The Supergravity Influence on the Melting Performance of Phase Change Material

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Abstract: With the continuous advancement of technology, aeronautical thermal management has emerged as a hotspot of concern. The use of phase change materials in thermal management is also gaining attention, thus the melting performance under different gravitational conditions needs to be investigated. In order to gain further insight into the melting properties of phase change materials under multiple gravity conditions, we constructed numerical models which enabled us to evaluate a number of key metrics, including the complete melting time, heat storage capacity, phase interface, temperature, velocity distribution and other relevant factors. The results indicate that the total melting time is reduced when the gravitational force is increased. In particular, the complete melting time at a gravitational force of 5g is 62% shorter than at 1g. Furthermore, the thermal efficiency also exhibits an increase with the rise in gravitational force. Furthermore, the increase in gravity enhances the natural convective heat transfer in the phase change material, which is conducive to improving the heat transfer performance of the material, as can be seen from the velocity, temperature and phase interface distributions. This study provides a theoretical basis and reference significance for application in practical engineering.
Keywords: Supergravity, Phase change materials, Melting behavior, Numerical simulation, Heat transfer properties

1. Introduction

In space, temperature regulation is one of the most complex and critical challenges for spacecraft [1-3]. Spacecraft experience extreme temperature variations, with surface temperatures rising to several hundred degrees Celsius when exposed to direct sunlight and plummeting to near absolute zero in the shadow of celestial bodies or in deep space, far from the sun. These dramatic temperature fluctuations can result in the malfunction or even catastrophic failure of spacecraft systems and components. The failure rates of these components increase exponentially as temperatures rise, leading to significant operational risks [4-6]. On the other hand, maintaining a stable and controlled environment, particularly for the life-support systems that sustain human presence on spacecraft, remains a formidable challenge. Therefore, it is essential to maintain a constant and stable temperature within a narrow operational range for spacecraft to function effectively. The development of effective thermal management systems is crucial for enabling long-duration missions, whether within Earth's orbit or on interplanetary voyages. One promising solution to this challenge is the application of phase-change thermal energy storage (TES) systems, which have gained widespread attention for their ability to store and release heat in a controlled and efficient manner [7-9].

Phase-change thermal energy storage systems utilize materials that absorb or release thermal energy during phase transitions, such as from solid to liquid or liquid to gas. These systems have several advantages over traditional heat transfer methods, including high energy storage density, a constant working temperature, and reliable performance over extended periods of time [10-12]. Unlike conventional heat conduction or radiation-based systems, phase-change materials (PCMs) can absorb and release heat at a nearly constant temperature, making them particularly well-suited for the stringent temperature control requirements of spacecraft. As such, PCM technology has been widely implemented in space applications, from the International Space Station (ISS) to the Chinese Space Station (CSS) and other space exploration missions [13-15]. Among the wide variety of phase-change materials investigated, paraffin wax has emerged as one of the most promising candidates for use in spacecraft thermal control systems due to its favorable properties, including low cost, high stability, and efficient thermal performance. Other types of PCMs, such as hydrated salts and molten salts, have also been explored, each with specific advantages and limitations [16, 17]. However, in the context of aerospace applications, where safety, reliability, and long-term stability are paramount, organic phase-change materials—particularly paraffin wax—have proven to be the most suitable option.

In recent studies, researchers have developed and tested various composite phase-change materials to enhance the thermal management capabilities of buildings and spacecraft. For instance, Wang et al. [18] prepared composite PCMs using daisy stems and paraffin wax for thermoregulation applications. The incorporation of these composite materials into building structures demonstrated a significant thermal buffering effect, resulting in more stable temperature regulation compared to conventional buildings that exhibit rapid temperature fluctuations. Similarly, Du et al. [19] conducted a quantitative and numerical investigation on the melting performance of four PCM configurations, including pure paraffin, fins, metal foam, and fin-metal foam. Their findings demonstrated that the incorporation of fins and metal foam significantly improved the melting performance and temperature uniformity, though it also reduced the overall heat storage capacity of the system. Boldoo et al. [16] studied the thermal properties and stability of emulsions made from four different paraffinic materials (Paraffin 56/58, n-Eicosane, n-Octadecane, and n-Heptadecane), measuring their latent heat and heat storage capacities at various PCM concentrations. Furthermore, Liang et al. [21] developed thermally conductive polyvinyl alcohol (PVA) and graphene composite PCMs, which exhibited high shape stability, low density, and enhanced thermal conductivity, showcasing the potential of combining PVA and graphene to produce thermally conductive aerogels for enhanced heat transfer in space applications.

Despite the promising advantages of PCM in space applications, there are still significant challenges related to their use in space environments. Most studies have primarily focused on the thermal properties of PCMs under normal gravity conditions, but the behavior of these materials under different gravitational conditions—especially in microgravity and supergravity environments—remains largely unexplored. In space, the lack of natural convection due to microgravity can lead to inefficient heat transfer in traditional PCM systems, limiting their effectiveness in controlling temperature fluctuations. Conversely, in supergravity environments, such as those generated during acceleration phases or in rotating systems, the behavior of PCMs may differ significantly from what is observed under normal gravity conditions, potentially impacting the melting rate and overall performance [22-24]. Understanding how PCMs perform under these unique conditions is critical for optimizing thermal management systems in space missions. Li et al.[32] have numerically investigated the melting process of phase change materials under supergravity conditions by the pore lattice Boltzmann method, and a comparative study has been carried out to illustrate the effects of gravitational acceleration and metal foam on the melting properties of phase change materials by utilizing the real microstructures of metal foam.

Several researchers have investigated the phase-change process of PCMs under microgravity and supergravity conditions. For example, Seta et al. [28] examined the melting process of PCM in a cubic vessel subjected to microgravity, highlighting the importance of thermal capillarity in the heat transfer process under such conditions. Chen et al. [29] numerically modeled the melting of PCMs in microgravity, noting that the absence of natural convection significantly weakened the melting performance, making the process largely dependent on heat conduction. Elshaer et al. [30] performed numerical simulations to investigate the thermal properties of PCM and PCM/fin composites in microgravity, showing that natural convection accelerates the melting process in a gravity environment but disappears in microgravity, resulting in reduced melting rates. García-Roco et al. [31] explored the melting of PCM driven by constant heat flux over a free surface, investigating key factors such as the aspect ratio of the vessel and the heating length, which significantly influenced the overall melting process.

Although there have been numerous studies on the application of PCM in aerospace, fewer studies have focused on the effect of supergravity on the melting properties of PCM, and comprehensive evaluation metrics for these conditions are still underdeveloped. To address this gap, we constructed a numerical model to simulate the melting process of PCM under various supergravity conditions. We evaluated key performance indicators such as melting time, melting rate, heat storage capacity, phase interface progression, temperature distribution, and velocity field dynamics. Our study aims to provide a comprehensive understanding of how supergravity affects PCM behavior and offers valuable insights for the design of more efficient thermal management systems for spacecraft. By investigating the effects of supergravity on PCM melting performance, we aim to contribute to the development of advanced thermal control technologies that can ensure the optimal performance of spacecraft in diverse gravitational environments.

2. Numerical Models

2.1 Problem Description

Phase change thermal storage (PCTS) units represent a promising technology for enhancing the thermal management capabilities of aerospace systems, ensuring their safe and efficient operation in the extreme conditions of space. These units' function as thermal protection elements, capable of storing excess thermal energy and releasing it in a controlled manner, which helps maintain the spacecraft's temperature within safe operational limits. The integration of PCMs into thermal control systems is particularly important in aerospace applications, where temperature fluctuations can be extreme, ranging from intense heat during sun exposure to sub-zero temperatures in the shadow of celestial bodies. **Figure 1** provides a schematic representation of the phase change thermal storage unit as applied in aerospace thermal management. In this configuration, the heating surface, positioned on the left side of the diagram, is responsible for providing thermal energy to the PCM, which is located on the right side of the system. The PCM is a paraffin wax-based material with a length of 100 mm and a width of 50 mm. Paraffin wax has been chosen for this study due to its advantageous thermophysical properties, such as high latent heat, stability, and relatively low cost, making it an ideal candidate for thermal management applications in space. The detailed thermophysical properties of paraffin wax, including its melting temperature, thermal conductivity, and specific heat, are summarized in **Table 1.**

To better understand the performance of the phase, change thermal storage unit under various operational conditions, we constructed a simplified two-dimensional numerical model based on the physical configuration shown in **Figure 1.** The numerical model allows for the simulation of the melting process of the PCM under different gravity conditions. In the model, the heating surface is treated as a constant heat flux boundary, providing a steady heat input of 5000 W/m^2. This heat flux value is representative of the thermal loading conditions that spacecraft may experience during certain phases of a mission. All other boundaries of the system are assumed to be adiabatic, meaning that no heat is exchanged across these surfaces, which simplifies the modeling of heat transfer and allows for the simulation of the melting process without external heat losses.

Additionally, this study evaluates the impact of different gravitational conditions on the performance of the phase change thermal storage unit. The model is run under varying gravity levels, including 1g, 2g, 3g, 4g, and 5g, as specified in Table 2. These gravity conditions are crucial for simulating the behavior of the PCM in space, where microgravity or supergravity environments may influence the melting process due to changes in convection and fluid dynamics. In particular, the absence or reduction of natural convection in low-gravity environments can lead to slower heat transfer, affecting the efficiency of the PCM in storing and releasing heat. By investigating the performance of the PCM under different gravity conditions, this study aims to provide insights into the feasibility and optimization of phase change thermal storage systems for space missions. Through this numerical analysis, we aim to enhance the understanding of how gravity influences the thermal behavior of PCMs and their potential applications in aerospace thermal control systems. The results of this study could inform the design and optimization of future spacecraft, helping to ensure that thermal management systems can effectively maintain the spacecraft's temperature within safe operating ranges, regardless of the gravitational conditions encountered during the mission.

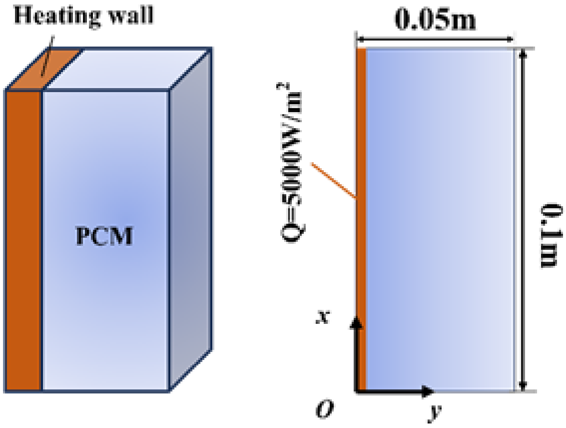

Figure 1 Geometric mode

Table 1 Thermophysical parameters of paraffin.

Property	Specific heat capacity (J·kg-1·K-1)	Thermal conductivity (W·m-1·K-1)	Density (kg·m3)	Latent heat (J·kg-1)
Values	2400(solid)/3200(liquid)	0.2(solid)/0.1(liquid)	800	2.4E5

In this study, we constructed a numerical model based on this physical model and simplified it to 2 dimensions. In this case, the heating surface is considered as a constant heat flow density heating surface with a heat flux of 5000 W/m^2 and the rest of the boundaries are considered as adiabatic to simulate the melting process, and the heat transfer properties are simulated under different gravity conditions (1g, 2g, 3g,4g,5g) as shown in **Table 2**.

Table 2 Numerical model cases

case	1	2	3	4	5
setting	1g	2g	3g	4g	5g

2.2 Governing Equations

In this study, the numerical model for simulating the phase transition process of phase change materials (PCMs) is implemented using COMSOL Multiphysics 6.2. The model relies on the finite element method (FEM) to solve the governing equations, allowing for the analysis of heat transfer and fluid dynamics within the PCM during the melting and solidification processes. The following key assumptions are made to simplify the model and focus on the primary physical mechanisms:

1) PCM is isotropic and the thermophysical properties do not change with temperature.
2) Volume changes are ignored during PCM melting.
3) Supercooling and superheating are not considered in the phase transition temperature interval.

The numerical solution is based on the governing equations for heat transfer and fluid dynamics, which describe the behavior of the PCM under varying temperature and gravity conditions. These equations include both the heat equation for energy conservation and the Navier-Stokes equations for fluid flow, with appropriate modifications to account for the phase change process. The key governing equations used in the model are as follows:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum equation:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\partial p}{\partial x}+S_{\mathrm{u}} \quad (2)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\frac{\partial p}{\partial y}+S_{\mathrm{u}}+\rho_{ref}g\beta(T-T_{ref}) \quad (3)$$

Energy equation:

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho hu)}{\partial x}+\frac{\partial(\rho hv)}{\partial y}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial y}\right)+S_{\mathrm{e}} \quad (4)$$

In this context, h represents enthalpy, λ stands for thermal conductivity, p denotes liquid pressure, ρ signifies density, μ is the viscosity, τ is the time, and u and v are the velocities in the x and y directions respectively.

The source terms S_u and S_v represent the momentum equations, which describe the momentum sink in the x and y directions due to the reduced porosity in the mushy zone. The source term of energy, S_e, is derived from the enthalpy formulation of convection-diffusion phase change and is dependent on the nature of the latent heat evolution. The aforementioned parameters can be calculated as follows:

$$S_u=\frac{(1-\beta)^2}{\beta^3+\xi}A_{mush}u \quad (5)$$

$$S_v=\frac{(1-\beta)^2}{\beta^3+\xi}A_{mush}v+\frac{\rho_{ref}g\delta(h-h_{ref})}{c_p} \quad (6)$$

$$S_e=\frac{\partial(\rho\Delta h)}{\partial\tau} \quad (7)$$

$$\beta=\begin{cases}0 & T<T_s\\ \dfrac{T-T_s}{T_l-T_s} & T_s\le T\le T_l\\ 1 & T>T_l\end{cases} \quad (8)$$

Subscripts l and s represent the liquid phase and solid phase respectively. Subscript p represents the PCM and L_p represents the latent heat of fusion. In addition, c_p is the specific heat capacity and λ_p is the thermal conductivity.

$$h=h_{ref}+\int_{T_{ref}}^{T}c_p dT+\Delta h \quad (9)$$

$$h=h_{ref}+\int_{T_{ref}}^{T}c_p dT+\beta L_p \quad (10)$$

2.3 Initial Conditions

As depicted in Fig. 1, the square cavity model used in this study features a heating surface located at the leftmost boundary, which is defined as a constant heat flux boundary. The heat flux density is set to 5000 W/m², simulating a typical scenario for phase change material (PCM) melting processes. The remaining walls of the cavity are treated as adiabatic boundaries, meaning no heat exchange occurs between the system and the external environment. The interior of the square cavity is filled with paraffin wax, which serves as the phase change material (PCM) in this study. The initial temperature of the PCM is set to 25°C, representing a baseline starting condition for the melting process. To ensure consistency across the numerical simulations, all experiments are conducted under these boundary and initial conditions, simulating the melting process under different gravity conditions.

2.4 Grid and Time step Independence

To ensure the accuracy and reliability of the numerical model while minimizing computational costs, it is essential to validate both grid independence and time-step irrelevance. In this study, grid independence is assessed by comparing the numerical models at 1g using different mesh resolutions: 12,317, 16,542, and 24,876 mesh elements. The results show that the deviation in the melting rate between the models with 16,542, and 24,876 meshes does not exceed 0.5%. Based on this observation, it can be concluded that a mesh resolution of 16,542 elements is sufficient to achieve grid independence for the current model. Similarly, time-step irrelevance is validated by comparing models with time steps of 0.05, 0.1, and 0.5 seconds. It was determined that a time step of 0.1 seconds ensures adequate accuracy while maintaining computational efficiency. Consequently, the final computational conditions for the simulations include a mesh resolution of 16,542 elements and a time step of 0.1 seconds. This configuration ensures both high model accuracy and computational feasibility for the subsequent simulations.

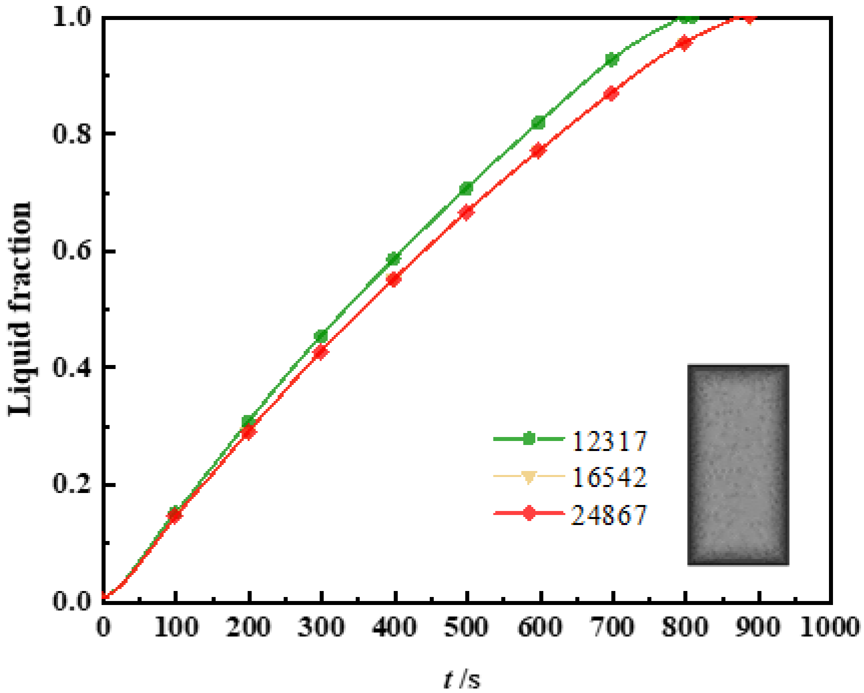

Figure 2 Grid and Time step Independence verification

3. Results and Discussion

3.1 Complete melting time

Figure 3 presents the time required for the complete melting of paraffin wax under varying gravity conditions. As shown in the figure, the time required for paraffin wax to fully transition from solid to liquid state under different gravitational accelerations (1g, 2g, 3g, 4g, and 5g) are 2100 s, 1000 s, 880 s, 830 s, and 810 s, respectively. The melting time decreases with an increase in gravity, with the fastest melting occurring under 5g and the slowest under 1g. This trend clearly indicates that the time required for complete melting decreases as the gravitational force increases, suggesting that higher gravity conditions enhance the phase change rate.

To further investigate the influence of gravity on phase change heat storage, a detailed analysis of the time-dependent melting rate was conducted. The overall trend revealed a gradual increase in the liquid phase rate over time across all gravity conditions from 1g to 5g. Specifically, the fastest melting rate occurred at 5g, followed by 4g, 3g, 2g, and 1g, with the 1g condition demonstrating a significantly slower melting rate compared to the other gravity conditions. At 1g, the phase change heat storage unit was fully melted in 2100 seconds, while increasing the gravity to 2g, 3g, 4g, and 5g resulted in increases in the melting rate by 53.6%, 57.8%, 60.7%, and 61.6%, respectively, compared to the 1g condition. These findings indicate that higher gravity facilitates the heat transfer process within the phase change thermal storage unit, thus accelerating the phase change.

At the initial stage of the phase change process, the impact of gravity on the melting rate was relatively modest. This can be attributed to the fact that during the early stages, the melting rate of paraffin wax is slow, and the temperature gradient within the phase change unit is minimal. As a result, heat transfer is primarily governed by conduction within the solid paraffin wax, and the influence of gravity on the heat transfer process is limited. However, as the melting process progresses, the volume fraction of liquid paraffin wax increases, which enhances the natural convection within the liquid phase. This natural convection becomes more pronounced under higher gravity conditions, thereby significantly increasing the convective heat transfer rate and the overall phase change rate. In conclusion, the results of this study suggest that an increase in gravity enhances the convective heat transfer effect within the phase change material, leading to a faster phase change process. This enhancement is particularly noticeable in the later stages of melting, where the combined effects of heat conduction and convection result in a more efficient phase change. Therefore, optimizing the gravity conditions in phase change heat storage systems could be a potential strategy for improving the thermal management performance in applications such as spacecraft and other aerospace technologies, where efficient heat transfer is crucial.

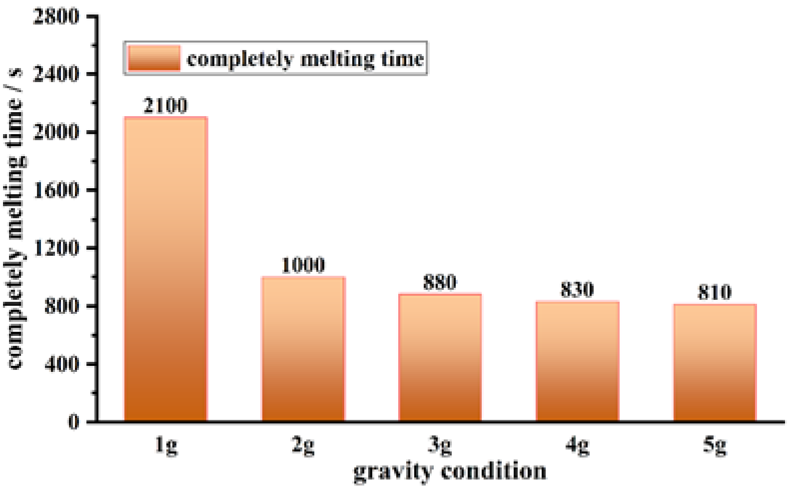

Figure 3 Complete melting time in different gravity fields

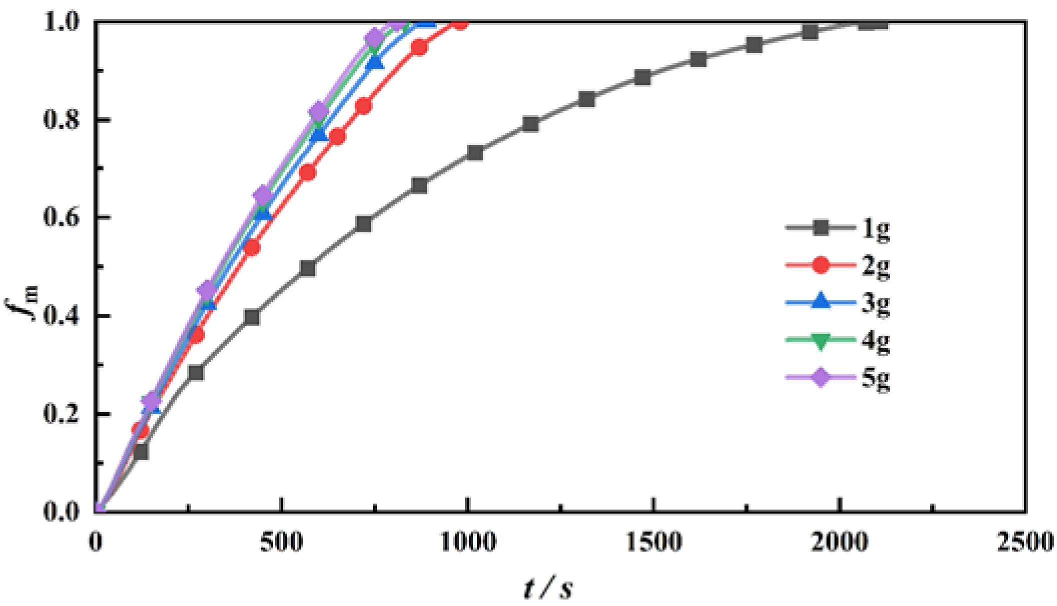

Figure 4 Variation of melting rate with time in different gravity fields

3.2 Thermal storage capacity

Figure 5 illustrates the variation in heat storage capacity over time for the phase change thermal storage unit under different gravitational conditions. Upon the complete melting of the material within the unit, the heat storage capacity is observed to reach a maximum value of 48 kJ. In the gravity range of 1g to 5g, the heat storage capacity increases progressively over time, demonstrating a clear dependence on gravity. Prior to the liquid phase rate reaching 100%, the heat storage capacity increases with the enhancement of gravity under identical time conditions. However, as time progresses, the rate of increase in heat storage capacity gradually decreases, suggesting that the influence of gravity on heat storage becomes less pronounced as the phase change nears completion. When comparing the different gravity conditions, it is evident that the heat storage capacity is significantly greater under higher gravity levels. Specifically, the average heat storage capacity at 2g, 3g, 4g, and 5g increased by 35%, 43%, 48%, and 51%, respectively, compared to the 1g condition. This trend highlights the facilitative role of gravity in promoting heat transfer within the phase change thermal storage unit. At the initial stage of melting, however, the effect of gravity on heat transfer efficiency is less pronounced. This is because, during this phase, the melting rate of the paraffin is relatively slow, the temperature gradient is small, and heat transfer is predominantly governed by conduction within the solid phase of the paraffin.

As the melting process progresses, the proportion of liquid paraffin increases, which in turn enhances natural convection within the liquid phase. This increase in liquid phase fraction promotes the efficiency of heat transfer through both conduction and convection. Consequently, the effect of gravity on the overall heat transfer efficiency becomes increasingly significant. In particular, under higher gravity conditions, the convective heat transfer within the phase change material is more pronounced, leading to a faster phase change process and a higher overall heat storage capacity. These results suggest that gravity plays a key role in enhancing the thermal performance of phase change heat storage systems, especially during the later stages of melting. By improving convective heat transfer, an increase in gravity accelerates the phase change process, thereby enhancing the overall heat storage capacity. Therefore, optimizing the gravity conditions could be a useful strategy for improving the efficiency of phase change heat storage systems, particularly in applications where rapid and efficient thermal management is critical, such as in spacecraft thermal control systems.

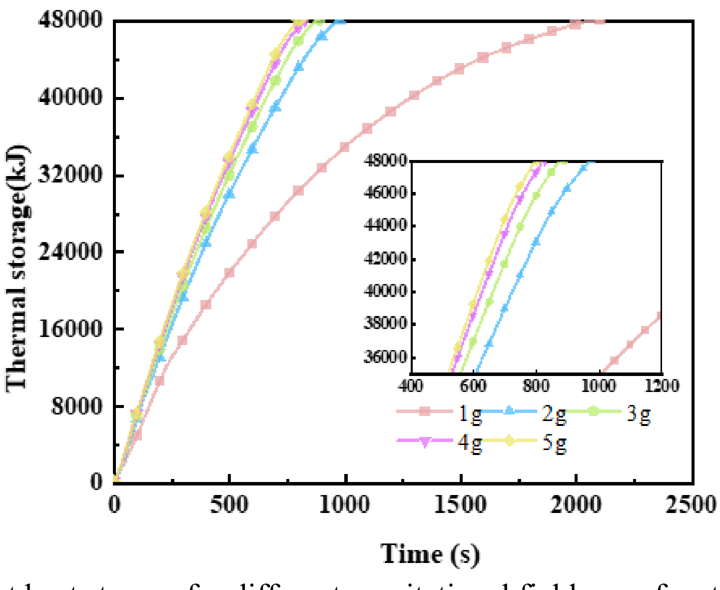

Figure 5 Latent heat storage for different gravitational fields as a function of time

3.3 Phase Interface, Temperature Field, and Velocity Field Distribution

To better illustrate the phase change heat storage process under varying gravity conditions, **Figures 6 to 8** display the phase interface, temperature, and velocity distributions at different time intervals (130 s, 260 s, 410 s, 580 s, 680 s, and 810 s). These figures provide a detailed analysis of how the phase change process evolves and how gravity influences various thermal dynamics.

The phase interface distribution during the phase change heat storage process demonstrates a clear progression with time. As the melting process advances, the liquid phase gradually expands, resulting in a conical distribution of the phase interface. Initially, the upper portion of the phase change material (PCM) melts faster than the lower portion, creating a refractory zone at the bottom. This behavior can be attributed to the fact that heat transfer is more efficient at the upper region where the heat is applied. Additionally, the rate of phase transition increases with higher gravity, enhancing the overall heat storage efficiency. Before 260 seconds, the difference in the liquid phase rate between the various gravity conditions is negligible. However, after 410 seconds, the differences become more pronounced, with the liquid phase area under 5g being significantly larger than that under 1g. By 810 seconds, the phase change process under 5g is complete, with the thermal storage unit fully melted, while a substantial amount of solid paraffin remains at the base of the 1g unit. This discrepancy in melting behavior can be attributed to the enhanced natural convection in higher gravity fields, which accelerates heat transfer within the PCM. As gravity increases, the convection-driven heat transfer improves, thus reducing the time required for the complete melting of the paraffin wax.

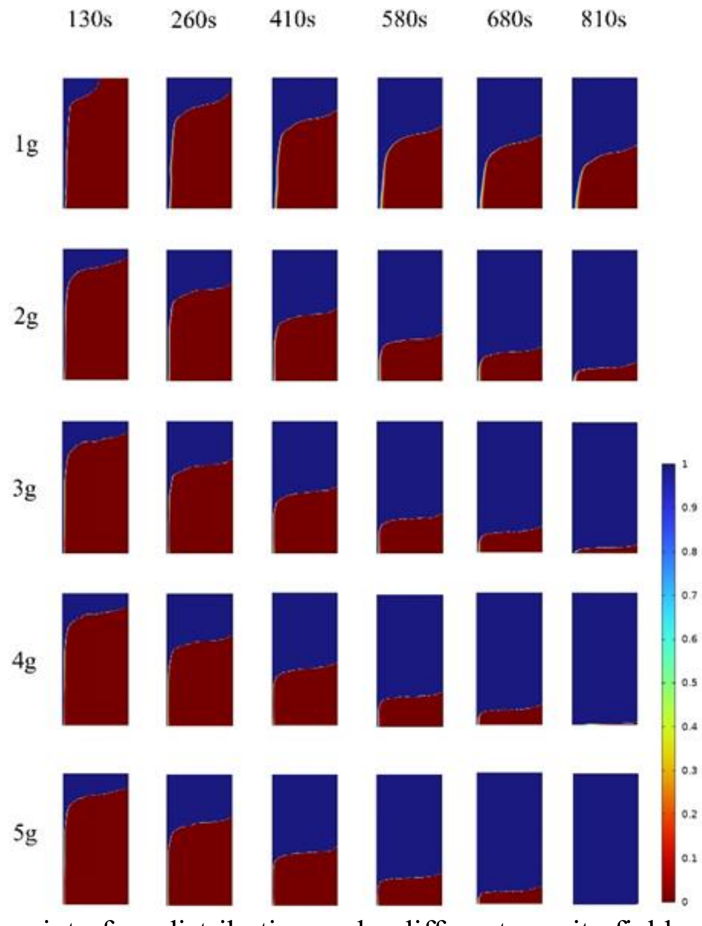

Figure 6 Phase interface distribution under different gravity field conditions

The temperature distribution follows a similar trend to that of the phase interface. As heat is transferred into the system, the temperature of the heat storage unit gradually increases over time. The temperature field exhibits a conical shape, with a more pronounced temperature gradient near the top of the unit and a smaller temperature difference near the bottom, resulting in natural convection at the lower regions. Notably, the temperature gradient is steeper in higher gravity conditions, which facilitates better heat distribution throughout the unit. Under normal gravity (1g), the heat tends to accumulate in the upper portion of the thermal storage unit as the melting progresses, which results in the formation of a refractory zone at the lower end. This phenomenon leads to a reduction in phase change efficiency, as the bottom layer remains largely solid due to poor heat distribution. As the gravity is increased from 1g to 5g, the rate of temperature increase is gradually reduced, and the overall temperature distribution becomes more uniform. This uniformity enhances the phase change efficiency, as more of the phase change material melts uniformly over time. The results clearly demonstrate that the enhancement of gravity not only improves the efficiency of the phase change process but also leads to better temperature uniformity across the thermal storage unit, thereby improving overall melting performance.

The velocity field, which represents the fluid dynamics of the molten phase, becomes increasingly pronounced over time, particularly during the later stages of the melting process. As the phase change progresses, the range of the velocity field expands, especially under higher gravity conditions. This is indicative of enhanced natural convection as the molten paraffin wax moves more vigorously in response to the increased gravitational force. Under 1g, the velocity field is primarily confined to the regions near the walls where the molten and solid paraffin meet. This results in the formation of small vortices at the interface, which are less effective in promoting heat transfer throughout the entire system. As the gravity increases, the velocity field becomes more expansive, indicating a broader convection current that facilitates more efficient heat transfer throughout the phase change material. The enhanced convection under higher gravity accelerates the overall melting process, which is consistent with the higher phase transition efficiency observed under 5g.

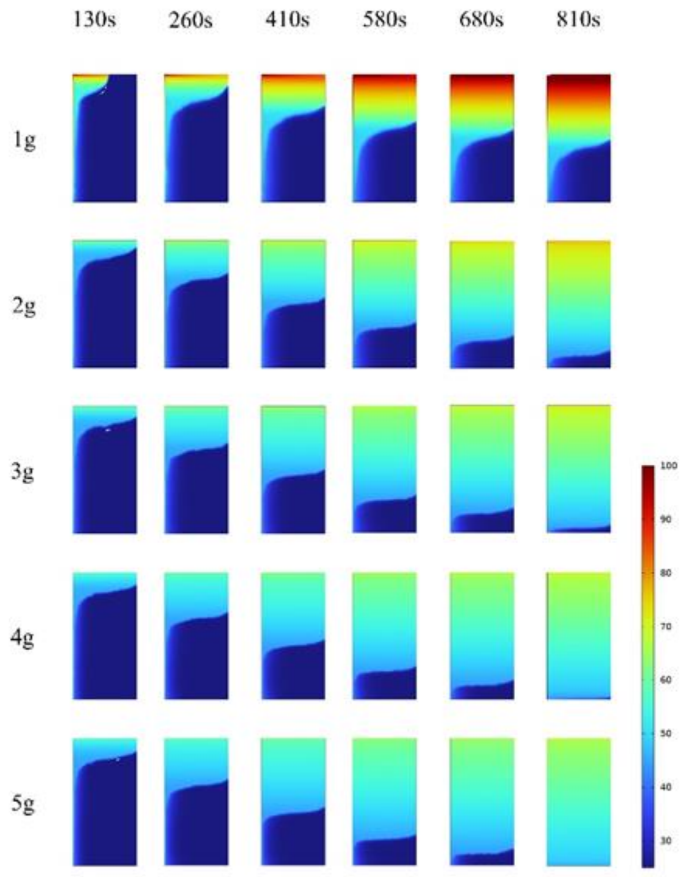

Figure 7 Temperature distribution under different gravity field conditions

In summary, the analysis of the phase interface, temperature, and velocity fields under varying gravity conditions reveals the significant impact of gravity on the phase change heat storage process.

As gravity increases from 1g to 5g, the phase transition efficiency improves, the temperature uniformity of the thermal storage unit enhances, and convective heat transfer becomes more pronounced. These findings highlight the critical role of gravity in optimizing the performance of phase change thermal storage units. The results suggest that higher gravity conditions not only accelerate the melting process but also improve the overall efficiency of phase change heat storage, making it a promising solution for thermal management in space applications, where gravitational forces can vary significantly. Therefore, adjusting gravity levels in phase change systems could provide a viable approach to enhancing thermal control in aerospace and other gravity-sensitive environments.

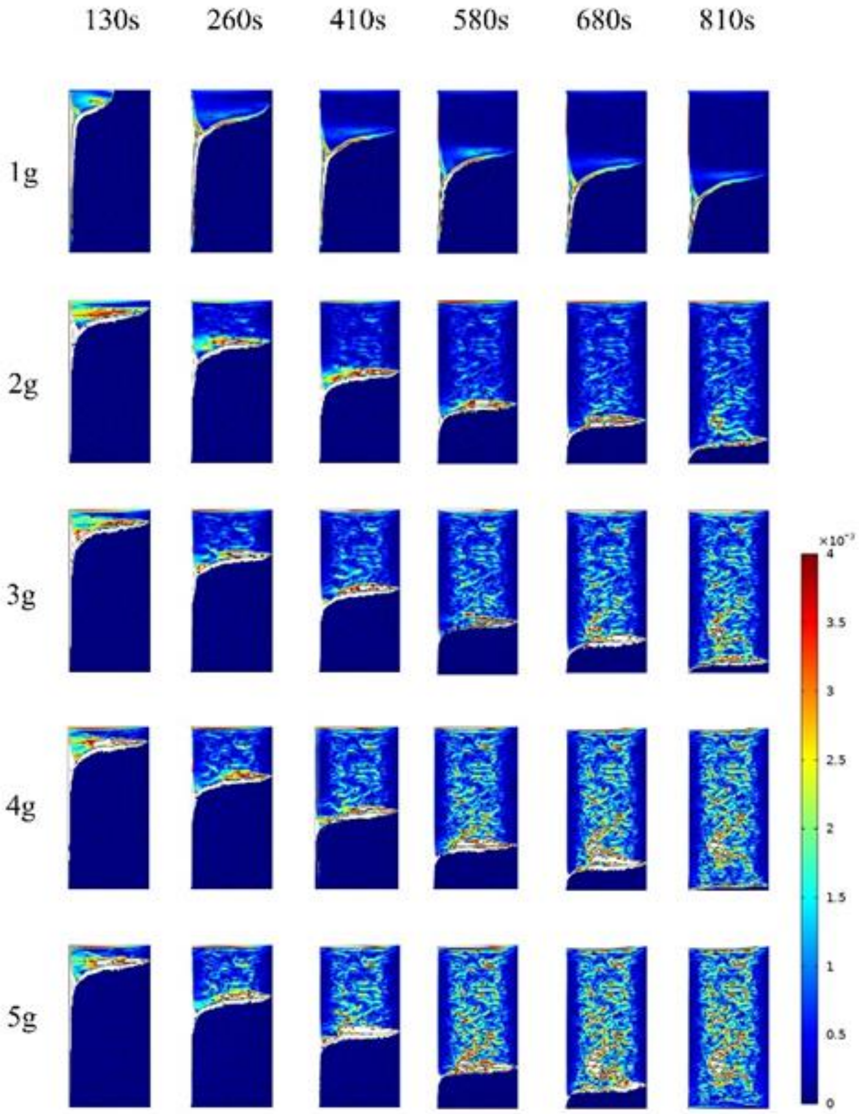

Figure 8 Velocity distribution under different gravity field conditions

4. Conclusions

This paper presents a detailed numerical analysis of the melting performance of phase change heat storage units under varying gravity fields. The study provides several key insights into the influence of gravity on the melting behavior, heat transfer efficiency, and thermal storage capacity of the units. The following conclusions can be drawn from the results:

At a gravitational field of 5g, the complete melting of the phase change thermal storage unit occurs in 810 seconds. Compared to the melting rates observed under 1g, 2g, 3g, and 4g, the melting time is significantly reduced, with increases in the melting rate of 61.6%, 19.0%, 8.0%, and 2.4%, respectively. These results highlight the positive effect of gravity on the efficiency of heat transfer within the phase change material (PCM), with higher gravity accelerating the melting process. This finding emphasises the significance of gravity in enhancing the overall thermal performance of phase change thermal storage systems, particularly in environments where gravitational forces can be controlled, such as in aerospace applications.

The heat storage capacity of the phase change thermal storage unit gradually increases over time across the 1g to 5g gravity range. However, as gravity increases, the rate of increase in heat storage capacity diminishes over time, eventually approaching a plateau when the liquid phase rate reaches 100%. This phenomenon indicates that while gravity enhances heat transfer within the unit, its impact diminishes as the PCM approaches full phase change. The increase in heat transfer efficiency with increasing gravity suggests that natural convection plays an increasingly important role in the heat transfer process as melting progresses, particularly under higher gravitational conditions.

The liquid phase rate within the thermal storage unit steadily increases over time across all gravity conditions (1g to 5g). The rate of increase is more pronounced at higher gravity levels, with the liquid phase advancing more rapidly in these conditions. Concurrently, the temperature distribution within the thermal storage unit becomes more uniform as gravity increases. The enhanced convection caused by higher gravity promotes a more homogeneous temperature field, which improves the overall efficiency of the heat transfer process. This is due to the more pronounced convective effects within the molten paraffin, which accelerate heat transfer and reduce temperature gradients. As a result, the phase change process is not only faster but also more efficient in higher gravity conditions.

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