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Evaluation of thermal storage system during freezing and loading nano-powders

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Abstract

In pursuit of advancing the efficiency of cold energy storage, a uniquely designed curved container has been employed, filled with a water-nanoparticle mixtureQ. The container is equipped with fins, strategically leveraging the enhanced conduction facilitated by the presence of nanoparticles. The simulation of the intricate unsteady phenomena in this study has been conducted using the finite element technique, providing a robust analytical framework. The incorporation of an adaptive grid ensures a refined resolution, particularly in the vicinity of the ice front region. The nanoparticle fraction (ϕ) emerges as a pivotal factor directly influencing the rate of solidifying. The dispersion of nano-powders leads to a noteworthy reduction in completion time, demonstrating a substantial 33.21% improvement. The diameter of the nano-powders (dp) introduces diverse effects on the solidification process, primarily due to its significant influence on the conductivity of the nanomaterial. An in-depth exploration of the impact of dp reveals compelling insights. As the dp increases from its smallest size to 40 nm, there is a commendable 15.12% reduction in the required freezing time. However, a subsequent increment in dp beyond this threshold results in a notable 36.56% increase in the freezing time. The findings presented here not only contribute to the fundamental understanding of freezing processes but also hold practical implications for the design and optimization of cold storage systems.

Keywords Transient phenomena · Solidification · FEM · Curved finned tank · Nanomaterial

Introduction

An effective solution to mitigate the alternating of energy lies in the use of latent heat storage units employing PCM (Phase Change Materials) [1–4]. Such units are frequently regarded as a highly efficient technology to bridge the gap between supply and demand of energy [5–8]. Based on the published literature on evaluating the productivity of these tools, selecting the most suitable tool remains an issue and perplexing endeavor [9–12], particularly when dealing with hybrid techniques involving the application of multiple enhancement strategies. Currently, the hybrid approach stands out as the most popular and extensively adopted improvement strategy due to its associated benefits [13–16]. Nevertheless, the challenge of designing and selecting compatible improvement methods that work synergistically has become increasingly complex [17–20]. For instance, challenges such as the extraordinary price of nanoparticles and their preparation, and technical difficulties associated with the design and manufacturing of TES systems that incorporate additional surface areas like permeable foams and fins [21–24]. Additionally, the incorporation of fins, permeable zone, or heat pipes may diminish free convection, thereby compromising the overall performance, as these elements occupy space that could otherwise be filled by PCM [25–28]. Yagci and team [29] conducted an experimental exploration of the complete cycle of paraffin within a vertical annular free space. Their outputs exposed that the addition of fins to the tube caused in a 29.8% decrement in the total freezing time compared to the case without fins. Sheikholeslami [30] explored the integration of a paraffin container with a PVT system. To enhance the electrical productivity of the system, he incorporated MWCNT nano-powders.

Castell et al. [31] investigated the impact of fins on melting of PCM. They conducted an experimental comparison and demonstrated that the install of fins declined the time required for heat transfer from the PCM to the water. In

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a collaborative effort between two laboratories in Iran and Italy, researchers delved into the productivity of PVT units and analyzed the detrimental effects of dust [32]. Subsequently, the same research group [33] proposed the utilization of nanofluid as a spectral filter and sustainable thermoelectrics to augment system productivity. Kozelj et al. [34] conducted a comparison among a traditional unit and hybrid storage unit. They showed that performance of hybrid unit enhances about 70%. In an effort to mitigate the detrimental effects of dust and improve system efficiency, Sheikholeslami et al. [35] employed a self-cleaning coating and NEPCM. The proposed structure has potential applications for building ventilation. Deng et al. [36] scrutinized a research to investigate the impact of the number and organization of fins on enhancing the melting rate of PCM in a circular configuration. They demonstrated a correlation to achieve optimal outputs. Sheikholeslami and Khalili [37, 38] harnessed various nanoparticle types with the aim of boosting the efficiency of solar panels. Their application of nanofluid extends beyond mere cooling, encompassing its role as a spectral filter as well. Acir and Canli [39] conducted experimental investigations on the charging process of paraffin with multiple fins under simulated irradiation. The researchers observed that the improvement ratio of the melting rate increased with a decrease in fin thickness, and typically, there was an optimal number of fins to maximize melting efficiency. Attempting to harness solar irradiation, Sheikholeslami [40] explored a novel system utilizing hot fluid in a double-pipe configuration, incorporating a paraffin zone for energy conservation. The outcomes designated that the utilization of a mixture of nano-powders and paraffin exhibited superior performance.

This research examines into the simulation of the solidification process of water within a uniquely designed curved container with integrated fins. The key innovation lies in the incorporation of nanoparticles to augment the cold storage process. Leveraging a numerical simulation approach based on the FEM with an adaptive mesh adds a layer of sophistication to the study, allowing for a more accurate simulation. Novelty in this work is evident in the meticulous consideration of various factors, treating additives with different concentrations and diameters as variables. The governing equations were intelligently simplified, focusing specifically on the freezing process while omitting the influence of velocity. The visual representation of simulation outcomes through contours and plots contributes to a more comprehensive understanding of system behavior under diverse conditions. In comparison with previous publications, the significance of this study becomes apparent. While existing research has explored freezing processes to some extent, the integration of nanoparticles and the meticulous consideration of variable factors represent a notable research gap. This study, therefore, not only builds upon existing knowledge but introduces a novel perspective, addressing a crucial aspect of cold storage efficiency. The importance of this research cannot be overstated. In various applications, from industrial settings to technological advancements, optimizing cold storage is of paramount importance. The ability to accelerate the freezing process, as demonstrated through the introduction of nanoparticles and the thoughtful consideration of variable factors, has practical implications for energy efficiency, resource management, and the overall performance of systems relying on cold storage. In essence, this study contributes to the broader understanding of freezing dynamics and establishes a foundation for more effective and efficient cold storage methodologies.

The description of cold storage unit

In this research, the acceleration of the freezing process is accomplished by presenting nanomaterial of varying sizes into the container, as depicted in Fig. 1. Excluding velocity terms and employing a single-phase preparation, the modeling strategy yields the definitive unsteady model. Current numerical tool allows for an in-depth investigation into the influence of nanoparticle characteristics on freezing. The ultimate transient equations take the following form [41]:

$$\left(\rho C_{\mathrm{p}}\right)_{\mathrm{nf}} \frac{\mathrm{d}T}{\mathrm{d}t} = \nabla\left(k_{\mathrm{nf}} \nabla T\right) + L_{\mathrm{nf}} \frac{\mathrm{d}S}{\mathrm{d}t} \quad (1)$$

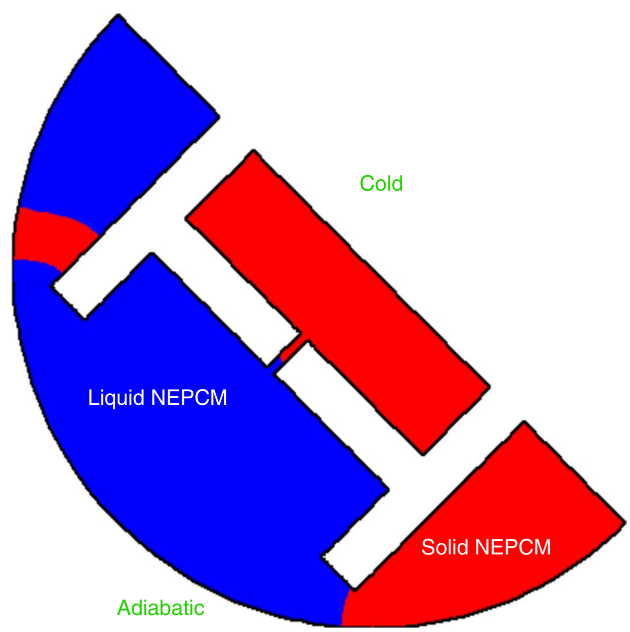


Fig. 1 Freezing within curved tank

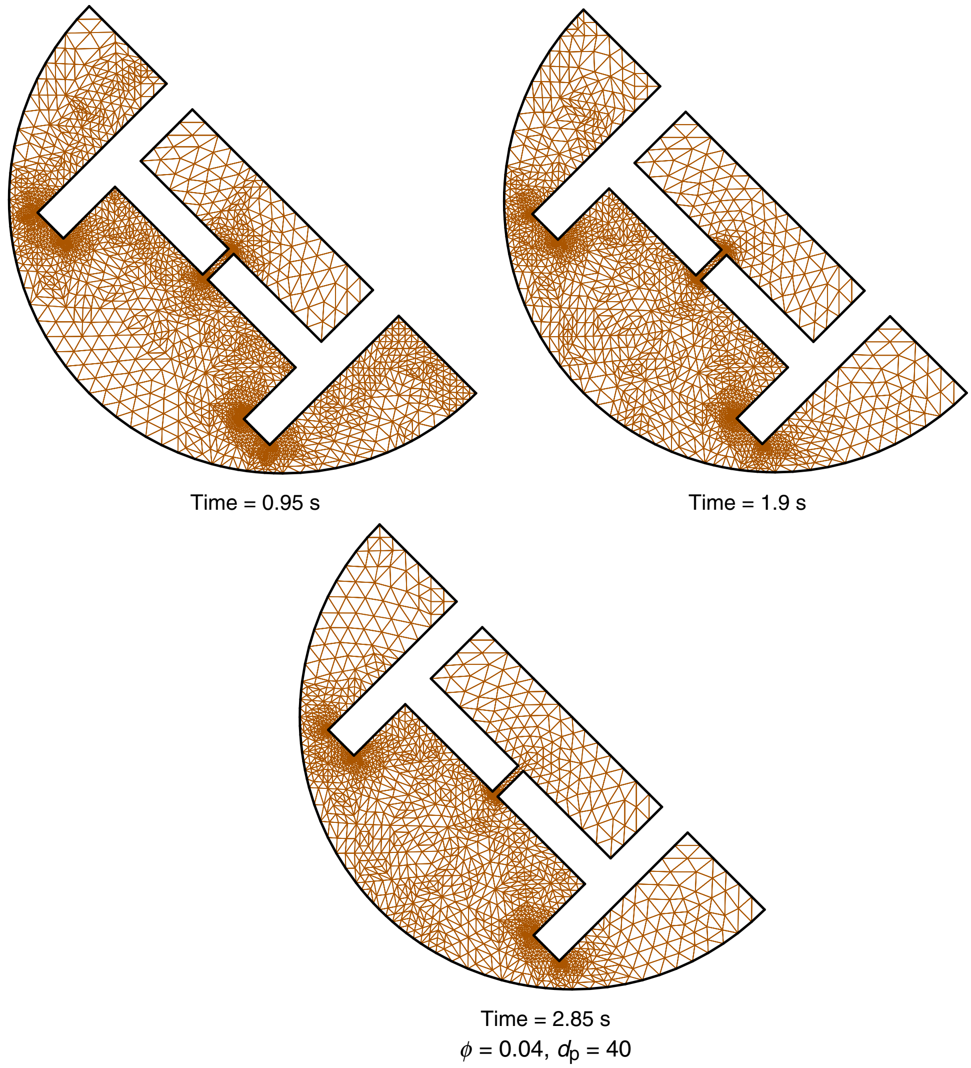


Fig. 2 Style of grid with promotion of time

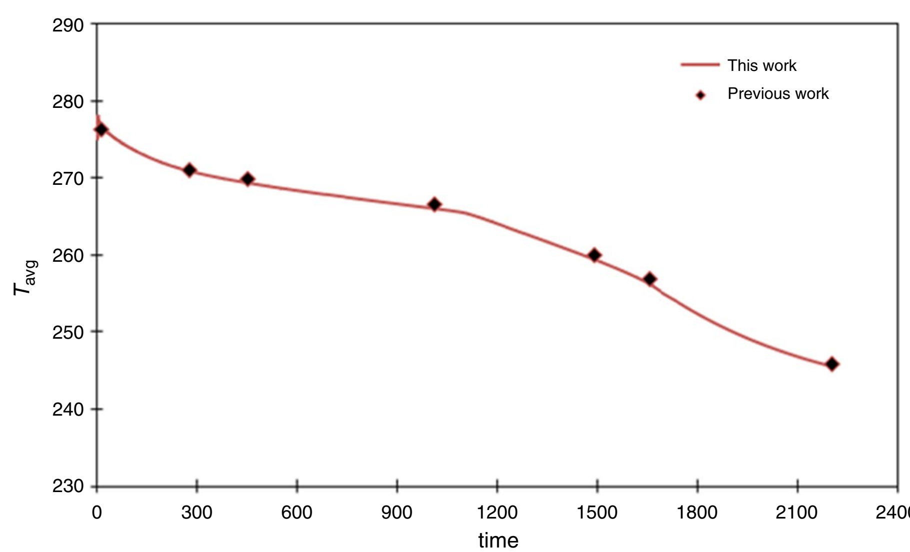


Fig. 3 Testing accuracy of code [42]

Fig. 4 Increment of freezing with augment of ϕ

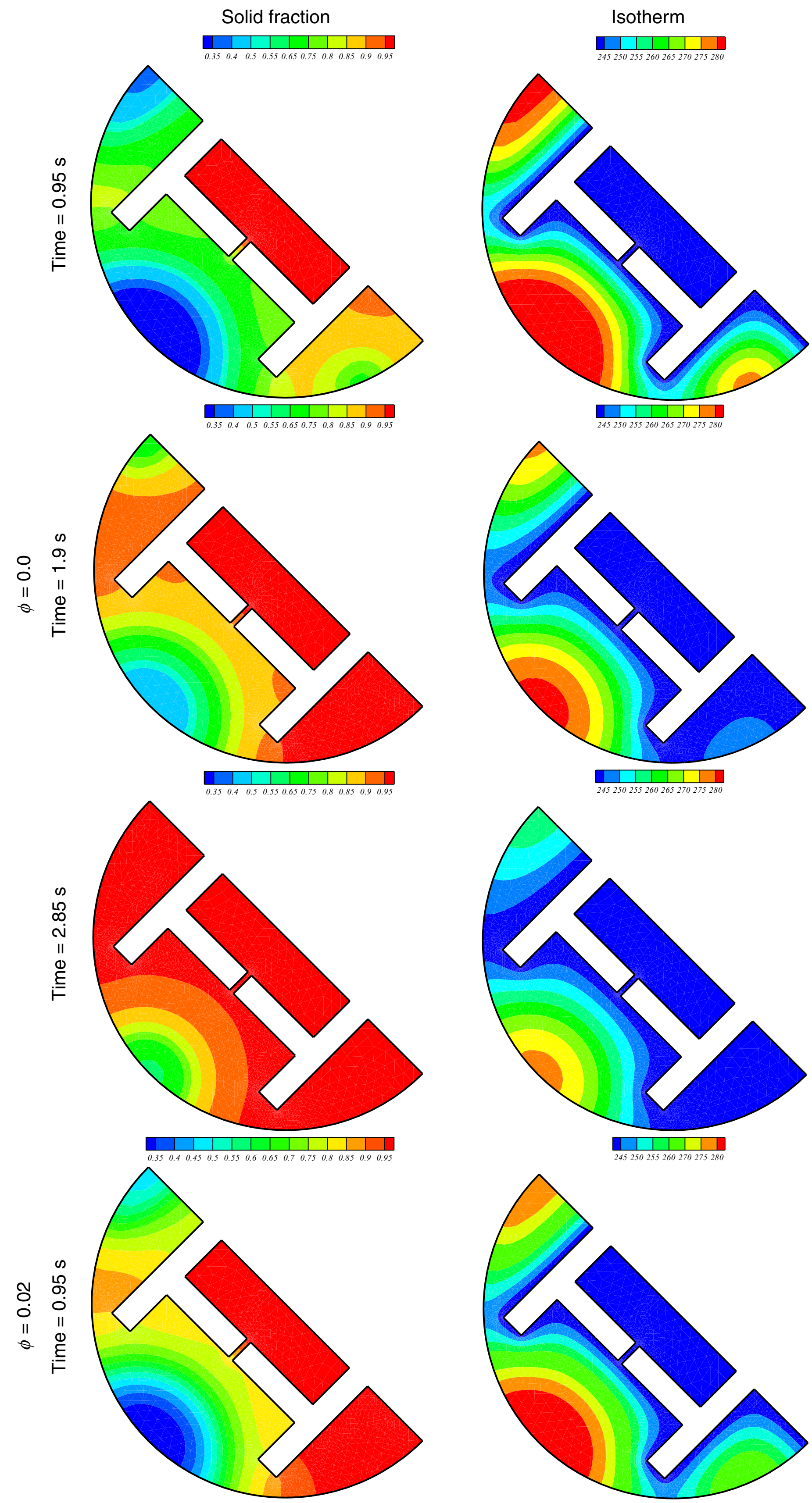


Fig. 4 (continued)

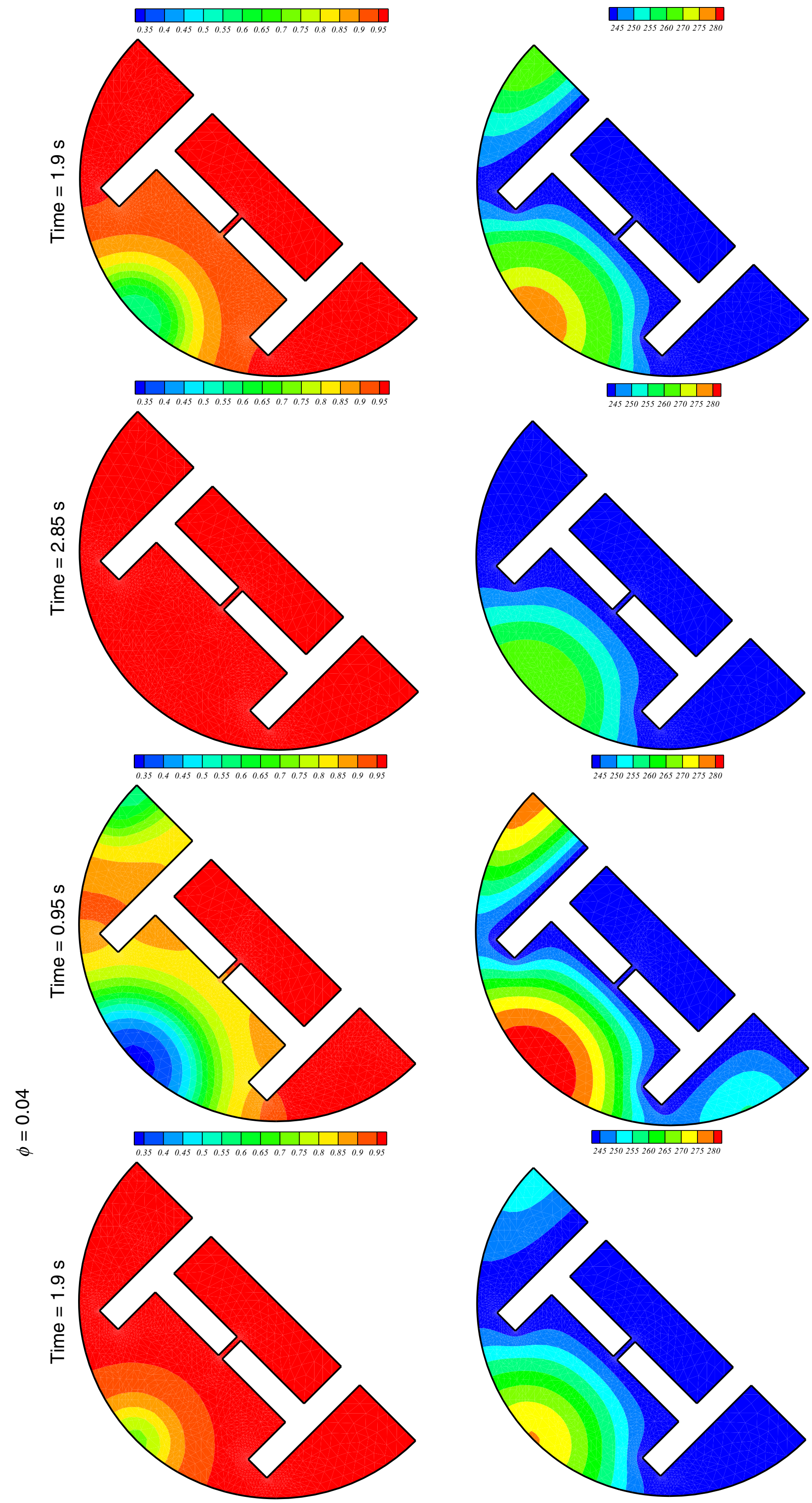
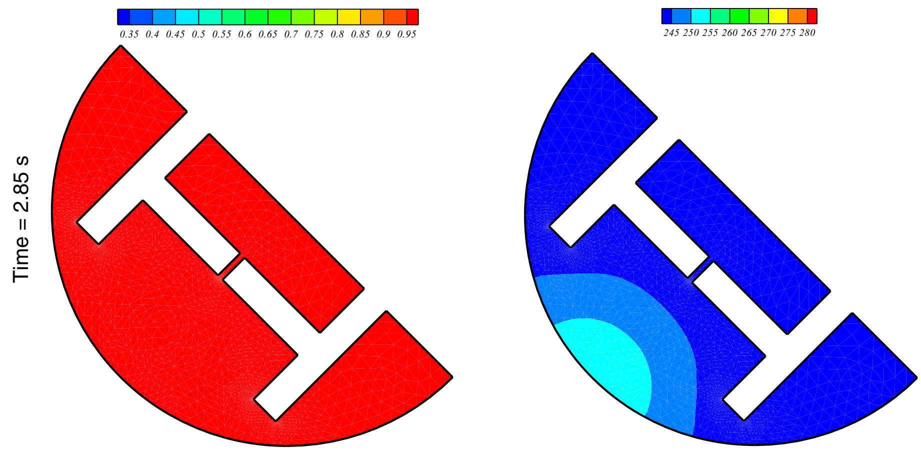


Fig. 4 (continued)



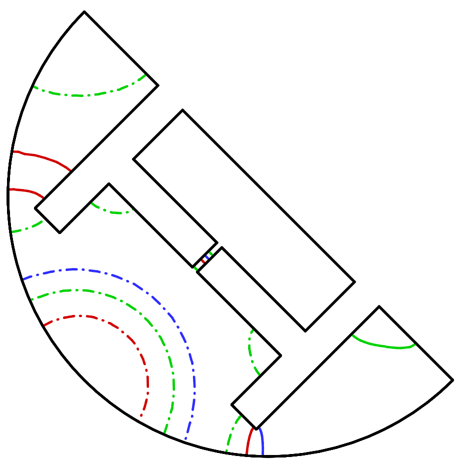


Fig. 5 Superior ϕ and progress of ice front

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

Through the application of an implicit method, the discretization of transient terms has been accomplished. The nanomaterial's formulation is applicable under the assumption of a uniform distribution of nanoparticles within the spatial domain [41]:

$$(L\rho)_{nf} = (L\rho)_f(1 - \phi) \tag{3}$$

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_p \tag{4}$$

$$(\rho C_p)_{nf} = (\rho C_p)_f(1 - \phi) + (\rho C_p)_p\phi \tag{5}$$

$$\wp = k_p/k_f,\ \frac{k_{nf}}{k_f} = 1 - 3\frac{(1-\wp)\phi}{(1-\wp)\phi + (\wp + 2)} + 5\times10^4\left(\frac{d_p\rho_p}{T\kappa_b}\right)^{-0.5} c_{p,f}\,g'(d_p, T, \phi)\phi\rho_f \tag{6}$$

In Eq. (6), the interplay between nano-powder size and nanoparticle concentration (ϕ) is evident. The solution to these equations is achieved through numerical techniques, specifically employing the finite element method along with an implicit approach and adaptive grid. This simulation methodology, founded by Sheikholeslami [41], has become a widely adopted practice for demonstrating the freezing process, finding widespread application in various publications.

Results and discussion

In this investigation, cold storage was simulated within a specially designed curved container equipped with fins, aiming to expedite cold storage. To enhance the cold storage efficiency, nanoparticles were introduced in addition to fins. The study employed a numerical simulation approach based on the FEM. Various factors, including additives with different concentrations and diameters, were treated as variables in the investigation. Governing equations for the freezing process were simplified by disregarding the impact of velocity. Simulation outcomes were visually presented through contours and plots, offering a comprehensive understanding of system behavior under different conditions. Furthermore, the time required for complete freezing was calculated for each case, serving as a critical metric directly related to the rate of cold storage. This comprehensive approach not only advances the understanding of freezing processes but also underscores the practical implications of optimizing cold storage, a critical aspect in various applications.

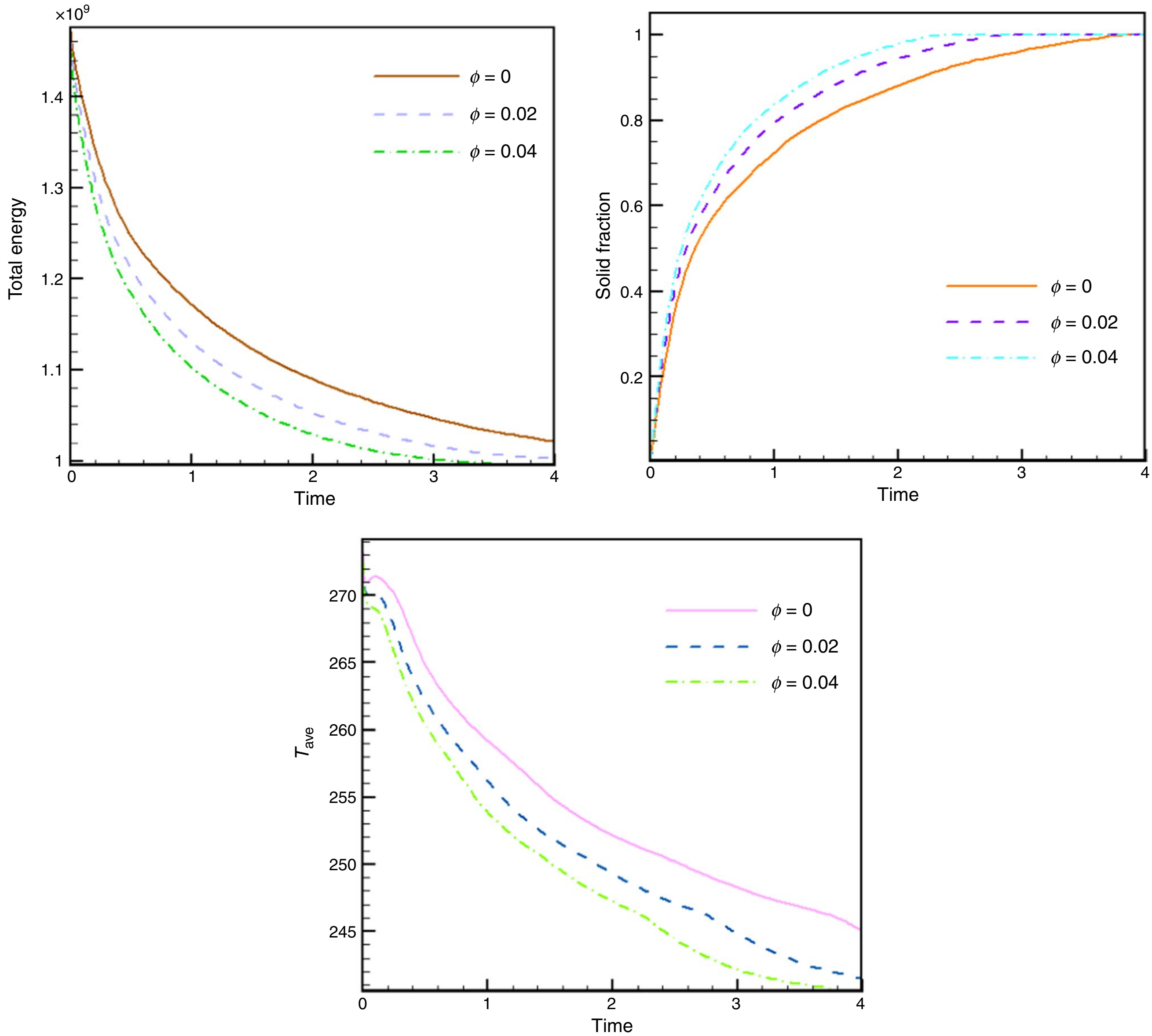


Fig. 6 Values of scalars for different levels of time and ϕ

The adaptive grid has been employed, representing a valuable technique for achieving high modeling accuracy in unsteady processes, particularly those involving phase change. The grid style for different time steps is illustrated in Fig. 2, revealing that the number of elements around the solid front is superior to that in other areas. This strategic distribution ensures that regions with higher temperature gradients have more nodes, enhancing the accuracy of the modeling process. To demonstrate the code's reliability and reasonable accuracy, a reproduction of previous benchmark work in the same field has been executed, and the outputs are presented in Fig. 3 [42]. The method employed exhibits good adaptability, making the code suitable for application in the current study. This validation process instills confidence in the accuracy and fidelity of the numerical approach adopted in the present article.

To illustrate the influence of ϕ on the cold storage process, Figs. 4, 5, and 6 are presented. The solid fraction, denoted as S, exhibits an increasing trend with the elevation of ϕ. Consequently, a greater proportion of the solid phase appears within the container, leading to a colder system. It is noteworthy that the energy of the system decreases as the concentration of additives upsurges. The ice front also moves at a faster rate in cases with higher ϕ. Examining the variation in ϕ from 0 to 0.02 and 0.04, the required freezing time changes from 4.35 s to 3.47 s and 2.9 s, respectively. These findings elucidate the direct relationship between ϕ and the efficiency of the cold

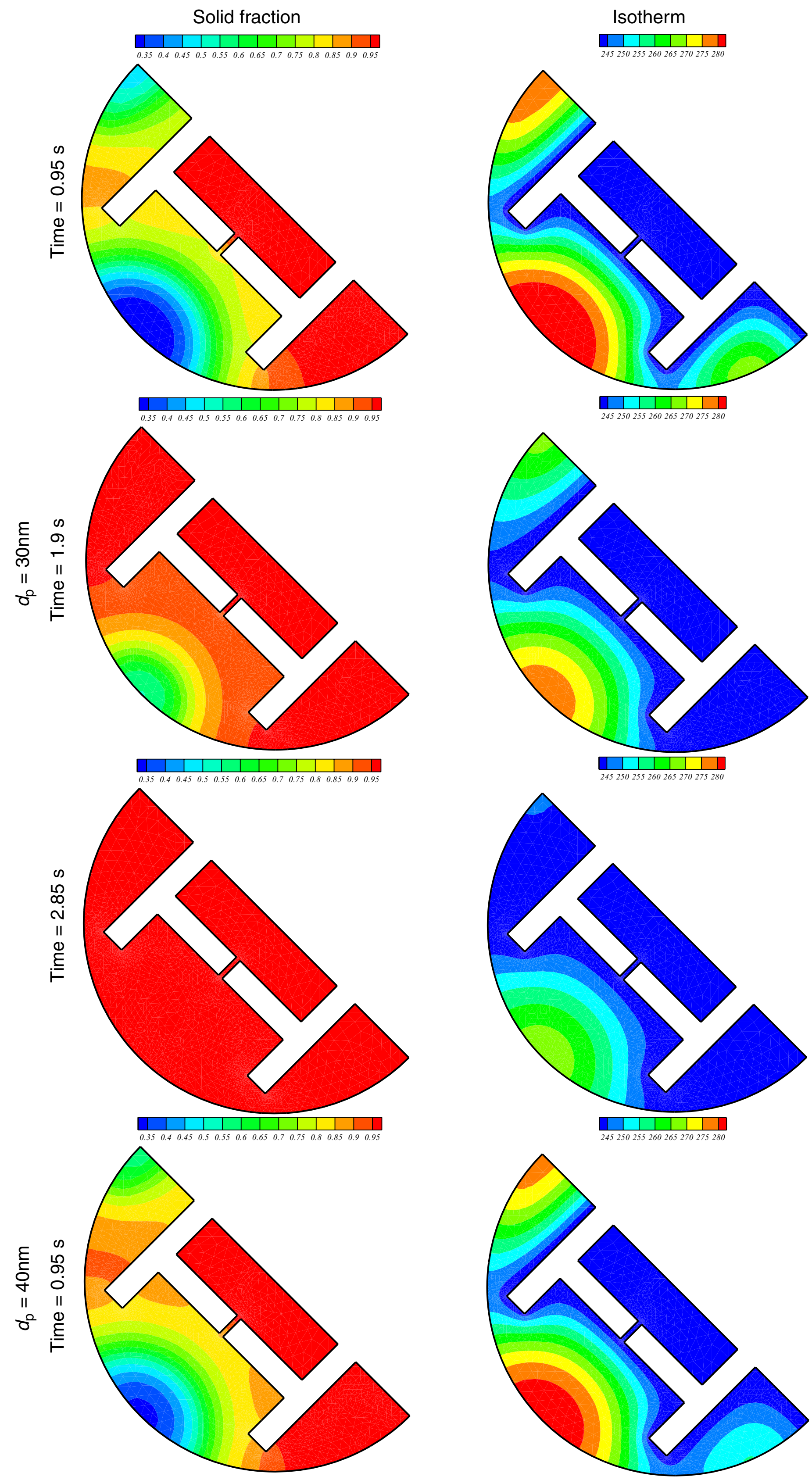


Fig. 7 Alternation of freezing with involving various dp

Fig. 7 (continued)

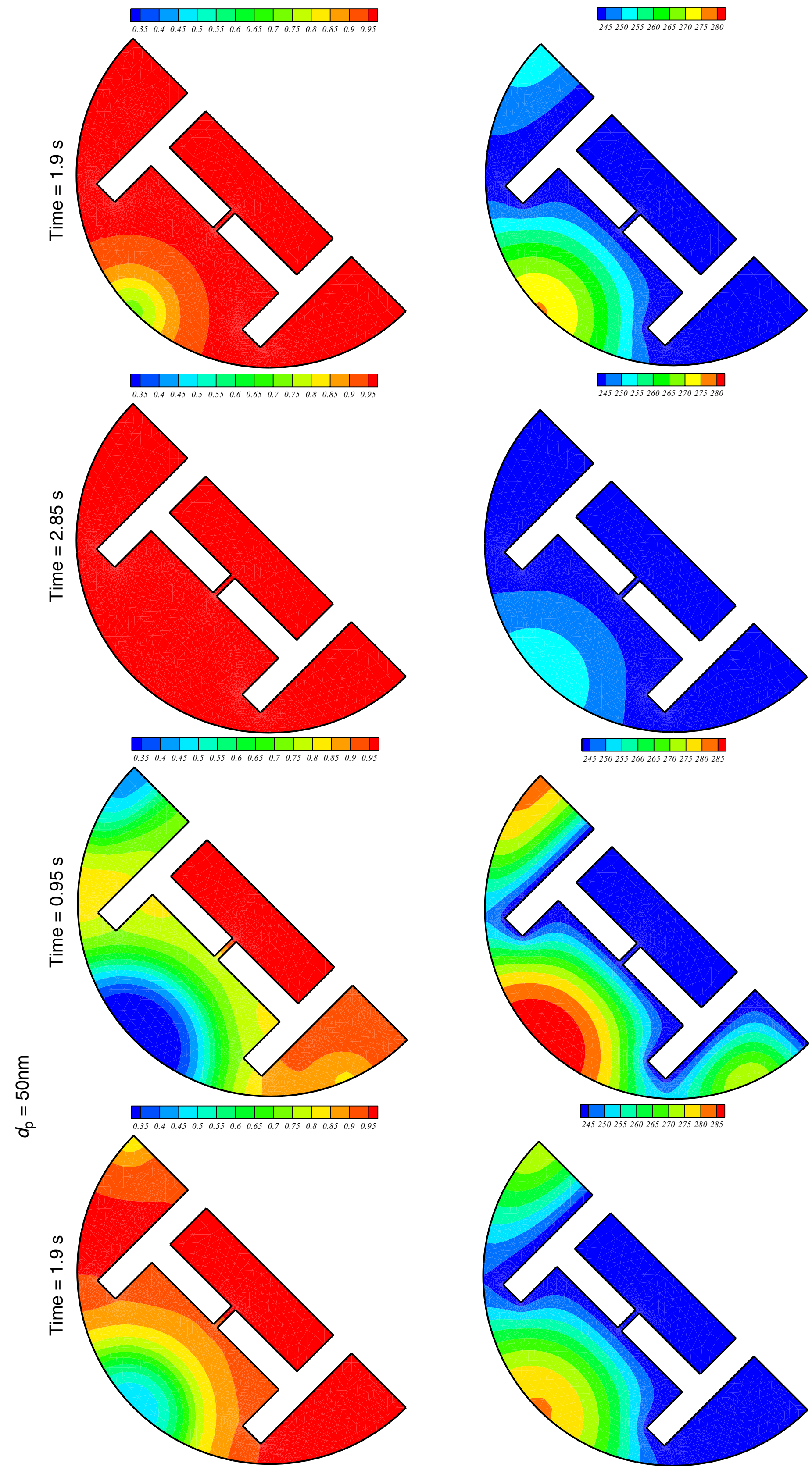
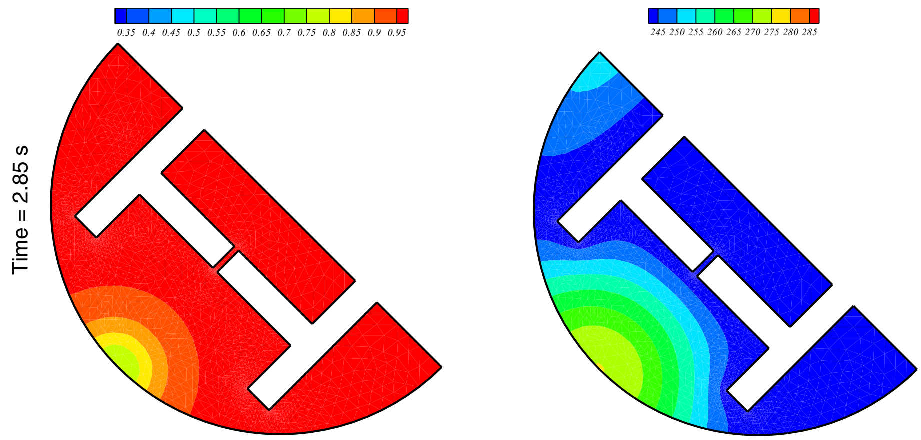


Fig. 7 (continued)



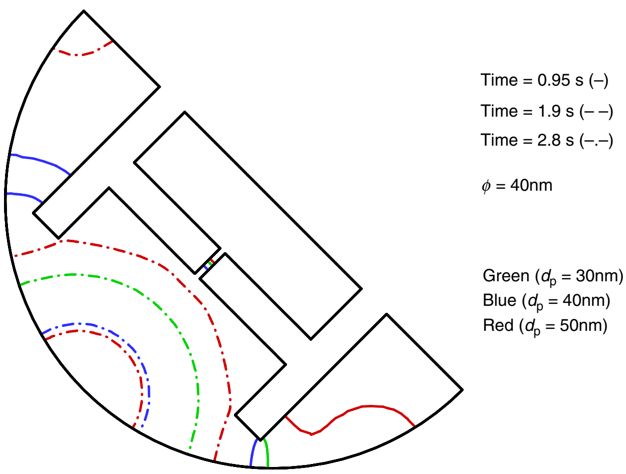


Fig. 8 Greater dp and progress of ice front

storage process, underscoring the potential for optimizing the system by carefully manipulating the concentration of additives.

Variations in dp exert a significant influence on the freezing process, as depicted in Figs. 7–9. The observed outcomes underscore the impact of employing additives of different sizes on the freezing dynamics. Consequently, identifying the optimized size that yields the highest cold storage rate becomes a crucial consideration. In this section of the article, three levels of dp are explored. The parameter T, representing the completion time, exhibits a decreasing trend over time, while S, indicative of the solidification rate, demonstrates an increasing tendency. Notably, for dp = 40 nm, the system reaches its highest S at a lower time level, highlighting the superior performance of such particles. The minimum value of T is achieved when dp = 40 nm. Examining the variation in dp from the minimum level to 40 nm and the greatest level, the required time shifts from 3.42 s to 2.9 s and 3.96 s, respectively. These results provide valuable insights into the nuanced relationship between dp and freezing time, contributing to the optimization of cold storage efficiency.

Figure 10 illustrates the impact of variables on the required freezing time. The introduction of nano-powders into water results in an enhanced freezing rate due to the increased conduction mode. In the context of cold storage, where conduction serves as the primary mechanism, any factor promoting heightened conductivity leads to a reduction in process time. The parameter ϕ exhibits a reverse relationship with the required time, with an optimal size identified for dp at the second level of this factor. Specifically, when $\phi = 0.04$, an increase in dp initially leads to a 15.12% decrease in completion time, followed by a subsequent 36.56% increase. Similarly, when $\phi = 0.02$, the process time initially decreases by 9.89% with dp growth and subsequently increases by 22%. In the lack of additives, the phenomena take 4.35 s to achieve full freezing, while the introduction of nanomaterial reduces this time significantly to 2.9 s, indicating a noteworthy 33.21% increase in the freezing rate. Notably, the impact of ϕ is most pronounced for medium-sized particles, with dp = 50 nm showing the least variation with an increase in ϕ. Considering the range of ϕ from 0 to its maximum level, the freezing time experiences a reduction of about 21.31% and 8.79% for dp values of 30 and 50 nm, respectively. These results emphasize the intricate relationship between ϕ, dp, and freezing time,

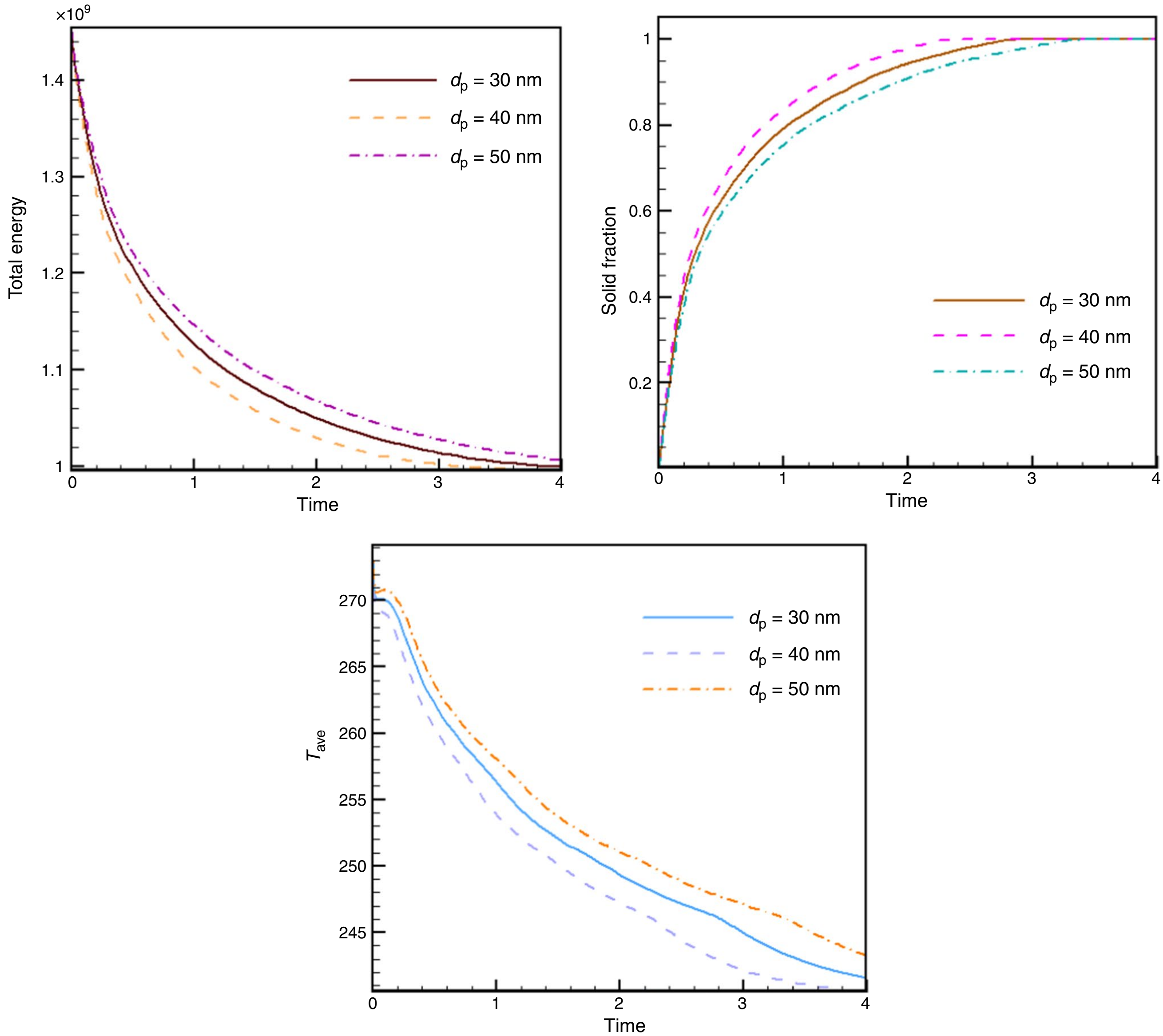


Fig. 9 Values of scalars for different levels of time and dp

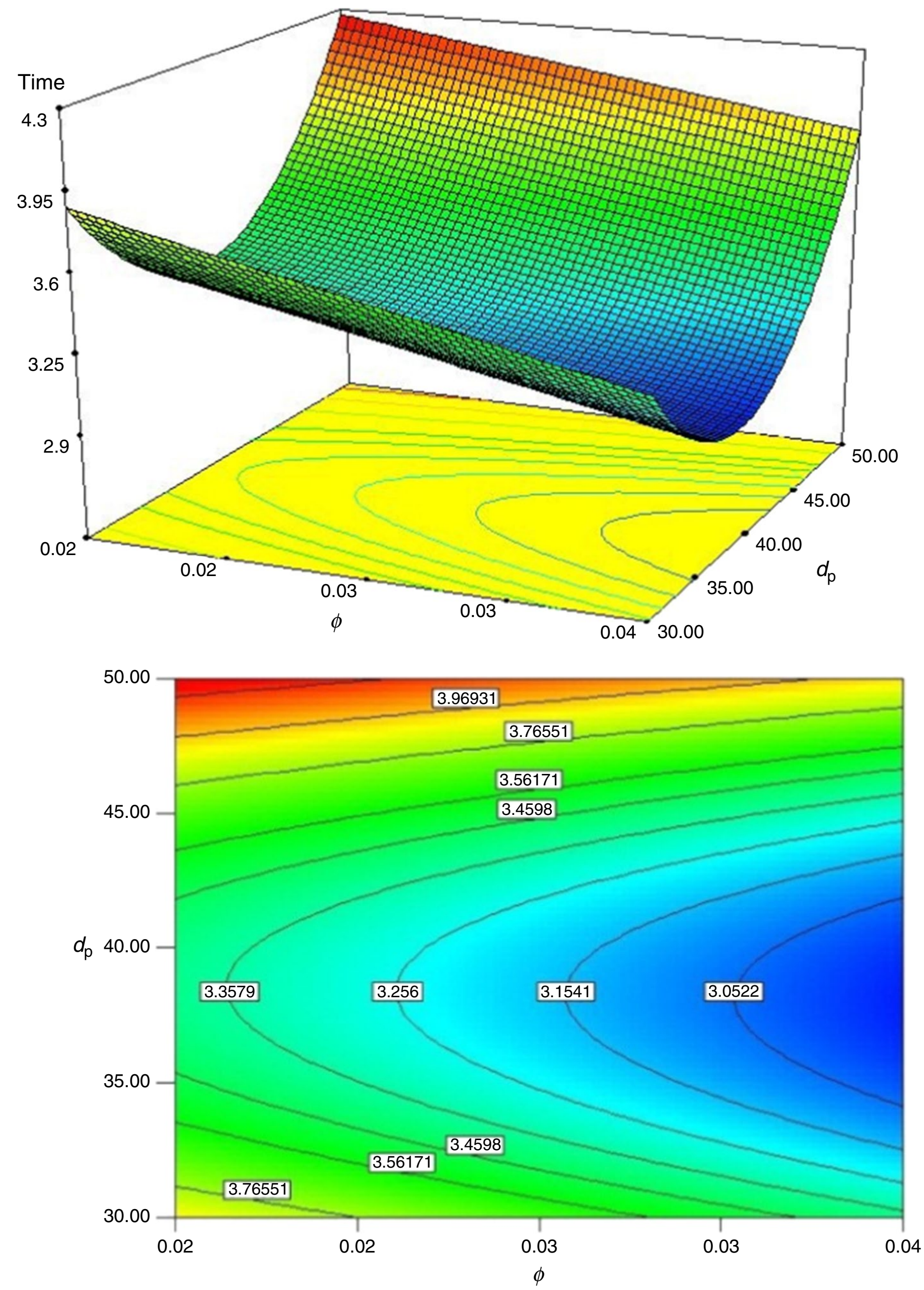


Fig. 10 Change of rate of freezing with change of two variables

providing valuable insights for optimizing the efficiency of cold storage systems.

Conclusions

Current attempt involved simulating the freezing process of water within a container featuring a curved design and integrated fins. The acceleration of cold storage was achieved through the incorporation of nanoparticles in conjunction with fins. The numerical simulation, based on the FEM and incorporating an adaptive grid, presented another dimension to the current investigation. The additives exhibited diverse concentrations and diameters, which were treated as variables in the study. Governing equations were streamlined to account for the freezing process, with the neglect of velocity impact. The outcomes were visualized through contours and plots, showcasing the impact of various concentrations and diameters. Additionally, the required time for complete freezing was determined for each scenario, emerging as a key determinant of cold storage efficiency. This comprehensive exploration contributes valuable insights into optimizing freezing dynamics. The primary driving force governing the cold storage process is conduction, wherein any factor promoting increased conductivity corresponds to a reduction in process time. The infusion of nano-powders into water serves to elevate the freezing rate by amplifying the conduction mode. The parameter ϕ exhibits an inverse correlation with the required time for freezing. As ϕ escalates from 0 to its maximum level, there is a notable 21.31% and 8.79% decrease in freezing time for dp values of 30 and 50 nm, respectively. In the absence of additives, the process takes 4.35 s to achieve full freezing. However, with the introduction of nanomaterials, this time significantly decreases to 2.9 s, signifying a remarkable 33.21% increase in the freezing rate. The impact of ϕ is most pronounced for medium-sized particles, with dp = 50 nm exhibiting the least variation with increasing ϕ. Concerning dp, the results reveal the existence of an optimal size, particularly at the second level of this factor. When $\phi = 0.04$, the completion time experiences an initial 15.12% decrease followed by a subsequent 36.56% increase as dp augments. The temperature (T) demonstrates a decreasing trend over time, while the solidification front position (S) exhibits an increasing tendency. The case with dp = 40 nm attains the highest S at a lower time level, indicating superior performance for such particles. In conclusion, the intricate interplay of ϕ and dp in the freezing process underscores the need for meticulous parameter selection to optimize the efficiency of cold storage systems. The findings not only contribute to a deeper thoughtful of freezing but also provide practical insights for the design and enhancement of cold storage technologies.

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Data availability statement No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest There is no conflict of interest regarding to this manuscript.

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