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Thermophysical Enhancement of Cold Energy Storage Systems Using Metal Foam and Ternary Nanoparticles: A Numerical Investigation

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Abstract: Cold thermal energy storage systems are widely employed in refrigeration, food preservation, and thermal management applications; however, their performance is often constrained by the inherently low thermal conductivity of phase change materials (PCMs), which limits the rate of solidification. Improving heat transfer during the freezing process therefore remains a central issue in the design of efficient storage systems. The present work examines the solidification behavior within a cold energy storage unit featuring a non-conventional container geometry with an elliptical cooling wall. Two enhancement strategies are considered in combination: the dispersion of a ternary nanoparticle mixture (TiO_2–Ag–Al_2O_3) in the base fluid at a volume fraction of 0.015%, and the incorporation of a metal foam structure to promote conductive heat transfer. A transient numerical model is established using a Galerkin-based finite element approach with adaptive mesh refinement to accurately capture the evolution of the solid–liquid interface. The results indicate that the addition of ternary nanoparticles leads to a reduction in total freezing time of approximately 13.12%, while the introduction of metal foam yields a substantially greater reduction of 82.35%. When both techniques are applied simultaneously, the freezing time decreases by 84.66%, demonstrating a clear synergistic effect. A comparative analysis further shows that the influence of foam porosity on the advancement of the solidification front is approximately 6.27 times greater than that of nanoparticle concentration. These findings suggest that structural enhancement through porous media plays a dominant role in accelerating heat transfer, and that prioritizing internal thermal pathways offers a more effective design strategy than relying solely on modifications of fluid properties. The results provide a quantitative basis for the development of high-efficiency cold energy storage systems in engineering applications.

Keywords: Cold energy storage system; Phase change heat transfer; Metal foam; Ternary nanofluid; Porous media; Engineering thermophysics

1 Introduction

Improving the efficiency of cold thermal energy storage systems has become a crucial focus of research, driven by the increasing need for effective cooling solutions in industries such as food preservation, medical storage, and smart building technologies. Central to these systems are phase change materials (PCMs). While PCMs offer high energy density, their widespread application is often limited by their low thermal conductivity [1–3]. To overcome this limitation, one effective solution is the combination of nano-powders into the PCM. Since the solidification rate is closely tied to the rate at which the PCM releases latent heat, the inclusion of nanomaterials accelerates the cold energy storage process, ultimately reducing the time needed for the PCM to fully freeze [4, 5]. Expanding on this idea, hybrid nanoparticles—composed of multiple types of nanomaterials—demonstrate even greater potential for enhancing thermal performance. By leveraging the distinct thermal properties of various nanoparticles, these multifunctional additives enhance dispersion, boost thermal stability, and optimize thermophysical behavior. Consequently, hybrid nanofluids provide a more effective and versatile solution compared to single-component nanofluids, particularly in accelerating the solidification process and improving overall system efficiency [6, 7]. In addition to the use of nanomaterials, incorporating high-conductivity porous media, such as metal foams, into the PCM container has proven to be another highly effective method for enhancing performance. These metallic structures, characterized by their high surface area and exceptional thermal properties, facilitate more uniform heat distribution and improve conduction throughout the storage medium. The presence of these porous networks plays a crucial role in reducing temperature gradients and accelerating the freezing front, thereby increasing the system's responsiveness and efficiency. By integrating advanced enhancement techniques such as nanoparticle dispersion, hybrid nanofluids, and porous metallic inserts, researchers are addressing the traditional thermal limitations of PCMs. This multifaceted approach not only accelerates the rate of cold energy storage but also enhances the overall performance of systems, enabling them to meet modern cooling demands with improved speed, efficiency, and consistency [7–9]. Li et al. [10] investigated the behavior of photovoltaic (PV) modules equipped with PCM. Their findings revealed that the inclusion of paraffin wax significantly enhanced power generation, leading to a 5.18% enhancement in performance.

Essa et al. [11] carried out experimental research on the behavior of PV systems, employing PCM. Their results demonstrated a significant temperature decrement of 15.04K in the PV system, highlighting the effectiveness of PCM in enhancing PV performance under high ambient temperatures. Pichandi et al. [12] utilized a PCM unit at the rear of PV to enhance performance by about 1.21%. Marudaipillai et al. [13] inspected the thermal management of PV using paraffin combined with an aluminum heat sink. Their results indicated a substantial improvement in PV efficiency, with an increase of 3.667%. Qu et al. [14] explored the behavior of PV integrated with PCM in indoor environments under different ambient conditions. They illustrated that incorporating PCM significantly improved the electrical efficiency, with an increase of 1.63%.

Despite the extensive body of work on PCMs for cold energy storage, most existing studies have focused on simplified geometries and isolated enhancement strategies, typically considering either nanoparticle additives or porous media separately. As a result, the coupled thermophysical interaction between complex container configurations, hybrid nanofluids, and porous conductive structures remains insufficiently understood. This limitation is particularly relevant from an engineering perspective, where system performance is governed not only by material properties but also by the internal heat transfer pathways shaped by geometry and structure. In addition, the relative contributions of structural parameters, such as foam porosity, and material parameters, such as nanoparticle concentration, have not been systematically quantified within a unified modeling framework. This makes it difficult to identify effective design priorities for improving freezing performance in practical cold storage systems. To address these issues, the present work investigates solidification behavior in a cold energy storage unit with an elliptical cooling wall, combining a ternary nanoparticle suspension with a metal foam structure. A Galerkin-based numerical approach with adaptive mesh refinement is employed to examine the influence of both porosity and nanoparticle loading, with particular emphasis on their comparative roles in heat transfer enhancement and solidification dynamics.

2 Solidification within Complex Container Configurations

In this study, a uniquely shaped cold storage container featuring an elliptical cold wall design (see Figure 1) is investigated for its ability to efficiently store cold energy. The container is packed with metal foam, a proven method to significantly enhance heat conduction within the domain by increasing the effective thermal conductivity. Additionally, the base fluid—water—is enhanced by dispersing ternary nanoparticles to accelerate the solidification process. The modeling primarily focuses on solving the transient energy equation, as the fluid velocity during freezing is minimal and thus the momentum equations can be reasonably neglected. Two key parameters are systematically examined through a series of simulations: the porosity of metal foam (γ), which influences thermal conduction pathways, and the nanoparticle volume fraction ϕ, which affects the thermal properties of the fluid.

By applying simplifying assumptions to the governing equations, the following model formulation can be derived [15]:

$$(\gamma(\rho C_\mathrm{p})_\mathrm{Tnf} + (1-\gamma)(\rho C_\mathrm{p})_\mathrm{GI})\frac{dT}{dt} = (\gamma k_\mathrm{Tnf} + (1-\gamma)k_\mathrm{GI})\left(\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial x^2}\right) + (L\rho)_\mathrm{Tnf}\frac{\partial S}{\partial t} \tag{1}$$

$$\begin{cases} T > (T_\mathrm{m} + T_0) \Rightarrow & S = 0 \\ (-T_0 + T_\mathrm{m}) < T < (T_0 + T_\mathrm{m}) \Rightarrow & S = (-T + 0.5T_0 + T_\mathrm{m})/T_0 \\ T < (T_\mathrm{m} - T_0) \Rightarrow & S = 1 \end{cases} \tag{2}$$

The scalar quantities at each node must be computed. Prior to solving the equations, the properties of the ternary nanoparticles need to be determined based on established correlations [16–19]:

$$(\rho C_\mathrm{p})_\mathrm{Thnf} = (1-\phi_1)\left[(1-\phi_2)\left((1-\phi_3)(\rho C_\mathrm{p})_\mathrm{f} + (\rho C_\mathrm{p})_\mathrm{s3}\phi_3\right) + (\rho C_\mathrm{p})_\mathrm{s2}\phi_2\right] + (\rho C_\mathrm{p})_\mathrm{s1}\phi_1 \tag{3}$$

$$(\rho L)_\mathrm{Thnf} = (\rho L)_\mathrm{f}(1-\phi_1)(1-\phi_2)(1-\phi_3) \tag{4}$$

$$\frac{k_\mathrm{nf}}{k_\mathrm{f}} = \frac{k_\mathrm{s3} + 2k_\mathrm{f} - 2\phi_3(k_\mathrm{f} - k_\mathrm{s3})}{k_\mathrm{s3} + 2k_\mathrm{f} + \phi_3(k_\mathrm{f} - k_\mathrm{s3})} \tag{5}$$

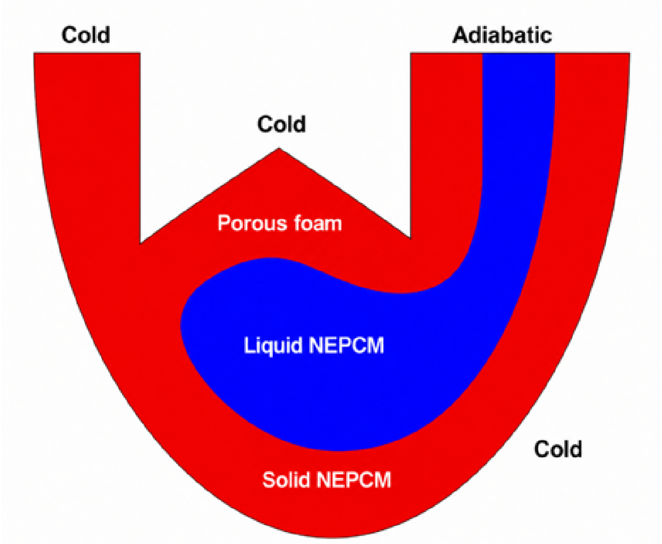

Figure 1. The new curved container filled with nano-enhanced phase change material (NEPCM) considering metal foam

$$\frac{k_{\mathrm{hnf}}}{k_{\mathrm{nf}}}=\frac{k_{\mathrm{s2}}+2k_{\mathrm{nf}}-2\phi_2(k_{\mathrm{nf}}-k_{\mathrm{s2}})}{k_{\mathrm{s2}}+2k_{\mathrm{hf}}+\phi_2(k_{\mathrm{nf}}-k_{\mathrm{s2}})} \tag{6}$$

$$\frac{k_{\mathrm{Thnf}}}{k_{\mathrm{hnf}}}=\frac{k_{\mathrm{s1}}+2k_{\mathrm{hf}}-2\phi_1(k_{\mathrm{hf}}-k_{\mathrm{s1}})}{k_{\mathrm{s1}}+2k_{\mathrm{hf}}+\phi_1(k_{\mathrm{hf}}-k_{\mathrm{s1}})} \tag{7}$$

$$\rho_{\mathrm{Thnf}}=\left[(1-\phi_1)\left[(1-\phi_2)\left((1-\phi_3)(\rho_{\mathrm{f}}+\rho_{\mathrm{s3}}\phi_3)\right)+\rho_{\mathrm{s2}}\phi_2\right]+\rho_{\mathrm{s1}}\phi_1\right] \tag{8}$$

The governing equations were solved numerically using a Galerkin-based code, well-suited for handling complex geometries with high accuracy. To enhance both precision and efficiency, an adaptive mesh refinement technique was applied throughout the grid generation process. This approach enables adaptive mesh refinement in regions with sharp gradients, particularly around the advancing solidification front, to better capture phase change behavior. An implicit scheme was used for discretizing the transient terms, improving numerical stability and allowing larger time steps while maintaining accuracy. This methodology was initially introduced to cold storage simulations by Sheikholeslami [15], who successfully applied it to various system configurations involving multiple source terms. His work confirmed that this method combined with adaptive meshing and implicit time integration is a powerful and reliable tool for modeling PCM. Building upon this foundation, the current study leverages these numerical techniques to rigorously analyze the solidification process within complex geometries enhanced by porous media and nanomaterials.

3 Results and Discussion

The current article introduces a comprehensive numerical analysis of cold energy storage within a specially designed container featuring a complex geometry defined by an elliptical cold wall. The proposed design deviates from conventional rectangular or cylindrical geometries, aiming to improve the thermal distribution. To accelerate solidification and improve thermal conductivity, the container is saturated with a high-conductivity metal foam—a proven passive technique for boosting conductive heat transfer within PCMs. Furthermore, a hybrid nanofluid composed of water blended with a ternary mixture is employed. This advanced combination significantly increases the effective thermal conductivity and enhances the freezing performance of the storage unit. The simulation framework developed in this work focuses primarily on solving the energy equation, as the momentum effects are minimal and can be neglected due to the very low velocities typical of freezing. To capture the detailed evolution of the solid-liquid interface and account for the complex heat transfer behavior, a Galerkin-based finite element method is adopted. An adaptive mesh refinement strategy is integrated into the simulation to enhance resolution near the solidification front, ensuring that regions with high thermal gradients are accurately resolved. This work is significant as it addresses key limitations in previous studies by simultaneously incorporating complex geometry, metal foam-enhanced conduction, hybrid nanofluid additives, and adaptive meshing. The findings pave the way for more efficient, compact, and high-performance solutions in refrigeration, energy conservation, and climate control applications.

Figure 2 illustrates the mesh style applied in the modeling. As time progresses, the mesh adapts dynamically, becoming increasingly refined near the advancing solidification front. This adaptive mesh refinement ensures a higher density of elements in critical regions where steep thermal gradients and phase change occur, thereby significantly improving the accuracy and resolution of the numerical solution. To validate the reliability of the numerical model, the code was tested by replicating results from a previously published study [16] involving a similar geometric configuration. A comparison of the present simulation results with the reference data is shown in Figure 3. The close agreement observed confirms the accuracy of the numerical approach and provides confidence that the model is robust and suitable for extension to the present, more complex scenarios.

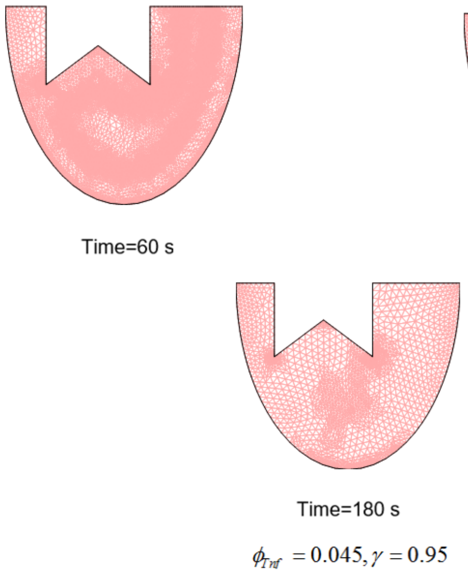

Figure 2. Three time levels and associated grid

Note: ϕ_{Tnf}, the ternary nanofluid volume fraction.

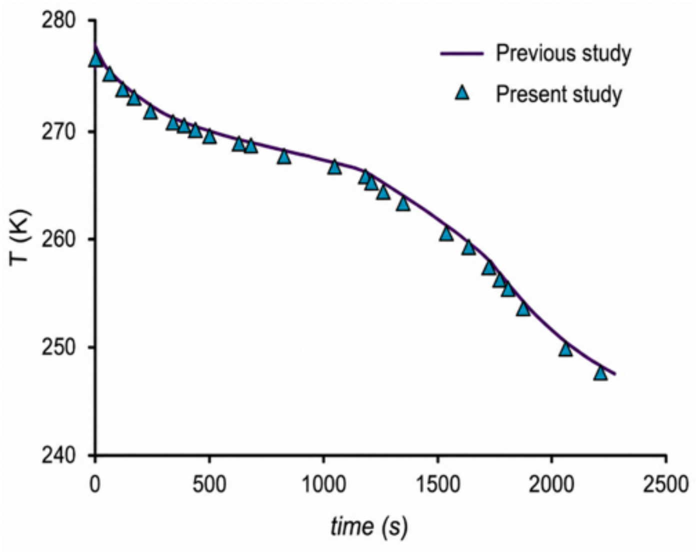

Figure 3. Validation of code

Note: Based on the previous study [16].

Figure 4, Figure 5, and Figure 6 offer the plots of two key scalar fields—temperature and solid fraction—to visualize the effects of various enhancement techniques on the solidification process. Initially, freezing begins near the cold wall as the surrounding liquid water rapidly transforms into ice, forming a moving solidification front that gradually propagates throughout the zone. As time grows, the solid phase expands and the average temperature across the container decreases. For the baseline case using pure water and no metal foam, the system requires 1144.07 seconds to reach complete solidification—representing the slowest freezing rate observed. When ternary nanoparticles are introduced into the base fluid, the freezing time decreases noticeably to 993.96 seconds, owing to improved thermal conductivity. In this case, the solidification time is dramatically reduced to just 175.39 seconds, highlighting the powerful role of porous structures in facilitating heat transfer.

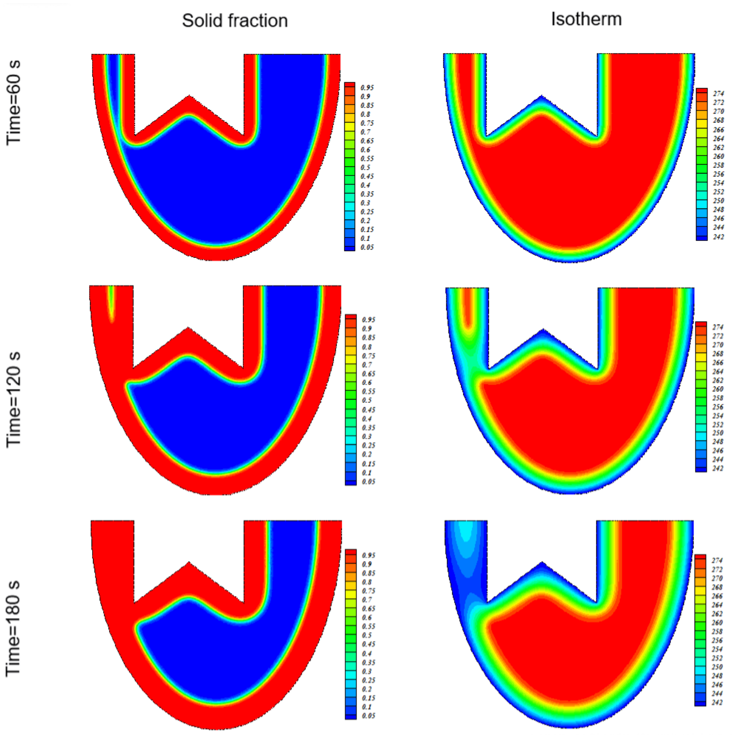

Figure 4. Changes in contours during process at $\phi_{\mathrm{Tnf}} = 0, \gamma = 1$

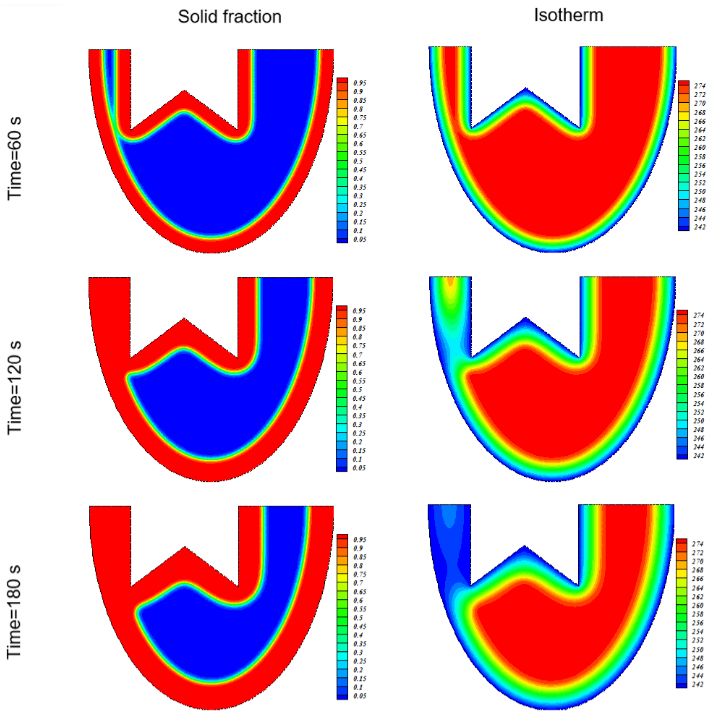

Figure 5. Changes in contours during process at $\phi_{\mathrm{Inf}} = 0.045, \gamma = 1$

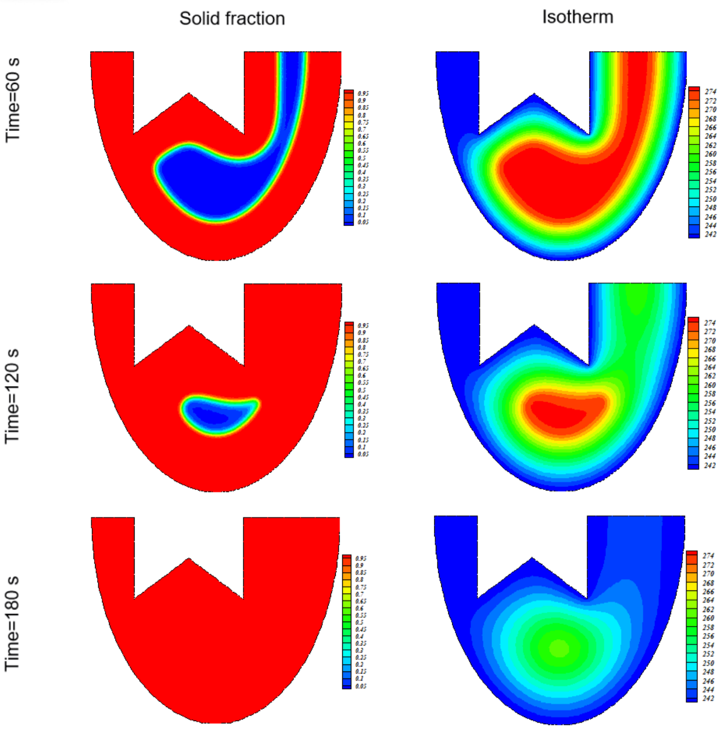

Figure 6. Changes in contours during process at $\phi_{\mathrm{Tnf}} = 0.045, \gamma = 0.95$

To further illustrate these effects, Figure 7 compares the advancement of the solidification front for different configurations. The results clearly show that the solid front progresses much faster in the presence of metal foam than in cases with only nanoparticle enhancement. Quantitatively, the impact of metal foam on the solidification front is approximately 6.27 times greater than that of the ternary nanoparticles, confirming that structural enhancements have a considerably stronger impact than material modifications alone.

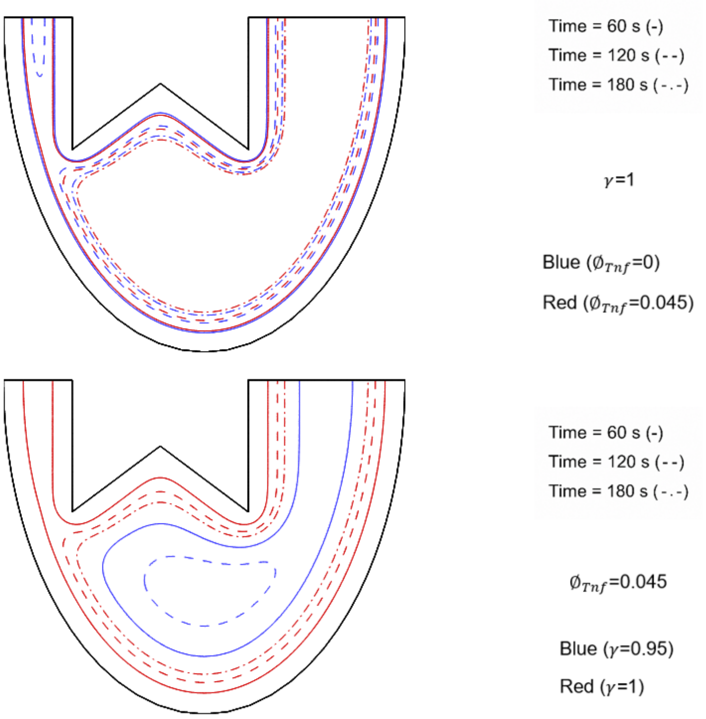

Figure 7. Change in solidification front speed

The time-dependent behavior of key thermal and phase change variables is presented in Figure 8 and Figure 9, where the average values of temperature, solid fraction, and energy are plotted over time. As the solid fraction increases during the freezing process, a corresponding decrease in temperature is observed throughout the domain. This trend reflects the progressive absorption of latent heat and the reduced availability of thermal energy as more liquid transforms into solid. These enhancement techniques facilitate more efficient heat extraction, thereby accelerating the growth of the solid front. However, they simultaneously lead to a reduction in the average temperature, as thermal energy is more rapidly removed from the system. While both parameters improve the freezing performance, the porosity has a dominant role in increasing the effective thermal conductivity and promoting uniform solidification. This finding underscores the superior influence of structural thermal management over material enhancement alone, highlighting the importance of optimizing the internal architecture of the cold storage container for maximum performance.

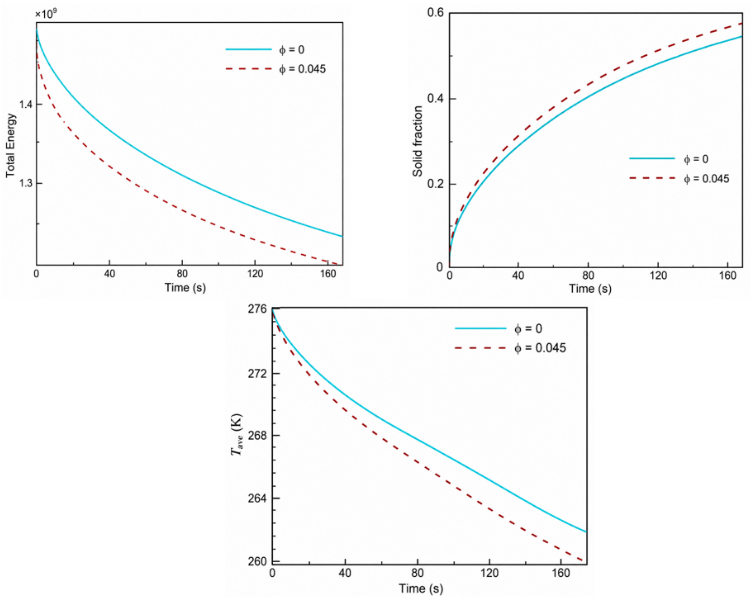

Figure 8. Analyzing behavior of system for two levels of ϕ

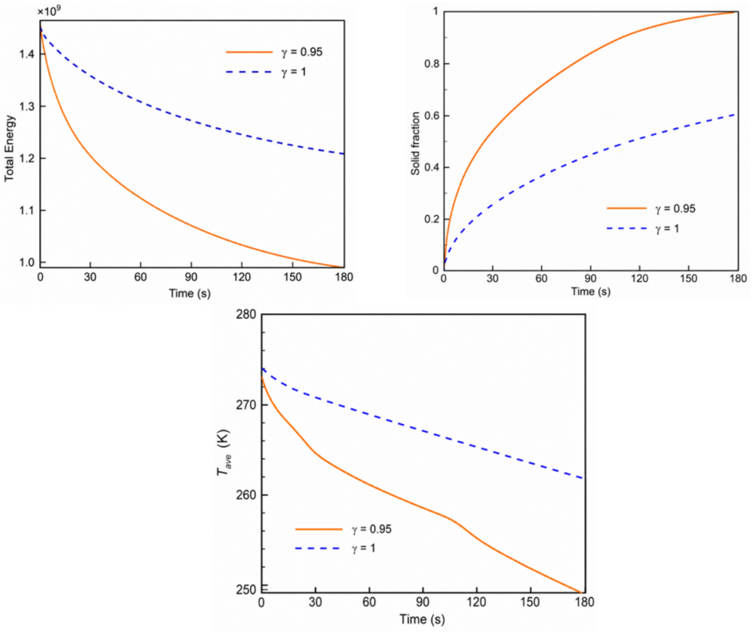

Figure 9. Analyzing behavior of system for two levels of γ

To provide a quantitative assessment of the freezing performance, the total time required to complete the freezing is depicted in Figure 10. The results show that increasing the ϕ leads to a noticeable decrease in freezing time—approximately 13.12%. The ternary nanoparticles act as thermal bridges within the fluid, facilitating faster heat removal. When metal foam is introduced into the storage container, the freezing time experiences a dramatic reduction of approximately 82.35%. This substantial improvement is primarily due to the high thermal conductivity and interconnected porous network of the foam, which distributes cold energy more uniformly throughout the domain. The presence of the foam considerably boosts conductive heat transfer, allowing the solid front to propagate more rapidly and uniformly. Furthermore, when both enhancement techniques—metal foam and nanoparticle dispersion—are applied simultaneously, the system achieves the best performance, with the freezing time reduced by an impressive 84.66%. This result highlights a strong synergistic effect between the two methods. However, it is evident from the comparative analysis that the impact of porosity in the metal foam is considerably more dominant than the influence of nanoparticle concentration. In fact, the role of porosity in accelerating the freezing front is significantly greater, indicating that optimizing the structure of the porous medium yields more substantial benefits than merely increasing nanoparticle loading. These findings underscore the effectiveness of combining conduction-enhancing strategies in advanced units and emphasize the critical role of thermal pathway optimization in achieving faster and more efficient phase change performance.

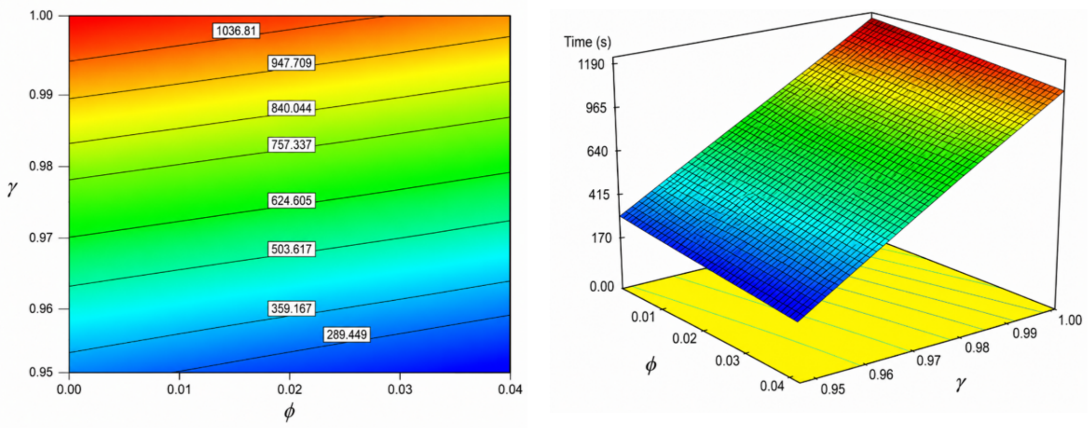

Figure 10. Needed freezing time for different configurations

4 Conclusion

This work examines the solidification behavior of a cold energy storage system employing a container with an elliptical cold wall, where both geometric configuration and thermophysical enhancement are considered simultaneously. The combination of metal foam and a ternary nanoparticle suspension is shown to modify the heat transfer process in a consistent and measurable manner.

The numerical results indicate that the phase change process initiates near the cold wall and progresses toward the interior as the solidification front advances, leading to a gradual reduction in temperature throughout the domain. The presence of metal foam has a pronounced effect on this process, reducing the total freezing time by approximately 82.35%. This behavior can be attributed to the formation of continuous conductive pathways within the porous structure, which facilitate more uniform heat extraction. In comparison, the addition of ternary nanoparticles leads to a reduction in solidification time of about 13.12%, reflecting an improvement in effective thermal conductivity, although its influence remains more limited.

A direct comparison between the two enhancement mechanisms shows that the influence of foam porosity on the advancement of the freezing front is approximately 6.27 times greater than that of nanoparticle concentration. When both approaches are applied simultaneously, the freezing time is reduced by 84.66%, indicating a clear interaction between structural and material modifications. In addition, both porosity and nanoparticle loading are associated with an increase in solid fraction and a corresponding decrease in temperature, reflecting accelerated heat removal during the phase change process.

From an engineering standpoint, these results indicate that structural modification of the storage domain plays a more decisive role than adjustments to fluid properties alone. Increasing nanoparticle concentration can improve thermal performance; however, its effect is secondary when compared to the influence of porous conductive networks. This distinction is relevant in practical applications, where considerations such as stability, cost, and implementation constraints may limit the extent to which nanofluids can be utilized.

The present findings suggest that optimizing foam porosity provides a more effective route for enhancing freezing performance than relying solely on nanoparticle loading. Accordingly, design efforts should focus on improving internal heat transfer pathways through structural modification, while material enhancement may be used to complement this approach. In this sense, the combined use of porous media and hybrid nanofluids offers a feasible strategy for improving cold energy storage systems, with clear implications for refrigeration and thermal management applications.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflicts of interest.

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