Solidification behavior of water based Al$_2$O$_3$ nanofluids phase change material for energy efficient cool thermal storage system

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Abstract. The present study aims to investigate the solidification behavior of water based Al$_2$O$_3$ nanofluid phase change material encapsulated in a spherical capsule suitable for cool thermal energy storage application. The nanofluid phase change material is prepared by dispersing the Al$_2$O$_3$ nanoparticles mixed with DI water, which is used as a base phase shift material with a volume fraction of 0.1 %. The experiments are conducted with DI water and the Al$_2$O$_3$ nanofluid phase change material at surrounding bath temperatures of -6, -9 and -12 °C respectively. The presence of Al$_2$O$_3$ acts as a nucleating agent that causes an elimination in under cooling. The enhanced thermal properties of the Al$_2$O$_3$ are very useful to dissipate the concealed heat faster and helps to operate the CTES at higher operating temperature for a lesser duration, when compared with PCM where the nucleating agent is absent. So, this act fetches an energy-saving potential.

1. Introduction

In recent years, cool energy storage systems are mainly an important and efficient system for the storage of the cool thermal energy and it is acting an important function in failing the high load demand for different thermal engineering applications like building air-conditioning, high power electronic cooling components and various industrial heating and cooling process etc. Among the many researchers more focus on the PCM based cool storage system due to an unbroken raise in the energy utilization needed for the aforementioned applications [1-2]. The cool thermal energy storage system using the phase change materials is greater valuable for the period of off-peak times as they have power over high storage mass density in a constant temperature approach for a specified temperature potential. PCMs base CTES systems are highly profitable for building cooling applications to run the refrigerating unit at a more COP by utilizing the lesser surrounding temperature environment of the night. As compared to all other types of phase change material, water is mostly used in the energy storage systems by reason of much great latent heat, superior thermal conductivity ratio and more accessibility etc. One of the major problems with base PCM (water) is the subcooling that occurs during the solidification process in the energy storage unit that demand s lesser evaporator temperature in the refrigeration and that minimizes the performance of the refrigeration unit [3].

In the CTES systems, it is a requirement to eliminate the effect of subcooling and reduce the solidification time, which leads to an increase in the performance of CTES systems. In that way many researchers focus on the special methods such as inserting fins [4-5], dispersing more conductive solid particles at nano to micro scale [6] and providing metal matrix [7] in the CTES systems. The selection of PCM is more important as it affects solidification, heat transfer rate and needs to be compatible with the encapsulation material. Several researchers worked on the mixing of nanoparticles or nano
powder to the PCM, minimize the solidification time and eliminated the subcooling extensively under changeable volume ratio of NFPCM and it is helps to the secondary refrigerant can achieve higher performance working temperature in the storage system [8]. The major characteristics necessary for excellent NFPCM are good thermal conductivity, superior specific heat capacity and more latent heat of fusion per unit volume etc. Adding various nanoparticles to the base PCM at various experimental factors was explored by the researchers. Generally, they used different nanoparticles such as copper [9], silver [10], copper oxide [11], TiO₂ [12], MWCNT [13]. Their outcomes undoubtedly mention that the mixing of nanoparticles to the phase change material enhanced the thermal behaviors of the phase change material considerably with slight vary in the latent heat and also concentration of the nanoparticles generally depended on the enhancement of thermal transport behaviors.

MWCNT with volume fractions of 0.15, 0.3, 0.45 and 0.6 percentage are used in base PCM. The results show that the presence of NFPCM improved the thermal behaviors and appreciable reduction in the subcooling has taken place [14]. The solidification performance of CuO nanofluid phase change material has resulted in the increase of heat transfer rate without subcooling [15]. The addition of graphene nanoplatelets with water in a spherical container resulted in minimize in the subcooling of DI water from -7 °C to -2.5 °C and falling of 25% of solidification time due to its high specific surface area and more thermal conductivity [16]. From the above research work, the present work is expected to study the solidification behavior of water based Al₂O₃ nanofluid PCM at constant bath temperature condition, in order to discover the opportunity of elimination of subcooling and reduce the solidification time.

2. Preparation of NFPCM

Preparation of nanofluid PCMs is the most excellent and important steps to improve the thermal properties of Phase change material in cool storage systems. Two-step technique was mostly preferred to prepare the nanofluid PCM. The base PCM like as the DI water and Al₂O₃ like as the nanoparticle, 0.1 wt. % Al₂O₃ nanoparticle was added with base PCM then the solution was stirred thoroughly by a magnetic stirrer via and the process was continuously done for 25 min. Then the next step is to be ultra-sonicated in an ultrasonic cleaner constantly at a frequency of 45 kHz for 45 min. In final steps, the solution was probe-sonicated in an ultrasonicator for 15 min.

![Figure 1. Magnetic Stirrer Machine](image_url)
Figure 2. Ultrasonic cleaner

Figure 3. Ultrasonic Probe-sonicator

Figure 4. Al$_2$O$_3$NFPCM
3. Experimental Setup

The layout of the solidification work process setup is shown in figure 5, to conduct the thermal characteristic behavior of the NFPCM for the duration of the solidification process in the cool storage system. The main components of the setup are primary refrigeration unit, spherical shape capsule, isothermal bath, Proportionate differential temperature controller and data logger with the temperature sensors. The secondary refrigerant consists of a mixture of 30% ethylene glycol and 70% water by volume and it is a heat transfer fluid filled in the isothermal bath. The isothermal bath was insulated with polyurethane and fabricated of stainless steel capacity of 0.0145 m³. A primary refrigeration system has a capacity of 3 kW which helps to achieve required bath temperature and a heating coil has a capacity of 3 kW using the proportionate differential temperature controller.

A mechanical stirrer was fixed at the top of the tank, which is used to keep up a constant temperature of the bath. In this work, two counts of a spherical shape capsule are taken and it is fabricated of low density polyethylene material diameter of 70 mm. The first capsule 90% of its total volume the NFPCM is filled and second one is 90% of base fluid is filled with the use of standard volumetric flasks. Each spherical capsule has four temperature sensors used to sense the temperature of the PCM and NFPCM during the solidification process. Among the four RTDs, One was fixed at the center of the capsule (RTD 4) and other RTDs were fixed at the bottom portion of the spherical capsule at the 18.9 mm (RTD 3), 13.1 mm (RTD 2) and 7.3 mm (RTD 1) from the bottom point respectively for both 70 mm spherical capsule. Starting the experiment, Initially the surrounding bath temperature was achieved at constant temperature and once constant temperature was attained the two spherical shape capsules are dipped in the isothermal bath at particular distance downward. The experiments were taken out with various constant ambient bath temperatures of -6,-9 and -12 °C. For every 30 sec, the nanofluid phase change material and base PCM temperature variation was continuously measured with the use of a data acquisition equipment. The measurement was nonstop awaiting the temperature of the PCM at the center of the spherical capsule reached at a constant ambient bath temperature.

**Figure 5. Layout of the experimental setup**
Figure 6. RTDs and spherical capsule arrangement

Figure 7. Constant temperature water bath
4. Results and Discussion

In this section discussion about the different between the solidification time and subcooling of DI water and Al$_2$O$_3$ nanofluid phase change material during the solidification process in the CTES system.

![Figure 8. Temperature history of DI water at -6 °C](image1)

![Figure 9. Temperature history of DI water + Al$_2$O$_3$ at -6 °C](image2)
From the figure 8, it is observed that the spherical capsule filled with DI water as PCM showed a highest subcooling of 2.86 °C at center. The solidification time for the centre of the capsule is 7320 seconds and at 18.9 mm, 13.1 mm, 7.3 mm distance from the bottom of the capsule is 5670, 2970, 2400 seconds, respectively. From figure 9, the spherical capsule filled with DI water + Al₂O₃ eliminated the subcooling at all the position of RTD’s and the solidification time for the centre of the capsule is 5280 seconds and at 18.9 mm, 13.1 mm, 7.3 mm distance from the bottom of the capsule is 3360, 1590, 690 seconds respectively.

**Figure 10.** Temperature history of DI water at -9 °C

**Figure 11.** Temperature history of DI water + Al₂O₃ at -9 °C

From the figure 10, it is observed that the spherical capsule filled with water as PCM showed a maximum subcooling of 1.4 °C at center and eliminated the subcooling at 7.3 mm distance from the bottom of spherical capsule. The solidification time for the centre of the capsule is 5160 seconds and at 18.9 mm, 13.1 mm, 7.3 mm distance from the bottom of the capsule is 3630, 2400, 1260 seconds.
respectively. From figure 11, the spherical capsule filled with DI water + Al₂O₃ totally eliminated the subcooling at all the position of RTDs and the solidification time for the centre of the capsule is 4350 seconds and at 18.9 mm, 13.1 mm, 7.3 mm distance from the bottom of the capsule is 2730, 1890, 660 seconds respectively.

Figure 12. Temperature history of DI water at -12 °C

From the above figure 12 and 13, it is observed that the completely eliminated the subcooling at a constant bath temperature of -12 °C. From figure 12, where only DI water is used and the solidification time for the centre of the capsule is 3510 seconds and at 18.9 mm, 13.1 mm, 7.3 mm distance from the bottom of the capsule is 2220, 1470, 630 seconds respectively and figure 13, where DI water + Al₂O₃ is used and the solidification time for the centre of the capsule is 2570 seconds and at 18.9 mm, 13.1 mm, 7.3 mm distance from the bottom of the capsule is 1740, 1100, 540 seconds respectively.

Figure 13. Temperature history of DI water + Al₂O₃ at -12 °C
5. Conclusion

- It is concluded that the solidification time for Al$_2$O$_3$ nanofluid phase change material is reduced as compared to the base phase change material (DI water) at all ambient bath temperatures of -6 °C, -9 °C and -12 °C.
- The subcooling of base phase change material (DI water) is reduced with decrease in the temperature range of constant temperature bath.
- The subcooling is eliminated when Al$_2$O$_3$ nanofluid phase change material is added to the base PCM at all set temperatures.
- As the solidification duration is less for nano-fluid based PCM, the overall energy consumption by the evaporator reduces, which fetches an energy-saving potential because of higher operating temperature.

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