption in the normal cooling system.

The phase shift material is the major investor in storing the cold thermal energy which can be used to reduce the energy wastage of the refrigeration and air-conditioning applications by treating the working fluid to maintain at a lower temperature. The packed bed concept is somewhat way ahead area in the field of freezing and storing the cold thermal energy. The latent heat storage concept is adopted so as to store the energy in the phase shift material and this is preferred over the sensible mode of storage because the storage density is higher [1]. This solidification technology can be made to implement by integrating with air conditioning applications and thereby reducing the inlet temperature of the ambient air and thus decreasing the load on the evaporator unit and thus fetching an energy-saving potential [2]. Cool thermal energy storage systems can be used to meet the energy demands during peak hours and during a power interruption. The energy can be stored in PCM during off-peak hours which can be used for the preservation of food and medicines [3].

Refat Al-Shannaq et al. (2019) [4] experimentally investigated cold thermal energy amassing system. They conducted the study with two novel capsules one is made of graphite composite (ID=75mm) and another one is of LDPE. The HTF set temperature range of around (-3.5, -5.5, -7.5°C) and with the inclusion of water as the base PCM and yielded a reduction in the time of solidification by 53.7% when compared with the conventional capsule material.
Narayanasamy et al. (2021) [5] studied the inclusion of HDPE capsule with the de-ionized water as the base PCM and pseudomonas as the nucleating agent (0.1-0.4ml) performed under different set point conditions like -6, -9 and -12°C and with the mass flow rate of around 6 lpm. They found a maximum reduction of subcooling is achieved with the addition 0.13% of nucleating agent. Cheralathan et al. (2007) [6] analysed the performance parameters of an industrial refrigeration system that is integrated with the packed bed storage system containing 250 HDPE capsules. They experimented with an HTF temperature range of around -2 to -15°C and reported that -5 to -8°C of HTF inlet has awarded an excellent outcome in the decrement of solidification time. Chan and Tan (2006) [7] investigated the freezing of n-hexadecane with paraffin and the procedure was conducted in horizontal bed storage where HTF is at various set points like 13, 8 and 3°C. They reported that lower HTF temperature drives the freeze front faster, which shorten the solidification time.

Bedecarrats et al. (1996) [8] studied the solidification of PCM in packed bed storage. They used water and eutectic salt as the base PCM filled inside the HDPE (2500 capsules) placed inside the storage tank and tested for flow rates of 0.9, 1.1 and 1.4 m³/h respectively. They reported that the solidification is faster with the increase in the flow rate of heat transfer fluid. Bedecarrats et al. (2009) [9] experimentally analyzed the freezing of PCM in spherical nodules. They conducted the experiments based on water + nucleating agent as the base PCM and mono ethylene glycol acts as a heat transfer and the temperature and flow parameters are subjected along 20 to -40°C and 0.5 to 2.5 m³/h. They construed that the use of nucleating agents has ended up with the reduction in the phase of under-cooling. Bedecarrats et al. (2009) [10] modelled and analyzed the freezing and the discharging phenomenon of the packed bed storage. They adopted the methodology of axial and incompressible flow and they simulated the results and compared them with the experimental model and finally construed that the time of charging is decreased by increasing the flow rate of the HTF fluid.

Ismail and Henriquez et al. (2002) [11] studied the phenomenon of solidification in terms of experimental and numerical analysis. They adopted the methodology of simulating the packed bed with the adiabatic condition containing capsule with water as the base PCM and ethylene glycol as the HTF with set points as -3 to -15°C with the flow rate of around 0.5 to 1.5 m³/h. They experimented with PVC, Cu, Al, acrylic and polyethylene and they construed that the copper nodule has performed a way superior in reducing the freezing time when compared with others. Chandrasekaran et al. (2015) [12] reported that the undercooling has decreased when the capsule size is increased and the freeze front is faster till 75% of phase shift material in the larger size capsule because the undercooling is very low and it contributes to the greater amount of heat flux. Chandrasekaran et al. (2015) [13] experimentally investigated the solidification process filled with 80-95% volume and reported that 95% fill volume has eliminated undercooling and maximizes heat flux, particularly at low temperature.

From the above literature, it is observed that only a few kinds of literature are available with the study of packed bed storage system particularly the solidification at various volumes. Hence, this study is focused to evaluate the temperature profiles at various set point conditions during the solidification process.

2. Material and methods

2.1 Experimental work

The packed bed solidification process is conducted in a cool thermal energy storage system which is shown in figure 1. The system is equipped with a vapor compression refrigeration system that helps to cool the lower bath whose volume is around 0.05m³ where ethylene glycol and water is mixed in the ratio of 70:30. The lower storage tank is used as a constant temperature bath in which the evaporator coil is integrated and the upper storage tank is were the 105 PCM capsules whose outer diameter is around 74mm is immersed in a solution of ethylene glycol and water, the double de-ionized water is the base PCM and RTD’S were used to measure the temperature of PCM as well as the HTF temperature at different layers which is shown in figure 2 and the experimental specifications are listed in table 1.
2.2 Experimental procedure

The experimental storage tank is filled with a capsule containing double de-ionized water with 90% fill volume and three capsules fitted with RTD’s. The wooden frame is used to support the capsules and sensors and their schematic view is shown in figure 3 and three RTD’S are placed inside the spherical capsules corresponds to 50, 75 and 100% volume in three spherical capsules and they are placed at different distances representing different layers through the wooden frame.

The VCR system is switched on and the desired set temperature is attained using PDTC. At first, the lower bath is made to attain the set temperature and the pump is used to circulate the HTF solution from the base tank to the upper tank the flow is measured using the flow meter and the flow is been controlled with the help of valves. So, that the optimum flow is achieved and in this the experimentation flow rate is around 500 LPH. The sensors are connected to the Agilent 34970A for measuring the inlet and the outlet heat transfer fluid temperature, as well as the temperature profile of
the PCM, is recorded. The solidification curve is obtained from the recorded data and the values are analysed.

### Table 1. Specifications of experimental set up

| Items                        | Details                      |
|------------------------------|------------------------------|
| Capsule material             | HDPE                         |
| Cryo pump                    | 0.025 Kw                     |
| Data acquisition and control system | Agilent 34970A             |
| Design temperature           | -23.3°C                      |
| Flow meter                   | 0 to 700 LPH                 |
| Heating coil capacity        | 3 Kw                         |
| HTF                          | Aqueous ethylene glycol      |
| HTF bath material            | Stainless steel tank         |
| PCM                          | Double de-ionized water      |
| Refrigerant                  | R134a                        |
| Sensor                       | PT100                        |
| Submersible pump             | 50 W                         |

### 3. Result and Discussion

Some of the selected observations from the experiment during the process of solidification of double de-ionized water in the spherical nodule are discussed and interpreted in this section. This includes the temperature history of the PCM and HTF at different layers and the ingress and egress of the HTF for varying HTF inlet temperatures of -6 and -9°C.

From figure 4, when the HTF inlet is at -6°C, it is evident that the temperature at layer 1 reduces rapidly below 0°C from room temperature. For the 50% volume level of the capsule, it takes 7200 seconds and for 75% and 90% volume level it reaches at 8820 and 9300 seconds and the HTF shows a rapid reduction in the temperature within a shorter interval till it reaches 0°C and after crossing the 0°C the time of temperature decrement is increased.

![Figure 4. Temperature history of PCM and HTF in Layer 1 at -6°C](image-url)
Figure 5. Temperature history of PCM and HTF in Layer 2 at -6°C

From figure 5, when the HTF inlet is at -6°C, it is evident that the temperature at layer 2 reduces rapidly below 0°C from room temperature. For the 50% volume level of the capsule, it takes 9870 seconds and for 75% and 90% volume level it reaches at 10380 and 10410 seconds and the HTF shows a rapid reduction in the temperature within a shorter interval till it reaches 0°C and after crossing the 0°C the time of temperature decrement is increased.

Based on figure 6, it is clear that layer 3 suffers to reach a lower temperature, when HTF is circulated at -6°C the main reason is that the capsules which are placed in the packed bed experiences an upward force and starts to float and immersion level reduces. So, the capsules suffer from frequent fluctuations in temperature and the time to attain below 0°C is also more when the comparison is executed between layer 1 and 2. It is clearly evident for layer 3 the temperature is reduced below 0°C for the 50% volume level of the capsule it takes 16080 seconds and for 75% and 90% volume level it takes 16500 and 17850 seconds respectively.

The HTF ingress and egress is also calculated for the constant bath temperature of -6°C using RTD’s and the values are also analysed which is shown in figure 7 from which the observation can be made like when the inlet and outlet temperature meets at a point in the temperature scale it is evident that the inlet HTF and outlet HTF temperature is same so that the capsules have been solidified 100% and so that the outlet HTF matches with an inlet (Tin=Tout) From this figure 7 it is shown that the HTF ingress is not equal to HTF egress it shows that the freezing process is not completed.

The HTF in the upper tank will be lower during the start of the experiment because the cold thermal energy is been stored because of the previous experimental run. So, that it will be exposed to the ambient for several hours before starting of the experiment but even though the temperature will be low which when circulated by the pump the temperature comes back to normal. So, that the curve drops rapidly and again stabilises in figure 7. The initial temperature of the constant temperature bath is -6°C, when the pump is switched on the HTF flows into the storage tank and the temperature ingress is raised to -5.2°C and even more.
Figure 6. Temperature history of PCM and HTF in Layer 3 at -6°C

Figure 7. HTF Temperature Profile at Inlet and Outlet of Packed Bed Storage at -6°C

The difference between ingress and egress is minimum at 35000 seconds when compared with the temperature history of layer 1 and 2 it is evident that the curve appears straight after 35000 seconds. This indicates the start of the solidification process and for layer 3 the curve still descends and needs more duration.
Figure 8. Temperature history of PCM and HTF in Layer 1 at -9°C

From figure 8, when HTF inlet is at -9°C, it is evident that the temperature at layer 1 reduces rapidly below 0°C from room temperature. For the 50% volume level of the capsule, it takes 3510 seconds and for 75% and 90% volume level it reaches at 4290 and 4920 seconds and the HTF shows a rapid reduction in the temperature within a shorter interval till it reaches 0°C and after crossing the 0°C it maintains a constant range of temperature, for a longer duration because of a constant amount of heat transfer occurs in between the PCM and HTF.

Figure 9. Temperature history of PCM and HTF in Layer 2 at -9°C
From figure 9, when the HTF inlet is at -9°C, it is evident that the temperature at layer 2 reduces rapidly below 0°C from room temperature. For the 50% volume level of the capsule, it takes 5070 seconds and for 75% and 90% volume level it reaches at 5520 and 5610 seconds and the HTF shows a rapid reduction in the temperature within a shorter interval till it reaches 0°C and after crossing the 0°C it maintains a constant range of temperature, for a longer duration because of a constant amount of heat transfer occurs in between the PCM and HTF.

**Figure 10.** Temperature history of PCM and HTF in Layer 3 at -9°C

From figure 10, when the HTF inlet is at -9°C, it is evident that the temperature at layer 3 reduces rapidly below 0°C from room temperature. For the 50% volume level of the capsule, it takes 9270 seconds and for 75% and 90% volume level it reaches at 10320 and 13500 seconds and the HTF shows a rapid reduction in the temperature within a shorter interval till it reaches 0°C and after crossing the 0°C it maintains a constant range of temperature, for a longer duration because of a constant amount of heat is been transferred between the PCM and HTF. Due to high disturbance occurs because of the floatation so that the curve appears to be straight from 30000 seconds, which means the PCM starts to solidify, because of the crystal growth which has occurred due to the upward disturbance caused by the capsules below the top layer as well as the upward force exerted by the fluid present in the storage tank.

**Figure 11.** HTF Temperature Profile at Inlet and Outlet of Packed Bed Storage at -9°C
From figure 11 it is evident that the inlet and outlet HTF temperatures though intersect at some points the freezing is not yet completed it is accessed that they do not intersect for a continuous duration. The inlet is not equal to the outlet temperature of HTF and the curve decreases rapidly at the start of the experiment because the previous experimental run has cooled the HTF which is exposed to ambient after the process but the cold energy will be available on the next proceeding run which then comes to normal when fluid circulates. So, from this a conclusion can be arrived that the solidification state is not attained only initiation of solidification has occurred which can be seen at layer 3 it is due to more layers present in the HTF tank and due to the presence of 105 capsules the solidification process is slower and the phase transformation needs more time to end up.

The initial temperature of the constant temperature bath is -9°C, when the pump is switched on the HTF flows into the storage tank and the temperature ingress is raised to -4°C. The difference between ingress and egress is minimum between 30000 seconds, when compared with the temperature history of layer 2 and 3 it is evident that the curve appears straight after 30000 seconds which indicates the start of the solidification process and for layer 1 the curve still descends and needs more duration.

4. Conclusion

This experimental study is a pathway to the packed bed cool thermal storage, the pilot experiment has declared the fact that due to certain shortcomings like the huge number of bulk layers, has increased the time for solidification and only partial initiation of solidification is been established. In this experimental run and the two reference layers in the bottom showed a good response in reaching to a lower temperature faster than top layer at -6°C but when the temperature of HTF is set to -9°C layer 3 initiates solidification due to the disturbances encountered. So, the growth of crystal occurs. The major conclusion drawn from the experiment is as follows.

- The flow rate has a greater effect on the heat transfer phenomenon which is stated as the formulation of working parameters.
- The lower the inlet temperature of the HTF and the faster is the flow rate the time for attaining a lower temperature is less.
- The floatation effect helps in initiating the nucleation behaviour and initiates the growth of the crystal.
- Greater undercooling is observed when HTF bath is at higher temperatures but the decrement of inlet temperature has yielded layer 3 at -9°C to initiate phase change.
- Further studies are to pave a proxy to attain a faster solidification case with the help of additives and nucleating agents thus ensuring to decrease the time to attain lower temperature and complete solidification of PCM inside the spherical capsules and to employ in refrigerating and air-conditioning applications to attain an energy-saving potential.

Acknowledgements
The authors are grateful to SRMIST for providing the required infrastructure to carry out this experimental work.

Conflict of interest
The authors do not have any sort of conflict of interests.
Nomenclature

HDPE                  High Density Polyethylene
HTF                     Heat Transfer Fluid
LDPE                   Low Density Polyethylene
LPH                     Litres Per Hour
PCM                    Phase Change Material
PDTC                  Proportionate Differential Temperature Controller
RTD                    Resistance Temperature Detector
VCR                    Vapor Compression Refrigeration System

References

[1] Sharma, S., & Sagara, K. 2005. Latent Heat Storage Materials and Systems: A Review. International Journal of Green Energy, 2(1), 1-56.
[2] Chaiyat, N., & Kiatsiriroat, T. 2014. Energy reduction of building air-conditioner with phase change material in Thailand. Case Studies in Thermal Engineering, 4, 175-186.
[3] Fang, G., Tang, F., & Cao, L. 2015. Dynamic characteristics of cool thermal energy storage systems—a review. International Journal of Green Energy, 13(1), 1-13
[4] Al-Shannaq, R., Young, B., & Farid, M. 2019. Cold energy storage in a packed bed of novel graphite/PCM composite spheres. Energy, 171, 296-305
[5] Narayanasamy, R., Vellaichamy, P., Sharma, M., & Ramalingam, V. 2021. Experimental investigation on packed bed cool storage system for supply-demand management in building air-conditioning system suitable for micro thermal grid. Thermal Science, 25(1 Part A), 95-106.
[6] Cheralathan, M., Velraj, R., & Renganarayanan, S. 2007. Performance analysis on industrial refrigeration system integrated with encapsulated PCM-based cool thermal energy storage system. International Journal of Energy Research, 31(14), 1398-1413.
[7] Chan, C., & Tan, F. 2006. Solidification inside a sphere—an experimental study. International Communications in Heat and Mass Transfer, 33(3), 335-341.
[8] Bédécarrats, J., Strub, F., Falcon, B., & Dumas, J. 1996. Phase-change thermal energy storage using spherical capsules: performance of a test plant. International Journal of Refrigeration, 19(3), 187-196.
[9] Bédécarrats, J., Castaing-Lasvignettes, J., Strub, F., & Dumas, J. 2009. Study of a phase change energy storage using spherical capsules. Part I: Experimental results. Energy Conversion and Management, 50(10), 2527-2536.
[10] Bédécarrats, J., Castaing-Lasvignettes, J., Strub, F., & Dumas, J. 2009. Study of a phase change energy storage using spherical capsules. Part II: Numerical modelling. Energy Conversion and Management, 50(10), 2537-2546
[11] Ismail, K., & Henriquez, J. 2002. Numerical and experimental study of spherical capsules packed bed latent heat storage system. Applied Thermal Engineering, 22(15), 1705-1716.
[12] Chandrasekaran, P., Cheralathan, M., & Velraj, R. 2015. Influence of the size of spherical capsule on solidification characteristics of DI (deionized water) water for a cool thermal energy storage system – An experimental study. Energy, 90, 807-813.
[13] Chandrasekaran, P., Cheralathan, M., & Velraj, R. 2015. Effect of fill volume on solidification characteristics of DI (deionized) water in a spherical capsule – An experimental study. Energy, 90, 508-515.