Power Engineering and Engineering Thermophysics
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Numerical Analysis of Time-Varying Temperature Profiles and Nanoparticle Concentration Effects on Nano-Enhanced Phase Change Materials in Enclosed Systems

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Received: 07-11-2024 **Revised:** 08-25-2024 **Accepted:** 09-06-2024

Citation: M. A. Khazaal, A. Daneh-Dezfuli, and L. J. Habeeb, "Numerical analysis of time-varying temperature profiles and nanoparticle concentration effects on nano-enhanced phase change materials in enclosed systems," *Power Eng. Eng. Thermophys.*, vol. 3, no. 3, pp. 148–157, 2024. https://doi.org/10.56578/peet030301.

Abstract: The thermal behavior and fluid dynamics of Nano-Enhanced Phase Change Materials (NEPCM) in enclosed systems have been investigated using numerical simulations, focusing on the effects of time-varying temperature profiles and nanoparticle concentration. The analysis reveals that the inclusion of nanoparticles significantly enhances the fluid flow velocity and streamlining within the enclosure, particularly for aluminium oxide (Al_2O_3), copper oxide (CuO), and zinc oxide (ZnO) nanoparticles. The results indicate that an increase in nanoparticle concentration leads to an acceleration in fluid flow and improved heat transfer efficiency, with distinct phase change dynamics observed across different concentrations. The study demonstrates that nanomaterials hold substantial potential for enhancing the thermal performance of NEPCM systems. These enhancements can contribute to greater efficiency in thermal energy storage (TES) and heat transfer processes, particularly in industrial applications requiring energy optimization. The findings align with previous research, emphasizing the positive correlation between nanoparticle concentration and velocity streamlining. This work provides valuable insights for the future exploration of different nanoparticle types and concentrations, paving the way for the development of more efficient NEPCM systems in advanced thermal systems.

Keywords: Varying temperature profiles; Nanoparticles; Fluid flow; Heat transfer characteristics; Velocity distribution; Numerical simulations

1 Introduction

In the case of TES materials, phase change materials (PCM) have gained much attention because of their heat storage capacity during phase transformation. NEPCM is PCM with added nanoparticles, which greatly enhances the thermal conductivity, and hence the heat transfer capabilities of the materials. Velocity streamline, which is the streamline along which a fluid particle moves under steady flow conditions, is also crucial to the performance of NEPCM. The velocity streamline is important in NEPCM since it affects the heat transfer process in the system directly. The addition of nanoparticles into PCM affects the fluid dynamics, the motion and path of fluid particles as well as the velocity streamline of NEPCM. The improvement of the velocity streamline can further increase heat conduction and convection, the rate of heat transfer and consequently the thermal efficiency of the NEPCM.

In addition, the nature and concentration of nanoparticles in the base PCM are capable of significantly influencing the velocities. Various nanoparticles possess distinct characteristics, namely size, morphology and thermal conductance, which affect the flow behavior in the NEPCM in a distinct way. The nanoparticle concentration is also important since it determines the viscosity of the PCM and thus affects the streamline pattern. In this study, a detailed two- and three-dimensional analysis technique was employed, aiming to examine the influence of nanoparticles on the velocity streamline in NEPCM. This study aims to describe the types and concentrations of nanoparticles and examine the way they influence the velocity distribution in the enclosure, thereby achieving the optimal NEPCM performance in TES applications. This study is expected to provide insights on NEPCM fluid dynamics, and offer a pointer to future research and application possibilities in this promising area of research.

2 Literature Review

Some studies have been conducted on the properties, possibility and impact of nanoparticle concentration on the velocity of NEPCM. Research interest in NEPCM has surged, driven by its versatility across a range of applications, including electronic cooling, building heating and cooling, TES, and the thermal management of electric vehicle battery systems. Despite this interest, the direct impact of nanoparticle concentration on the velocity distribution within NEPCM remains insufficiently examined in the existing literature.

Ho et al. [1] studied the TES in a micro-encapsulated PCM-filled enclosure and concluded that PCM can be useful in heat storage. They assumed that packaging PCM might enhance the thermal conductivity and heat transfer rate. Nevertheless, the influence of nanoparticle concentration on velocity was not examined directly. Daneshazarian et al. [2] assessed the feasibility of using NEPCM for thermal storage with an emphasis on its heat storage ability. As for the effect of nanoparticle concentration on velocities, their work provides a valuable addition to the thermal properties of NEPCM. However, more investigations are still required.

In a study by Ghalambaz et al. [3], a deformed mesh method was employed to numerically examine the heat transfer characteristics of nano-enhanced non-Newtonian octadecane containing mesoporous silica particles in a tilted enclosure. Although they suggested the impact of concentration of nanoparticles on heat transfer characteristics, they did not study the impact on velocities. In a sinusoidal enclosure filled with PCM-containing nanoparticles, Li et al. [4] conducted a simulation. The research is extremely helpful in the understanding of the thermal characteristics of NEPCM under various conditions. However, the impact on the velocity streamline was not explored in detail.

Several researchers concentrated on the convection effect and the melting process of nano-PCM within porous enclosures. They pointed out the significant role of velocities in the NEPCM, but did not discuss the effect of the nanoparticle concentration on velocities [5, 6]. Other research also has the same pattern of focusing more on thermal behavior than flow behavior. Elbahjaoui et al. [7], Dadvand et al. [8], Faraji et al. [9], and Ma [10] all assisted in the understanding of the thermophysical characteristics, phase change, and heat transfer of NEPCM. Nevertheless, the relationship between nanoparticle concentration and velocities was not investigated in these studies.

Hajiyan et al. [11] investigated the impact of vibration on the melting of PCM within a cylinder, providing a novel perspective. This study provides the opportunity to investigate how vibrations and nanoparticle concentration can affect the velocity streamline in NEPCM. Kean and Sidik [12] investigated numerically the melting of different nanoparticles enhanced by PCM within a square enclosure. Although their work shed light on the effects of various nanoparticle types on the melting behavior of PCM, the explicit relationship to velocity streamline remains unexplored.

Several researchers investigated TES and heat transfer of NEPCM in shell and tube TES units and optimization of characterizations of nano-additives for enhancing the performance of the shell and tube TES systems, respectively [13, 14]. These studies contribute to the optimization of NEPCM systems. However, they do not directly address the impact of nanoparticle concentration on velocity.

Bouzennada et al. [15] simulated the effect of the position of the heat source on the melting of NEPCM. Although their research is highly relevant to comprehending the dynamics of NEPCM, it does not address how nanoparticle concentration influences the velocity streamline.

Despite the voluminous literature on NEPCM, several issues remain unexplored such as the effects of time-dependent temperature and nanoparticle concentration on the NEPCM properties. Several researchers have studied heat transfer and phase change with nanoparticles. However, few of them have focused on time-varying temperature profiles, nanoparticle concentration, heat transfer, and the performance of NEPCM for applications in TES. This observation indicates a strong demand for further investigations on this particular aspect.

Curiously, the impact of nanoparticle type, shape and distribution on the velocity streamline inside NEPCM requires further investigation. Moreover, the dynamics like vibrations or external force, as discussed in the work of Hajiyan et al. [11], or the relation between the position of a heat source and concentration of nanoparticles, as discussed in the work of Bouzennada et al. [15], require a deeper investigation. However, it would be more interesting to know how nanoparticle loading or, conversely, how the geometry of the encapsulation space affects the phase change characteristics in NEPCM systems.

Khazaal et al. [16] concluded that the nanoparticles had an inverse relationship between the concentration and the mass fraction. Although the melting behavior of the NEPCM was improved, the CuO was considered as the most effective due to its low density and high thermal conductivity. The study is useful for identifying the trends of nanoparticle concentrations in relation to the phase change properties of PCM and improving the understanding of the nanoparticle characteristics on the thermal properties of PCM.

Khazaal et al. [17] aimed at the thermal characterization of NEPCM with a focus on the temperature variation and nanoparticles in the enclosure. The effect of temperature conditions on the NEPCM was demonstrated and the changes in its physical and thermal properties were established. Incorporation of different nanoparticles such as Al_2O_3, CuO and ZnO enhances the heating process by increasing thermal conductivity, the heat transfer coefficient and the surface tension of paraffin. They also revealed important information about the effect of temperature on NEPCM behaviour and performance to improve the thermal management system. Temperature has a great impact on the efficiency of NEPCM applications. Thus, it should be regulated.

PCM enhances the efficacy of the solar power system since it stores excess energy during phase change. But due to their low conductance, it limits the charging and discharging [18]. Scientists studied the NEPCM for enhanced thermal properties and stability of the material for a longer period. The interaction between nanoparticles and PCM affects thermophysical properties. While NEPCM has demonstrated improvements in both thermal conductivity and heat storage enthalpy, some studies have reported a decrease in heat storage capacity over time.

In summary, previous research on nanoparticle concentration in NEPCM has significantly enhanced people's understanding. However, it would be good to learn more about how nanoparticle concentration and changing temperature over time affect the phase change properties of NEPCM in these materials. This research gap presents an opportunity for future research to contribute to the development of NEPCM and their practical applications.

3 Methodology

This study uses numerical simulations to investigate the time-vary temperature profiles and effects of nanoparticle concentration on the behavior of NEPCM. It reveals distinct phase change dynamics and thermal performance characteristics in response to varying nanoparticle concentrations.

i) Numerical model

The numerical model to be discussed in this study is predominately based on the solution of the Navier-Stokes equations for fluid flow and the enthalpy-porosity method for the phase change process. Included in the governing equations are continuity, momentum, and energy. In addition, a nanoparticle concentration equation was provided to account for nanoparticle concentration variations within the NEPCM. The equations were discretized using the finite volume method, and the commercial Computational Fluid Dynamics (CFD) software package, ANSYS (version 19.1), was employed to solve them. Figure 1 shows the CFD flowchart.

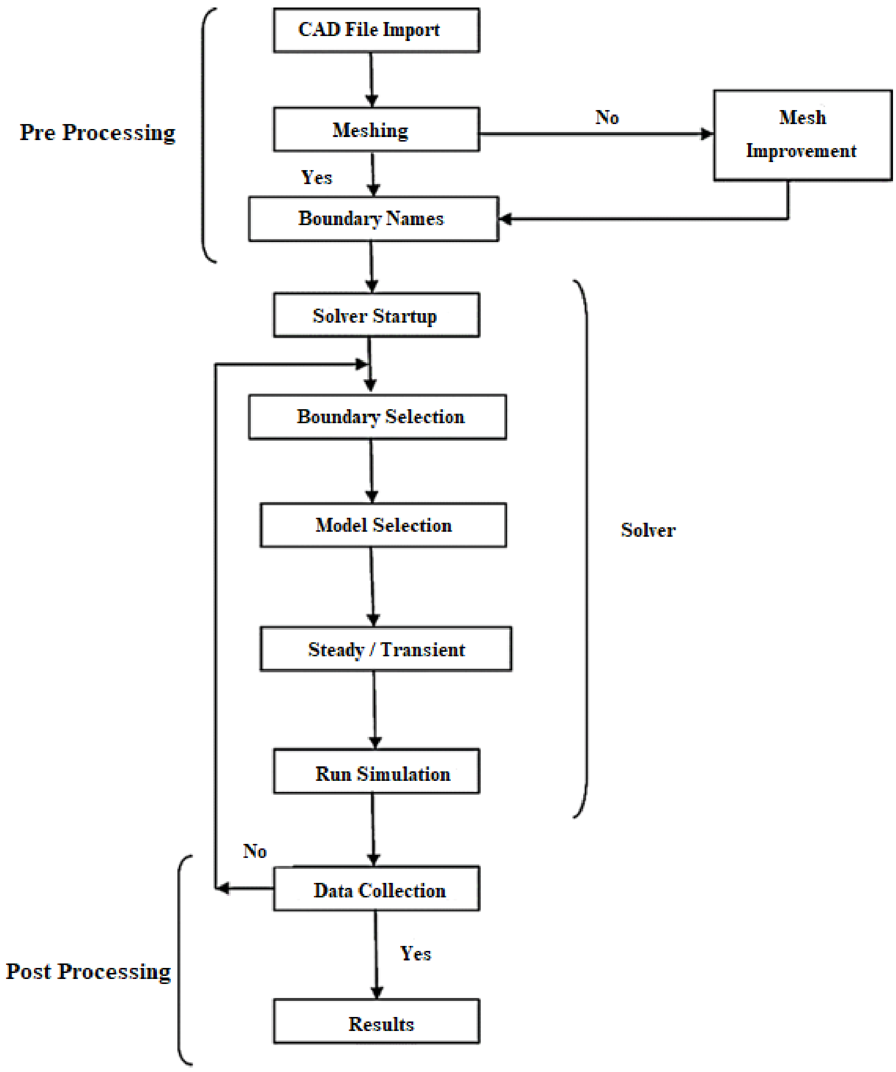

Figure 1. Flow chart of CFD

Continuity equation:

$$\nabla \cdot u = 0 \tag{1}$$

Momentum equation:

$$\rho(\partial u/\partial t + u \cdot \nabla u) = -\nabla p + \mu \nabla\hat{}2u + \rho g \tag{2}$$

Energy equation:

$$\rho Cp(\partial T/\partial t + u \cdot \nabla T) = \nabla \cdot (k \nabla T) + Q \tag{3}$$

where, u is the velocity vector, p is the pressure, ρ is the fluid density, μ is the dynamic viscosity, g is the gravitational acceleration, T is the temperature, Cp is the specific heat capacity, k is the thermal conductivity, and Q is any volumetric heat sources or sinks.

A square-shaped 10 cm ×10 cm (width × length) two-dimensional model was created. The unstructured tetrahedron grids were selected for the current investigation because they work well with complicated geometry. ANSYS supports the generation of solid geometry meshes and three-dimensional models with minimal user input from a single phase.

ii) Simulation setup

The simulation was run with different concentrations of nanoparticles (Al_2O_3, CuO, and ZnO) from 0.1 wt% to 0.5 wt% to find out how they affect the NEPCM. The enclosure walls were given appropriate boundary conditions, such as a gradually varying temperature over time as a Cos profile at the melting case for paraffin after the addition of nanoparticles. In this case, it is based on these three types of concentrations and nanomaterials. Figure 2 depicts a gradually varying temperature over time with a Cos profile, the varying temperature and the geometry and boundary conditions.

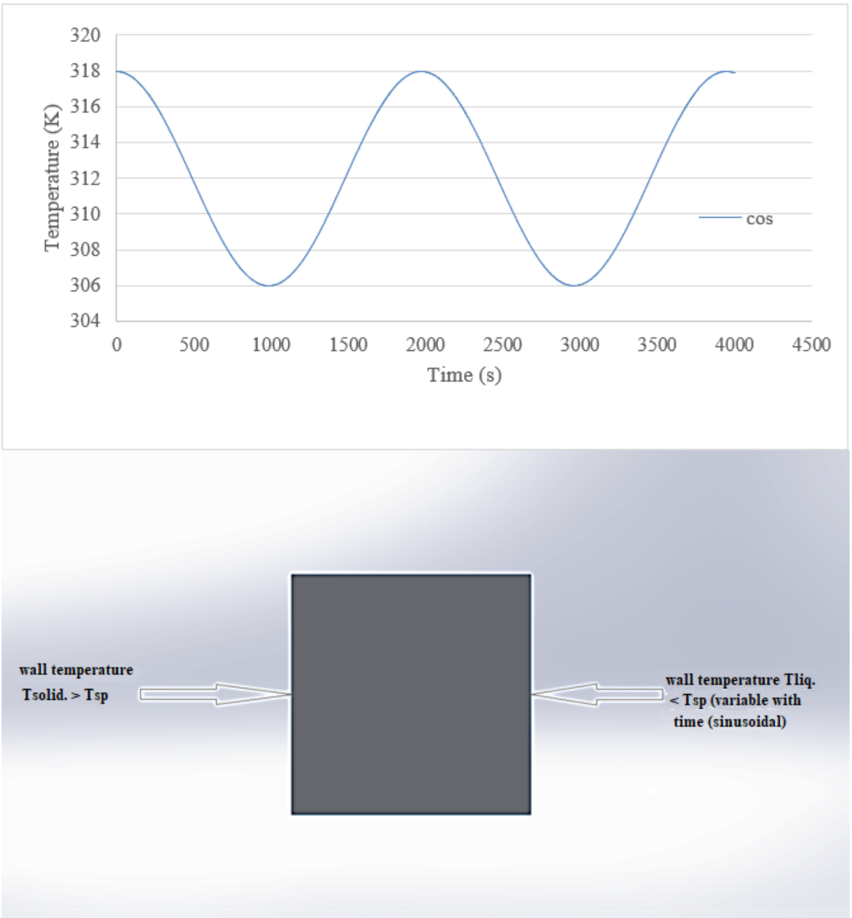

Figure 2. Gradually varying temperature over time as a Cos profile

iii) Assumptions

Several assumptions were made to simplify the numerical modeling and simulation process in this study.

a) Due to the relatively low velocities and temperatures involved in the process, the flow within the enclosure is assumed to be laminar and incompressible.

b) It is assumed that the phase change process is one-dimensional, with no phase change occurring along the insulated enclosure walls.

c) Initial nanoparticle distribution within the NEPCM is assumed to be uniform.

d) Using the Boussinesq approximation, the momentum equation accounts for the buoyancy effect, which is caused by density differences within the NEPCM due to temperature changes.

e) During the phase change, the properties of the NEPCM and nanoparticles are assumed to remain constant.

This model provides a reasonable approximation of the actual physical process and valuable insights into the impact of nanoparticle concentration on the behavior of NEPCM.

Thermal conductivity, a thermal material property, is affected by the concentration of nanofluids. After measuring the temperature data of Al_2O_3, CuO, and ZnO at three concentrations, they were compared with the standard. The results show an increase in temperature as the nanoparticle concentration increases. Al_2O_3 shows the highest increase in temperature, with 3.608 to 9.56 W/m.K for liquid and 3.689 to 9.605 W/m.K for solid. CuO material shows the highest increase, with 1.908 to 9.06 W/m.K for liquid and 1.989 to 9.105 W/m.K for solid. The study suggests that increased thermal conductivity of nanoparticles could enhance the performance of the coolant process.

4 Results and Discussion

Nanoparticle concentration and time-varying temperature affect the behavior of NEPCM. Two-dimensional simulations show how nanoparticle types affect mass fraction and velocity distribution. The effects of nanoparticle addition on fluid flow and heat transfer were also examined. The numerical simulations performed using ANSYS-FLUENT focused on nanoparticles of Al_2O_3, CuO, and ZnO within a 10 cm × 10 cm enclosure, where two sides were maintained at low temperatures while the other sides experienced time-dependent temperature variations. The concentration effects of the nanofluids' thermal properties were numerically calculated. To explain the differences between materials at different nanoparticle concentrations (0.1, 0.3, and 0.5 wt.%), the mass fraction, velocity streamline, and temperature profile were discussed.

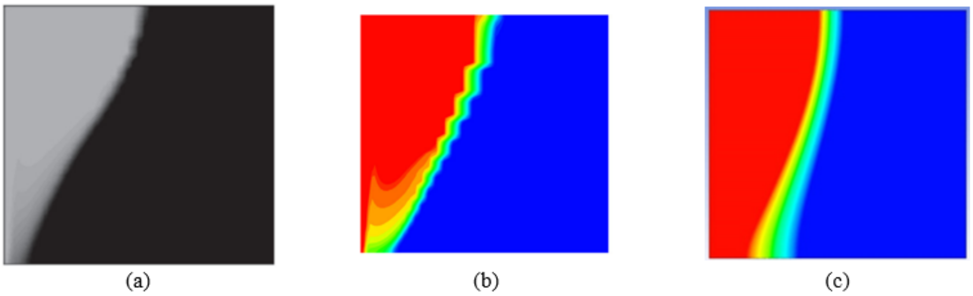

Figure 3. Validation of (a, b) previous studies and (c) this study

The results of this study were validated against the findings of Ebrahimi and Dadvand [19] and Arasu and Mujumdar [20] under similar conditions, focusing on the melting behaviour of paraffin wax with embedded nanoparticles over a period of 4,000 seconds. As illustrated in Figure 3, the comparison reveals a gradual decline in the shape of the melting front relative to the referenced studies, which can be attributed to the influence of nanoparticle concentration at the specified temperature conditions. This observation highlights the significance of nanoparticle selection and concentration in optimising the thermal performance of NEPCM.

Subgraph (c) of Figure 3 shows the heating process varying with time as a Cos profile at the melting case for paraffin after adding nanoparticles. Figure 4 shows different concentrations for the three nanomaterials and indicates a decreasing mass fraction of paraffin with temperature variation. The types of material indicate an effective mass fraction at the same concentration. When the concentration increases, the mass fraction decreases in all cases.

Paraffin melting with nanoparticles is shown as a time-varying Cosine profile in Figure 5. As depicted in Figure 5, the nanoparticles caused significant changes in the velocity streamline of paraffin, which increased for all three types of nanoparticles with varying ratios of increase (0.187 for Al_2O_3, 0.163 for CuO, and 0.165 for ZnO). As the concentration of each type was altered, the velocity increased. As for Al_2O_3, the maximum velocity is 0.187 m/s at 0.1 wt.%, 0.205 m/s at 0.3 wt.%, and 0.240 m/s at 0.5 wt.%. At concentrations of 0.1, 0.3, and 0.5 wt.%, the velocity of copper oxide is 0.163, 0.205, and 0.233 m/s, respectively. The same mechanism occurs when the concentration of copper oxide increases. For the same concentrations, the increasing rates for zinc oxide are 0.165, 0.238, and 0.240 m/s, respectively.

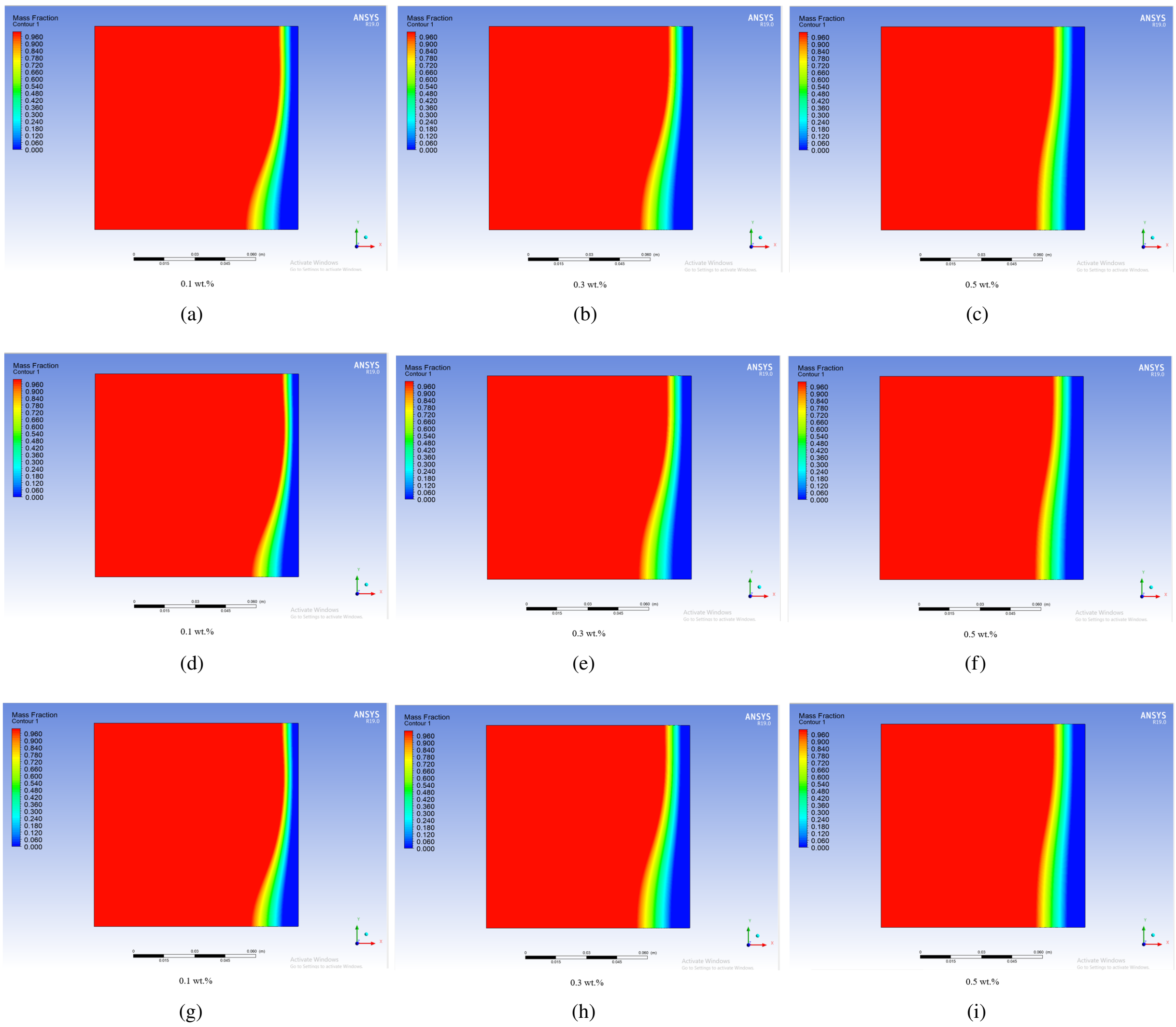

Figure 4. Effect of wall temperature on volume fraction with 0.1, 0.3, and 0.5 wt.%, respectively (a-c) Paraffin + Al_2O_3; (d-f) Paraffin + CuO; (g-i) Paraffin + ZnO

The distribution in the paraffin is less than that of the other tested and uniform materials. However, the use of the nanomaterials improved heat transfer, as shown in Figure 6, which illustrates how this parameter has a significant impact on the performance of PCM and the nanomaterials. The melting near the wall enhanced when concentration was increased when comparing the concentration effects of all nanomaterials.

The addition of Al_2O_3, CuO, and ZnO nanoparticles to PCM involves assessing factors such as thermal properties, phase change behavior, stability, cost, and environmental impact. Al_2O_3 nanoparticles have high thermal conductivity, which can significantly enhance the thermal conductivity of PCM. CuO nanoparticles also exhibit high thermal conductivity and offer effective heat transfer enhancement. ZnO nanoparticles have moderate thermal conductivity and, therefore, their use in enhancing heat transfer is limited. In general, Al_2O_3 nanoparticles do not impose a shift in phase change behaviour of the PCM but only improve the heat transfer properties. CuO nanoparticles can affect the phase change behavior of PCM to a marginal extent because of their interaction with the PCM matrix. ZnO nanoparticles may also be expected to have a relatively small influence on the phase change behaviour of PCM and may act mainly to improve the thermal conductivity of the material. Al_2O_3 nanoparticles are chemically inert and could be incorporated into a wide range of PCM matrices, while CuO and ZnO nanoparticles may not be compatible with some PCM matrices. Al_2O_3 nanoparticles usually help to increase the thermal cycling durability of PCM composites by increasing thermal conduction and decreasing thermal stresses. CuO and ZnO nanoparticles may also cost differently depending on the purity, particle size, and the method used in the synthesis; nevertheless, they are relatively cheaper than CuO nanoparticles. For the enhancement of PCM, there exists the competition of Al_2O_3, CuO and ZnO nanoparticles based on an array of parameters like thermal conductivity, stability, cost and the impact on the environment. Al_2O_3 nanoparticles provide good thermal conductivity and compatibility and thus can be used in many PCM applications.

The study also illustrates the heating procedure of the paraffin melting cases which contain nanoparticles and the change in the mass fraction of paraffin as the temperature changes. The concentration of nanomaterials influences the velocity streamline of paraffin in a noticeable and changeable manner. It is noted that the samples with higher Al_2O_3 content have the highest velocity. The composition of the synthesized nanocomposite was found to include 0.1 weight percent cobalt oxide and 0.3 weight percent zinc oxide at 0.238 weight percent. The heating procedure is shown as a time-varying Cos profile, and the distribution of paraffin is lower than that of other uniform materials. Nevertheless, their application enhanced the heat transfer, thus proving the impact of the parameter in PCM performance. The melting near the wall was higher when the concentration was higher when comparing the effects of all nanomaterials. The study proves the application of nanomaterials in increasing the heat transfer and performance of the paraffin melting cases. The research conclusions of velocity distribution based on nanoparticle concentration are in tandem with the prior research findings [1, 4]. An increase in velocity with the increase in the concentration of nanoparticles is in good agreement with the stated findings. This investigation focuses on the influence of nanoparticles on the velocity streamline of NEPCM. In this study, two-dimensional analysis was carried out to assess the impact of various nanoparticle types and concentrations on the velocity profile within the NEPCM enclosure. The outcome shows that the addition of nanoparticles affects the fluid flow characteristics and enhances velocity. The study is useful because it outlines some considerations for the improvement of velocity streamlining in NEPCM with the prospects for better thermal energy management.

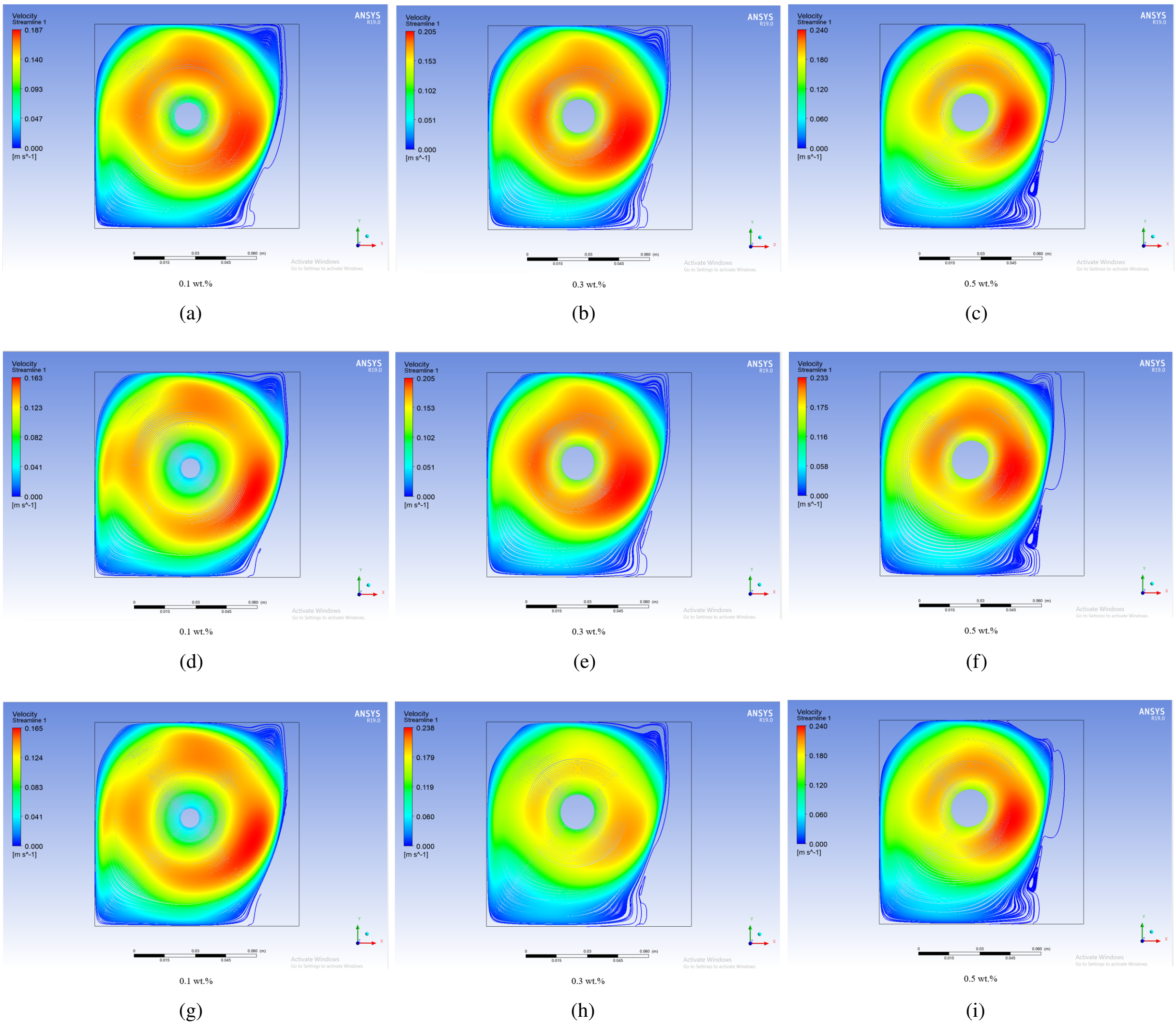

Figure 5. Effect of temperature varying with time on velocity streamline with 0.1, 0.3, and 0.5 wt.%, respectively (a-c) Paraffin + Al_2O_3; (d-f) Paraffin + CuO; (g-i) Paraffin + ZnO

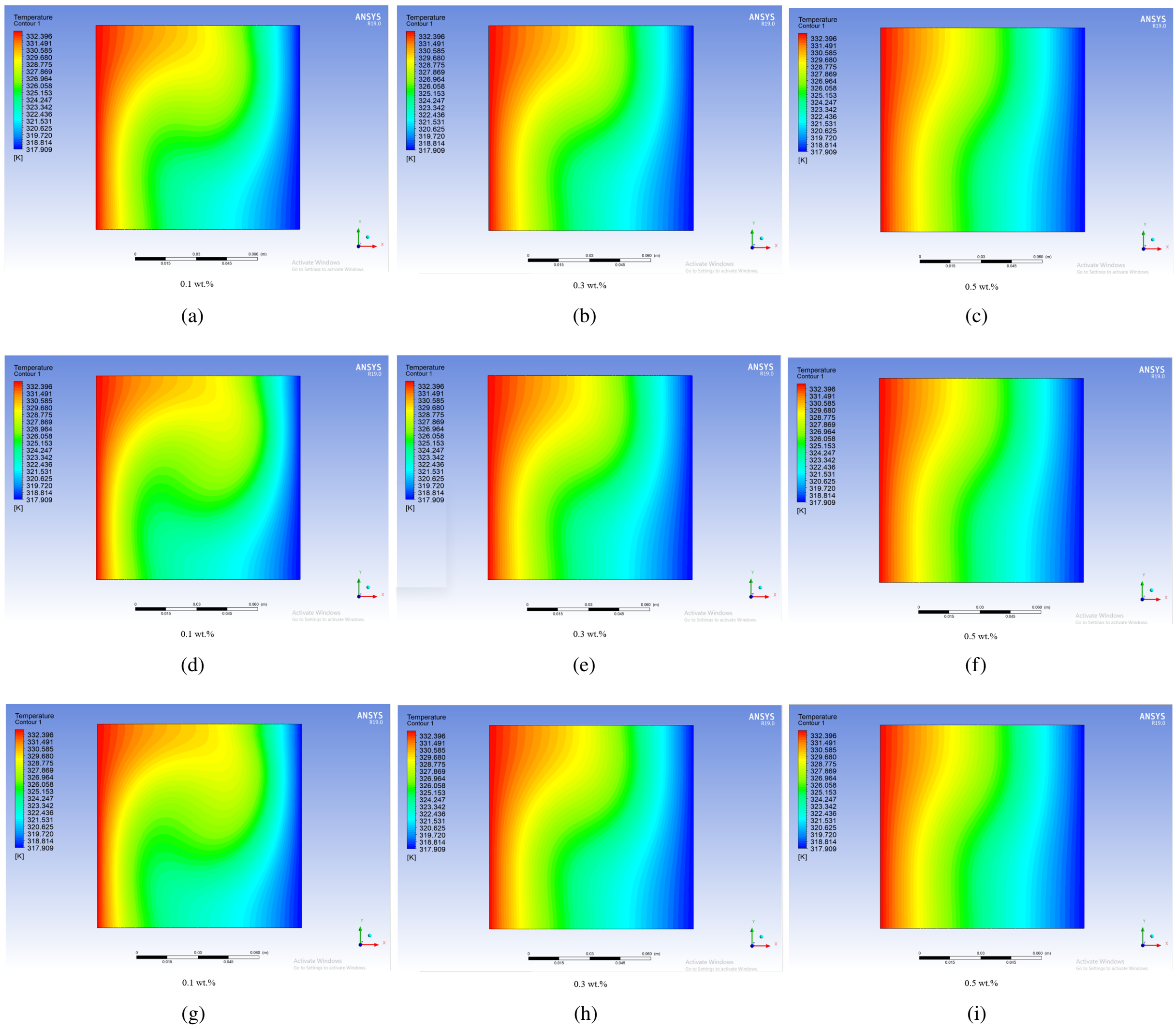

Figure 6. Temperature contours with 0.1, 0.3, and 0.5 wt.%, respectively (a-c) Al_2O_3 %; (d-f) CuO %; (g-i) ZnO %

5 Conclusions

This study focuses on comparing the results and efficiency of NEPCM used in enclosed systems. It suggests a quantitative comparative study of various types of nanoparticles (Al_2O_3, CuO, and ZnO) in order to compare their efficiency. This comparison entails temperature profiles, heat transfer coefficients, phase change behavior, and the best nanoparticle concentrations that yield the best thermal performance. This study evaluates the thermal performance and stability during constant cycling or working conditions. In addition, it measures factors such as thermal decay, nanoparticle sintering, and stability of the working performance. Sensitivity analysis assesses the robustness of the key performance indicators to changes in nanoparticle type and its concentration and determines the critical parameters that have a substantial impact on NEPCM performance. Hence, it should be further fine-tuned. This quantitative comparative analysis may offer a broad view of the effects of these parameters on the thermal characteristics and performance of NEPCM which may be helpful in decision-making for TES applications. As for the behavior enhancement of NEPCM, the findings of this study are as follows:

• NEPCM properties can be tailored for thermal management by varying the concentration of nanoparticles, showing good control of their response to heat.

• In NEPCM systems with Cos temperature profiles, the introduction of nanoparticles enhances heat transfer and melting characteristics, leading to enhanced energy efficiency and performance.

• The velocity streamline becomes faster in NEPCM by using nanoparticles. As for Al_2O_3, CuO, and ZnO, the speed-up depends on the concentration. CuO nanoparticles, in particular, show the greatest velocity enhancement, reaching 0.311 m/s at 0.5 wt.% concentration.

This study confirms the results of other studies in terms of the behavior of NEPCM. It shows that the shape of the material changes gradually and that the effect of nanoparticle concentration is consistent. The study optimizes NEPCM systems for velocity streamlining, improving heat transfer, and TES. Research on nanoparticle types and concentrations can help design NEPCM systems. This study demonstrates that the concentration of nanoparticles has a big effect on thermal behavior, improves heat transfer and melting, and makes the velocity streamline bigger. In addition, this study suggests that nanoparticle types and concentrations can improve TES and performance.

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