EXPERIMENTAL INVESTIGATION OF FREEZING BEHAVIOUR OF NFPCM IN SPHERICAL CAPSULES OF DIFFERENT DIAMETERS

A PROJECT REPORT

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BONAFIDE CERTIFICATE

Certified that this project report titled " **EXPERIMENTAL INVESTIGATION OF FREEZING BEHAVIOUR OF NFPCM IN SPHERICAL CAPSULES OF DIFFERENT DIAMETERS**" is the bonafide work of "**ABHISHEK KUMAR** [1021310473], **AMMRATANSH GHILDYAL** [1021310484] and **MARKANDEYA TRIPATHI** [1021310527] "who carried out the project work under my supervision. Certified further, that to the best of my knowledge the work reported herein does not form any other project report or dissertation on the basis of which a degree or award was conferred on an earlier occasion on this or any other candidate.

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ABSTRACT

The objective of the present work is to investigate the freezing behavior and solidification characteristics of nanoparticle enhanced phase change material (NFPCM) for various cooling applications at different experimental conditions. The NFPCM was prepared by dispersing the carbon Nano tube (CNT) at concentration of 0.3% wt in DI water as the base PCM. The surfactant used was sodium dodecyl benzene sulphate (SDBS) and the thermal conductivity of NFPCM was measured at atmospheric temperature. The experimental results show that 16 % enhancement in the thermal conductivity with addition of 0.3% wt of CNT to the base PCM, due to the increase in surface area and high thermal conductivity of CNT. The experiment was also conducted to explore the effect of CNT alone in water at various surrounding bath temperatures. The results clearly showed that the presence of high conductive CNT acted as a nucleating agent to initiate the solidification of the NFPCM in advance to that the base PCM through considerable reduction in the degree of sub cooling. The addition of CNT also reduced the solidification duration of the NFPCM by 10-12% than that of the base PCM at the surrounding bath temperature of -12°C.

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LIST OF SYMBOLS AND ABBERIVIATIONS

PCM	Phase Change Materials
TES	Thermal Energy Storage
LHTES	Latent Heat Thermal Energy Storage
SHTES	Sensible Heat Thermal Energy Storage
SHS	Sensible Heat Storage
CTES	Cool Thermal Energy System
NFPCM	Nano Fluid Phase Change Material
NEPCM	Nanoparticle enhanced phase change material
m	Total mass of the flank with NFPCM(kg)
m_f	Mass of empty flask(kg)
C_p	Specific heat capacity (kJ/kgK)
V_{nf}	The volume of NFPCM
RTD	Resistance Temperature Detectors
K	Thermal ConductivityW/mK)
T_{surr}	Surrounding bath temperature(°C)

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In an industry or any process when either energy is created or energy is consumed a residual energy is formed which is called heat energy. This heat energy is produced because energy conversion in industries is not from high grade energy instead the conversion is done from low grade energy like electricity and when low grade energy is converted to other form through some process we cannot get 100% efficiency and this loss in efficiency is due to heat generation. This heat generated need to be removed or we will observe the efficiency of the system will decrease even more and even the working atmosphere does not remain sustainable to human being. To reduce this heat generated we use coolant in industries, refrigeration and electronics. This coolant can be in different states like liquid, solid or gas. Solid coolant includes use of metal which have the capacity to conduct the heat through them, then in liquid state we have most popular coolant water but the thermal conductivity of water is also found to be low like 0.509W/mK, in gaseous state the coolant available most popularly is air which is used most often in electronics. These are the conventional type of coolant used and also their value of thermal conductivity is less but in order to improve their thermal conductivity scientist started their research on the dispersed fluid.

The concept of using dispersed fluid was observed in many experiment as they were showing higher value of thermal conductivity, the reason behind the high thermal conductivity was the Brownian motion and which was observed in the dispersed fluid.

THERMAL ENERGY STORAGE SYSTEM

The ability of thermal energy storage (TES) systems to facilitate energy savings, renewable energy use and reduce environmental impact has led to a recent resurgence in their interest. The second edition of this book offers up-to-date coverage of recent energy efficient and sustainable technological methods and solutions, covering analysis, design and performance improvement as well as life-cycle costing and assessment. As well as having significantly revised the book for use as a graduate text, the authors address real-life technical and operational problems, enabling the reader to gain an understanding of the fundamental principles and practical applications of thermal energy storage technology. The use of the TES system has the following significant benefits:

- Reduced energy costs.
- Reduced energy consumption
- Improved indoor air quality

- Increased flexibility of quality
- Reduced initial and maintenance costs
- Reduced equipment size
- More efficient and effective utilization of equipment
- Conservation of fossil fuels(by facilitating more efficient energy use and or fuel substitution).
- Reduced pollutant emissions.

TYPES OF THERMAL STORAGE SYSTEM

Sensible heat storage system

Sensible storage is the most common method of heat and cold storage. Properties important in this technology are price and thermal capacity [$\rho.c_p$], operational temperatures, thermal conductivity and dif-fusivity, vapour pressure, compatibility with container materials and heat-loss coefficient. In more recently developed applications, such as large-scale sensible heat storage in solar power plants, other highly valued properties are availability, conflict of use and the lifecycle environmental impact of the plant.

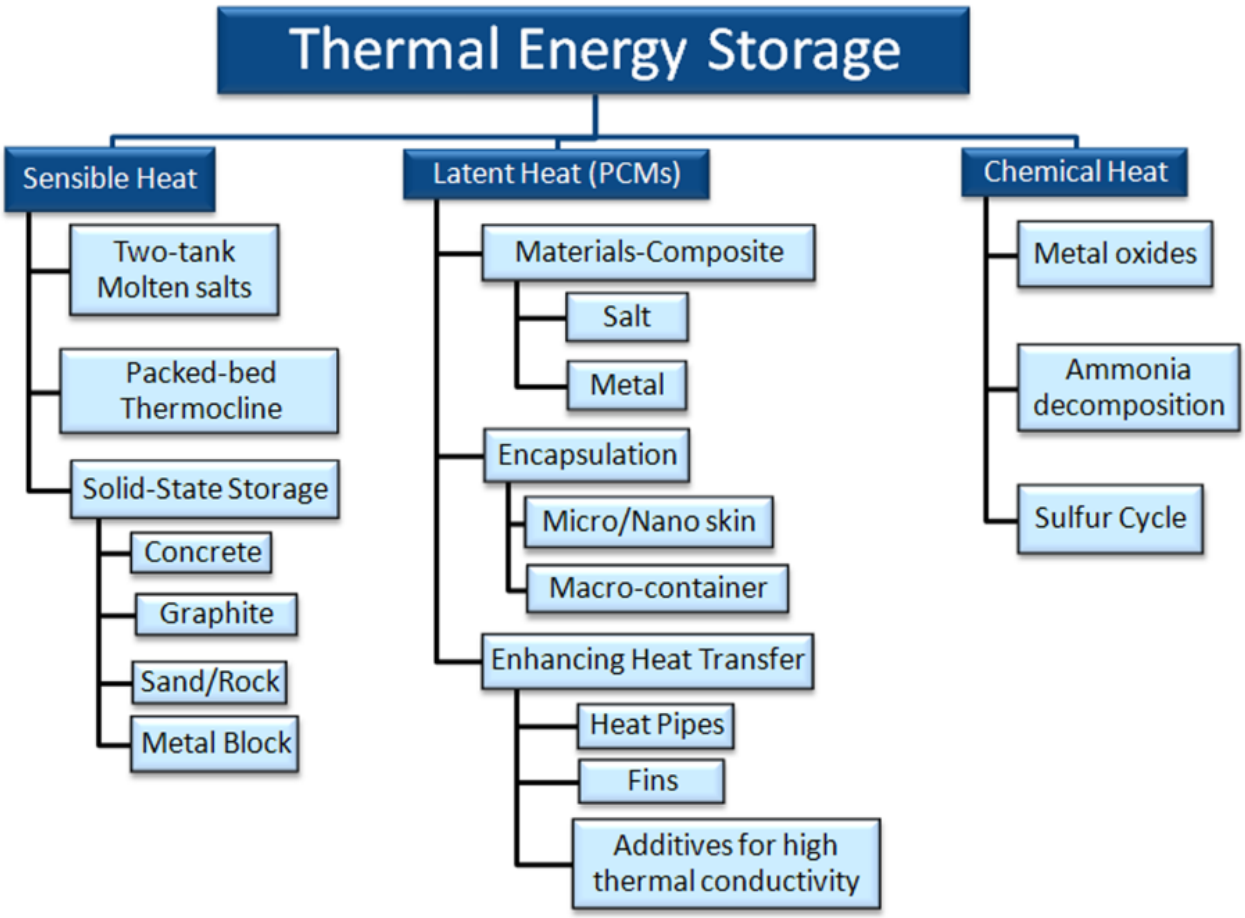
Latent Heat Storage System

Latent heat storage system use the energy absorbed or released during the isothermal phase change of materials. A first selection of suited storage materials is based on the melting temperature which should be close to the saturation temperature which is dependent on the pressure of the steam. Since systems using direct steam generation are operated at pressures between 30 and 100bar the melting temperature of phase change materials (PCM) should be in the range of 230°C and 330°C. Due to cost aspects metallic materials like tin or lead can't be used, instead salts like sodium nitrate or potassium nitrate are typical candidate materials. A direct contact between storage material and steam is not possible, so thermal energy has to be transferred within the storage material. Cost effective storage systems demand high internal heat fluxes, which depend mainly on the heat conductivity of the storage material. Non-metallic storage materials usually show low heat conductivities, especially the solid phase behaves like a thermal isolator. Essential for the development of cost effective storage systems is the increase of the effective heat conductivity in the storage material. DISTOR include research on three different concepts for PCM-storage:

Chemical Heat Storage System

Thermochemical materials (TCMs) are a promising solution for seasonal heat storage, providing the possibility to store excess solar energy from the warm season for later use during the cold season, and with that all year long sustainable energy. With our fixed bed, vacuum reactors using zeolite as TCM, we recently demonstrated long-term heat storage with satisfactory output power. For domestic application, however, it will be necessary to

considerably increase storage density and to reduce system costs. In this paper, we discuss issues on system, component and material levels for realizing a commercially attractive system. We first discuss a modular, fixed bed concept with a hot water storage. We show that with proper dimensioning of TCM modules and hot water storage, one can obtain a system where daily storage and on-demand heat delivery can be arranged by the hot water storage, while demands on output power, power control and material stability during operation are relaxed as much as possible. We also discuss atmospheric and central reactor concepts, which may provide lower-cost TCS systems. An important issue on component level is the implementation of a low temperature source providing evaporation heat in winter. We discuss several options, including the application of solar collectors in winter. Heat storage density can be increased by an order of magnitude by applying hydration reactions of hygroscopic salts, but this introduces physical and chemical stability issues during repeated cycles of hydration and dehydration. We discuss several of these stability issues as well as possible stabilization in a composite TCM, which should also provide sufficient vapor and heat transport.



Thermal Energy Storage Materials

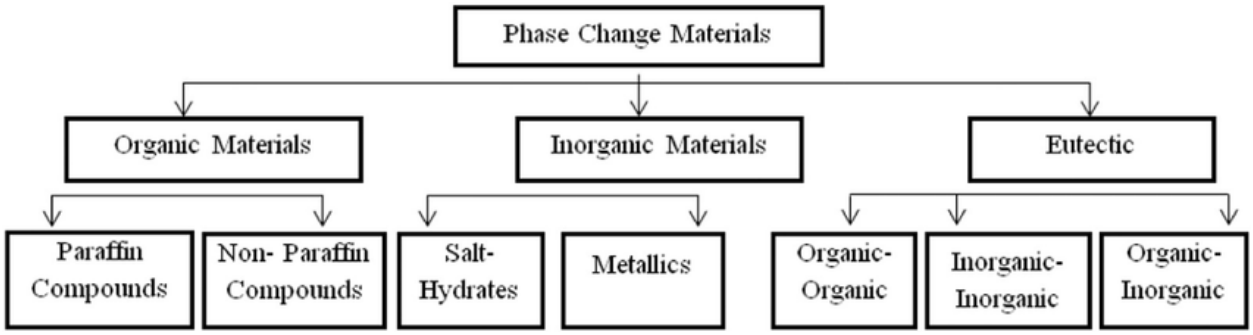
SENSIBLE HEAT STORAGE MATERIALS

Heat stored by changing the temperature of a storage medium (such as water, air, oil, rock beds, bricks, concrete or sand), is stored as sensible heat. The amount of energy stored is proportional to the temperature rise, the specific heat capacity of the storage medium and the mass of the medium. Choices of medium are usually based on the heat capacity of the medium, the range of temperatures at which the store will operate and the space available for it.

PHASE CHANGE MATERIALS

A **phase change material** (**PCM**) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units.

The application of PCMs in buildings can have two different goals (Pasupathy, Velraj & Seeniraj, 2008). First, the PCMs can be used to utilize natural heat and cold sources. For instance, solar energy for heating during the evening/night or the use of night cold for cooling during the day. Second, PCMs can use manmade heat or cold sources.



1.2 **CONCEPT OF NANOFLUID**

Fluids with inclusions of higher thermal conductivity particles are being considered as an option to improve the thermal properties of such fluids with a minimal increase in viscosity. Many research activities have been carried out in the past to improve the thermal properties of these fluids by seeding a small quantity of highly thermally conductive macro/micro sized particles in it [1]. However, this has not been very successful because of settling of the solid particles due to their large size [1]. Recent developments in the field of Nanoscience have led to the development of a new class of fluids termed "Nanofluids" [2]. Over the past decade, Nanofluids—colloidal dispersions prepared by uniformly dispersing nanostructures such as Nanoparticles, Nanotubes and Nanosheets in conventional heat transfer fluids—have gained attraction worldwide because of their superior thermal performance [3-5].

1.3 **MULTI WALLED CARBON NANOTUBE**

Since the discovery of carbon nanotubes (CNTs) in the early 1990s there has been a growing interest in nanotube based research as indicated by reported trends in published articles and patents. The high surface area and large aspect ratio (length to diameter ratio) of this material, along with low mass density, make carbon nanotubes an ideal for preparation of nanofluid. However, as a result of the nanoscopic dimensions and high aspect ratio of MWCNTs, deviations from expected physical behavior from traditional equations are found. This behavior is indicative of the increased shear thinning phenomenon and also the effect of Brownian motion. A variety of chemical and physical techniques have been employed in the literature to process nanotubes as individuals. Specifically, bulk rheological properties of the system were measured revealing the unique viscoelastic behavior of this new class of material. It was found that the nanotubes formed an elastic network above a critical concentration and show nonBrownian behavior under imposed shear. Additionally, an interesting low shear aggregation phenomenon was discovered. Comparative analysis with respect to varying nanotube surface chemistry was performed in order to determine what controlling factors are responsible for dispersion stability.

1.4 THERMO-PHYSICAL PROPERTIES OF NANO FLUID

Over the last several decades, many researchers have focused their efforts on developing fluids with better heating or cooling performance compared to conventional heat transfer fluids such as water, ethylene glycol or engine oil. One of the recent techniques to improve heat transfer is suspending small amount of some species of metallic or non-metallic nanoparticles with high

intrinsic thermal conductivity in these common fluids. In this regard, Choi [6] was one of the first researchers who developed nanoparticles and then dispersed them in a fluid that he called nanofluid. In recent years, various studies have been conducted on the heat transfer performance of nanofluids due to their noticeable advantages including enhanced thermo-physical properties, long-time stability, remarkable convective heat transfer enhancement as well as little penalty in pressure drop increment. Although these benefits might not occur together, some of the existing published studies associated with the thermo-physical properties and heat transfer behavior of nanofluids are cited as follows. There is a host of researches on the thermo-physical properties of nanofluids. Lee et al. [7] investigated the thermal conductivities of CuO-ethylene glycol nanofluids. They found that thermal conductivity of 4 vol. % nanofluid was up to 20% higher than that of the base fluid. Choi et al. [8] conducted experiments on the thermal conductivity of CNT-engine oil nanofluids and reported thermal conductivity enhancement of 160% for 1.0% vol of CNT nanofluids. The viscosity of water with copper oxide nanoparticle suspensions was measured by Li et al. [9]. They observed that the viscosity of the suspensions was higher than that of water by 15%-30% and higher particle concentrations resulted in higher viscosities. He et al. [10] investigated the effects of particle concentration on the viscosity of TiO2 nanoparticles dispersed in water. They concluded that the viscosity ratio of nanofluids increases nonlinearly with an increase in concentration of nanofluid. A large number of investigations have been carried out to investigate the heat transfer and flow behavior of nanofluids in both laminar and turbulent flow regimes [11-15]. Li and Xuan [16] observed 60% heat transfer enhancement with 2.0% volume concentration of Cu nanofluid flowing through a brass tube under laminar flow condition. Wen and Ding [17] examined laminar convective heat transfer of Al2O3-5 distilled water nanofluid flowing through a copper tube under constant heat flux boundary condition. They reported that the Nusselt number increased by 47% when 1.6% volume fraction of Al2O3 nanoparticles is dispersed in distilled water. Nonetheless, the results for convective heat transfer coefficient of water-based carbon nanofluids in turbulent regime are contradictory and controversial. For such a fluid flow, open literature reports i) an increase in heat transfer rate [18]-[19]; ii) a decrease in heat transfer rate [20-23]; or iii) not noticeable effect on heat transfer [24]. Amrollahi et al. [18] investigated the convective heat transfer of MWCNT-water nanofluids in both laminar and turbulent flow regimes. Their experimental results indicate that the convective heat transfer coefficient of these nanofluids increases by up to 33–40% at the concentration of 0.25% weight concentration compared to that of pure water in laminar and turbulent flows, respectively. Duangthongsuk and Wongwises [24] observed 26% heat transfer enhancement

with TiO2-water nanofluid at 2.0% volume concentration flowing in a horizontal double tube counter flow heat exchanger under turbulent flow conditions. Sadeghinezhad et al. [19] carried on an experimental study to evaluate the heat transfer characteristics and the pressure drop of a grapheme nano platelet (GNP) nanofluid in a turbulent flow condition. They reported that the convective heat transfer coefficient of the GNP nanofluid is higher than that of the base fluid by approximately 13−160%, while the increase in the pressure drop ranged from 0.4% to 14.6%. As mentioned before, some studies are found in the literature, however, showing a decrease in heat transfer coefficient after adding nanoparticles to the base fluids [20-23]. In an early study, Piratheepan and Anderson [25] built a copper tube-in-tube heat exchanger to probe the heat transfer characteristics and flow behavior of MWCNT-water nanofluid. They reported that using multi-walled carbon nanotube nanofluids in turbulent flows resulted in an increase in pumping power and also a decrease in the observed convective heat transfer characteristics. As a result, this study is carried out to answer this question: "Do water-based carbon nanofluids increase the heat transfer rate compared to base fluids?" In addition, majority of the authors used the existing 6 thermo-physical property models to compute the thermal conductivity and viscosity of nanofluids which may cause a small error in the results. Therefore, the objective of this experimental investigation is to study the effect of particle loading and Reynolds number on convective heat transfer and pressure drop of MWCNT, TiO2, CuO-ethylene glycol nanofluids in turbulent flow regime. In addition, thermo-physical properties of nanofluids at various nanoparticle concentrations and temperatures are measured using highly accurate measuring instruments.

CHAPTER 2

Literature review

Reviews of the available literature was carried out pertaining to CTES on the selection of PCM, geometry of encapsulation and heat transfer enhancement and the thermal performance of commonly used secondary refrigerant and these are presented below:

Felix Regin et al. [2] review the development of available latent heat thermal energy storage technologies. The different aspects of storage such as material, encapsulation, heat transfer, applications and new PCM technology innovation have been investigated.

Kumaresan et al. (2013) studied experimentally the solidification behavior of nanofluid PCM (NFPCM) with water as the base PCM and MWCNT as the nanoparticle and reported the possible energy saving potential of 6% - 9% in the cool thermal storage system through appreciable reduction of subcooling. In continuation to the above research work, the present research work aimed to investigate the solidification characteristics of NFPCM with the addition of nucleating agent at various operating temperature conditions, in order to explore the possibility of eliminating the subcooling. It was reported that the presence of multi wall carbon nanotubes (MWCNT) acts as nucleation agent that caused an appreciable reduction in the cooling process. Further, the presence of accelerating charging during solidification was investigated in detail for energy efficient design of the CTES system.

The extensive review (Li et al., 2012; Oro et al., 2012) articles have been reported on the materials, encapsulation geometry and heat transfer in the field of CTES applications. Most of the CTES systems commonly use water as the storage medium, because of its high thermal transport properties and only limited systems use the PCMs other than water like hydrated salts, eutectic mixtures and brine solutions.

C. J. Ho and J. Y. Gao prepared the PCM embedded with nanoparticles by emulsifying Al2O3 nanoparticles in paraffin (n- octadecane) by means of non-ionic surfactant. The formulated nanoparticles in paraffin emulsions contain of 5 wt. % and 10 wt. % respectively. Their effective thermo physical properties, such as latent heat of fusion, density, dynamic viscosity, and thermal conductivity, were investigated experimentally. The experimentally measured density of the emulsions agrees excellently with that predicted based on the mixture theory.

F. L. Tan et al. describe the method using CAD software and digitizing software to estimate the melt fraction of PCM during melting inside sphere. The method described could be useful in the analysis of experimental data in materials processing or other research areas. From the above literature we conclude that presence of the nanoparticles in the PCM increases significantly the effective thermal conductivity of the fluid and consequently enhances the heat transfer characteristics and reduces the melting and solidification period.

N. Ukrainczyk et al. carried the experimental study in order to determine the thermo physical properties of five technical grade paraffin waxes. Different instrumentation has been used to measure the different properties of paraffin waxes. Results shows despite its thermal conductivity, the investigated paraffin waxes possess satisfactory thermal characteristics for TES applications.

Tun-Ping Teng and Chao-Chieh Yu develop nano-composite enhanced phase change materials (NEPCMs) using the direct synthesis method by mixing paraffin with alumina (Al2O3), titana (TiO2), silica (SiO2) and zinc oxide (ZnO) as prepared experimental samples. Through both the heat conduction and DSC experiments, investigate the effect of varying the concentration of nano-additives on heat conduction and heat storage performance. Experimental results demonstrate TiO2is more effective than the other nano additives in modifying the heat conduction & heat storage performance of paraffin.

Jeong et al.(2013) reported that thermal conductivity of bio-based PCM with impregnation of exfoliated graphene was enhanced by 3.75 times than the base PCM. However, the latent heat of composite was only 75% of the base PCM and the presence of exfoliated graphene reduced the subcooling appreciably.

Han et al. (2008) investigated experimentally the thermal conductivity, viscosity, and specific heat of indium/polyalphaolefin nanofluids synthesized by using one-step nanoemulsification method. Their results showed 20% increase in the effective volumetric specific heat for the PCM nanofluid containing volume fraction of 8% indium nanoparticles.

R. Velraj et al. discussed various methods of heat transfer enhancement for latent heat storage applications. Conducts three different experiments to augment heat transfer and discussed the results. The heat transfer enhancement with fin configuration for storage tubes and by using lesser rings in storage tanks is appreciable. These two methods are highly suitable for solidification enhancement. Lessing rings are used to enhance the surface contact with base material.

Fan and Khodadadi (2012) experimentally investigated the thermal properties of CuO nanoparticle enhanced cyclohexane as phase change material. The thermal conductivity was measured using the transient plane source technique for both solid and liquid phases.

Song et al. (2007) studied the thermal stability of phase change material microcapsules that were dispersed with silver nanoparticles. The microcapsules were fabricated by the technique of in situ polymerization, with aminoplast as the wall and phase change material bromo-hexadecane (PCM BrC16) as the core.

Chandrasekaran et al. suspended 0.1 wt. % multiwall carbon nanotubes (MWCNT) in deionized water (DI water) along with pseudomonas as a nucleation agent for cool thermal energy storage (CTES) system at different HTF surrounding temperature (−6, −9, −12 °C) .The results concluded that there is an enhanced heat transport properties of the NFPCM which belongs to elimination of under cooling and accelerating charging, which result in the operating chiller at higher temperatures which save energy consumed through the solidification process.

Laurier L. Schramm et al. review the surfactants and their respective use in different applications Different factors such as nature and physical properties of surfactant, type of base fluid and detergency are considered. These in turn lead to a vast array of practical application areas. These are illustrated in terms of mineral and petroleum processing, biological systems, health and personal care products, foods, and crop protection.

A. Sathishkumar et al. reported that only 9% of the volume around the center of the capsule got solidified during 22% of total solidification time. Hence, there is a significant energy saving potential in the CTES system by operating the chiller for a period of 78% of the total solidification time at −12 °C surrounding temperature.

The following major observations were made based on the above literature.

- The thermal conductivity of PCM gets enhanced by the use of nano materials.
- The charging time was reduced by 20-25 % in all the setups at respective conditions.

- Mostly water was used as the base fluid in the above experiments.
- In all the above analysis the effects due to the change in the capsule sizes were not studied.

Considering the requirement of enhanced thermal transport properties of the PCM and utilizing the recent advancement in nanotechnology, the present work aims to explore the influence of adding multi wall carbon nanotubes in water and to quantify the energy saving potential in a chiller integrated with the CTES system for building cooling applications.

CHAPTER 3

PREPARATION OF NFPCM

3.1 Material Selection

In this section the procedure adopted for the preparation of nanoparticle enhanced PCM is presented along with justification for the selection of base PCM and nanomaterial.

3.1.1 Selection of base PCM

Considering the operating temperature of the chiller(-12°C), water is selected as the base PCM due to its high latent heat, easy availability and high solid to liquid conductivity. The thermo physical properties of water is shown in table 3.1

Table 3.1 Thermophysical properties of water

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PROPERTY	VALUE
Liquid thermal conductivity at 20°C	0.598 $Wm^{-1} K^{-1}$
Solid thermal conductivity	2.2 $m^{-1} K^{-1}$
Solid density	920 kg m^{-3}
Liquid density at 4°C	1000 kg m^{-3}
Melting freezing temperature	0°C
Latent heat of melting	334 kJ kg^{-1}
Specific heat water	4.187 kJ $kg^{-1}K^{-1}$
Specific heat ice	2.108 kJ $kg^{-1} K^{-1}$

3.1.2 Selection of Nanomaterial

Commonly used nanoparticle for the preparation of nanofluids are metallic materials such as copper, gold, aluminum etc. and metal oxides such as copper oxide, iron oxide, titanium oxide and alumina etc. and carbon based such as carbon nano tubes (CNT) and graphene. Higher thermal conductivity (k= 2000 to 6000 W/mK), lower density and large scale production of CNT with minimum environmental impact are the important factors for selection of CNT as nano material. The CNT was produced from cheap tubes USA and its specifications are provided by the manufacturer. Figure 3.1 shows the TEM image of the CNT and the size of the CNT is found to be 30 nm thickness

Table 3.2 Nanomaterial specification

Material specification	
Material	Carbon nano tubes
Inside diameter	5-1 nm
Outside diameter	20-30 nm
Thermal conductivity	2000-6000 W/mK
Thermal stability	>600°C
Electrical conductivity	>100 S/cm
Bulk density	0.28 g/cm^3

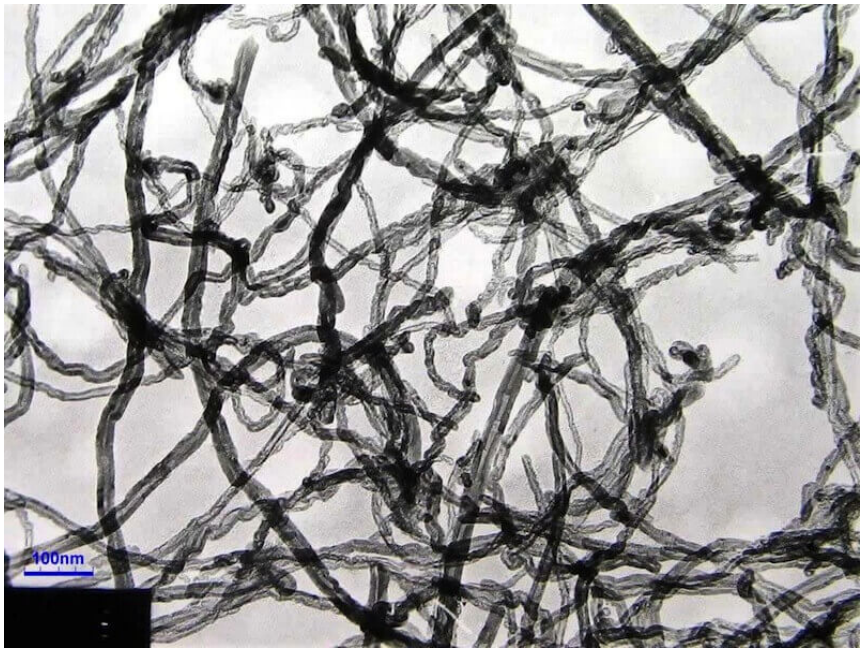


Figure 3.1 TEM image of the CNT

3.2 PREPARATION OF NFPCM

The NFPCM is of vital importance when using it a working fluid in any thermal system. The term NFPCM does not mean a simple mixture of nano particles and a base fluid. The proper mixing and stabilization of nanoparticle is required in order to prepare stable NFPCM. The rwo basic methods of preparing NFPCM are given below,

1. Single step method: Direct evaporation and condensation is carried out in nanoparticle material in the base fluid to prepare stable nanofluids.
2. Two step method: In this method first the nanoparticles are obtained by different methods and then are dispersed into the base fluid.

Two step method are used to prepare NFPCM and the following methodology is used to prepare the NFPCM.

The surfactant (0.3wt, %) is mixed with known volume of DI water(250ml) and the mixture for 15min using a magnetic stirrer. The CNT is then dispersed in the above mixture and the solution is stirred for 30 mins. The solution is then placed in the ultrasonicator and the dispersion of CNT in solution is achieved by continuous ultrasonification of the solution for 180 min. the process involved in the preparation is presented as a flow chart 3.2

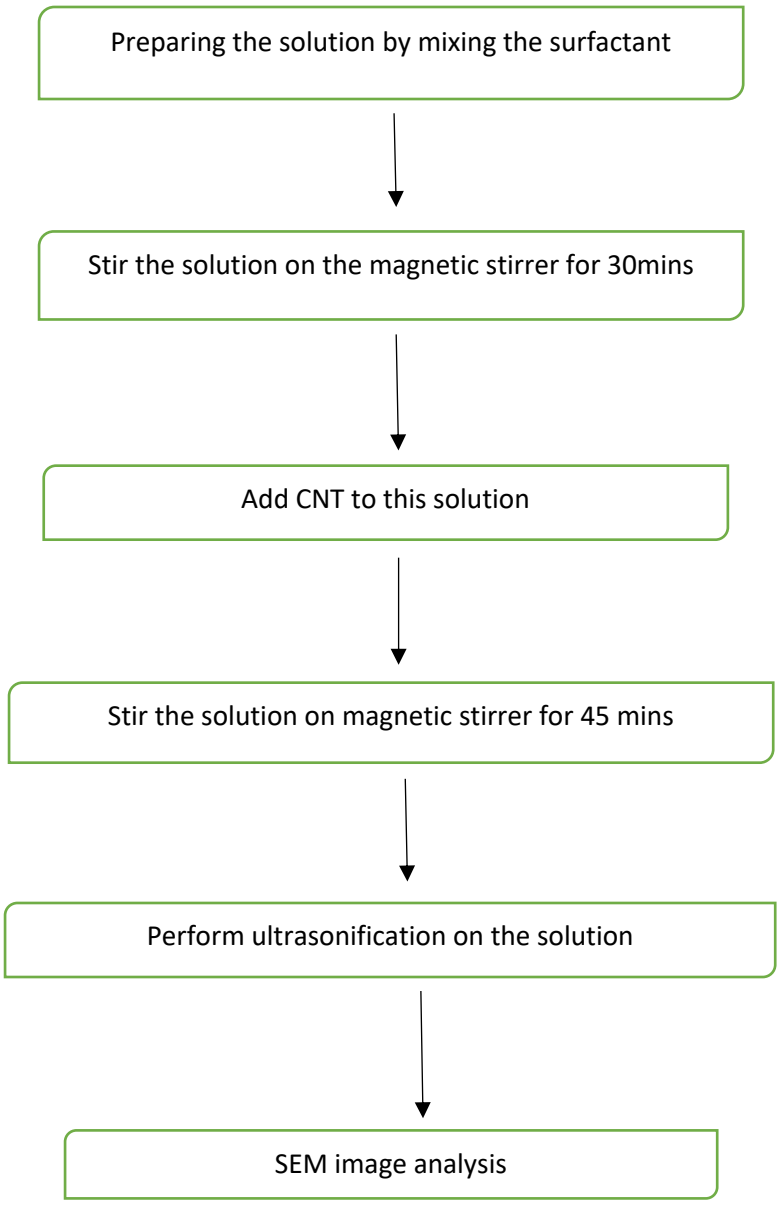
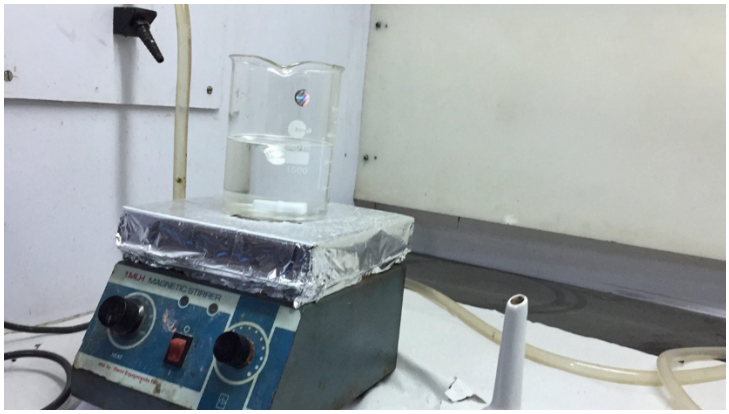


Figure 3.2: Preparation method of NFPCM


MLH MAGNETIC STIRRER

MLH MAGNETIC STIRRER

3.5L (H)
ULTRASONIC BATH SONICATOR

Using two step method around the sample was prepared by using SDBS (sodium dodecyl benzene sulphate). It has been notified that there was no visual sedimentation observed even after few weeks period of the preparation of the sample in case of NFPCM using SDBS.

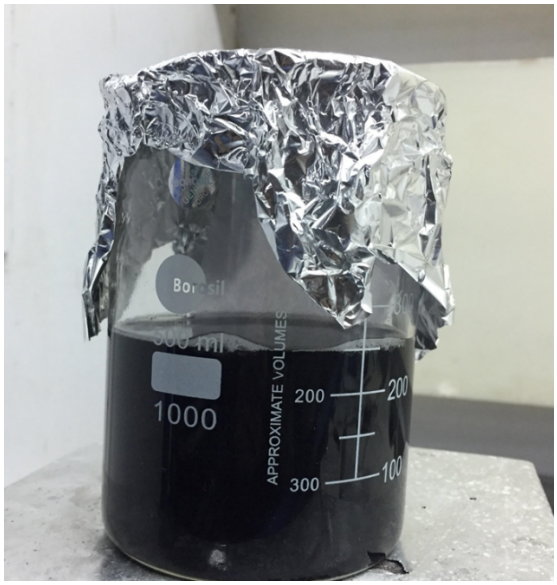


Figure 3.3 Photographic view of prepared sample using SDBS

After observing no visual sedimentation the size of the CNT dispersed in the solution is measured using scanning electron microscopy (SEM). The SEM images are shown in the figure3.4(a-d). it has been seen from the figures that the CNT in the solution are around 50-60mnm in diameter.

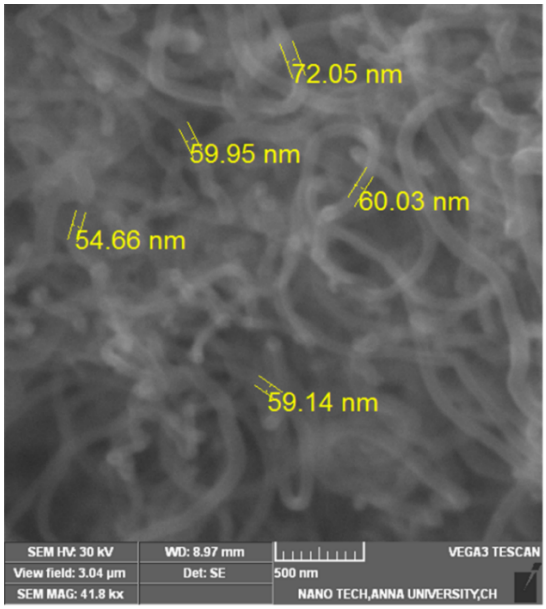


Figure 3.4(a)

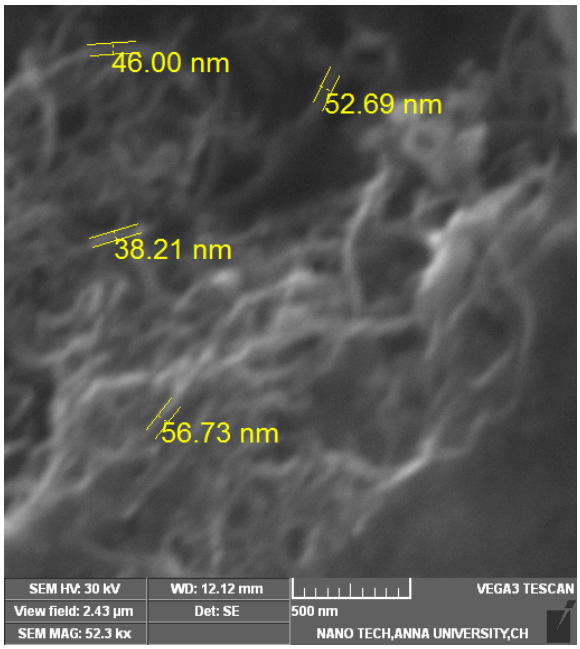


Figure 3.4(b)

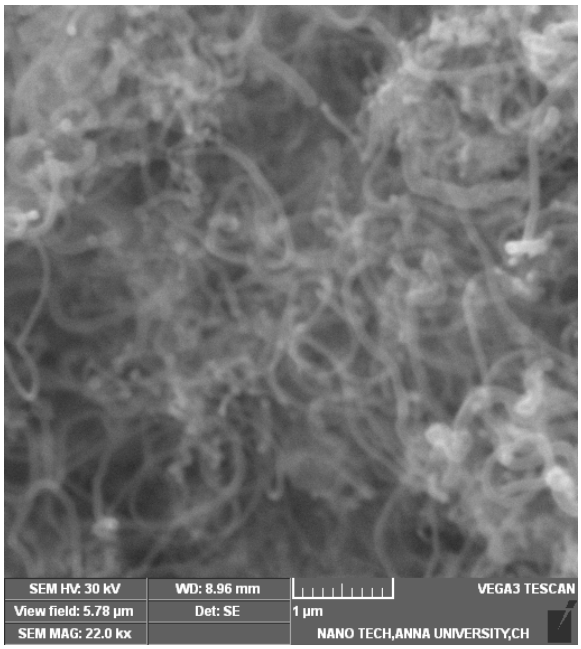


Figure 3.4(c)

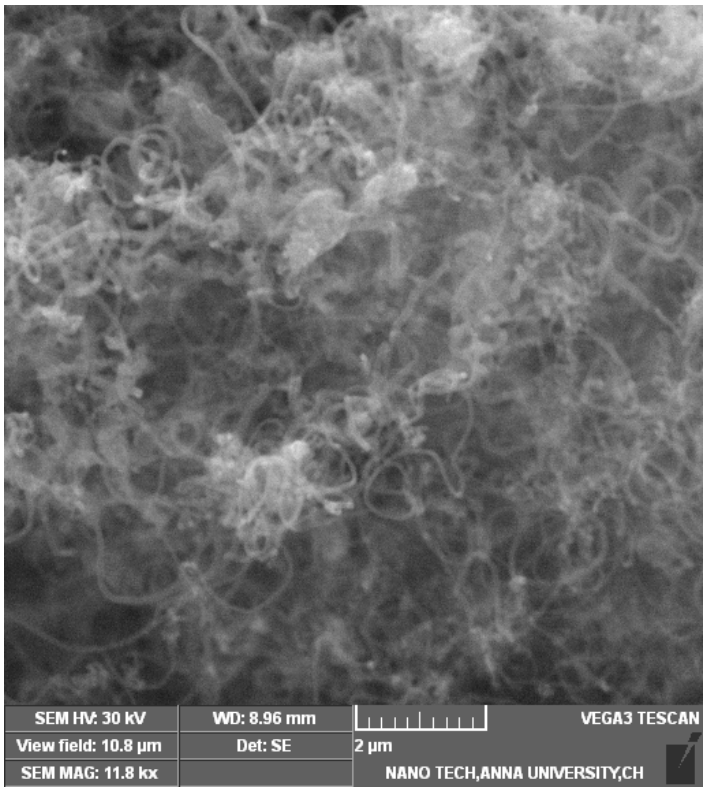


Figure 3.4(d)

CHAPTER 4

EXPERIMENTAL SETUP

The major parameter such as density ,solidification rate of NFPCM were measured and reported in this following section.

DENSITY MEASUREMENT

The density of both the waterand NFPCM are measured at room temperature by weighing a fluid sample in a standard volumetric flask of 25 ml and 50 ml using a high precision electronic balance with airlock container.

Samples	Composition	m_t (kg)	m_{fl} (kg)	P (kg m^{-3})	% of increase in density
Sample1	DI water	0.05280	0.02803	991	-
Sample 2	0.30%	0.05300	0.02803	998.8	0.787

$$\rho_{NF} = \frac{m_t - m_{fl}}{V_{nf}}$$

M_t = Mass of flask and PCM

M_{fl} = mass of empty flask

Sample calculation: Density (ρ) = (0.05300-0.02804)/(25*10^{-6}) = **998.8 Kg/m3**

Schematic Diagram of the Experimental setup.

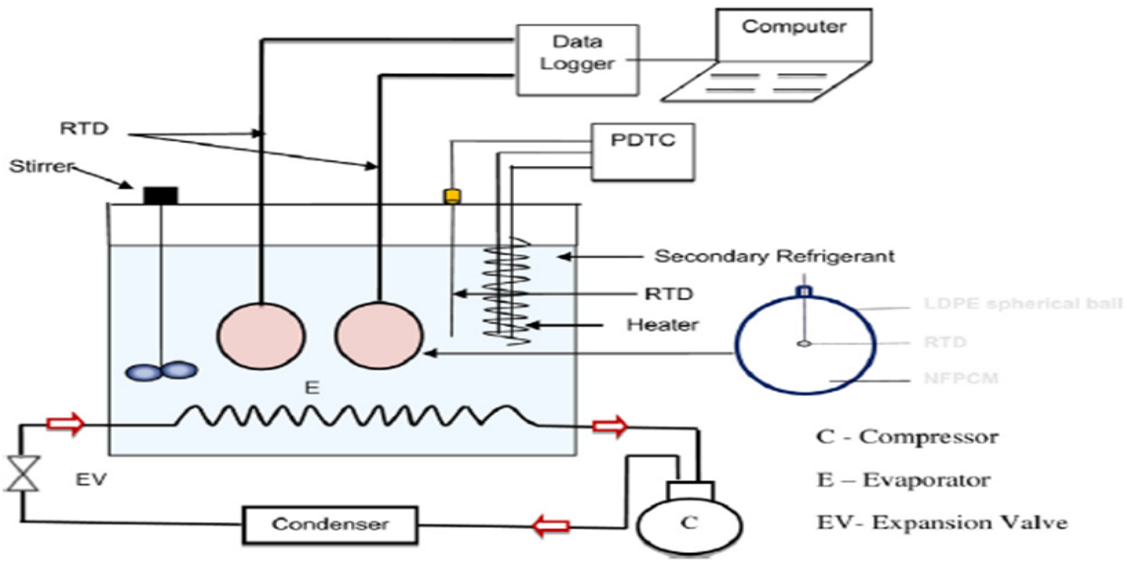


Fig. 3 — Schematic diagram of the experimental setup.

The setup consists of a polyurethane insulated stainless steel. The tank capacity is 12l . The tank is filled with water and glycol. The water solution is 70% and the glycol solution is 30%.

The heating coil which is used inside the having the capacity of 2000 W. The chiller unit is of capacity of 5000W. Mechanical stirrer by a 9 W electrical motor of 1280 rpm.

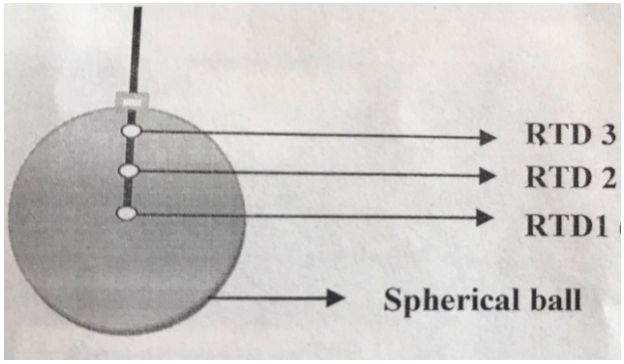
EXPERIMENTAL SETUP FOR THE SOLIDIFICATION TEST

	BALL 1	BALL 2	BALL 3
CIRCUMFERENCE(mm)	280	240	200
OUTER DIAMETER(mm)	88	76	62
INNER DIAMETER(mm)	84	72	58
VOLUME(ml)	310	195	102

In order to assess the role of MWCNT it is proposed to study the solidification characteristic of NFPCM using the experimental setup. This setup consists of a polyurethane insulated stainless steel tank of 0.01 m3, filled with a mixture of 60% water and 40% ethylene glycol by volume. A heating coil of the capacity 2,000 w and chiller unit of the capacity 5 kw are used to simulate the required bath temperature in the tank. The chiller unit is operating at a constant load and in order to maintain the required constant temperature of the bath, a proportionate temperature differential controller is used,which varies the heating coil output based on the temperature of the bath measured by the RTD sensor.

For the experiment with water based NFPCMs , spherical balls made up of steel with the different diameter.

The three RTD are placed in various location of the spherical ball . The distance of the RTDs are 12mm each. RTD one set at the centre of the ball.



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 experiment.

The experiment were performed with water and water+surfactant at the surrounding bath temperature of -12c.

In constant temperature bath -12c is maintained for the solidification analysis .The temperature is continuously monitored by one RTD sensor and another temperature control valve. The ball is fix in the centre of the constant temperature bath. A photographic view of the experimental set up for the solidification is shown.

Figure 4.5: Solidification setup

CHAPTER 5

RESULT AND DISCUSSION

5.1 DENSITY OF THE NFPCM

Table 3 shows that there is no much variation in the densities of the de-ionized water and the NFPCM sample. It has also been observed from the table 3 that the density of water increased up to 0.787 % when 0.30 wt. % of MWCNT was added to it.

Table 5.1 :

Samples	Composition	m_t (kg)	m_{fl} (kg)	P (kg m^{-3})	% of increase in density
Sample 1	DI Water	0.05280	0.02803	991	-
Sample 2	0.30%	0.05300	0.02803	998.8	0.787

5.2 TRANSIENT TEMPERATURE VARIATION OF THE NFPCM DURING SOLIDIFICATION TEST

5.2.1 Transient temperature variation of the NFPCM in Ball 1 (T_{surr} = -12ºC)

Fig. 5.1(a) shows the transient temperature variation of the NFPCM when placed in BALL1 at surrounding temperature of -12ºC. Only a negligible effect of the MWCNT has been observed on the heat transfer in the region of sensible cooling up to density inversion point (-4ºC).In that region both the DI water and NFPCM followed the same temperature drop trend with respect to time. This could be due to the increase in viscosity of the NFPCM with addition of MWCNT that suppresses the natural convection effects. It is also noticed that DI water was sub-cooled to a temperature -7ºC and the onset of solidification began after 1150s. Sub-cooling was eliminated when MWCNT of 0.30 wt. % was added to DI water. This is due to the presence of multi wall carbon nano-tubes (MWCNT) acts as nucleation agent that caused an appreciable reduction in the cooling process.

It is also evident that the onset of solidification advanced in proportion with the reduction in the degree of sub-cooling. For example, the onset of solidification commenced after 1725s and 1215s respectively for the DI water and NFPCM in Ball 1 at T_{surr} = -12ºC. Therefore, the addition of MWCNT is highly beneficial to advance the onset of solidification in the case of liquids that undergo sub-cooling during freezing. Moreover the experimental results showed a notable reduction in the solidification duration in the case of all NFPCM compared to that of the base PCM. The reduction in solidification time (from initial condition to -1ºC) for Ball 1 filled 80% of its volume with MWCNT 0.3 wt. % was 12%. This is well explained by the enhanced thermal conductivity of the NFPCM, owing to presence of high conductive MWCNT, which in turn enhances the heat transfer rate in the NFPCM.

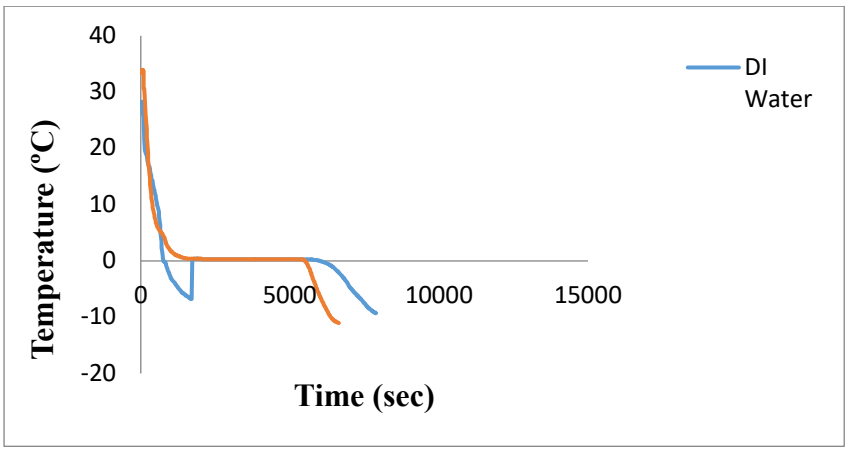


Fig 5.1 Transient temperature variation of DI water 3 (T_{surr} = -12 ºC)

Fig. 5.1 Transient temperature variation of the MWCNT (0.30 wt. %) and DI water during entire period of experimentation in BALL 1 (T_{surr} = -12 ºC)

5.2.1 Transient temperature variation of the NFPCM in BALL 1, 2 and 3 at T_{surr} = -12ºC

The results of the experiment conducted by filling the NFPCM in balls of different dimensions at surrounding temperature of -12 ºC are presented in Fig 5.2. It is seen from the figure that onset of solidification commenced first in Ball 3 at 645s then in Ball 2 at 990s and lastly in Ball 1 at 1215s. It is noticed that the solidification time follows the same trend. The maximum reduction in solidification time was 72% between Ball 1 and Ball 3.

This is due to the decrease in the volume of the NFPCM solution in the Balls. It was noticed that only 9% of the volume around the center of the capsule got solidified during 28% of total solidification time. Hence, there is a significant energy saving potential in the CTES system by operating the chiller for a period of 72% of the total solidification time at Tsurr = −12 °C.

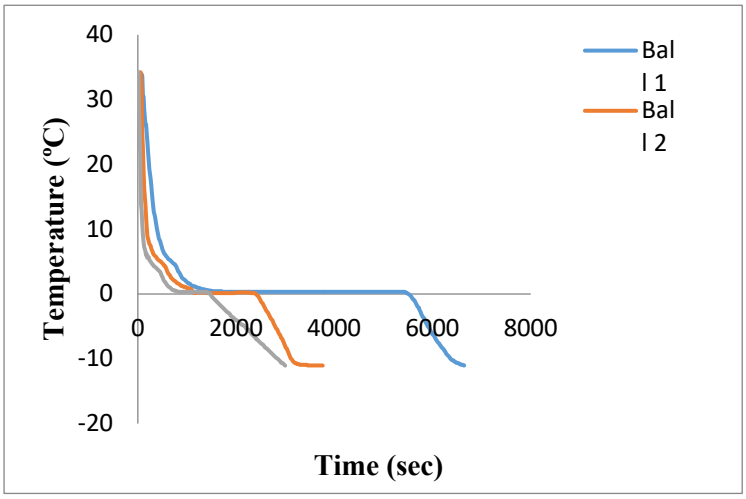


Fig 5.2 Transient temperature variation of the NFPCM during entire period of experimentation in BALL 1, 2, 3 (T_{surr} = -12 ºC)

CHAPTER 6

CONCLUSION

The results obtained during the measurement of density and solidification rate of NFPCM in capsules of different dimensions are presented and discussed in detail.

- The measurement of density data reviewed that the increasing density is not appreciable when compared with that of other metal/metal oxide nano-materials.
- The presence of high conductive MWCNT acted as a nucleating agent to initiate the solidification of the NFPCM in advance to the base PCM through eliminating sub-cooling. The addition of the MWCNT also shortened the solidification duration of the NFPCM by 12% than that of base PCM at surrounding bath temperature of -12 ºC.
- There is a significant energy saving potential in the CTES system by operating the chiller for a period of 72% of the total solidification time as only 9% of the volume around the center of the Ball 1 got solidified during 28% of total solidification time at Tsurr = −12 °C. Furthermore solidification time can be reduced by using multiple capsules of smaller dimensions than a one capsule of larger dimension.

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