Experimental investigation on solidification behavior of water based CNT nanofluids for cool thermal storage system

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ABSTRACT

This study aimed to investigate the thermal performance of a new sort of nano enhanced phase change material (NEPCM) for cool thermal storage energy storage (CTES) system. The NEPCM was prepared by suspending 0.1 wt. % multiwall carbon nanotubes (MWCNT) in deionized water (DI water) along with the nucleating agent. The stabilizing agent, sodium dodecylbenezene sulphonate (SDBS), was used to stabilize the MWCNT in water. The experiments were conducted at various surrounding bath temperatures with the NEPCM. The results evidently showed that reduction in freezing duration of ~ 25% compared to that of DI water and the presence of pseudomonas diminished the sub-cooling completely. Further, the fraction of mass solidified at various time intervals revealed that 50% of the PCM was frozen in 25% of the total freezing time for both the cases of the water PCM and NEPCM. The enhanced heat transport properties of the NEPCM without sub-cooling and accelerating charging will be very useful in designing energy efficient CTES system.

Keywords: NEPCM, sub-cooling, carbon nanotubes, nucleation, cool thermal energy storage.

1 INTRODUCTION

Considering environmental protection and the great uncertainty over future energy supplies, the researchers, policy makers, environmentalists and building architects are mainly focusing on the utilization of sustainable energy sources and energy conservation methodologies. Among the various energy consuming industries, the building sector consumes nearly *40%* of the world's energy consumption and the major portion of this energy is being utilized for air conditioning applications in large buildings. There is an immense potential for reducing the energy demand and improvement in energy-efficiency of the buildings, through the integration of cool thermal energy storage (CTES) system by storing the cool energy during the off - peak hours and shifting the usage of the stored cool energy to the peak hours. Among the various CTES methods, the most promising and preferred method is the latent heat thermal storage (LHTS) system using phase change materials (PCMs), due to its high storage density and small temperature variation from storage to retrieval [1]. However, the major limitations are its inherent low thermal conductivity and sub cooling behavior, that reduce the performance of the LHTS system considerably.

The pioneering advancements in the field of nanotechnology play a vital role to to improve the thermal transport properties of PCM by dispersing the nanometric solid particles in the base PCM. The present research work attempts to overcome the above addressed challenges in the heat transfer fluid and PCM, by developing suitable nano heat transfer fluids and nanofluid phase change materials. Recently, the thermal performace of the nano enhanced PCM were experimentally studied for various base PCMs dispersed with the nanoparticles such as alumina [2,3], copper [4], silver [5], TiO_2 [6], SiO_2 [7], graphene [8] and MWCNT [9]. Their results have clearly shown that the addition of nanoparticles increased the thermal transport properties of the PCM appreciably with negligible change in the latent heat and the enhancement mainly depended on the concentration of the nanoparticles. It is also found from the literature that the solidification characteristics of water based CNT nanofluids for the CTES application was not reported. Considering the pressing need to enhance the performance of CTES system, this research work aimed to investigate the solification characteristics of water based MWCNT nanofluids encapsulated in a spherical container at various operating temperature conditions.

2 EXPERIMENTAL DETAILS

2.1 Preparation of Nano-Enhanced PCM (NEPCM)

Preparation of NEPCMs is the major key step to enhance the heat-transfer performance of PCM in thermal storage application. The proper mixing and stabilization of the nanoparticles in the base PCM are required in order to prepare stable NEPCM. It is well-known that CNTs are hydrophobic, and prone to aggregation and precipitation in water and the inherent bundling of the tubes caused by strong Van der Waals forces, non-reactive surface properties, very large specific surface areas, and aspect ratios, make the preparation of more challenging. In the present study, deinonised water as the base PCM (DI water), sodium dodecyl benzene sulphonate (SDBS) as a surfactant, pseudomonas as a nucleating agent and multi-walled carbon nanotubes (MWCNT) as nano-material were used to prepare the NEPCM by two step method. In order to disentangle the nanotubes, the ball milling of the MWCNT was carried out using 10 mm tungsten carbide balls for 45 min, followed by ultra-sonication for 60 min under dry conditions. The nucleating agent (0.1 wt. %) and DI water along with the SDBS (0.1 wt. %) were mixed homogeneously using a magnetic stirrer for 10 mins. The MWCNT (0.1 wt. %) were added to water solutions and the stirring was continued for next 20 mins. The suspension was transferred into an ultra-sonic vibrator and sonicated for 1 h ata frequency of 40 kHz. The size of the dispersed MWCNT was measured using Scanning Electron Microscope and the size of dispersed MWCNT was 36 to 55 nm as shown in Figure 1.

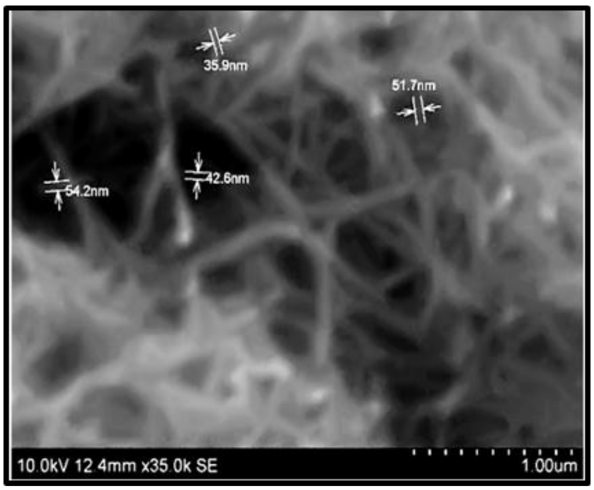


Figure 1 SEM image of the dispersed MWCNT

2.2 Experimental setup

Figure 2 shows the schematic of the experimental setup to conduct the heat transfer studies during the solidification of the NEPCMs. This setup consists of a polyurethane insulated stainless steel tank of capacity 0.01m^3, filled with a mixture of 70% water and 30% ethylene glycol by volume (normally used as secondary refrigerant in cool thermal storage systems employed in large scale air conditioning applications). A heating coil of the capacity 2,000 W and a chiller unit of the capacity 5 kW were used to simulate the required bath temperature in the tank. In order to maintain the desired temperature of the bath, a proportionate temperature differential controller (PTDC) was used to vary the heating coil output based on the temperature of the bath measured by the RTD sensor. A mechanical stirrer driven by an electrical motor of capacity 9 W (speed 1,280 rpm) was provided from the top, to maintain a uniform temperature of the bath in the tank. A Low Density Poly Ethylene (LDPE) spherical capsule of 68 mm inner diameter made of two hemispheres screwed together is filled with the NEPCM to 90% of its full volume. Five numbers of RTDs (PT-100) with an accuracy of ± 0.1°C were placed at various radial locations; one was at the center of the spherical capsule as shown in the figure insert and the remaining RTDs were at a distance of 15 mm, 25 mm, 30 mm and 34mm from the center of the spherical capsule. All the RTDs are connected to a data logger of Agilent make (34970A) with an accuracy of 0.004% to store the continuous data generated during the experiments.

The temperature of the surrounding bath was maintained at a desired value, below the solidification temperature of the PCM through the PTDC. Two spherical capsules filled with the NEPCM were immersed into the tank at a specified depth, and the test was initiated. Two different experiments were conducted to determine the total freezing time and the frozen mass fraction for every predetermined time interval during the solidification process. In the first experiment, the temperatures measured by the RTDs located at the various locations in the spherical capsule were monitored continuously for every 30 s and the experiment was continued until the PCM in the center of the spherical capsule attained a temperature very close to the surrounding heat transfer fluid. In the second experiment, two spherical capsules were immersed in the bath during the first trial, and they were taken out from the bath one by one at a predetermined time interval of 10 mins after the commencement of freezing. The capsules were then unscrewed and the liquid NEPCM present inside the spherical capsule was drained. The mass of the drained NEPCM was measured using a high precision electronic balance with the accuracy of ±0.002 g. The solidified mass

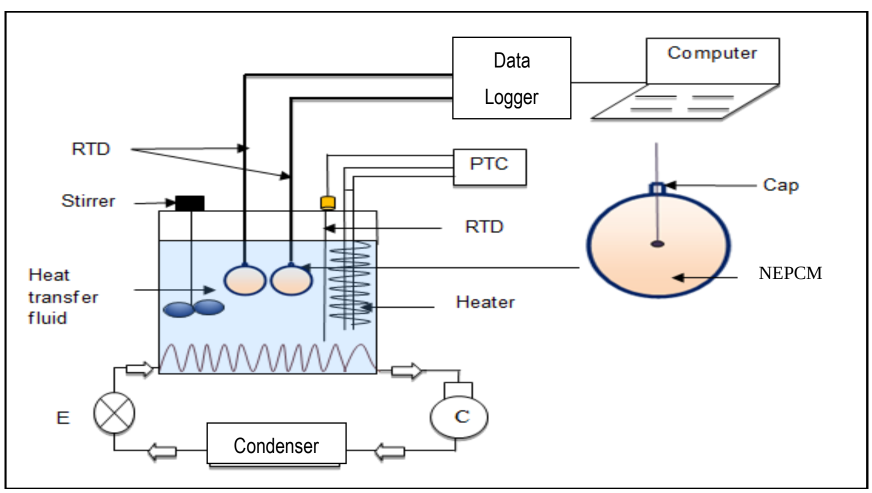


Figure 2 Schematic of the experimental setup

was calculated by subtracting this measured value from the initial weight of the NEPCM. Another batch of two such spherical capsules were kept in the tank to determine the frozen mass beyond 20 minutes after the onset of freezing, and this process was continued till the completion of freezing. The experiments were carried out at different bath temperatures of -2°C and -6°C with the NEPCM. The experimental trails were also conducted with the NEPCM at the surrounding bath temperature of -9°C and -12°C without the nucleating agent in order to assess the reduction in the sub-cooling of the PCM with the presence of MWCNT.

3 RESULTS AND DISCUSSIONS

3.1 Transient temperature of the NEPCMs

Figure 3 shows the temperature-time history at the center of the spherical capsule for the water PCM and NEPCM without the nucleating agent at the various surrounding bath temperatures. It is noticed from the figure that the presence of MWCNT reduced the sub-cooling considerably compared to pure water PCM depending on the cooling rate. This is due to enhanced thermal conductivity of water PCM with the addition of MWCNT. However, the existence of sub-cooling demands the lower evaporator temperature in a chiller to initiate the nucleation of the PCM, which affects the performance of the CTES system significantly. Hence, it was proposed to study transient solidification behavior of the NEPCM with the nucleating agent at the bath temperature of -2°C and -6°C.

Figure 4 shows the temperature - time history at the center of the spherical capsule for the water PCM and NEPCM, when the surrounding bath temperature was maintained at -2°C. The figure shows clearly the distinct phases of sensible cooling in the liquid region, the start of freezing, end of freezing and the sensible cooling in the solid region are clearly shown in the figure. It is observed from the figure that the start of solidification commences after 30 minutes for both the cases and there is a reduction in the freezing duration of 25% in the case of NEPCM compared to that of water PCM (135 and 180 min in the case of NEPCM and water PCM respectively). Figure 5 shows the results of the similar experiment conducted by maintaining the surrounding bath temperature at -6°C. During this experiment, the start of solidification commenced after 25 minutes for both the cases. The freezing duration was 115 min in the case of NEPCM and 155 min in the case of the water PCM, which showed a reduction of 26% in the freezing duration with NEPCM. It is construed from the above two results that the addition of MWCNT has much influence on freezing compared to the results achieved by increasing the temperature potential between the HTF and PCM. In addition to reduction in freezing duration, the presence of pseudomonas diminished

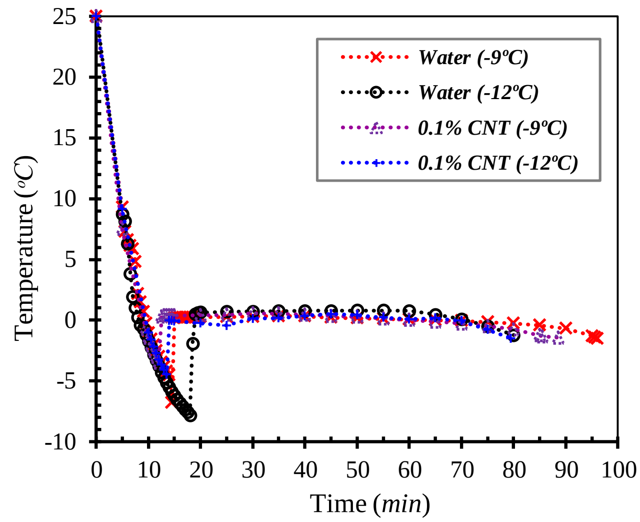
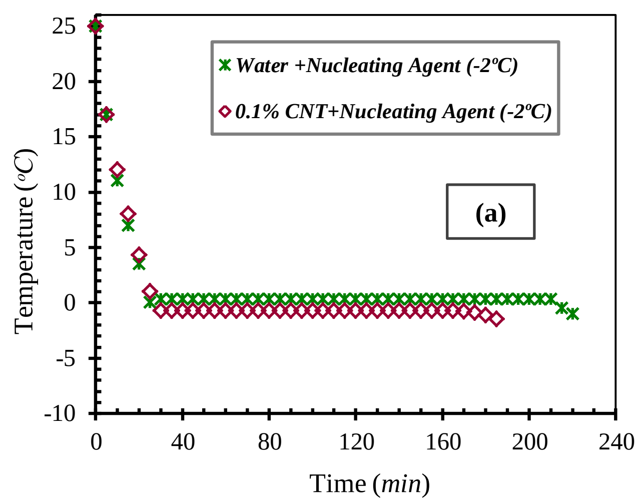


Figure 3 Transient temperature variation of water PCM and NEPCM



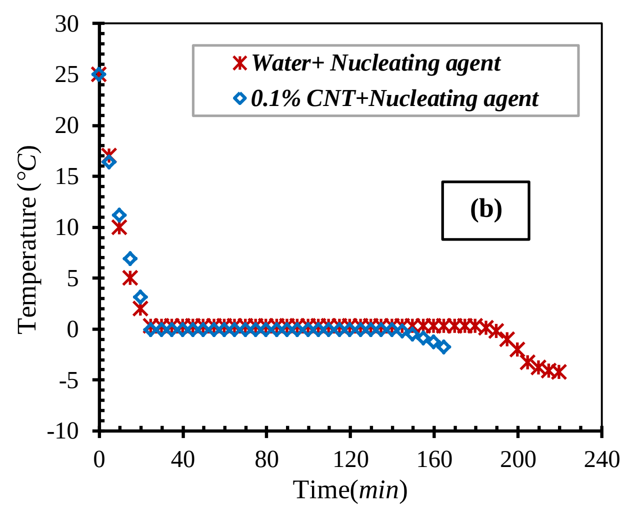


Figure 4 Temperature-Time history at centre (a)T_{surr} = - 2°C (b) T_{surr} = - 6°C

the sub-cooling completely that allow the CTES to operate at the máximum posible high temperature depending on the applications for which the CTES is to be designed.

3.2 Mass Fraction Solidified

Figures 5(a) and (b) show the mass fraction solidified at various time intervals during the solidification process for the experiments conducted with the water PCM and NEPCM, when the surrounding bath temperature was maintained at -2°C and -6°C respectively. It is observed from the figures that for both the cases, the freezing starts only after 25 to 30 min from the start of the experiment. During this period, the sensible cooling occurs from 25°C to 0°C, and the effect of the MWCNT is not significant in enhancing the heat transfer. This is due to increase in the viscosity of the NEPCM that suppressed the free convection during the sensible cooling.

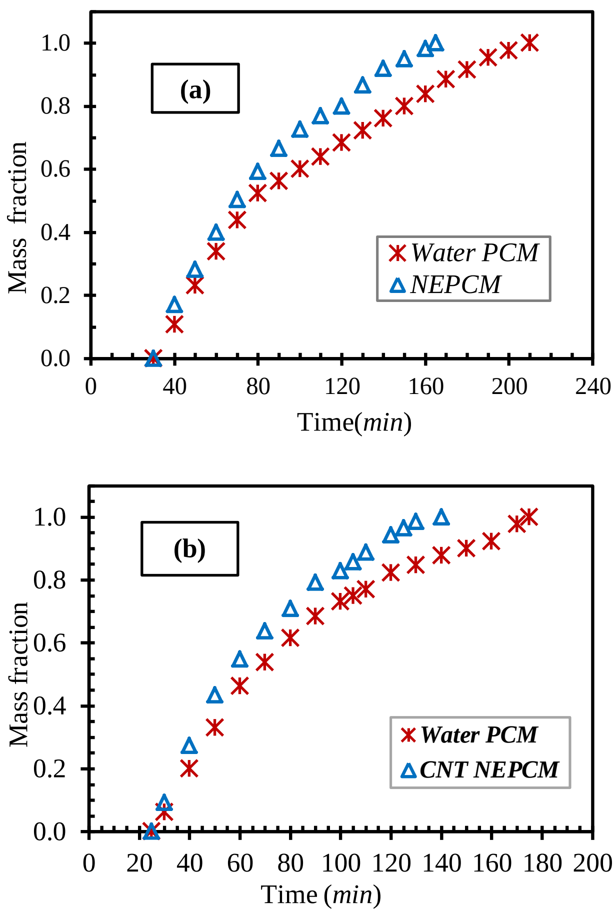


Figure 5 Mass fraction solidified with respect to time (a)T_{surr} = - 2°C (b) T_{surr} = - 6°C

Further, it is observed from the present results that more than 50% of the PCM was frozen in 25% of the total freezing time for both the cases of the water PCM and NEPCM when the bath temperature was at -2°C. Another 25% of the PCM was frozen in the next 25% of time and during the last 50% of the solidification time, only 25% of the remaining PCM was frozen. This shows that accelerated charging prevailed during the first 25% of the freezing time, average charging prevailed during the next 25% of the freezing time, and decelerated charging prevailed during the remaining 50% of the time. Hence, it is construed from the above results that the solidification rate during the first 25% of the total duration is twice the average rate, and hence, the consideration of 50% of the PCM in the spherical ball for designing the required capacity of the thermal storage system will provide efficient short duration charging and discharging.

4 CONCLUSIONS

The following conclusions are arrived at, based on the experimental results. The presence of pseudomonas diminished the sub-cooling of the PCM completely and this will help the CTES to operate at the highest possible surrounding heat transfer fluid temperature. The presence of MWCNT resulted with the reduction in the freezing duration of 25% in the case of NEPCM compared to that of water PCM. Further, the major problem of non uniform charging and discharging encountered in the latent heat storage system can be alleviated, by considering only 50% of the PCM while designing the CTES system for the applications that demand the large uniform thermal energy in a short duration.

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