Energy Proceedings
Vol 51, 2025
ISSN 2004-2965

Numerical Simulation of PCM Melting Characteristics in a Rectangular Container with Non-Uniform Longitudinal Fins Added at the Bottom Region#

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ABSTRACT

This paper employs a 3D numerical simulation to investigate the effect of various non-uniform longitudinal fins at the bottom region of a rectangular container on natural convection and RT42 phase change material (PCM) melting characteristics. Using a container with rectangular fins as a baseline, the influence of the geometric structure and arrangement of the fins on PCM melting characteristics is explored by varying the heights of the left (L_l) and right (L_r) non-uniform fins. The results indicate that adding non-uniform longitudinal fins at the bottom enhances the heat transfer of PCM at the bottom and corners of the container, significantly reducing melting time and improving temperature uniformity and heat storage rate. Optimal performance is achieved when L_l = 3 mm and L_r = 7 mm, with a reduction in melting time by 27.5% and an increase in heat storage rate by 37.3% compared to the baseline case.

Keywords: non-uniform longitudinal fin, rectangular container, phase change material, numerical simulation

NONMENCLATURE

Abbreviations	
LHS	Latent heat storage
PCM	Phase Change Material
Symbols	
L	Length of the enclosure, mm
L_b	Length of the fin, mm
L_l	Left height of fin, mm
L_r	Right height of fin, mm
T_{fin}	Fin thickness, mm
t	Time, s

1. INTRODUCTION

Latent heat storage (LHS) is currently the most common and effective approach for addressing the intermittent and unstable nature of renewable energy utilization [1, 2]. The melting process of PCM in energy storage units results from the combined effects of heat conduction and convective heat transfer. Based on the dominant heat transfer mode of PCM during the melting process, the process can be divided into the thermal conductivity stage, convective enhancement stage, weak convective stage, and final melting stage [3]. PCM located at the corners of the container during the final melting stage increases the melting completion time and significantly limits the heat storage efficiency [4]. Previous studies have shown that approximately 10% of the remaining PCM in the final melting stage of LHS units accounts for 30-40% of the total melting time [5].

Adding fins to the LHS units can effectively improve heat transfer efficiency and strengthen heat storage rates. To balance the relationship between heat conduction and convective heat transfer during the PCM melting process, scholars have conducted research on enhanced heat transfer by adjusting the inclination angle, length, and geometric structure of the fins [6-8]. The results indicate that incorporating longer fins and non-uniform arrangements in LHS units leads to a more effective enhancement in heat transfer. Additionally, the utilization of V-shaped, T-shaped, and stepped fins can enhance PCM heat transfer at the container corners, thereby further improving the PCM melting rate [9-11].

The arrangement of fins significantly impacts the flow and heat transfer of liquid PCM. However, fins in rectangular LHS units are typically arranged horizontally, which severely limits the natural convection of the liquid PCM. Additionally, most numerical simulations employ two-dimensional models, neglecting the influence of container boundaries during the final melting stage. Therefore, this paper employs three-dimensional numerical simulations to explore the effect of adding non-uniform length longitudinal fins at the bottom of a rectangular container with side wall heating on the RT42 PCM melting characteristics. This setup is compared with a container that has longitudinal rectangular fins on the side wall. The study aims to reduce the impact of the final stage of PCM melting on the overall melting time while enhancing the heat transfer effect of natural convection.

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

2. MATERIAL AND METHODS

2.1 physical model

As shown in Fig. 1(a) and (b), the longitudinal fins added at the lower region of the rectangular container, and the length (L_b) of is equal to the length of the container (L=10 mm). Nine types non-uniform longitudinal fins are individually designed by varying the height of the fins on the left and right (L_l and L_r). As depicted in Fig. 1(c), a longitudinal rectangular fin model (L_l= 10 mm and L_b= 5 mm) as a basic case was established for comparison. To investigate the influence of the fin arrangement and geometric structure, the volume of PCM remains constant (V = 990 mm^3). The specific geometric parameters of various models are shown in Table 1.

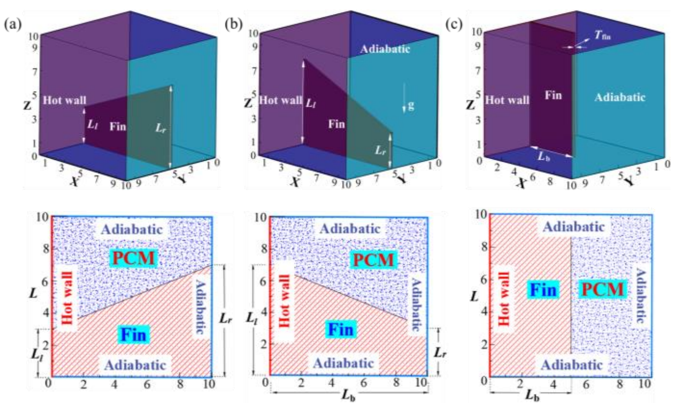

Fig. 1. Three-dimensional (top) and two-dimensional sectional (below) diagrams of various longitudinal fins added at the bottom region (a, b) and on the left wall (c) of a rectangular container.

Table 1. Geometric parameters of different types of longitudinal fins added within the rectangular cavity.

Case	L_l (mm)	L_r (mm)	L_b (mm)	T_{fin} (mm)
1	10	-	5	0.2
2	9	1	10	0.2
3	8	2	10	0.2
4	7	3	10	0.2
5	6	4	10	0.2
6	5	5	10	0.2
7	4	6	10	0.2
8	3	7	10	0.2
9	2	8	10	0.2
10	1	9	10	0.2

Paraffin has the advantages of a wide temperature range, stable performance, and non-toxic properties. Hence, RT42 is selected as the PCM, and aluminum is used as the material for the shell and fins. The specific thermal properties parameters are shown in Table 2.

Table 2. Thermophysical properties of RT42 and aluminum [4].

Properties	RT42	Aluminum
Solidus temperature, T_s	38	-
Liquidus temperature, T_l	42	-
Density, ρ	760	2710
Specific heat, c_p	2000	871
Latent heat, L_h	165000	-
Dynamic viscosity, μ	0.2	-
Thermal expansion coefficient, γ	0.2	-
Thermal conductivity, k	0.2	202.4

2.2 Mathematical model

This paper employs the commonly used enthalpy-porosity method to simulate the melting process of PCM. To simplify, the model is based on the following assumptions. (1) Liquid PCM is incompressible, and the flow is laminar. (2) The effect of volume expansion during PCM phase change is ignored. (3) The thermophysical properties of RT42 remain constant, except for the density ρ, which satisfies the Boussinesq approximation in the gravity forces term [12].

Based on the above assumptions, the continuity equation, energy equation, and momentum equation representing the PCM melting process are as follows [4]:

$$\frac{\partial \rho}{\partial t}+\nabla\cdot\left(\rho\mathbf{u}\right)=0, \tag{1}$$

$$\frac{\partial\left(\rho H\right)}{\partial t}+\nabla\cdot\left(\rho\mathbf{u}H\right)=k\nabla^2 T, \tag{2}$$

$$\frac{\partial\left(\rho\mathbf{u}\right)}{\partial t}+\nabla\cdot\left(\rho\mathbf{uu}\right)=-\nabla P+\mu\cdot\nabla^2\mathbf{u}+\mathbf{S}+\rho\mathbf{g}\gamma\left(T-T_{\mathrm{m}}\right). \tag{3}$$

where k denotes the PCM thermal conductivity, **u** is the velocity vector. μ represents the dynamic viscosity of liquid PCM, $\rho g\gamma(T-T_m)$ is presented as the buoyant term. H represents the total specific enthalpy value of PCM, which is equal to the sum of sensible heat (h_s) and latent enthalpy value (h_l),

$$H=h_s+h_l, \tag{4}$$

$$h_s=h_{\mathrm{ref}}+\int_{T_{\mathrm{ref}}}^{T}c_p dT, \tag{5}$$

$$h_l = \beta L_h. \tag{6}$$

The source term **S** is defined as follows [13],

$$\mathbf{S} = \frac{A_{mush}(1-\beta)^2}{\beta^3+\varepsilon}\mathbf{u}, \tag{7}$$

The enthalpy-porosity method determines the liquid fraction *β* of PCM based on the static temperature (*T*) in the calculation region, as described below [4],

$$\beta = \begin{cases} 1 & if\ T_l \le T, \\ \dfrac{T-T_s}{T_l-T_s} & if\ T_s < T < T_l. \\ 0 & if\ T \le T_s. \end{cases} \tag{8}$$

here, T_l and T_S represent the solidus temperature and liquidus temperature, respectively.

3. RESULTS AND DISCUSSION

3.1 Impact of fin structure and arrangement on PCM melting rate

From Fig. 2(a), it can be observed that the PCM melting rate is nearly identical in the initial stage. As the melting progresses, the rate decreases to varying degrees in different containers. Among them, the container with longitudinal rectangular fins added to the left wall (case 1) exhibits a rapid melting rate in the initial stage. However, as the melting progresses, the rate decreases rapidly. In the final melting stage, the melting rate is much lower than that of the units with non-uniform longitudinal fins. The melting rate of non-uniform longitudinal fins with $L_r > L_l$ (cases 7-10) is slower in the initial stage. However, as melting progresses, the melting rate gradually exceeds that of LHS units with fins $L_l \ge L_r$ (cases 2-6). This is because the rectangular fin added to the left wall has a relatively short extension distance, resulting in a larger contact area and temperature difference between the fin and the PCM near the hot wall, leading to faster initial melting. As the amount of liquid PCM increases, the enhanced heat transfer effect gradually weakens after the phase interface crosses the fin. In contrast, the fins at the bottom have a longer extension distance, which strengthens the melting rate of PCM near the right wall. Thus, the melting rate decreases more slowly as melting progresses. As depicted in Fig. 2(b), the melting time for adding non-uniform longitudinal fins at the bottom of the container is much shorter than that for adding longitudinal fins on the side wall. Additionally, as the L_l of the fins decreases, the melting completion time first decreases and then increases. There exists an optimal geometric structure for non-uniform longitudinal fins that minimizes the melting completion time. Among the cases, case 8 ($L_l = 3$, $L_r = 7$) has the fastest melting rate, reducing the melting completion time by 27.5% compared to case 1

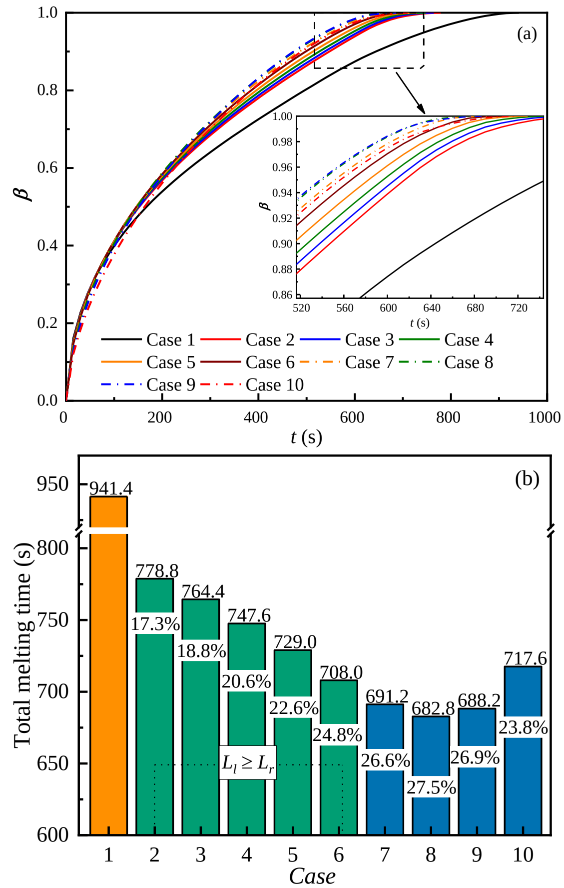

Fig. 2. Variation of liquid fraction and melting completion time in energy storage units with longitudinal fins of different arrangements and geometric structures.

3.2 Impact of fin structure and arrangement on heat storage characteristic

Fig. 3 shows a comparison of heat storage capacity and heat storage rate in the LHS units with various longitudinal fins upon completion of PCM melting. It can be observed that case 1 has the maximum heat storage capacity, while the total heat storage of units with longitudinal fins added at the bottom of the container initially decreases and then increases as L_l decreases. Among them, case 7 has the smallest heat storage capacity, approximately 0.57% lower than that of case 1. The change in heat storage rate is opposite to that of heat storage capacity. Case 1 has the lowest heat storage rate, while case 8 has the highest heat storage rate, approximately 37.3% higher than that of case 1. This is mainly because the addition of rectangular fins on the left wall has a poor heat transfer enhancement effect on the PCM near the right wall. In the final melting stage, the PCM melts slowly, increasing the melting completion time and resulting in uneven temperature distribution, which stores more sensible heat in the container. The non-uniform fins at the bottom of the container promote the heat transfer of PCM at the corners, reducing the limitation of the final melting stage on the melting rate. Additionally, the liquid PCM at the top of the container can flow and transfer heat more effectively, resulting in a relatively uniform temperature distribution. Therefore, the heat storage rate is relatively high.

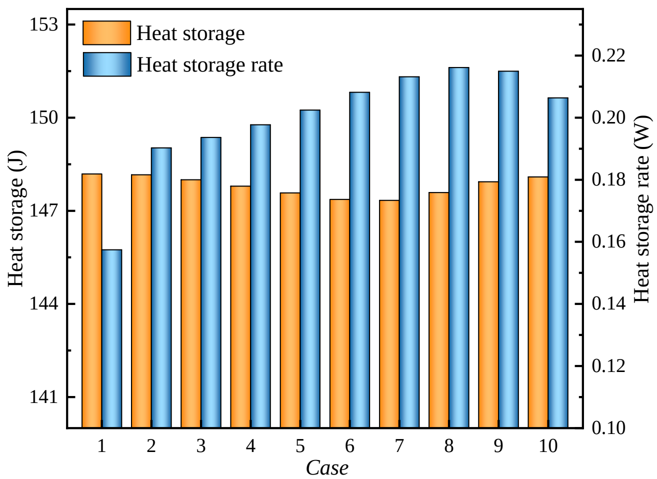

Fig. 3. Comparison of heat storage capacity and heat storage rate in rectangular containers with various fin structures and arrangements.

3.3 Impact of fin structure and arrangement on PCM flow behavior

Fig. 4 compares the average velocity over time of LHS units with various longitudinal fins during a heating period of 960 s. It can be observed that the average velocity inside the container initially increases and then decreases. Among the cases, the average flow velocity in the LHS units with fins $L_l \geq L_r$ (cases 2-6) exhibits relatively higher average flow velocities, with case 2 showing the highest average velocity, which is 21.57% higher than that in case 1. Notably, case 1 exhibits the highest velocity during the initial melting stage but starts to decline around 300 s, becoming lower than that of the LHS units with fins added at the bottom of the container. By t=570 s, the average velocity gradually decreases, and the maximum velocity is relatively small. This is because the rectangular longitudinal fins added in Case 1 have a shorter extension distance. As the liquid PCM crosses the fins, the enhancing effect gradually weakens. After the liquid PCM reaches the right wall, it enters a stage of weak convection, and the velocity gradually decreases. Additionally, a larger L_l results in a larger contact area between the fins near the hot wall and the PCM. This not only increases the temperature of the liquid PCM near the hot wall but also reduces the obstruction of the fins to flow. Consequently, the maximum flow velocity is relatively high.

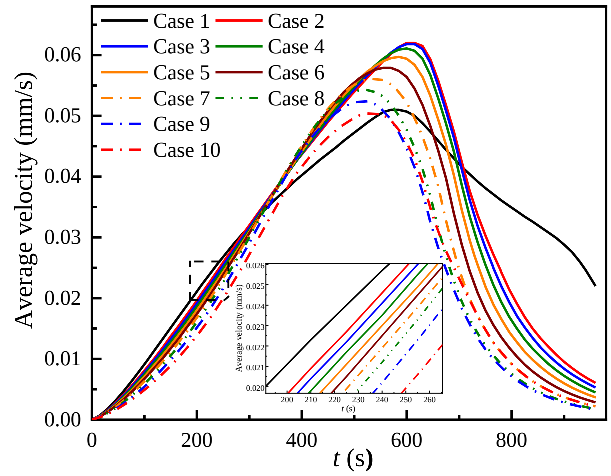

Fig. 4. Variation of average velocity with time in rectangular containers with various fin structures and arrangements.

3.4 Impact of fin structure and arrangement on temperature distribution

To compare the influence of the arrangement and structure of fins on PCM melting characteristics, Fig. 5 presents the evolutions of the temperature distribution contour of cases 1, 4, 6, and 8 at different times. Clearly, the average temperature at the upper part of the container is relatively high, whereas it is comparatively lower in the lower-right corner of the enclosure. This difference is primarily due to buoyancy-driven convection. At t=480 s, the longer extension length of the rectangular fin added to the left wall of case 1 results in a higher melting rate and average temperature of the PCM at the top of the container compared to cases 4, 6, and 8. However, the addition of longitudinal fins at the bottom of the container enhances heat transfer at the bottom, significantly increasing the melting rate and temperature of the PCM near the fins. At t=570 s, the liquid PCM of case 1 has traversed the fins and contacts the right wall, while a substantial amount of solid PCM remains at the bottom of the container. Thus, there is a significant temperature difference between the PCM in the upper and lower regions of the container. The melted PCM near the bottom of the fins in Cases 4, 6, and 8 merges with the liquid PCM at the top of the container.

As a result, solid PCM exists only at the right corner of the container, with the average temperature near the right wall significantly higher than in case 1. At t=690 s, a significant amount of solid PCM remains at the bottom of case 1, while the PCM in the units with fins added at the bottom of the container has almost melted. Case 8 exhibits the most uniform temperature distribution, with the average temperature of the PCM in the lower-right corner of the container approximately 7-9 °C higher than that of other LHS units.

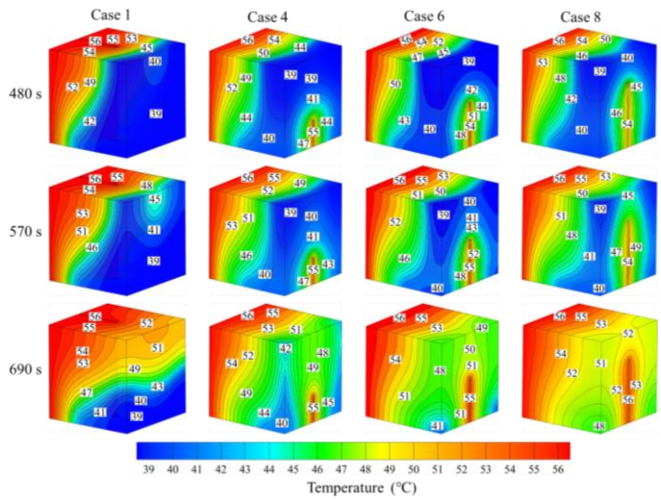

Fig. 5. Comparison of temperature distribution in a rectangular container with various fin structures and arrangements.

4. CONCLUSIONS

This paper proposes a rectangular container with non-uniform longitudinal fins added to the bottom, aimed at enhancing convective heat transfer while mitigating the impact of the final melting stage on the overall melting rate. Through three-dimensional numerical simulation, we investigated the influence of the height of the left (L_l) and right (L_r) of the longitudinal fins added at the bottom on the convective heat transfer characteristics of PCM. The main conclusions are as follows:

(1) The addition of longitudinal fins at the bottom of the rectangular container enhances heat transfer efficiency compared to adding rectangular longitudinal fins on the hot wall (case 1). Compared to case 1, the melting completion time of the optimal fin structure (case 8) can be reduced by 27.5%, and the heat storage rate can be increased by 37.3%.

(2) The addition of longitudinal fins at the bottom of the container can significantly reduce the impact of PCM on the melting rate in the final melting stage and improve the uniformity of temperature distribution. At t=690 s, the average temperature at the bottom corner of case 8 can be increased by 9 °C compared to case 1.

(3) When the geometric parameters of the non-uniform longitudinal fins are L_l=3 mm and Lr =7 mm, the effect of natural convection and the final stage of melting on the melting process is balanced, resulting in optimal heat storage performance.

ACKNOWLEDGEMENT

This work is supported by the National Natural Science Foundation of China (Grant No. 52076017) and Chongqing Municipal Training Program of Innovation and Entrepreneurship for Undergraduates (Project No. 202410611093)

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