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Investigation the thermal performance of Nano-Enhanced Phase Change Material (NEPCM) in an enclosure

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ABSTRACT

Phase change materials (PCMs) play a vital role in thermal energy storage applications, as they provide efficient and dependable heat storage and release capabilities. This study provides a comprehensive evaluation of the thermal performance of Nano-Enhanced Phase Change Material (NEPCM) in an enclosure, with a focus on the effect of temperature variation and the role of nanoparticles. Variable temperature regimes significantly influence the physical and thermal properties of the NEPCM, as revealed by numerical simulations. The enthalpy-porosity approach for the phase change process and the solution of the Navier-Stokes equations for fluid flow serve as the primary foundations for the numerical model that will be covered in this study. With only a single phase of user input, ANSYS facilitates the creation of three-dimensional models and solid geometry meshes. Notably, an increase in the temperature of the heat-supplying wall resulted in substantial changes to the NEPCM, which we have thoroughly investigated and quantified. It has been demonstrated that the incorporation of various nanoparticles (Al_2O_3, CuO, and ZnO) into paraffin enhances the heating process, thereby enhancing the thermal conductivity, heat transfer coefficient, and surface tension of the NEPCM. The three nanoparticles decrease the mass fraction of paraffin in the range of 0.00 to 0.960 at the same concentration and testing temperature. In addition, increasing nanoparticle concentration under higher temperature regimes resulted in a faster and more uniform nanoparticle synthesis, significantly enhancing the NEPCM's thermal performance. Particularly, as the temperature increased, the NEPCM near the wall melted more rapidly. The study reveals the crucial role that temperature plays in modulating the behavior and performance of NEPCM, thereby providing valuable insights for thermal management systems. These results demonstrate the significance of temperature control for maximizing the potential of NEPCM in a variety of applications. As the temperature rises, one side becomes covered in the blue color (solid), while in the standard case, the melting curve shows a little red region (melting) at the other side that starts to increase when the nanomaterial's are added.

1. Introduction

Recently, Nano-enhanced phase change materials (NEPCMs) have emerged as a promising development in this field, as they exhibit superior thermal properties and performance compared to conventional PCMs. The incorporation of nanoparticles such as Al_2O_3, CuO, and ZnO into NEPCMs has demonstrated the possibility of enhancing thermal conductivity, heat transfer efficiency, and overall thermal performance. This study aims to examine the temperature variation and thermal performance of NEPCM within an enclosure. Recognizing the behavior of

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NEPCM at increasing temperatures is essential for optimizing its application in thermal energy storage systems. This research seeks to investigate the effect of temperature on the movement of nanoparticles within NEPCM.

By examining the temperature behavior of various nanoparticle types and concentrations, it is possible to gain valuable insights into the thermal performance of NEPCM in practical applications. The findings of this study will contribute to the advancement of thermal energy storage systems, enabling the development of more efficient and effective solutions for numerous industries, including renewable energy, HVAC systems in buildings, and thermal management in electronic devices.

2. Literature Review

In thermal energy storage systems, phase change materials (PCMs) with their significant heat storage and release capacities have emerged as key components. Nano-Enhanced Phase Change Materials (NEPCMs) have been the subject of recent research, where nanoparticles are incorporated into PCMs to improve their thermal properties and overcome their inherent low thermal conductivity, [1] The study of the behavior of NEPCM under varying temperature conditions has attracted considerable interest. Kashani et al. [2] study is notable because they conducted an exhaustive investigation into the solidification of NEPCMs in a trapezoidal cavity. They utilized computational fluid dynamics (CFD) to examine the impact of temperature changes on the thermal behavior of NEPCMs. It has been reported that nanoparticles have a notable effect on the thermal conductivity, heat transfer coefficient, and surface tension of NEPCM. The significance of Huang et al. 's [3] study lies in their characterization of medium-temperature PCMs for solar thermal energy storage. Their research demonstrated that the incorporation of nanoparticles into PCM increases thermal conductivity, heat transfer coefficient, and surface tension. Sheikholeslami [4] research centered on numerical modeling of NEPCM solidification in a metallic-finned enclosure. The study revealed that as the temperature rose, nanoparticle movement within the NEPCM increased, thereby enhancing the material's thermal performance. These results laid the groundwork for comprehending the effect of temperature variations on the thermal behavior of NEPCM. In contrast, Talebizadeh Sardari et al.[5] investigated the phase-change material melting process embedded in porous media. They focused specifically on the effect of heat storage size, yielding crucial insights into the impact of temperature variations on the thermal behavior of NEPCM. In spite of the abundance of information provided by these studies, a comprehensive understanding of the effect of temperature variations on NEPCM within an enclosure is still lacking. In this work, the interfacial heat transfer coefficient between the fluid and porous media at each place and time is calculated using user-defined functions (UDF) in ANSYS-FLUENT software to solve the governing equations. The pressure correction equation's Presto scheme and the momentum and energy equations' QUICK scheme are used in the discretization of the governing equations by the SIMPLE method. For the pressure, velocity, energy, and liquid percent, the under-relaxation parameters are set to 0.3, 0.6, 1, and 0.9, respectively. The energy equation's convergence requirement is set at 10^{-9}, whereas the continuity and momentum equations' conditions are set at 10^{-6}. It should be noted that larger values for the convergence criteria are also examined, and the outcomes show no difference. Further research, such as that conducted by Tofani et al., [6], elucidated the role of NEPCMs in latent heat and thermal energy storage systems. They presented a comprehensive review that highlighted the superior thermal performance of NEPCMs. In spite of the progress made in understanding NEPCMs, they emphasized the need for more targeted research into the temperature variations and thermal performance of NEPCMs in various enclosures.

Benlekkam et al. [7] investigated a nano-enhanced hybrid PCM for latent thermal energy storage systems. They conducted a numerical study which revealed that the hybrid nanoparticles significantly enhanced the temperature behavior and thermal performance of the NEPCM. Their results highlighted the potential of NEPCMs to improve thermal energy storage.

Several researchers have considered a variety of NEPCM performance optimization parameters. Algarni et al. [8] examined the optimization of nano-additive characteristics to improve the efficiency of a shell and tube thermal energy storage system. Using various modeling techniques, they concluded that controlling the nanoparticles' characteristics could significantly affect the temperature behavior of the NEPCM. In addition, special heat transfer fins designed for the melting process of PCM and NEPCM have been the subject of research, as noted in the study by Kok [9]. The author reported that the temperature variations and melting process of the NEPCM were affected by specific fin designs. These findings represented a significant advance in comprehending the factors influencing the thermal performance of NEPCM under different conditions. Bouzennada et al. [10] conducted a numerical simulation of the influence of heat source position on the melting of NEPCM. Their research provided crucial insights into temperature variations and their effects on NEPCM. However, their study focused primarily on the position of the heat source, leaving room for additional research into the influence of temperature variations on the thermal performance of NEPCM in an enclosure. Similarly, Ghalambaz et al. [11] investigated the thermal energy storage and heat transfer of NEPCM in a shell-and-tube thermal energy storage unit, taking into account a partial layer of eccentric copper foam. The findings of this study highlighted the significant impact of temperature on the thermal properties of NEPCM and emphasized the need for further research into the effects of temperature variation. Rashed et al. [12] discussed the behavior of nanofluids adjacent to a moving vertical plate with variable Brownian and thermal diffusion coefficients. Their findings shed new light on the influence of variable parameters on the thermal behavior of NEPCM, indicating that temperature variation has the potential to significantly impact the thermal performance of NEPCM.

Ghalambaz et al. [13] examined the effect of variable-length fins and various high thermal conductivity nanoparticles in a bio-based phase change material-containing energy storage unit. They reported that temperature variations had a significant effect on the unit's performance, indicating the need for additional research on temperature variations in NEPCM. Huang et al. [14] add to the discussion with their numerical analysis of the melting process in a rectangular enclosure with varying fin placements. While the work provides valuable findings on the fin locations, the ramifications of temperature variations on the thermal performance of NEPCM are understudied and thus require additional research. Kothari et al. [15] investigated the thermal properties of finned and unfinned NEPCM-based heat sinks for thermal management systems. Their work highlights the integral role of NEPCMs in thermal system management and highlights the need to investigate the effects of temperature variation on the thermal performance of NEPCMs. Soliman et al. [16] provide a numerical simulation and experimental confirmation of the constrained melting of PCM in a cylindrical enclosure subject to a constant heat flux. Even though they provide experimental support for the theoretical framework, the examination of temperature variations and their effect on the thermal behavior of NEPCMs requires additional investigation. In his master's thesis, Ma [17] sheds light on the melting of PCM around a heated nanoparticle with natural and forced convection. His research is a significant contribution to the field, but the specific impact of temperature variations on the thermal performance of NEPCMs in an enclosure remains an area of limited research.

This study investigates the variation in temperature and thermal performance of NEPCMs in an enclosure. It has revealed the potential of NEPCMs to enhance thermal performance and the need for additional research into temperature variations within NEPCMs within an enclosure. Previous research has increased our knowledge of the thermal behavior of NEPCMs under various conditions and configurations, but the current literature lacks a thorough investigation of the impact of temperature variation on the thermal performance of NEPCMs housed within an enclosure. The investigation of the effect of temperature variations on the thermal performance of NEPCMs will add to the scientific community and improve the practical applications of these materials in thermal energy storage systems. This study seeks to address this deficiency and contribute to the broader field of thermal energy storage by investigating the complex relationship between temperature variation and NEPCM performance.

3. Methodology

This study used numerical simulations to investigate the temperature variation and thermal performance of the Nano-Enhanced Phase Change Material (NEPCM) within an enclosure. The methodology for this study is grounded in numerical modeling, which allowed us to solve the governing equations for energy conservation and nanoparticle dispersion. A comprehensive computational model was designed and implemented using the finite volume method, which allowed us to solve the governing equations for energy conservation and nanoparticle dispersion.

a) Numerical modeling approach

This study's numerical model relies heavily on the solution of the Navier-Stokes equations for fluid flow and the enthalpy-porosity method for the phase change process. The governing equations are discretized using the finite volume method and solved using a commercial CFD software application. Under the assumption of local thermal equilibrium between the base fluid and nanoparticles [18], the computational domain was discretized into a structured mesh and the transient behavior of heat transfer was modeled. To address phase change issues, the enthalpy-porosity method was utilized, while Brownian motion and thermophoresis effects were considered to predict the nanoparticle distribution. Using unstructured tetrahedron grids, a square-shaped, 10-centimeter-wide and 10-centimeter-long, two-dimensional model was created. ANSYS facilitates the generation of solid geometry meshes and three-dimensional models from a single phase with minimal user input.

The simulation model solves continuity, momentum, and energy equations while simulating fluid flow and heat transfer inside the NEPCM enclosure. The governing formulas for an incompressible flow with heat transfer are as follows:

Continuity Equation:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

Momentum Equation:

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = \frac{1}{\rho}\left(-\nabla P + \mu \nabla^2 \vec{V} + \rho \vec{g} \beta \left(T - T_{ref}\right)\right) + S_m \tag{2}$$

Energy Equation:

$$\frac{\partial h_{sens}}{\partial t} + \frac{\partial h_{lat}}{\partial t} + \nabla \cdot \left(\vec{V} h_{sens}\right) = \nabla \cdot \left(\frac{k}{\rho c_p} \nabla h_{sens}\right) \tag{3}$$

$\vec{V}$: velocity vector, P: pressure, ρ: fluid density, μ: dynamic viscosity, g: gravitational acceleration, T: temperature, c_p: specific heat capacity, and k: thermal conductivity.

To ensure computational efficiency and simplify numerical simulations, several presumptions and simplifications are made:

1. It is assumed that the NEPCM is incompressible, ignoring density fluctuations that vary on temperature and pressure.
2. Turbulence effects are ignored and laminar fluid flow inside the NEPCM is considered.
3. The density, specific heat capacity, thermal conductivity, and viscosity of the NEPCM are thought to be temperature-invariant thermophysical characteristics.
4. The phase shift process is modeled using an enthalpy-porosity method or an effective specific heat approach, taking into account the latent heat of fusion.
5. The effects of any natural convection can be taken into consideration by adding the

proper buoyancy factors to the governing equations.

6. Except for the stated boundary criteria, the enclosure walls are taken to be adiabatic.

A mesh independence must be created to observe the obvious difference while altering the element count and the output results, as it ceases when the output results stabilize. This is necessary to acquire correct and trustworthy results. With only a single phase of input from the user, ANSYS can generate three-dimensional models and solid geometry meshes, see figure (1).

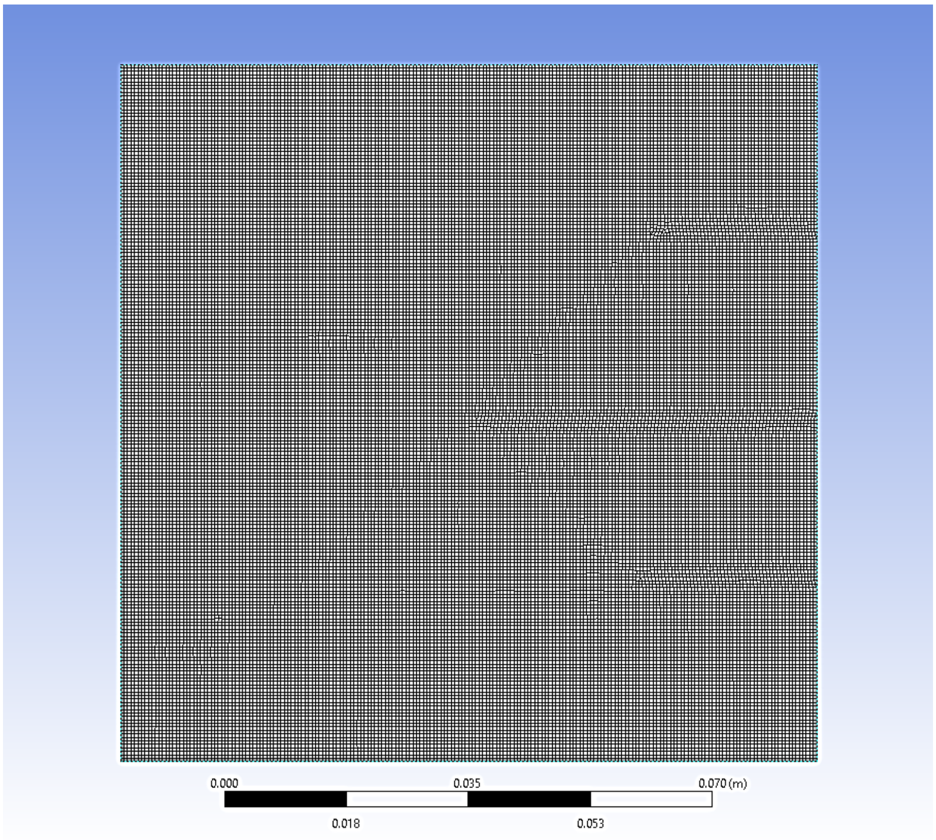

Figure 1: Geometry meshes.

The number of cells taken, in this study was (51330) and the element size is set to 0.0005 m, see table (1).

Table 1: Mesh independency.

Case	Node	Element	Max. velocity (m/s)
1	21576	18356	0.087
2	31267	28705	0.068
3	41236	38653	0.062
4	51330	48254	0.061

b) NEPCM composition, nanoparticle types, concentrations, and boundary conditions

The simulation compares temperature variation and thermal performance for 0.1, 0.3, and 0.5 wt.% nanoparticle concentrations. The enclosure walls have variable temperatures with the feeder's temperature change over time. This study used NEPCM made of paraffin wax (melting point 48 °C to 66 °C and chemical formula is CnH2n+2) and three nanoparticles: Al_2O_3, CuO, and ZnO. Specific heat capacity (Cp) and thermal conductivity (K) are crucial. Al_2O_3, CuO, and ZnO (K) data were compared to the standard for three concentrations. The test results in table (1) show that increasing nanoparticle concentration increases (K). Al_2O_3, CuO, and ZnO (Cp) data at those concentrations were compared to the standard. These nanoparticles were chosen to improve NEPCM thermal properties. NEPCM composition and nanoparticle types were chosen based on material thermal behavior at different temperatures. By combining numerical modeling, careful material selection, and the setting of pertinent geometric and thermal conditions, the described methodology aims to yield comprehensive insights into the temperature behaviour of NEPCMs, thereby enhancing their application in thermal energy storage.

Table 1: Properties of NEPCM [1], [19].

properties	PCM	Al_2O_3	CuO	ZnO
K_{liquid} [W/m. K]	0.12	35	18	19
K_{solid} [W/m. K]	0.21	35	18	19
Cp [J/kg.K]	2890	765	540	544
properties	PCM	Al_2O_3 0.1%	Al_2O_3 0.3%	Al_2O_3 0.5%
K_{liquid} [W/m.K]	0.12	3.608	5.484	9.56
K_{solid} [W/m.K]	0.21	3.689	5.547	9.605
Cp [J/kg.K]	2890	2677.5	2185	1717
properties	PCM	CuO 0.1%	CuO 0.3%	CuO 0.5%
K_{liquid} [W/m.K]	0.12	1.908	5.484	9.06
K_{solid} [W/m.K]	0.21	1.989	5.547	9.105
Cp [J/kg.K]	2890	2655	2185	1715
properties	PCM	ZnO 0.1%	ZnO 0.3%	ZnO 0.5%
K_{liquid} [W/m.K]	0.12	2.008	5.784	9.56
K_{solid} [W/m.K]	0.21	2.089	5.847	9.605
Cp [J/kg.K]	2890	2655.4	2186.2	1717

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4. Results and Discussion

One important discovery, as Figure 2 illustrates, is the increase in volume fraction with time. The findings show a noticeable rise in the curve, with a significant peak at 4,000 seconds where the fraction—previously reported in the Ebrahimi study [20] at 0.65—increases to 0.87 in the current investigation.

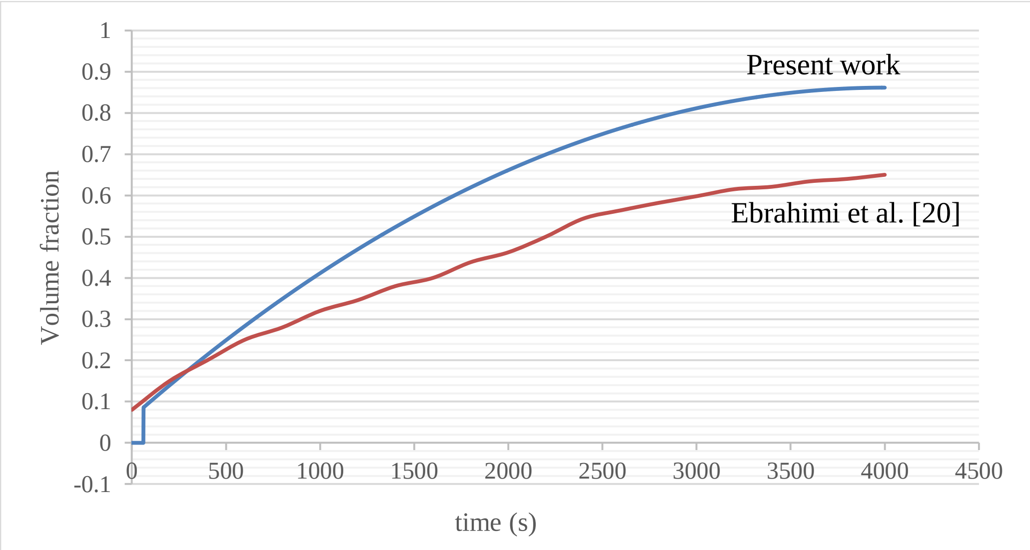
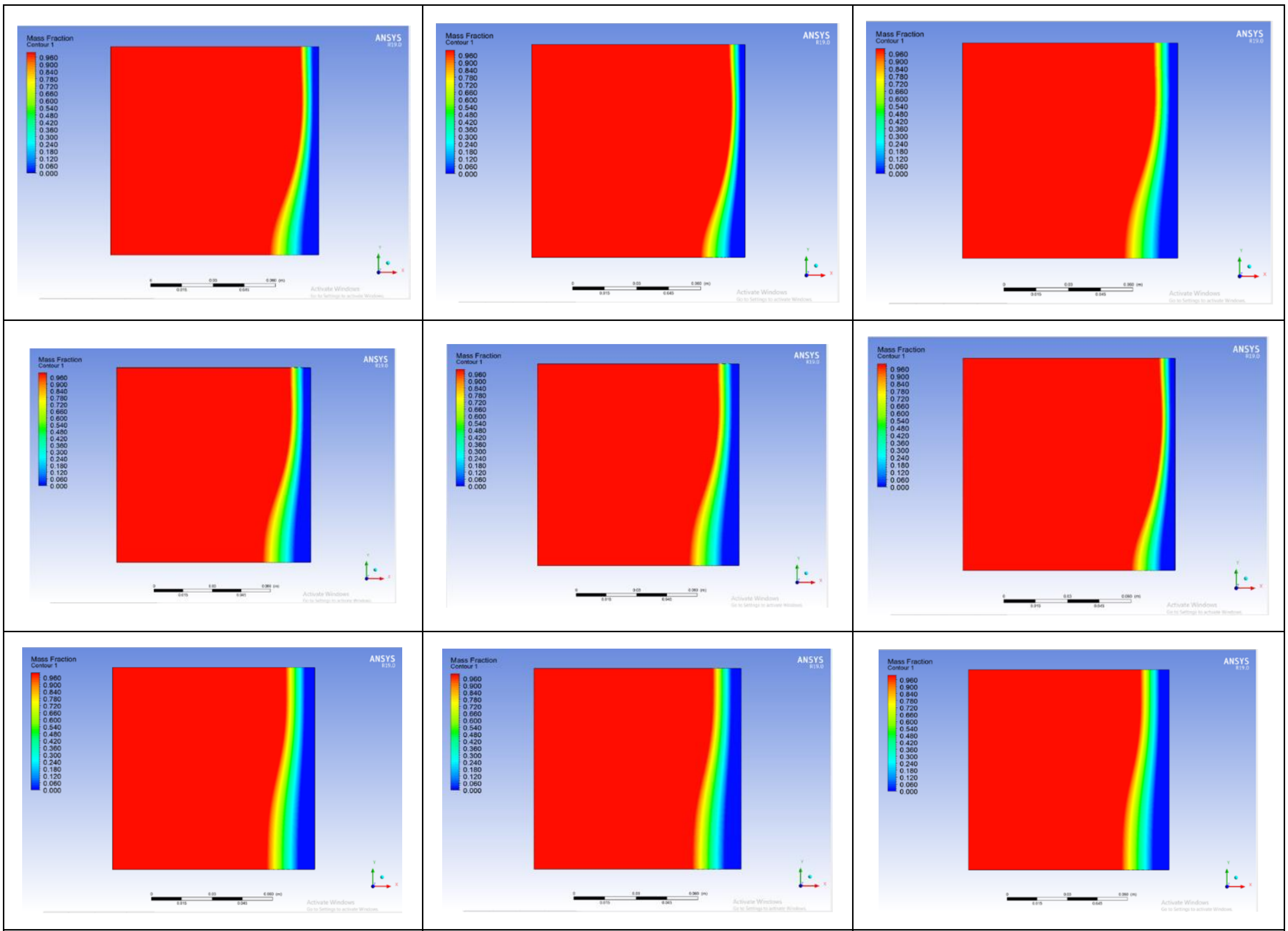


Figure 2. Mass fraction validation chart.

The numerical simulations revealed that the thermal performance of the nano-enhanced phase change material (NEPCM) within the enclosure varies significantly under different temperature. As the temperature rose, it was observed that the NEPCM underwent substantial physical changes that significantly affected its thermal properties.

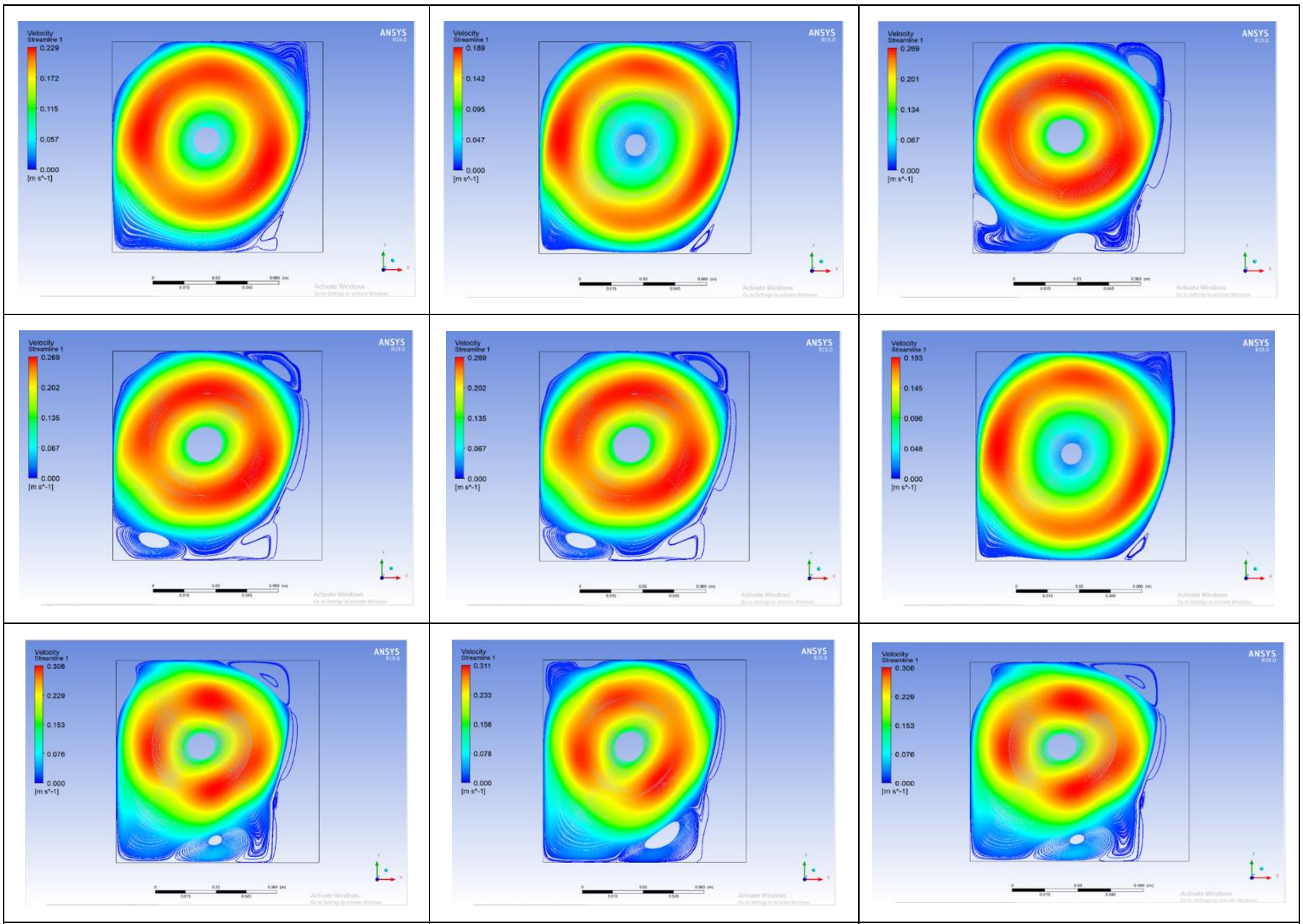
The increase in temperature of paraffin after adding nanoparticles and the changes that happen to the parameters over a known period of time are discussed. Figure 2=3 shows that the three nanoparticles decrease the mass fraction of paraffin in the range of 0.00 to 0.960 at the same concentration and testing temperature. The increasing concentration of nanomaterial leads to a decrease in mass due to the inverse relationship, which is explained on the right side of the shapes, where the curve increases in the blue area.



Paraffin + Al_2O_3	Paraffin + CuO	Paraffin + ZnO

Figure 3: The effect of temperature increases with time on mass fraction for paraffin and different nanoparticles with 0.1, 0.3, and 0.5 wt.%, respectively.

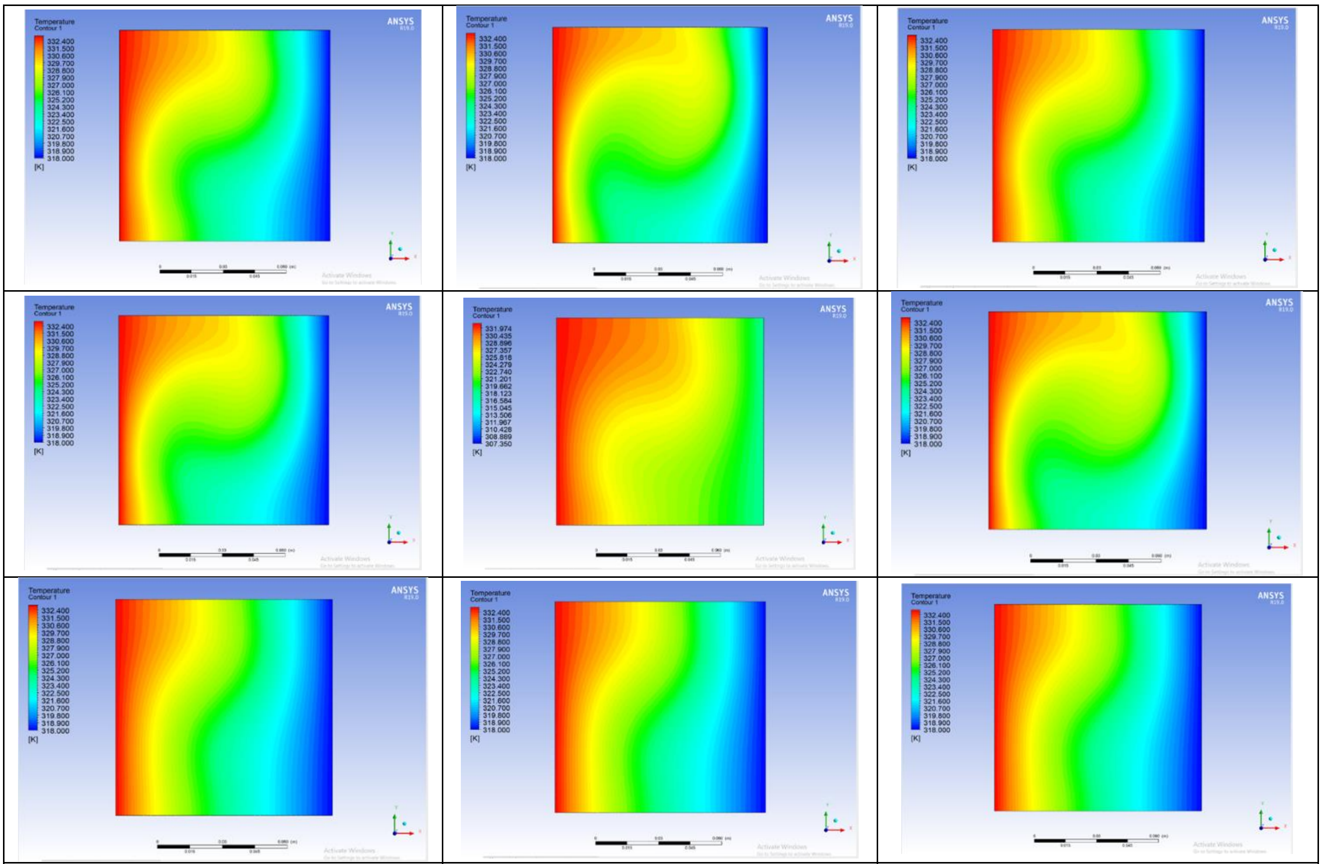
The increase in paraffin's temperature following the addition of nanoparticles, as well as the variations in parameters over a predetermined time period, are examined. When nanoparticles are added to the main material while the temperature is slowly going up, the mass fraction of these particles goes up. This is because temperature affects the density of these materials, as shown in Figure 4, where the high mass fraction for Al_2O_3 was 0.229 m/s at a mass fraction of 0.1 wt.%. As shown below, at 0.1 wt.% higher Al_2O_3 concentration, the velocity was 0.229 m/s; at 0.3 wt.%, it was 0.269 m/s; and at 0.5 wt.%, it reached a maximum value of 0.306 m/s. At 0.1 wt.%, 0.3 wt.%, and 0.5 wt.% copper oxide concentrations, the velocity will be 0.189 m/s, 0269 m/s, and 0.311 m/s, respectively. In addition, for the zinc oxide (0.269 m/s, 0.193 m/s, and 0.289 m/s, respectively, for the same concentrations, as shown in Figure 4), it was determined that CuO, which has a value of 0.311 m/s due to its low density, had the highest value. In addition, the increase in temperature plays a significant role by increasing the Reynolds number of the material through the heat transfer processes that occur between the nanomaterial' particles.



Paraffin + Al_2O_3	Paraffin + CuO	Paraffin + ZnO

Figure 4: The effect of temperature increases with time on velocity streamline for paraffin and different nanoparticles with 0.1, 0.3, and 0.5 wt.%, respectively.

The changes in parameters over a predetermined time period and the rise in temperature of paraffin after the addition of nanoparticles are investigated. By raising the temperature while maintaining the same concentration, the temperature distribution among the nanoparticles was improved. When the temperature rises, the right side is covered by the blue color (solid), as shown in Figure 5, whereas the curve of the melting gives a small red region (melting) at the left in the standard case, beginning by increasing with the addition of the nanomaterials as well. The findings demonstrate that the thermal conductivity of nanoparticles decreases as temperature rises and increases as concentration rises. With an increase in nanoparticle concentration, the tested nanofluids' viscosity and thermal conductivity increased. Because the density of Al_2O_3 was over three times that of pure paraffin, density also increased. However, because it is lower than the specific heat of wax paraffin, the specific heat of Al_2O_3 decreased as the concentration of nanoparticles increased. When the temperature and mass concentration rose, the Pr number fell. While the Ra number grew as the temperature rose and slightly fell as the mass concentration rose.



concentrations of Al_2O_3	concentrations of CuO	concentrations of ZnO

Figure 5: Temperature profile for third case of all materials with paraffin and different.

In summary, the results presented demonstrate a comprehensive investigation of the thermal performance of a nano-enhanced phase change material (NEPCM) under various temperature regimes. The effects of various conditions and the addition of nanoparticles (Al_2O_3, CuO, and ZnO) to paraffin were the focus of numerical simulations. Observations revealed that the temperature of the heat-supplying wall was a crucial variable, as its increase led to significant physical changes in the NEPCM. When nanoparticles were added to paraffin, the heating process was enhanced, and higher nanoparticle concentrations led to enhanced melting near the wall. The nanoparticles' temperature distribution was improved by increasing the temperature while maintaining the same concentration. As the temperature rose, the movement of nanoparticles increased, leading to a consistent increase in kinetic energy, thermal conductivity, and heat transfer coefficient, as well as a decrease in surface tension. With increasing temperatures, the nanoparticle synthesis became more uniform and accelerated.

These results are consistent with studies indicating that the addition of nanoparticles to PCMs improves their thermal performance, as compared to the existing literature. Several research articles, such as [21], confirm that the incorporation of nanoparticles significantly enhances the heat transfer capabilities of PCMs. However, the precise performance varies based on the types of nanoparticles used, their concentration, and the temperature conditions, as demonstrated by this study. Nonetheless, additional research is necessary to confirm these findings, given that specific heat decreased with increasing nanoparticle concentration and that nanomaterial type had varying effects, as demonstrated by this study and others in the field.

5. Conclusions

The following are some conclusions that can be drawn given the subject matter:

1. Enhanced Thermal Conductivity: Nano-enhanced phase change materials (NEPCMs) have significantly higher thermal conductivity than traditional PCMs, solving the inherent low thermal conductivity issue of PCMs. High-conductivity nanoparticles make heat transfer more efficient.
2. Temperature Regulation: NEPCMs' advanced thermal properties help regulate and manage enclosure temperatures. This is crucial in thermal energy storage, electronic cooling, and building insulation.
3. Efficient Energy Storage and Release: NEPCMs' high thermal performance comes from their efficient energy storage and release. In variable-temperature environments, this can reduce energy waste and provide continuous power.
4. Reliability and Repeatability: NEPCMs exhibit consistent performance under cycling conditions. Thermal properties, energy storage, and release capabilities do not degrade significantly after repeated melting and solidifying cycles, indicating a dependable, long-term application potential.
5. At the same concentration and testing temperature, the mass fraction of paraffin (melting) falls; the ideal melting condition is achieved by adding CuO material.
6. The paraffin and nanoparticles behaved better when the temperature was raised.
7. The behavior of the paraffin and nanoparticles improved with an increase in supplied temperature.
8. The rate of velocity streamlining was increased by adding nanomaterials to paraffin wax.
9. The velocity rate increased as all nanomaterial concentrations increased; the greatest value recorded at CuO with 0.5 weight percent.
10. When the temperature of all kinds of nanoparticles increased, the majority of the material's physical characteristics, such as heat capacity and thermal conductivity, also increased.
11. The melting instance close to the enclosure wall was improved by raising the concentration of nanoparticles.
12. The velocity streamline particles are influenced by nanoparticles in three dimensions, with a maximum velocity being reached for 0.1 weight percent Al_2O_3.
13. Future Research: Current results are promising, but nanoparticle synthesis and dispersion within the PCM must be optimized to maximize thermal conductivity enhancement. NEPCMs' long-term stability and environmental impact must also be examined before widespread adoption.

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