



Numerical Investigation of Fin Height Effects on the Melting and Solidification Behavior of PCM in a Rectangular Latent Heat Storage Unit

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Abstract

Latent heat thermal energy storage (LHTES) systems using phase change materials (PCMs) have attracted growing interest due to their high energy storage density and their ability to maintain a nearly constant temperature during phase transition, making them well suited for renewable energy applications, building thermal regulation, and industrial waste heat recovery. Among available PCMs, paraffin-based materials such as n-eicosane are widely used owing to their favorable thermophysical stability; however, their inherently low thermal conductivity limits both melting (charging) and solidification (discharging) rates, restricting their use in applications requiring rapid heat transfer. To address this limitation, the present study numerically investigates the effect of fin height on the melting and solidification behavior of an n-eicosane-based rectangular storage unit equipped with vertical fins attached to the heated/cooled wall. The two-dimensional governing equations are solved using the enthalpy-porosity method within a finite-volume framework, and the numerical model is validated against benchmark experimental and numerical data from the literature. Four fin heights ($h = 0, 0.5, 1.0$, and 1.5 cm) are considered to assess their influence on the evolution of the solid-liquid interface and the liquid fraction. The results show that increasing the fin height substantially enhances heat transfer during both processes, reducing the total melting time by up to 77.8% and the solidification time by up to 85% compared with the finless configuration. Melting is found to be governed by a combination of conduction and buoyancy-driven natural convection, while solidification remains predominantly conduction-controlled. These findings confirm that fin height is a key design parameter for improving the charging and discharging performance of LHTES systems.

Keywords: Phase change material; Latent heat thermal energy storage; Fin height; Melting; Solidification; Enthalpy-porosity method

Nomenclature

$Amush$	mushy zone constant	$kg/(m^3 \cdot s)$
C_p	specific heat capacity	$J/(kg \cdot K)$
E	cavity depth	m
e	fin thickness	mm
f	liquid fraction	–
g	gravitational acceleration	m/s^2
k	thermal conductivity	$W/(m \cdot K)$
L	storage unit length	m
L_f	latent heat of fusion	kJ/kg
P	pressure	Pa
Pr	Prandtl number	–
Ra	Rayleigh number	–
S_x, S_y	momentum source terms (x, y directions)	N/m^3
Ste	Stefan number	–
T	temperature	K
t	time	s
U, V	velocity components (x, y directions)	m/s
x, y	Cartesian coordinates	m

Greek letters

β	thermal expansion coefficient	K^{-1}
ΔH	latent heat enthalpy term	J/kg
ΔT_f	phase-change temperature range	$^{\circ}C$
μ	dynamic viscosity	$kg/(m \cdot s)$

Subscripts

l	liquid
pcm	phase change material
s	solid

1. Introduction

The steadily increasing global demand for energy has driven the development of technologies aimed at reducing energy consumption and has motivated researchers to explore renewable and efficient energy sources. Within this context, thermal energy management remains a major challenge, and developing materials with high energy storage capacity is a key research priority. Among the available techniques, latent heat thermal energy storage (LHTES) has emerged as one of the most promising solutions, relying on Phase Change Materials (PCMs) as the storage medium [1].

PCMs are used in a wide range of applications, including solar heating systems, thermal regulation of photovoltaic panels, building temperature control, electronic cooling, battery thermal management, refrigeration, and waste heat recovery [2]. However, the major drawback of PCMs is their low thermal conductivity, which reduces the heat transfer rate and limits their use in large-scale LHTES units [2]. To overcome this limitation, several techniques have been proposed to enhance the thermal conductivity of PCMs, such as the use of fins [2], high-conductivity porous structures [3], and the dispersion of nanoparticles [4].

Several studies have investigated the effect of fins on the melting behavior of PCMs. Kamkari and Shokouhmand [5] conducted an experimental study on the melting of a PCM in a rectangular cavity with and without horizontal fins, showing that increasing the number of fins tends to reduce the melting time. To further improve melting performance, Ji et al. [6] proposed the use of inclined parallel fins and found, through numerical investigation, that a fin inclination angle of -15° accelerates the melting process. Similarly, Kamkari and Kamkari [7] carried out an experimental study on the melting enhancement of lauric acid using fins installed at different inclination angles in rectangular cavities. Their results showed that tilting the enclosure itself can be more effective in accelerating melting than adding fins to a vertical cavity, and that increasing the number of fins beyond a certain threshold (three fins) leads to a decline in thermal performance. This behavior was attributed to the fact that, while additional fins increase the heat transfer surface area, they simultaneously increase the flow resistance of the liquid PCM, thereby weakening natural convection and reducing the overall heat transfer rate. Mousavi et al. [8] numerically investigated the melting performance of a cylindrical storage unit equipped with horizontal copper fins and filled with a PCM containing Al₂O₃ nanoparticles. Their results indicated that increasing the number of fins alone reduced the melting time by up to 25.7%, whereas adding 5% Al₂O₃ nanoparticles without fins improved melting time by only 5.5%. The combination of nano-enhanced PCM (5% Al₂O₃) with fins (three fins) yielded the best performance, reducing melting time by up to 28.3%.

The influence of fins has also been widely studied for the solidification process. Stritih [9] experimentally examined heat transfer characteristics in a storage unit equipped with rectangular fins and reported that heat transfer was accelerated by conduction, reducing the solidification time by 40%. Ereik et al. [10] carried out a combined numerical and experimental study on thermal energy storage in an annular tube containing radially distributed fins of different aspect ratios, showing that the effects of the Reynolds and Stefan numbers on the stored energy were more significant than the fin shape effect, with good agreement between numerical and experimental results. Sheikholeslami et al.

[11] performed a finite element numerical study to assess the influence of snowflake-shaped fins compared with the dispersion of Cu nanoparticles on solidification time, finding that fins reduced the discharge time more effectively, with a solidification rate 4.5 to 7.8 times faster than in a finless configuration.

The combined effect of fins and nanoparticles has also received attention. Hosseinzadeh et al. [12] numerically studied the addition of an Al_2O_3 -GO hybrid nanofluid to a water-based PCM in a finned storage unit and concluded that finned configurations were more effective in enhancing solidification than the dispersion of hybrid nanoparticles alone. Huang et al. [13] numerically investigated a finned storage unit and identified fin height as the most influential structural parameter affecting solidification performance. Khatra et al. [14] developed a mathematical model to study the effect of fin length on the solidification of a PCM inside a rectangular enclosure with internal rectangular fins, showing that longer fins weaken natural convection in the liquid layer while increasing the heat exchange surface area, resulting in a 40.5% reduction in solidification time. Hajizadeh et al. [15] examined the combined effect of fins and CuO nanoparticles dispersed in RT35 PCM, reporting a 70.06% improvement in solidification time. In contrast, Gürtürka and Kok [6] experimentally and numerically studied the effect of different fin geometries on the melting and solidification of RT55 paraffin wax and found that the tested fin designs had no significant effect on the solidification process, attributing this result to the supercooling behavior of the PCM.

The present study investigates the influence of fins with different dimensions on the melting and solidification processes of a phase change material confined within a differentially heated rectangular cavity.

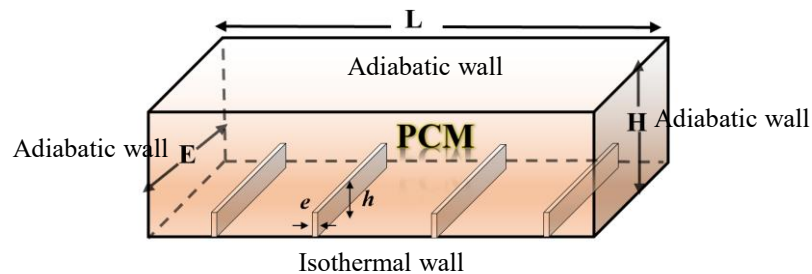


Figure 1: Physical model

2. Mathematical formulation

2.1 Physical model

The physical model considered in this study is illustrated in Fig. 1. It consists of a rectangular enclosure with a length L , a height H , and a depth E , filled with PCM. Vertical copper fins of thickness e are attached to the bottom wall of the enclosure. To investigate

the influence of fin height on the melting and solidification processes, different fin heights h are considered, while the enclosure dimensions, fin thickness, and fin spacing are kept constant throughout the study. The corresponding geometric parameters are summarized in Table 1. All walls of the enclosure are assumed to be thermally insulated except the front wall, which is maintained at a constant temperature under isothermal conditions. The thermophysical properties of the PCM and copper are listed in Table 2.

2.2 Assumptions of the Model

In the present model, the problem is considered two-dimensional. The flow of the liquid PCM is assumed to be laminar, Newtonian, and incompressible, with constant thermophysical properties except for the density variation in the buoyancy term, which is treated using the Boussinesq approximation. No-slip boundary conditions are applied at all solid walls of the enclosure.

Table 1 Geometrical dimensions of the LHTES unit.

Parameter	Value
Storage unit height	$H = 2 \text{ cm}$
Storage unit length	$L = 4 \text{ cm}$
Fin height	$h = 0, 0.5, 1.0, \text{ and } 1.5 \text{ cm}$
Fin length	E (equal to the cavity depth)
Fin thickness	$e = 1 \text{ mm}$

Table 2 Thermophysical properties of the PCM and aluminum[17].

Property	n-Eicosane	Copper
Density, ρ (kg m^{-3})	910 (solid) / 769 (liquid)	8960
Specific heat capacity, C_p ($\text{J kg}^{-1} \text{K}^{-1}$)	1926 (solid) / 2400 (liquid)	385
Thermal conductivity, k ($\text{W m}^{-1} \text{K}^{-1}$)	0.423 (solid) / 0.146 (liquid)	401
Dynamic viscosity, μ ($\text{kg m}^{-1} \text{s}^{-1}$)	3.845×10^{-3} (liquid)	–
Thermal expansion coefficient, β (K^{-1})	8.161×10^{-4} (liquid)	–
Latent heat of fusion, L_f (kJ kg^{-1})	248	–

2.3 Governing equations:

The two-dimensional phase change is governed by the following equations for conservation of mass, momentum and energy [18]:

$$\frac{\partial U}{\partial t} + \frac{\partial V}{\partial t} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + \frac{\partial UU}{\partial x} + \frac{\partial UV}{\partial y} = -\frac{1}{\rho_{pcm}} \frac{\partial P}{\partial x} + \frac{\mu_{pcm}}{\rho_{pcm}} \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) + S_x \quad (2)$$

$$\frac{\partial V}{\partial t} + \frac{\partial UV}{\partial x} + \frac{\partial VV}{\partial y} = -\frac{1}{\rho_{pcm}} \frac{\partial P}{\partial y} + \frac{\mu_{pcm}}{\rho_{pcm}} \left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) + \beta_{pcm} g (T - T_{ref}) + S_y \quad (3)$$

$$\frac{\partial H}{\partial t} + \frac{\partial(UH)}{\partial x} + \frac{\partial(VH)}{\partial y} = \frac{k_{pcm}}{\rho_{pcm}} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4)$$

In the above equations, S represents source term which is defined as [18]:

$$S_x = \frac{(1-f)^2}{f^3 + \varepsilon} A_{mush} U, S_y = \frac{(1-f)^2}{f^3 + \varepsilon} A_{mush} V \quad (5)$$

where $\varepsilon=0.001$ to prevent division by zero, A_{mush} is the mushy zone constant and f is the liquid fraction.

Enthalpy, H is the sum of sensible enthalpy, h' , and the latent heat of fusion, ΔH [18]:

$$H = h' + \Delta H \quad (6)$$

$$h' = h_{ref} + \int_{T_{ref}}^T C_p dT \quad (7)$$

$$\Delta H = fL_f \quad (8)$$

The enthalpy approach requires a single domain in which the solid and liquid phases of PCM are modeled by the same governing equations [18, 19]. Within a specific temperature range ($\Delta T_f = 1^\circ\text{C}$), the solid-liquid phase transition occurs, creating an artificial mushy zone at the boundary between the solid and liquid phases. In this mushy zone, the melt percentage varies from 0 to 1, while the fluid velocity changes from zero at the solid boundary to the natural convection velocity at the liquid boundary. The phase change in both cases is represented by the melt fraction using the following equation:

$$f = \begin{cases} 0 & , T < T_{solidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & , T_{solidus} \leq T \leq T_{liquidus} \\ 1 & , T > T_{liquidus} \end{cases} \quad (9)$$

3. Numerical approach, grid test, and validation

The numerical simulations were carried out the finite volume method for solving the governing equations of fluid flow and heat transfer. The PRESTO scheme was employed

for pressure interpolation, whereas the Second-Order Upwind scheme was used to discretize the transport equations. Pressure–velocity coupling was achieved using the SIMPLE algorithm. The convergence criteria were specified as 10^{-10} for the energy equation and 10^{-6} for the continuity and momentum equations. For each time step, a maximum of 500 iterations was performed, with a constant time step size of 0.1 s. The computational domain was discretized using a structured non-uniform mesh, as shown in Fig. 2. A grid independence study was conducted using four different meshes: 80×100 , 100×150 , 150×200 , and 200×250 cells. The effect of mesh resolution was evaluated by comparing the evolution of the liquid fraction during the melting and solidification process in the cavity without fins (Fig. 3). The results obtained with the 100×150 , 150×200 , and 200×250 meshes showed negligible differences, indicating that the solution was independent of further mesh refinement. Therefore, the 150×200 mesh was selected for all subsequent simulations, as it provides an excellent compromise between numerical accuracy and computational cost.

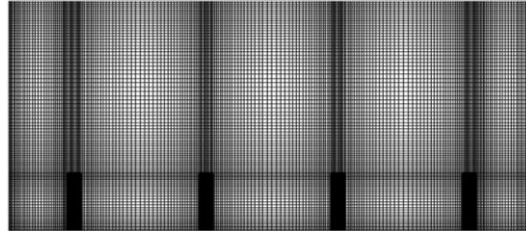


Figure 2: Computational mesh.

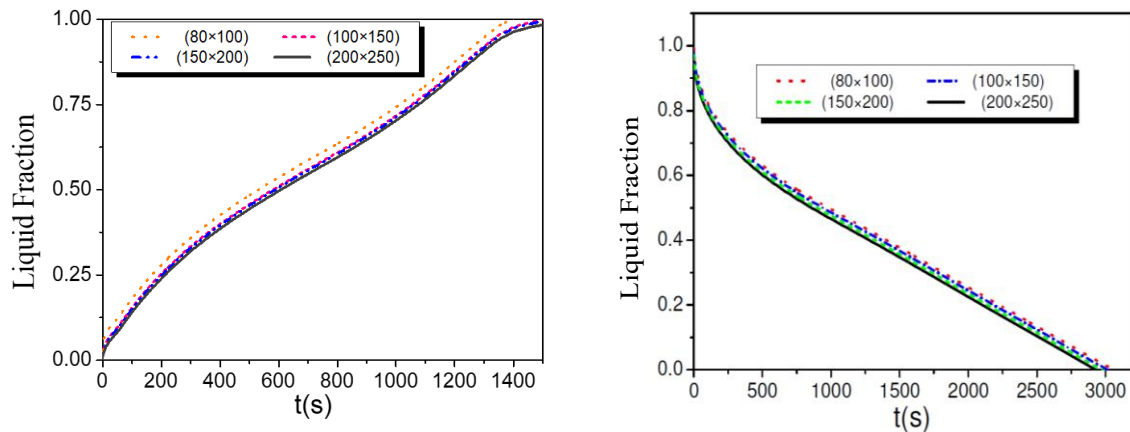


Figure 3: Effect of Mesh Resolution on the Evolution of the Liquid Fraction: (a) Melting and (b) Solidification.

The reliability and accuracy of the present numerical study are validated by comparing its results with those previously experimental data of Gau and Viskanta (1986) [19] and the numerical predictions of Brent et al. (1988) [20] for gallium melting in a rectangular cavity ($6.35 \text{ cm} \times 8.89 \text{ cm}$) at $Pr = 0.0216$, $Ste = 0.039$, and $Ra = 6 \times 10^5$.

Figure 5 compares the evolution of the gallium solid–liquid interface during melting. The present results show excellent agreement with both the experimental and numerical

reference data, demonstrating the accuracy of the adopted numerical model.

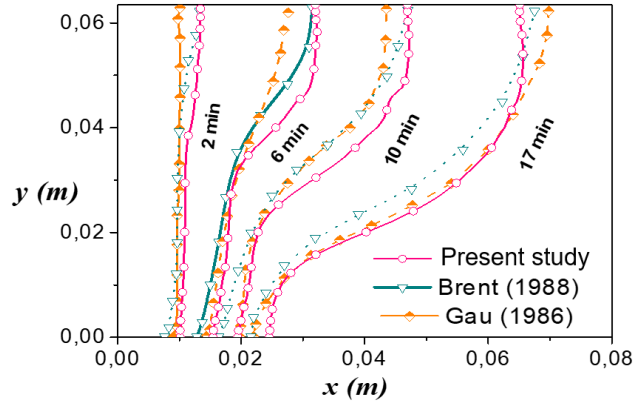


Figure 5 : Comparaison du front de fusion à différents instants obtenue par la présente étude et des travaux antérieures.

An additional validation was carried out by comparing the evolution of the solid–liquid interface during melting in a finned square cavity with the numerical results of Arıcı et al. (2020) [21] at different time instants (Fig. 6). A good agreement is observed between the two results, confirming the accuracy of the present numerical model

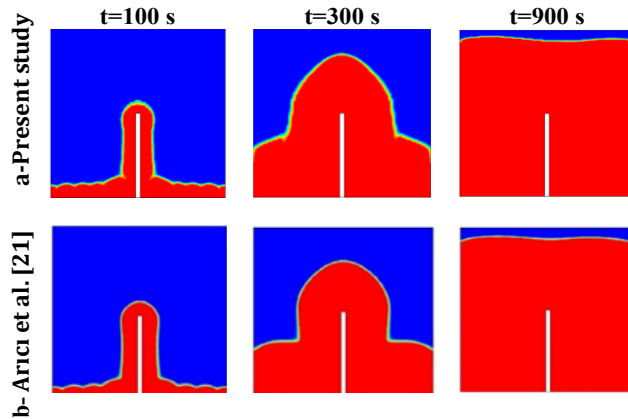


Figure 6: Comparison of the Solid–Liquid Interface Evolution during Melting in the Cavity: (a) Present Study and (b) Arıcı et al. [21] .

4. Results and discussion

4.1 Evolution of the solid–liquid interface

Figures 7 and 8 illustrate the evolution of the solid–liquid interface during the melting and solidification processes, respectively, at identical time intervals (10, 50, 100, 200, 300 and 400 s). These figures enable a direct comparison of the phase-change behavior and highlight the influence of fin height on the charging and discharging processes.

During melting (Fig. 7), the liquid region gradually expands from the heated wall toward the opposite side of the cavity. At the early stage, the melting front remains nearly parallel to the heated wall, indicating a conduction-dominated regime. As melting progresses, the interface becomes increasingly curved due to the development of buoyancy-driven natural convection in the liquid PCM. Increasing the fin height noticeably accelerates the melting process by enlarging the heat transfer area and reducing the heat conduction path. As a result, the finned configurations exhibit a larger molten region at any given time than the cavity without fins, with the highest fins providing the fastest melting rate.

In contrast, the solidification front (Fig. 8) advances progressively from the cooled wall while remaining nearly planar and parallel to the cooling surface throughout the process. This behavior indicates that solidification is primarily governed by heat conduction. The addition of fins also accelerates the discharge process by facilitating heat extraction from the PCM, although the effect is less pronounced than during melting. Overall, the comparison between Figs. 7 and 8 shows that melting proceeds faster and exhibits a more irregular interface due to the contribution of natural convection, whereas solidification remains predominantly conduction-controlled, resulting in a smoother and more uniform solid–liquid interface.

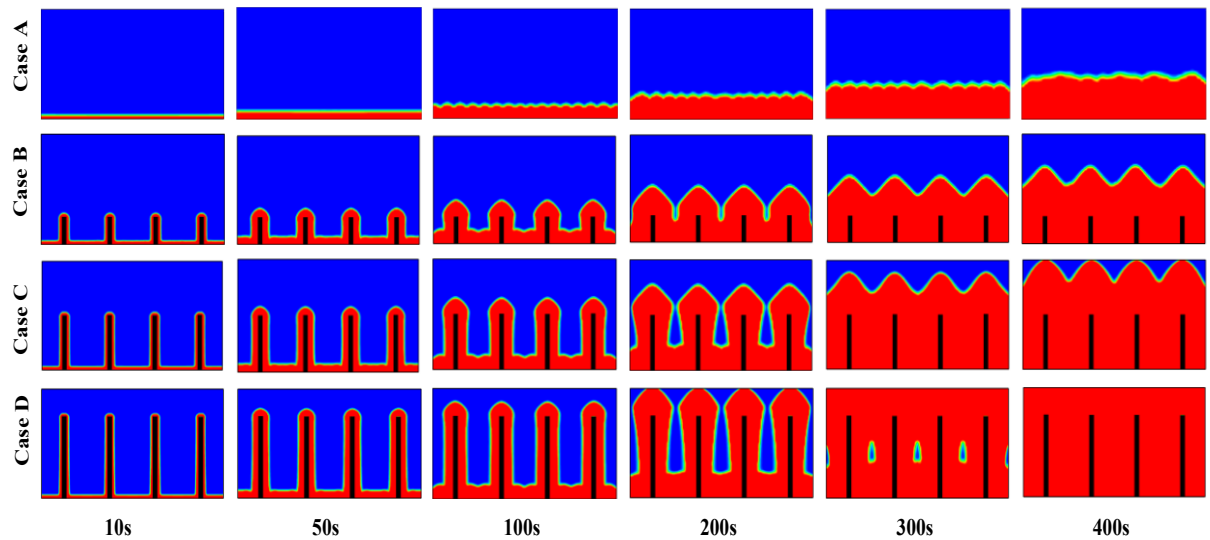


Figure 7: Evolution of the solid–liquid interface during the melting process for different fin heights.

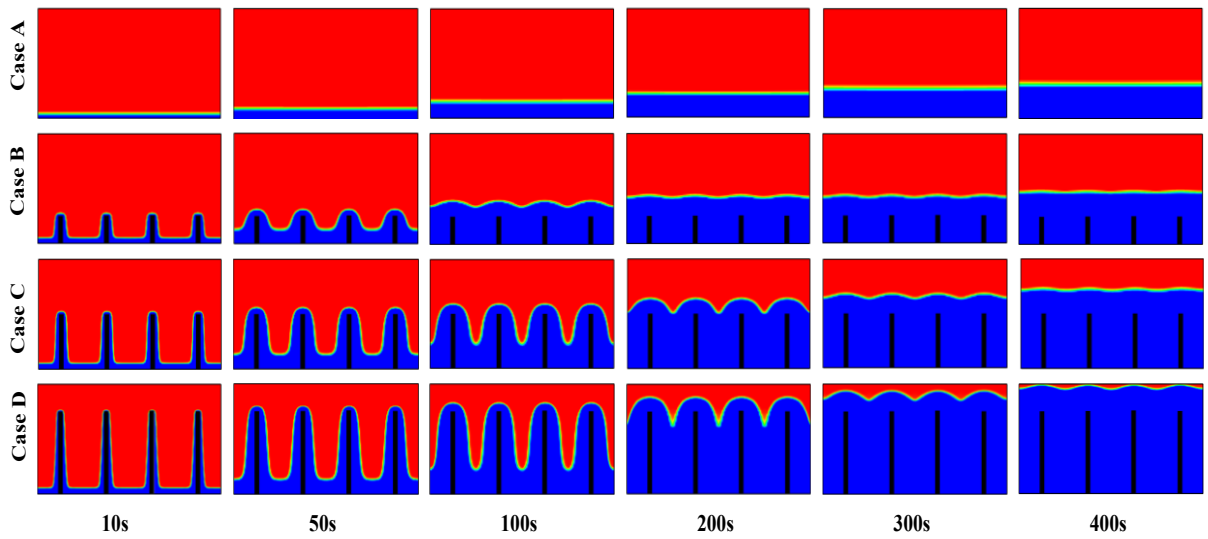


Figure 8: Evolution of the solid-liquid interface during PCM solidification for different fin heights at selected time intervals.

4.2 Evolution of the Liquid Fraction

Figure 9 illustrates the evolution of the liquid fraction for the four investigated configurations (Cases A–D) during (a) melting and (b) solidification. The liquid fraction represents the ratio of the molten PCM volume at a given time to the initial total PCM volume. It is therefore a direct indicator of the phase-change progress and provides a quantitative basis for comparing the charging and discharging performances of the different configurations.

As shown in Figure 9(a), the liquid fraction increases continuously with time until complete melting is achieved. During the initial stage, the melting rate is relatively low because heat transfer is mainly governed by conduction through the solid PCM. As the liquid layer develops, buoyancy-induced natural convection becomes increasingly significant within the molten region, leading to a more rapid increase in the liquid fraction. The beneficial effect of the fins becomes progressively more pronounced throughout the melting process. Increasing the fin height significantly reduces the melting time by enlarging the heat transfer surface area and shortening the conduction path between the heated wall and the PCM. Consequently, Case D exhibits the fastest melting rate, followed by Cases C and B, whereas Case A (without fins) requires the longest time to achieve complete melting. These results confirm the effectiveness of extended surfaces in enhancing the charging performance of the latent heat thermal energy storage unit.

A similar trend is observed during the solidification process, as illustrated in Figure 9(b), where the liquid fraction gradually decreases from unity to zero as the PCM releases its latent heat. At the beginning of solidification, the liquid fraction decreases rapidly

because of the large temperature difference between the liquid PCM and the cooled wall. As the solid layer thickens, heat must be conducted through this growing layer, progressively increasing the thermal resistance and consequently reducing the solidification rate. The incorporation of fins enhances heat extraction by increasing the heat transfer area and reducing the conduction path. As a result, the solidification time decreases with increasing fin height, with Case D exhibiting the shortest discharge time and Case A the longest.

A comparison between Figures 9(a) and 9(b) indicates that increasing the fin height enhances both the charging and discharging processes. However, the improvement is more pronounced during melting because the fins enhance not only conductive heat transfer but also promote the development of buoyancy-driven natural convection within the molten PCM. In contrast, solidification remains predominantly conduction-controlled due to the progressive formation of a solid layer adjacent to the cooled wall, which limits heat transfer. Nevertheless, increasing the fin height substantially reduces both the melting and solidification times, demonstrating that fin-assisted configurations significantly improve the overall thermal performance of the latent heat thermal energy storage unit.

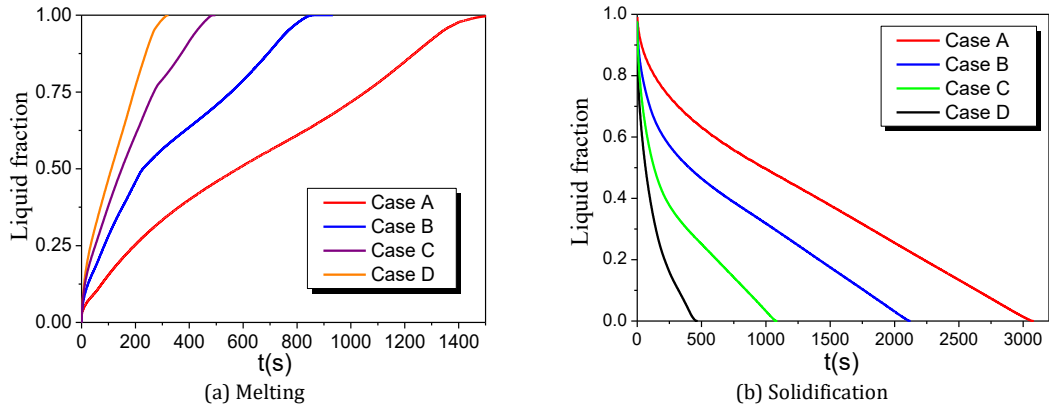


Figure.9: Effect of Fin Insertion on the Evolution of the Liquid Fraction: (a) Melting and (b) Solidification.

4.3 Improvement in Melting and Solidification Times

To quantify the effectiveness of fin insertion in enhancing the thermal performance of the latent heat thermal energy storage unit, the percentage reduction in the total melting and solidification times was calculated for the four investigated configurations. The corresponding results are presented in Figure 10, where Figure 10(a) shows the reduction in melting time and Figure 10(b) the reduction in solidification time.

As illustrated in Figure 10(a), the incorporation of fins significantly reduces the total melting time compared with the cavity without fins (Case A). The improvement

increases progressively with fin height, reaching 37.8%, 65.48%, and 77.8% for Cases B, C, and D, respectively. This remarkable enhancement is attributed to the larger effective heat transfer area provided by the fins, which promotes deeper heat penetration into the PCM and considerably shortens the conduction path. Consequently, the PCM melts more rapidly, particularly in Case D, where the longest fins provide the most efficient heat distribution throughout the storage unit.

A similar trend is observed for the solidification process, as shown in Figure 10(b). The total solidification time is reduced by 31.14%, 64.82%, and 85% for Cases B, C, and D, respectively, demonstrating that fin insertion also substantially enhances the discharging performance. During cooling, the fins facilitate heat extraction from the PCM by providing highly conductive pathways between the solidifying PCM and the cooled wall, thereby reducing the thermal resistance associated with the growing solid layer. Consequently, the PCM solidifies more rapidly as the fin height increases.

A comparison between Figures 10(a) and 10(b) reveals that fin insertion is beneficial for both the charging and discharging processes. However, the enhancement is slightly greater during solidification, particularly for Case D, where the reduction in solidification time reaches 85%, compared with 77.8% during melting. This difference indicates that increasing the conductive heat transfer area is especially effective during the discharge process, which is predominantly conduction-controlled. Overall, these results confirm that increasing the fin height is an effective and practical strategy for accelerating both energy storage and energy release, thereby significantly improving the overall thermal performance of the latent heat thermal energy storage system.

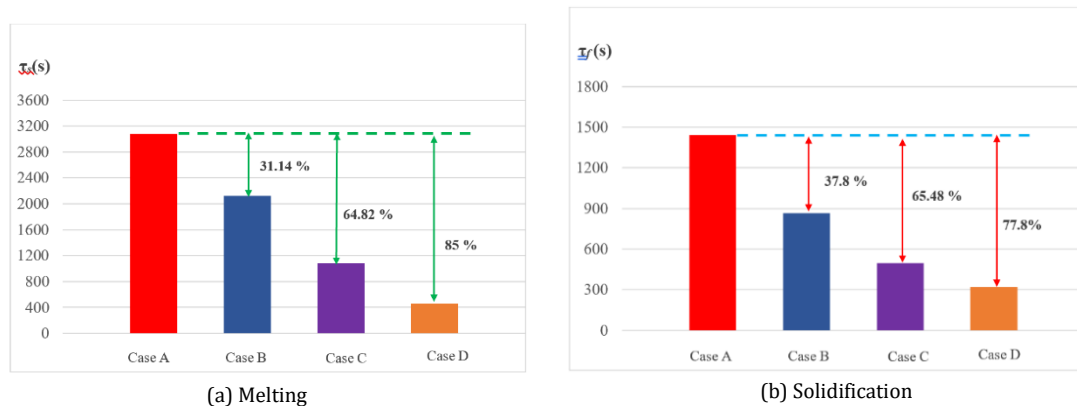


Figure 10:Effect of Fin Insertion on the Reduction of Melting and Solidification Times: (a) Melting and (b) Solidification.

5. Conclusion

This study presented a numerical investigation of the influence of fin height on the melting and solidification behavior of an n-eicosane-based rectangular latent heat

thermal energy storage (LHTES) unit. The two-dimensional governing equations were solved using the enthalpy-porosity method, and the numerical model was validated against experimental and numerical benchmark data available in the literature, showing excellent agreement in both cases. Four configurations, corresponding to fin heights of 0, 0.5, 1.0, and 1.5 cm, were investigated to assess their effect on the evolution of the solid-liquid interface and the liquid fraction during both charging and discharging processes.

The main findings of this study can be summarized as follows:

The addition of fins significantly enhances heat transfer during both melting and solidification by increasing the effective heat exchange surface area and reducing the conduction path within the PCM.

Increasing the fin height progressively accelerates the melting process, with the total melting time reduced by up to 77.8% for the highest fin configuration (Case D) compared with the finless cavity.

A similar trend is observed for solidification, where the discharge time is reduced by up to 85% for the same configuration, confirming that fin insertion is even more effective during the conduction-dominated discharging process.

Melting is governed by a combination of conduction and buoyancy-driven natural convection, resulting in a curved, irregular solid-liquid interface, whereas solidification remains predominantly conduction-controlled, producing a smoother and more uniform interface.

Despite these clear thermal benefits, the incorporation of fins reduces the effective PCM volume within the storage unit, highlighting an inherent trade-off between heat transfer enhancement and energy storage capacity that must be carefully balanced in practical LHTES design.

Overall, this work confirms that fin height is a key geometric parameter governing the thermal performance of LHTES systems and provides quantitative guidelines for optimizing fin-assisted PCM units for applications requiring both rapid and efficient thermal energy storage and retrieval.

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