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Freezing and Melting Characteristics of Nano Enhanced Phase Change Material for Heating and Cooling Applications

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Abstract— ***A substance known as a phase change material (PCM) possesses the capability to and brings forth substantial quantities of thermal energy when it transitions between solid and liquid or liquid and gas phases. Work has also been going on towards improving the freezing and melting characteristics of phase change materials in order to improve the amount of thermal energy that can be stored as well as the freezing and melting times. This can be achieved by the addition of nanomaterials to the phase change material. Nanomaterials that are commonly used include Al_2O_3, CuO, graphene Nano platelets (GnP) and carbon nanofibers. In our work we experimentally investigated the freezing and melting behavior of nanoparticle-enhanced phase change material (PCM). The nanoparticle used for our work was graphene Nano platelets along with phase change material (PCM) using an operational range of 29 ºC. With intervals of 0.1%, the volume fraction of graphene nanoplatelets ranged from 0.1% to 0.5%. Various properties of the nano-enhanced PCM such as were experimentally tested. The behavior of freezing and melting of the nano-enhanced PCM was measured. As the concentration of graphene nanoplatelets within the phase change material (PCM) rose, improvements in the thermal conductivity and freezing and melting times were seen.***

Index Terms— ***Freezing, Melting, Nanocomposite, Phase Change Material, Thermal Energy Storage.***

I. INTRODUCTION

There are several difficulties that the world must overcome in order to store, have access to, and meet the urgent energy demands. The primary kind of energy that may be stored is heat, and phase change materials (PCM) are used to do this in the form of latent heat. In many different applications, including solar thermal power plants, building cooling/heating systems, and cold storage applications, thermal energy storage (TES) systems have drawn a lot of interest as efficient ways to store and use excess heat energy.

Phase change material (PCM) selection and thermal properties have a significant impact on TES system performance. Numerous studies have been done to improve the thermal characteristics and overall energy storage capacities of traditional PCMs in order to solve their drawbacks. The PCM has the capability to efficiently store and release substantial quantities of thermal energy when undergoing phase transitions between solid and liquid or liquid and gas phases [1-3].

The most promising technique has been identified as latent heat thermal energy storage (LHTES), which incorporates composite phase change material (PCM) [4,5]. During the period of energy consumption, LHTES is possible to switch from peak to off-peak periods, resolving the discrepancy between energy supply and demand [6-8]. The LHTES has so far been used quite widely in building energy conservation, including solar space heating and cooling applications in buildings [9], building insulation walls [10-12], and phase change cement board [13].

Bista et al. [14] conducted an experimental study to evaluate the impact of incorporating phase change material (PCM) thermal energy storage on the performance of a vapor compression refrigeration system. The researchers placed the PCM in different locations within the system, including the evaporator/condenser side and the food compartment, and analyzed its effects on various parameters. Overall, the study demonstrated that incorporating PCM in a refrigeration system can have both positive and negative effects on its performance.

However, the PCMs' poor heat conductivity makes it difficult to improve system performance using TES [14]. After solidification begins, the PCM's conduction heat transfer is what drives the energy storage process, hence increasing the PCM's thermal conductivity is essential for better system performance. Numerous strategies have been put out to increase the PCMs' thermal conductivity. Recent research demonstrates that the thermal conductivity of PCMs is greatly improved by the inclusion of nanomaterials [15-19].

The thermal characteristics and improvement of thermal conductivity of a composite PCM employing metal foam and myristyl alcohol are the main topics of this paper. The findings demonstrated that the inclusion of metal foam considerably enhanced the composite's thermal conductivity, resulting in accelerated heat transfer rates and increased thermal performance [20].

Before employing PCM in actual TES systems, it is crucial to understand how nanoparticles affect the solidification and melting processes in a container. This clarifies how nanocomposites behave in terms of energy storage and release [21-22]

A study by Sathishkumar et al. [23] focuses on examining the solidification properties of a water-based graphene nanofluid phase change material (PCM) in a spherical capsule for cool thermal energy storage applications. The authors want to investigate the possibilities of using graphene nanofluids as PCM to improve the effectiveness and performance of cool thermal energy storage systems. Consequently, there was a decrease in the solidification time.

The choice of material for a storage container is crucial. The effectiveness of various materials for storing nano-enhanced PCM varies. Studies employing copper-made capsules are hardly accessible because the majority of earlier research efforts used different materials for capsules. Due to its excellent ductility and low weight, copper may be easily molded into a variety of sizes and forms. It can be curved without losing its qualities and capabilities. A strong metal with a high melting point is copper. When exposed to temperatures below 0 degrees Celsius, they don't crack or shatter [24].

This study intends to experimentally investigate the freezing and melting behavior of a graphene nanoplatelets-enhanced PCM with an operating temperature range of 29 ºC. The volume fraction of graphene nanoplatelets in the PCM was varied from 0.1% to 0.5%, and measurements were recorded to determine diverse properties, including density, viscosity, specific heat capacity, and thermal conductivity.

The behavior of freezing and melting of the nano-enhanced PCM was also measured using a cylindrical copper capsule placed inside a constant temperature bath. The chief goal of this study is to evaluate the performance of graphene nanoplatelets enhanced PCM and determine the optimal volume fraction of graphene nanoplatelets for achieving efficient freezing and melting characteristics. The findings of this research could have important implications for the development of more efficient and effective thermal energy storage systems utilizing phase change materials.

II. MATERIALS AND METHODS

A. Material Selection

The selection of the PCM was based on careful consideration of the precise operational temperature range necessary for the investigated application. For a building cooling application, such as air conditioning, the typical operating temperature would be around 29 ºC on average. For this study, the PCM chosen possesses a phase change temperature of 29 ºC. For the current study, the researchers selected a commercially available PCM from Tan90 Thermal Solutions in India. This particular PCM had a phase change temperature range of 25-29 degrees Celsius, which made it suitable for the application under investigation. A comprehensive listing of the PCM's properties can be found in Table 1. ADG Graphene Nanoplatelets (GnPs) were used in this study which exhibited a diameter of 10 µm, thickness ranging from 5-10 nm, and a density of 0.1 g/cm³. The GnPs were purchased from Ad Nano Technologies in India.

Table 1: Properties of TN+29 PCM

Design Parameter	Value	Unit
Melting Point	29	ºC
Latent Heat	220	KJ/Kg
Density	1533 1706	Kg/m^3
Specific Heat Capacity	2.07 1.40	KJ/Kg-K
Thermal Conductivity	0.548 1.008	W/mK
Max operating temperature	100	ºC
Safety	Nontoxic, Safe to handle	
Material	Salt Hydrate	
Flammability	No	

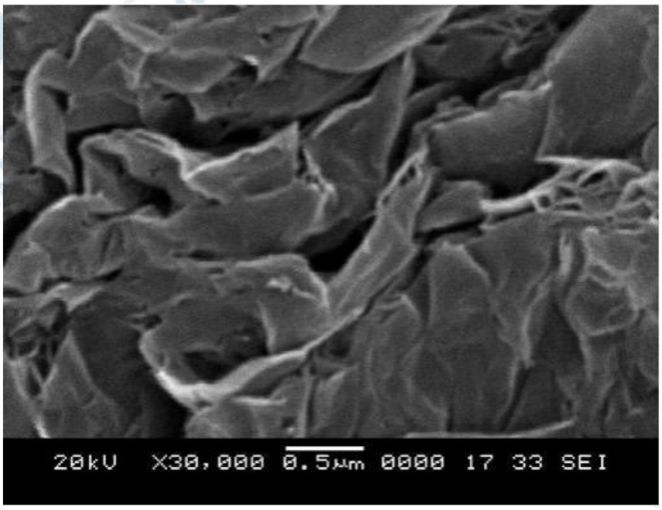

Figure 1: SEM Visualization of GnPs

B. Preparation of Nano-enhanced PCM

The dispersion of GnPs within the liquid PCM to prepare 0.1vol% of functionalized GnPs was achieved by utilizing a hot plate magnetic stirrer. The same process was repeated to create PCM nanocomposites with varying volumes of functionalized GnPs (0.2 to 0.5 vol%). The resulting specimens were left untouched for 5-6 days to ensure that there was no settling of GnPs. Visual confirmation was used to verify the absence of any settlement.

C. Experimental Facility

The experimental setup used in this study included a cylindrical copper capsule (outer diameter of 48 mm, height 85 mm and thickness 3 mm), a constant temperature refrigerating bath, a compressor, a condenser, expansion valves, an evaporator, a heater coil, and a data logger. The experimental setup is illustrated in the schematic diagram presented below in Figure 3. To investigate the freezing and melting behavior of the PCM, three K-type thermocouple sensors were placed at different locations inside the cylindrical capsule, as illustrated in Figure 2. The copper capsule was not filled completely with the PCM to allow for the expansion of water upon freezing. The measurement of temperature variations of the nanocomposites was carried out using a data logger, which recorded the transient temperature continuously.

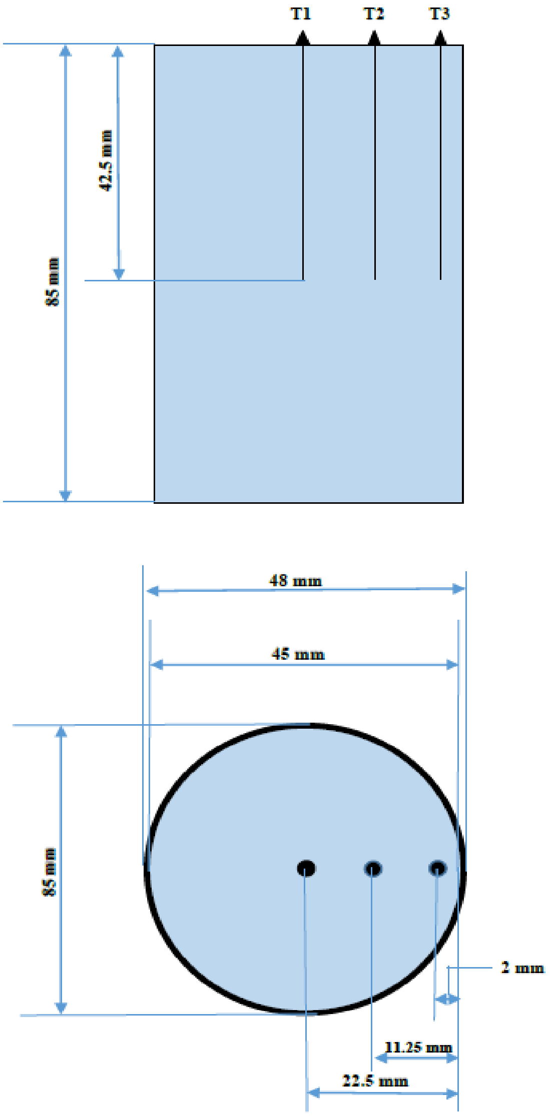

Figure 2: Side and top view of positioning of Sensor inside the capsule

D. Experimental Procedure

The refrigeration unit, equipped with a pump, was activated to achieve the desired bath temperature of 15°C and 20°C, which was set using a temperature controller. Once the target temperature was accomplished, the controller effectively modulated the power supply to sustain a constant temperature throughout the experiment. Similarly, the heating unit, along with the pump, was turned on to reach the requisite bath temperature of 35°C and 40°C, which was also set utilizing the temperature controller. Once the target temperature was accomplished, the controller effectively modulated the power supply to sustain a constant temperature throughout the experiment. Temperature measurements were taken at different positions within the capsule to monitor the temperature distribution of the PCM nanocomposite. Subsequently, this process was replicated for various volume percentages of GnPs, including 0.2, 0.3, 0.4, and 0.5 vol%.

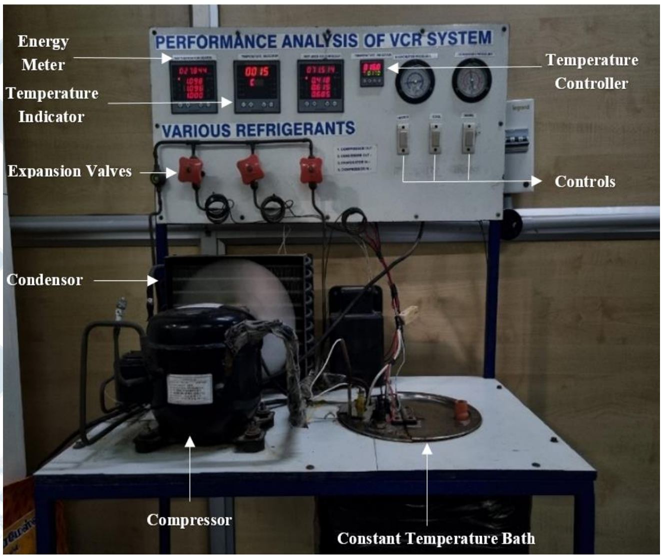

Figure 3: Constant temperature bath experimental setup

III. RESULTS AND DISCUSSIONS

A. Freezing Characteristics

The experiment involves a phase change material (PCM) solution that is initially in a liquid state at ambient temperature of 32 ºC. The freezing point of the PCM solution is achieved by immersing it in a cold bath sustained at the prescribed temperature. During the cooling process of the PCM solution, solidification initiates at the outermost surface of the nano-enhanced PCM, which is in direct contact with the heat-conducting surface, leading to the sequential solidification of subsequent layers. As the solidification process goes on, the PCM's halfway point solidifies. The final solidification occurs when the entire PCM solution solidifies. After the solidification process is completed, the solidified sample is sensibly cooled until the nano-enhanced PCM reaches 16 ºC. The freezing experiment is carried out at two different bath temperatures: 15 ºC and 20 ºC.

The freezing curve of both the base fluid and nanocomposites, exhibiting different volume percentages of GnPs from 34 °C to 16 °C at two discrete bath temperatures (15 °C and 20 °C) is shown in the accompanying Figure 4 and Figure 5 respectively. For bath temperature 15 ºC time taken by base fluid (0.0% volume fraction) to solidify was 5.88 min, while the time required for solidification by 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 % volume fraction nanocomposites was 5.63 min, 5.32 min, 4.82 min, 4.52 min and 4.43 min respectively. Thus, reducing the freezing time was made possible by the inclusion of nanoparticles by 4.25%, 9.52%, 18.02%, 23.12% and 24.65% for 0.1%, 0.2%, 0.3%, 0.4% and 0.5% volume fractions respectively. For bath temperature 20 ºC, time taken by base fluid (0.0% volume fraction) to solidify was 6.40 min, while the time required by 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 % volume fraction nanocomposites was 6.02 min, 5.82 min, 5.43 min, 5.05 min and 4.62 min respectively. Thus, reducing the freezing time was made possible by the inclusion of nanoparticles by 5.93%, 9.06%, 15.15%, 21.09% and 27.81% for 0.1%, 0.2%, 0.3%, 0.4% and 0.5% volume fractions respectively.

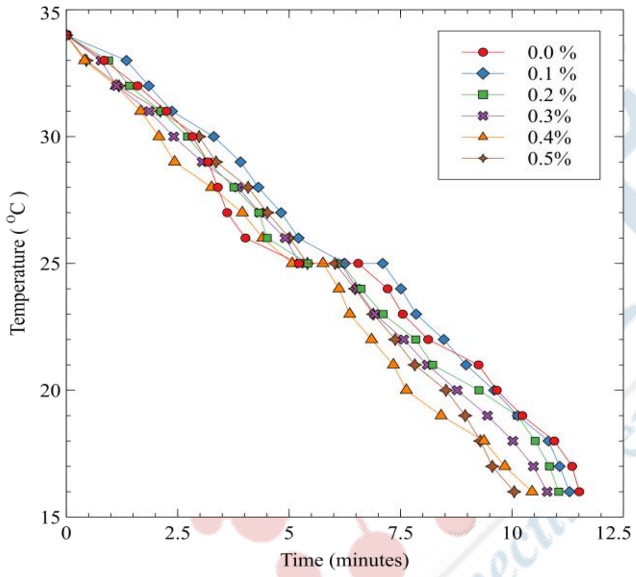

Figure 4: Freezing Curve from 34 ºC to 16 ºC with bath temperature at 15 ºC

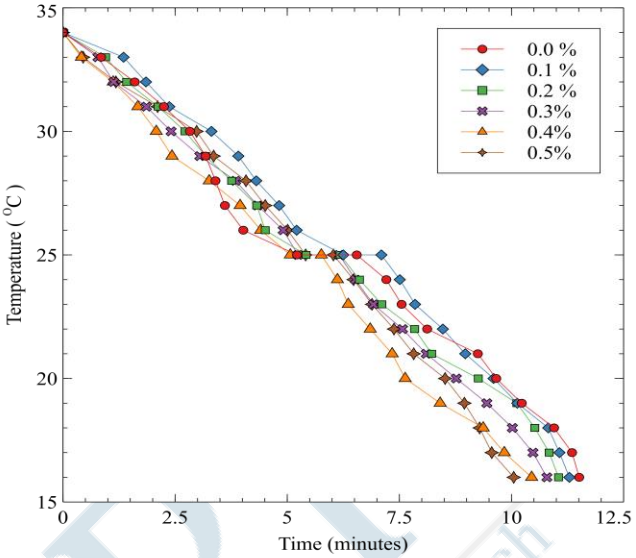

Figure 5: Freezing Curve from 34 ºC to 16 ºC with bath temperature at 20 ºC

B. Melting Characteristics

After solidification, the PCM solution is gradually heated to its melting point by submerging it in a hot bath. As the PCM solution is heated, the outermost surface that conducts heat (i.e., the surface in contact with the heat source) begins to melt first, causing the outermost layer to dissolve. As the PCM solution is further heated, the midway of the nano-enhanced PCM melts entirely. The sample is then heated gradually until it reaches thermal equilibrium with the hot bath. Both the base fluid and the nano-enhanced PCM undergo the melting experiment. The experiment is carried out at two discrete bath temperatures, 35 °C and 40 °C. The experiment continues until the nano-enhanced PCM reaches 34 °C.

The melting curve of the base fluid and nanocomposites with varying volume percentages of GnPs from 16 °C to 34 °C at two different bath temperatures (35 °C and 40 °C) is shown in the accompanying Figure 6 and Figure 7 respectively. For bath temperature 35 ºC time taken by base fluid (0.0% volume fraction) to melt completely was 2.78 min, while the time required by 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 % volume fraction nanocomposites was 2.35 min, 1.97 min, 1.65 min, 1.28 min and 1.13 min respectively. Thus reducing the melting time was made possible by the inclusion of nanoparticles by 15.46%, 29.13%, 40.64%, 53.95% and 59.35% for 0.1%, 0.2%, 0.3%, 0.4% and 0.5% volume fractions respectively. For bath temperature 40 ºC time taken by base fluid (0.0% volume fraction) to melt completely was 2.47 min, while the time required by 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 % volume fraction nanocomposites was 2.18 min, 1.82 min, 1.43 min, 1.05 min and 0.95 min. Thus, reducing the melting time was made possible by the inclusion of nanoparticles by 11.74%, 26.31%, 42.10%, 57.48% and 61.53% respectively.

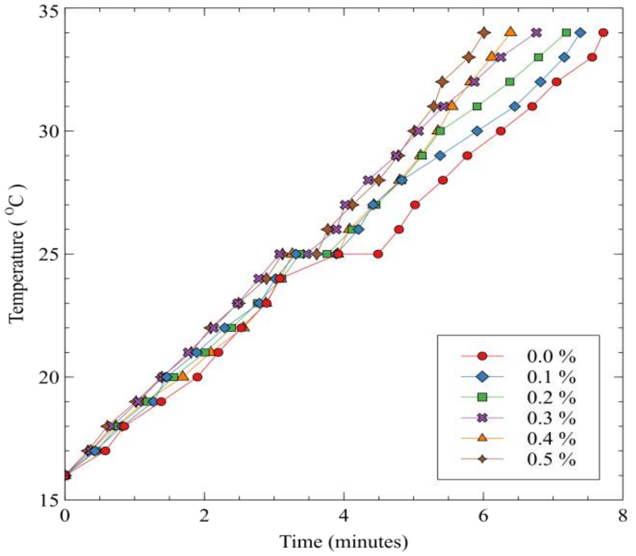

Figure 6: Melting curve from 16 °C to 34 °C with bath temperature at 35 °C

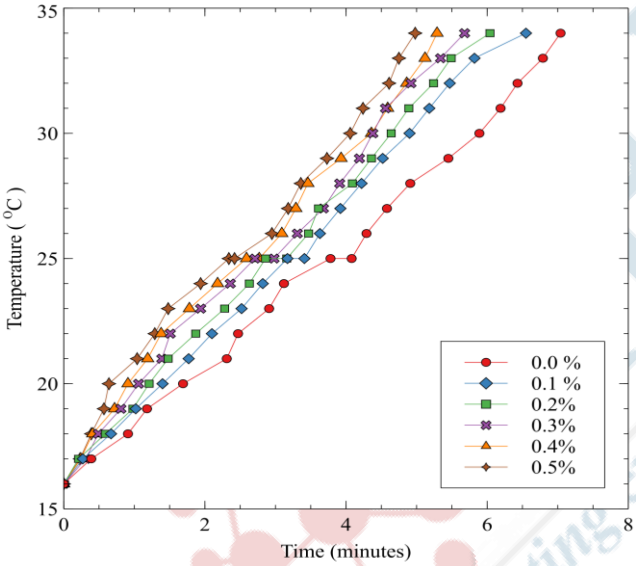

Figure 7: Melting curve from 16 °C to 34 °C with bath temperature at 40 °C

IV. CONCLUSION

In this study, the researchers aimed to enhance the freezing and melting properties of phase change material (PCM) by adding graphene nanoplatelets (GnP) in varying volume fractions (0.1%, 0.2%, 0.3%, 0.4%, and 0.5%). Thermal conductivity measurements were also taken for both the base PCM and the five volume fractions in liquid form. The findings demonstrated that the 0.5% volume fraction exhibited the highest thermal conductivity, showcasing a notable increase of 22.88% in comparison to the base PCM. Experimental investigations were carried out to research on identifying the freezing and melting times at different temperatures inside a constant temperature bath. The results demonstrated that both the freezing and melting times decreased as the volume fractions of GnP surged. The 0.5% volume fraction showed the best performance, with a 27.81% reduction in freezing time and a 61.53% improvement in melting point compared to the base sample.

The potential applications of this Nano-enhanced PCM-based thermal energy storage include waste heat recovery, cooling of heavy electronic equipment, HVAC, medical and agriculture applications, among others. The findings of this study support the development of materials and manufacturing techniques to enhance various heat transfer mechanisms using Nano-enhanced PCM for thermal energy storage.

However, there were some limitations during the experimental work. One of the challenges was fixing the three-temperature sensors at the specified distance inside the cylindrical copper capsule. Proper placement and connection of the sensors were necessary to ensure accurate readings. Additionally, it was crucial to seal the capsule's cap perfectly once placed inside the constant temperature bath to avoid the risk of water from the tank entering the capsule.

Author Contributions

Shoubhik Chatterjee: Conceptualization, Methodology, Formal Analysis, Investigation, Original Draft-writing, **Yuvraj Singh:** Conceptualization, Methodology, Formal Analysis, Investigation, Original Draft-writing,

Dr. C. Selvam: Conceptualization, Data visualization, Data validation, Writing–review & editing, Supervision**.**

Competing interests

The authors affirm that there are no potential conflicts of interest to disclose.

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