

Numerical Analysis of Fin Position Effects on PCM Melting and Natural Convection in a Rectangular Enclosure

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Abstract

Phase change materials (PCMs) are promising materials for latent heat thermal energy storage because they can store and release substantial amounts of thermal energy during the solid–liquid phase transition. However, the relatively low thermal conductivity of many PCMs limits the rate of heat transfer and results in prolonged melting periods. In the present study, a numerical investigation is carried out to examine the influence of fin position on the melting behavior of PCM contained within a rectangular enclosure. A heated wall is used as the primary heat source, while fins are positioned at different distances from the base of the enclosure to enhance heat transfer and modify the melting process. The transient thermal behavior of the PCM is evaluated by analysing the temperature field, liquid fraction, and velocity distribution during the melting period. As melting progresses, the PCM near the heated wall absorbs thermal energy and transforms from solid to liquid. The resulting density variations generate buoyancy-driven natural convection, causing the heated liquid PCM to rise while cooler liquid descends and establishes a circulating flow within the enclosure. The fin position influences both the conductive heat-transfer pathway and the natural-convection pattern, thereby affecting the rate and uniformity of PCM melting. The numerical results are used to compare the evolution of liquid fraction and velocity profiles for the different fin locations. The study demonstrates that an appropriate fin position can improve thermal transport within the PCM and accelerate the melting process. The findings provide useful insight into the design and optimization of fin-assisted PCM-based latent heat thermal energy storage systems.

Keywords: Phase change material, latent heat thermal energy storage, fin, melting, liquid fraction, natural convection

1. Introduction

The increasing demand for energy, together with the intermittent nature of renewable energy resources, has created a strong need for efficient thermal energy storage (TES) technologies. Thermal energy storage provides an effective approach for storing excess thermal energy and recovering it when required, thereby improving energy utilization and reducing the mismatch between energy supply and demand. Among the different TES technologies, latent heat thermal energy storage (LHTES) using phase change materials (PCMs) has received considerable attention because PCMs can store and release a large amount of thermal energy during phase transition within a relatively narrow temperature range [1-3]. This characteristic makes PCM-based systems attractive for applications including solar thermal energy storage, building thermal management, waste-heat recovery, electronic cooling, and thermal management systems [4]. The thermal energy storage capability of a PCM is primarily associated with its latent heat of fusion. During the charging process, the PCM absorbs heat and undergoes a transition from solid to liquid after reaching its melting temperature. During the discharging process, the stored energy is recovered as the liquid PCM solidifies. Although PCMs can provide high energy-storage density, their relatively low thermal conductivity can limit the rate of heat transfer and consequently increase the required melting and solidification times. Therefore, improving heat transfer within the PCM is essential for achieving rapid and effective utilization of its latent heat capacity. Various heat-transfer enhancement techniques have consequently been investigated to improve the thermal performance of PCM-based latent heat storage systems [2-5]. The selection of PCM properties can also significantly influence the thermal performance of an energy-storage system. For example, Uniyal et al. investigated the thermal efficiency of coaxial evacuated tube collectors considering the influence of PCM selection, demonstrating the relevance of PCM properties to the performance of solar thermal systems [6].

The melting of PCM involves a coupled interaction between heat conduction, phase transformation, and natural convection. At the initial stage of melting, heat transfer through the solid PCM is predominantly governed by conduction. As the temperature of the PCM adjacent to the heated surface reaches the melting point, a liquid region develops. The liquid PCM close to the heated wall becomes warmer and less dense and consequently moves upward under the influence of buoyancy, while comparatively cooler and denser liquid moves downward. This upward and downward movement establishes a natural circulation loop within the liquid PCM. As melting progresses, the size and shape of the liquid region continuously change, resulting in a corresponding modification of the circulation pattern. The resulting natural circulation plays an important role in transporting heat from the heated region to the unmelted PCM and therefore strongly influences the melting rate and liquid-fraction distribution [1,-6].

Natural circulation has been extensively investigated in thermal systems because it provides fluid motion without requiring an external pumping mechanism. The characteristics of such systems depend strongly on geometry, heating conditions, fluid properties, and operating parameters [7-10]. Rai et al. investigated the steady-state characteristics and stability of supercritical-water natural circulation loops with different heater and cooler arrangements, demonstrating the importance of system configuration and operating conditions in determining circulation behavior [11]. Further numerical studies by Rai et al. examined Ledinegg flow excursions, dynamic instabilities, and the influence of geometry and operating parameters on supercritical natural circulation loops [12-15]. Rai et al. also investigated density-wave oscillations under different geometrical and operating conditions and showed that the system configuration can significantly influence the resulting flow behavior [16]. Mathematical modelling of density-wave instability in supercritical natural circulation loops has also been reported [17]. More recently, Rai et al. investigated the flow characteristics, stability, and safe operating limits of a supercritical natural circulation loop under different heating-power profiles [18]. These studies demonstrate the strong relationship between geometry, thermal conditions, and buoyancy-driven circulation. The stability and flow characteristics of natural circulation systems are also strongly influenced by the arrangement of the heater and cooler. Rai et al. investigated the stability of a supercritical water natural circulation loop containing vertical heater and cooler sections [19]. Their work demonstrated the importance of system configuration in predicting flow stability. Numerical investigations of heat-transfer deterioration and density-wave instability in supercritical water reactors have further highlighted the coupling between heat transfer and fluid-flow behavior [20]. Computational investigations of static flow instabilities have also been reported for supercritical natural circulation loops [21]. In addition, Rai et al. presented a comprehensive overview of the advancements, applications, and impact of supercritical-fluid natural circulation loops [22], while subsequent work addressed the reliability, sustainability, and safety of supercritical water reactors and supercritical natural circulation loops [23-37]. These studies provide a useful foundation for understanding buoyancy-driven flow and thermal-fluid behavior, which are also important when analysing the natural-convection flow generated during PCM melting.

The interaction between natural convection and phase change is particularly important in a rectangular PCM enclosure. When the enclosure is heated from one side, the molten PCM generally rises along the heated boundary and moves toward the upper region, where heat is transferred to the surrounding material. The cooled liquid subsequently descends through the relatively colder region, thereby completing the circulation loop. This circulation can produce a non-uniform melting pattern, with faster melting near the heated region and slower melting in regions where the heat-transfer rate is relatively low. Consequently, understanding the internal velocity field and its relationship with the liquid fraction is essential for evaluating the melting performance of PCM systems [1-6].

In addition to natural convection, enhanced heat-transfer structures have been developed to overcome the low thermal conductivity of PCMs. Fins or extended surfaces are among the most investigated techniques for improving heat transfer during PCM charging and discharging. Fins increase the effective heat-transfer area and provide conductive pathways through which heat can be transported from the heated boundary into the PCM. The effectiveness of a fin-assisted PCM system depends on several parameters, including fin material, length, thickness, number, orientation, spacing, and location [38]. Among these parameters, fin position is particularly important because it determines the distribution of heat within the enclosure and can modify the natural circulation pattern of the molten PCM.

The location of a fin can influence both conduction and natural convection during PCM melting. A fin positioned close to the heated wall can receive a high amount of thermal energy and enhance heat transfer near the heat source. However,

its ability to transport heat into remote regions of the PCM may be limited. In contrast, a fin positioned farther from the heated wall can provide a conductive pathway toward regions that would otherwise experience slower melting. At the same time, the presence of the fin modifies the local temperature field and consequently the buoyancy forces responsible for natural circulation. Thus, the optimum fin position is expected to depend on the interaction between heat conduction through the fin and buoyancy-driven circulation. Huang et al. [6] numerically investigated the melting process in a rectangular enclosure with different fin locations, highlighting the importance of fin placement in determining the melting behavior of PCM. Comprehensive reviews of fin-assisted latent heat thermal energy storage have likewise emphasized the influence of fin parameters on system performance [2,4,5]. The use of advanced heat-transfer configurations such as microchannels has also received considerable attention in thermal management applications. Microchannels can provide a high heat-transfer surface-area-to-volume ratio and enhanced thermal transport in compact systems. Rai et al. investigated the influence of microchannel geometry and surface topography through laser micromachining, demonstrating the importance of geometric and surface characteristics in controlling heat-transfer performance [7]. Rai et al. also conducted numerical and experimental investigations of two-phase flow through microchannels for the development of heat-dissipation correlations [8]. A review of microchannel heat sinks further emphasized their relevance to reliability, sustainability, safety, and high-performance electronic cooling applications [22].

Numerical investigations of microchannel heat transfer have further demonstrated the importance of channel geometry and operating conditions. Nimesh and Rai investigated flow and heat transfer through MEMS microchannels using numerical methods [30], while Singh et al. examined two-phase boiling heat transfer through microchannels [31]. Hussain and Rai subsequently investigated heat transfer in microchannels under different boundary conditions for laminar flow [35]. These investigations demonstrate the importance of flow configuration, surface characteristics, boundary conditions, and geometry in determining heat-transfer performance [7,8,22,30,31,35]. Although these studies primarily concern microchannel-based thermal systems rather than PCM melting, they provide useful insight into the broader role of geometry and heat-transfer enhancement in thermal systems.

The relationship between material properties and heat-transfer performance is also important in the development of advanced thermal systems. Kumar et al. investigated the grain-size-responsive behavior of polycrystalline nano copper under different temperature and strain-rate conditions [18]. Rai et al. and co-workers have also contributed to research involving advanced materials and nanomaterials for engineering applications [34,36]. Although these investigations are not directly related to PCM melting, they demonstrate the broader importance of material characteristics in the development of advanced thermal and energy systems. The broader development of natural circulation, microchannel heat transfer, and PCM-based thermal storage indicates a continuing movement toward compact, passive, and efficient thermal management technologies. Natural circulation can provide passive fluid motion, microchannels can enhance heat-transfer rates through compact geometries, and fins can provide additional conductive pathways within PCM storage systems. Other thermal-fluid investigations, including studies of instability in parallel channels of supercritical fluids and thermal-hydraulic performance of roughened ducts, further demonstrate the importance of geometry and flow configuration in thermal systems [26,32]. Combining an understanding of these mechanisms is therefore important for improving the thermal performance of latent heat storage systems.

Rising global energy demand, dwindling fossil fuel reserves, and the urgent need to cut greenhouse gas emissions have increased interest in efficient energy storage technologies. Renewable sources such as solar and wind are intermittent, so their supply often does not match demand in time, intensity, or location. Thermal energy storage (TES) addresses this mismatch: surplus thermal energy is stored and released when needed, which improves the reliability and overall efficiency of energy systems [39]. Thermal energy can be stored in three main ways: as sensible heat, as latent heat, or through thermochemical reactions. Latent heat thermal energy storage (LHTES) using phase change materials (PCMs) has received particular attention because it stores a lot of energy in a small volume at a nearly constant temperature [40-41]. PCMs absorb and release large amounts of energy as latent heat when they change phase, usually between solid and liquid. As a PCM is heated to its melting point, it absorbs heat while its temperature stays almost constant. When it cools, it solidifies and releases the stored heat. Because of this, a PCM can store 5–14 times more heat per unit volume than conventional sensible storage media such as water, masonry, or rock [42]. Solid–liquid transitions are the most

widely used in practice. Liquid–gas transitions involve large volume changes, and solid–solid transitions have relatively low latent heat, which limits both [43].

PCMs are generally divided into three groups. Organic PCMs, such as paraffins and fatty acids, melt congruently, are chemically stable, and show little supercooling. However, their thermal conductivity is low and they are flammable. Inorganic PCMs, mainly salt hydrates and metallic alloys, have high volumetric latent heat and higher thermal conductivity. However, they are prone to supercooling, phase segregation, and corrosion. Eutectic PCMs are mixtures of two or more components. Their melting temperatures can be tailored to specific applications[4445]. A suitable PCM should have a melting temperature within the operating range, high latent heat and thermal conductivity, good thermal and chemical stability over repeated cycles, low cost, and minimal environmental impact [46]. PCMs are now used in many fields. Examples include solar water heating and solar thermal power plants, building envelopes for passive thermal regulation, waste heat recovery, thermal management of electronics and batteries, textiles, and cold-chain logistics [47]. In buildings, PCMs built into walls, floors, and ceilings raise the thermal mass. This reduces indoor temperature swings and shifts peak cooling and heating loads, which lowers energy use [48]. Despite these advantages, several challenges limit wider use of PCMs. The most important is the low thermal conductivity of most PCMs, typically 0.2–0.5 W/m·K for organic materials. This slows charging and discharging [49]. Researchers have tried several ways to improve heat transfer, including:

- adding extended surfaces (fins)
- embedding metal foams or expanded graphite
- encapsulating the PCM
- dispersing high-conductivity nanoparticles to form nano-enhanced PCMs

Long-term cycling stability, leakage during melting, and compatibility with container materials also remain active research areas. This study therefore aims to [state your specific objective here], contributing to the development of more efficient and reliable PCM-based thermal energy storage systems.

However, most studies of natural circulation loops and microchannels have focused on conventional single- or two-phase flow, whereas PCM melting involves a moving solid–liquid interface and a continuously changing flow domain. Similarly, although fin-assisted PCM systems have received considerable attention [2,4,5], the influence of the fin position measured from the base of a rectangular enclosure on the combined liquid-fraction evolution and natural-circulation velocity field requires further investigation. In particular, the manner in which fin position modifies the internal circulation loop and consequently affects the progression of melting remains an important design consideration. The numerical investigation of different fin locations in a rectangular PCM enclosure reported by Huang et al. [6] provides an important basis for further investigation of this problem. Therefore, the present study numerically investigates the effect of fin position on the melting of PCM in a rectangular geometry. Different fin positions measured from the base of the enclosure are considered while maintaining the other principal parameters constant. The transient melting behavior is evaluated through the evolution of the liquid fraction and velocity profiles. Particular attention is given to the development of the buoyancy-driven natural circulation loop and its interaction with the fin during the melting process. The objective is to determine how fin position influences heat transfer, internal circulation, melting progression, and the overall thermal performance of the PCM system. The results are expected to provide useful guidance for optimizing fin placement in PCM-based latent heat thermal energy storage systems.

2. Numerical Methodology

2.1 Numerical Model

The melting behavior of the phase change material (PCM) was numerically investigated using ANSYS Fluent 15.0. The built-in solidification/melting model available in Fluent was employed to simulate the transient phase-change process. The numerical formulation is based on the enthalpy-porosity technique, which enables the solid–liquid transformation to be represented without explicitly tracking the instantaneous location of the solid–liquid interface. In this approach, the PCM computational domain is divided into a number of finite-volume cells, and each cell is assigned a liquid fraction,

which represents the proportion of the cell occupied by the liquid phase. The liquid fraction varies between zero and unity. A value of zero corresponds to a completely solid cell, whereas a value of one indicates that the cell is fully molten. Intermediate values represent the mushy region where solid and liquid phases coexist. At every computational time step, the liquid fraction is updated from the local enthalpy balance. Consequently, the phase-change interface is automatically represented through the distribution of liquid fraction within the computational domain. During melting, cells progressively change from a solid state to a liquid state as thermal energy is absorbed. The region containing intermediate liquid-fraction values behaves numerically as a porous medium. The resistance to fluid motion in this region decreases as the liquid fraction increases.

For a completely solid PCM region, the effective porosity approaches zero and the velocity is consequently suppressed. As melting progresses, the porosity of the mushy region increases, allowing fluid motion to develop. This formulation enables the simultaneous treatment of heat conduction, phase transformation, and buoyancy-driven convection within a single computational framework.

2.2 Assumptions

The numerical model was developed under the following assumptions:

1. The PCM melting process is transient and is represented using a two-dimensional computational domain.
2. The PCM is considered an incompressible Newtonian fluid in the molten state, with fluid motion primarily governed by buoyancy-induced natural convection.
3. The thermophysical properties of the PCM, including density, dynamic viscosity, and thermal conductivity, are considered to vary in a piecewise-linear manner over the phase-change temperature range.
4. The effects associated with viscous dissipation and volumetric expansion are neglected.
5. The PCM domain is assumed to have no internal heat generation.

These assumptions provide a simplified representation of the physical melting process while retaining the principal heat-transfer and fluid-flow mechanisms governing PCM melting.

2.3 Geometry and Computational Domain

A two-dimensional rectangular enclosure containing PCM was considered for the numerical investigation. The computational domain has a width of 0.040 m and a height of 0.60 m, as illustrated in Figure 1.

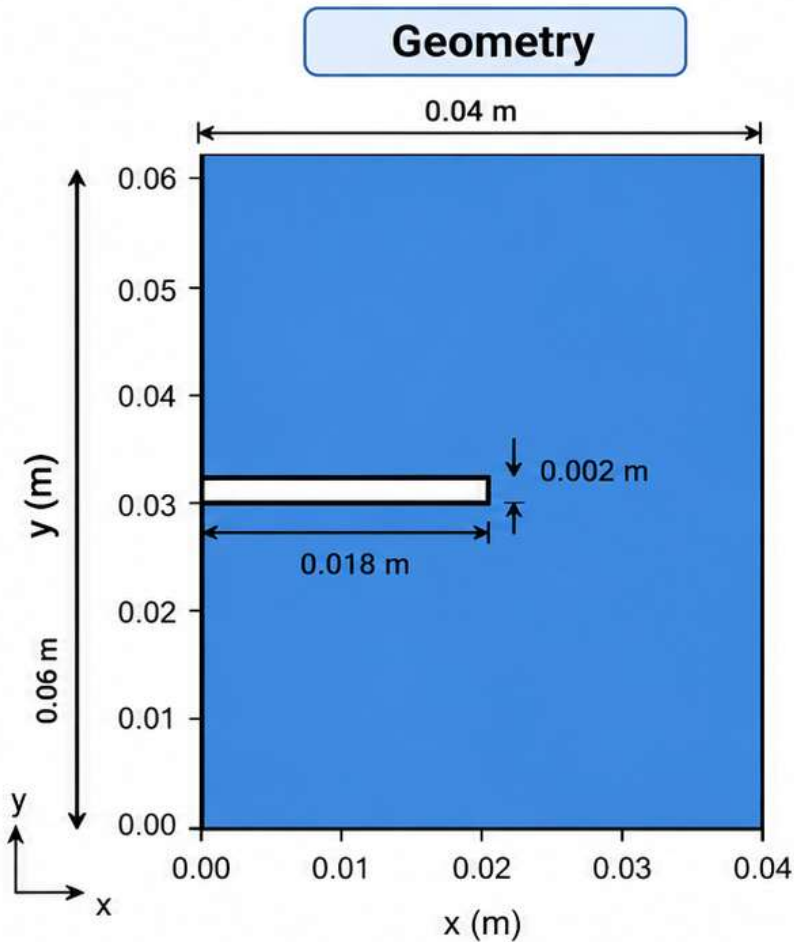


Figure 1: Schematic diagram of rectangular shape geometry with fin and PCM

A horizontal aluminum fin was attached to the right heated wall of the enclosure. The fin has a length of 40 mm and a thickness of 5 mm. The position of the fin was systematically varied to investigate its influence on the melting behavior of the PCM. The vertical distance between the lower surface of the fin and the bottom wall of the PCM enclosure is denoted by (d). A dimensionless fin-position parameter, (d_f), is used to characterize the location of the fin within the enclosure. In the present investigation, (d_f), was varied from 0.03 to 0.55 in order to examine the effect of fin location on the melting process. A constant wall temperature, (T_w), was prescribed at the right-hand heated boundary. The remaining three walls namely, the top, left, and bottom boundaries were treated as adiabatic surfaces. Thus, heat transfer to the PCM occurs primarily through the heated right wall and the attached aluminum fin.

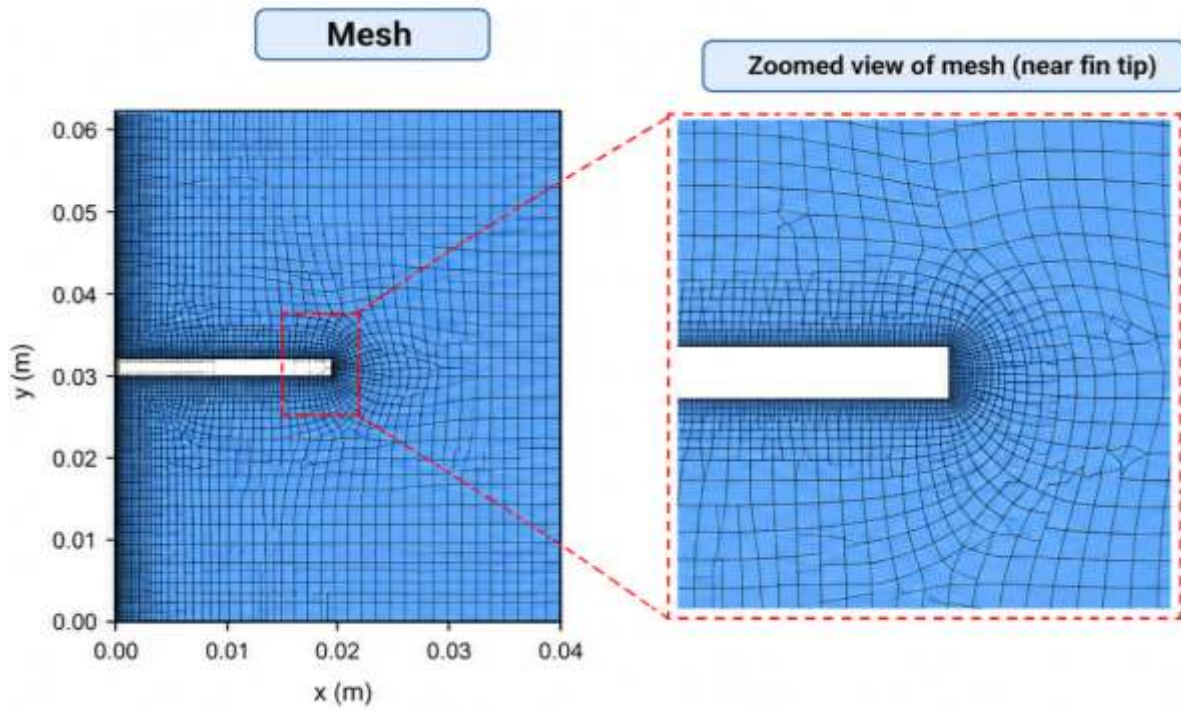


Figure 2 illustrates the computational configuration and the arrangement of the PCM enclosure and fin.

Lauric acid was selected as the PCM, while aluminum was used as the fin material. The thermophysical properties of the PCM used in the numerical simulations are presented in Table 1.

Table 1. Thermophysical properties of lauric acid

Property	Value
Melting temperature (°C)	48.2
Solidification temperature (°C)	43.5
Latent heat (kJ/kg)	187.21
Specific heat of solid (kJ/kg·K)	2.18
Specific heat of liquid (kJ/kg·K)	2.39
Density of solid (kg/m ³)	940
Density of liquid (kg/m ³)	885
Thermal conductivity of solid (W/m·K)	0.16
Thermal conductivity of liquid (W/m·K)	0.14
Thermal expansion coefficient (1/K)	0.0008

3. Mathematical Formulation

The transient melting process of the PCM was described using the governing conservation equations for mass, momentum, and energy. These equations account for the coupled effects of fluid motion, heat transfer, and phase transformation.

Mass Conservation

The continuity equation governing conservation of mass can be expressed as

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0 \quad (1)$$

where (ρ) represents the PCM density, (u) denotes the velocity component, (t) is time, and (x) represents the spatial coordinate.

Momentum Conservation

The momentum equation governing the fluid motion within the PCM can be written as

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial p}{\partial x} - \frac{\partial}{\partial x} \left[\mu \frac{\partial u}{\partial x} \right] - \rho g = S = 0 \quad (2)$$

where (p) is the pressure, (μ) is the dynamic viscosity, (g) denotes gravitational acceleration, and (S) represents the momentum sink associated with the mushy-zone treatment. The momentum sink term introduced through the enthalpy-porosity formulation restricts fluid movement in regions where the PCM remains predominantly solid. As the liquid fraction increases, the resistance decreases and fluid motion becomes progressively established.

Energy Conservation

The energy equation used to describe heat transfer and phase transformation within the PCM is given by

$$\frac{\partial(\rho H)}{\partial t} + \frac{\partial(\rho u H)}{\partial x} + \frac{\partial}{\partial x} \left[\lambda \frac{\partial T}{\partial x} \right] = 0 \quad (3)$$

where (H) is the total specific enthalpy, (λ) denotes thermal conductivity, and (T) represents temperature. The total enthalpy incorporates both the sensible and latent components of energy. Therefore, the energy absorbed during the solid-to-liquid transformation is included directly in the enthalpy formulation.

Heat Transfer Rate

The heat transfer rate can be estimated from

$$Q = \dot{m} c_p (\Delta T) f \quad (4)$$

Where (Q) is the heat transfer rate, ($\dot{m}$) is the mass flow rate, (c_p) represents the specific heat capacity, is the temperature difference, and (f) represents the relevant correction or fraction term. The average convective heat-transfer coefficient is subsequently obtained from

$$Nu = \frac{h D_h}{K} \quad (5)$$

Where (h) is the average heat-transfer coefficient and (A) represents the effective heat transfer area. Where (D_h) is the hydraulic diameter and (K) represents the thermal conductivity.

The Reynolds number is evaluated using.

$$Re = \frac{\rho u D_h}{\mu} \quad (6)$$

where (u) is the characteristic fluid velocity.

The hydraulic diameter is defined as

$$D_h = \frac{4A_{cr}}{P} \quad (7)$$

where (A_{cr}) is the cross-sectional flow area and (P) is the corresponding wetted perimeter.

3.1 Initial and Boundary Conditions

The initial and boundary conditions were specified according to the physical configuration of the PCM enclosure shown in Figure 2. The computational domain consists of a two-dimensional rectangular PCM region measuring 40 mm in width and 60 mm in height.

At the beginning of the simulation, i.e., at ($t=0$) s, the entire PCM is assumed to be at a uniform temperature of

$$T_i = 25^\circ C$$

and the initial velocity is set to $u=0$

Thus, the PCM is initially stationary and remains below its melting temperature. The top, left, and bottom walls of the enclosure are considered thermally insulated. Therefore, the heat flux through these boundaries is zero and can be expressed as

$$q = 0 \text{ W/m}^2$$

A constant temperature boundary condition is imposed on the right-hand wall, which acts as the primary heat source for the PCM. The temperature of the heated wall is maintained at

$$T_w = 70^\circ C$$

Consequently, heat is transferred from the right heated wall into the PCM, initiating the melting process. As the PCM temperature increases and reaches the melting range, the solid PCM progressively transforms into liquid. The resulting density variation in the molten region generates buoyancy forces, which establish natural convection and influence the subsequent evolution of the melting front. The complete numerical model therefore accounts for the interaction between heat conduction, latent heat absorption, phase transformation, and buoyancy-driven natural convection, while the different fin positions are used to evaluate their influence on the melting characteristics of the PCM.

4.Result and Discussions

4.1 Liquid Fraction Evolution During PCM Melting with a Mid-Height Single Fin

The transient behavior of the liquid fraction inside the PCM enclosure with a single fin at the mid position (0.50H) is shown in figure 3. Initially ($t = 0$ s), the PCM is solid state and has a liquid fraction near zero across the enclosure. Once the heating starts, the melting process begins next to the left wall that is being heated directly by the wall. After 30 s, a thin layer of the PCM is melted along the heated wall and most of the PCM is still solid. As time goes on, the melted zone grows larger and larger and at $t = 60$ s, an appreciable melted fraction is seen near the heated wall and around the fin, which indicates the augmentation that the fin provides to heat transfer. The melting interface is less and less uniform when the natural convection in the liquid PCM develops buoyancy-driven flow at $t = 90$ s. Because the liquid is heated as it climbs up the enclosure, the relative temperature of the liquid is lower as it passes down the enclosure, causing only a portion of the fin to melt. A significant amount of liquid is formed in the vicinity of the heated wall at $t = 120$ s with

the highest amounts of liquid in the upper and lower parts near the heated wall. The upward extension of the melted region in the molten section shows the effect of natural convection in this region, while the shape and motion of the melting front are affected by the effect of the fin on the local heat-transfer pathway and flow structure. Overall, the results show that the melting of the PCM is dominated by the interactions between the melting process and the heat conduction through the heated wall and fin, as well as by the buoyancy-induced natural convection, especially at the mid-height of the fin, which has a significant effect on the development of the liquid fraction during the transient melting process.

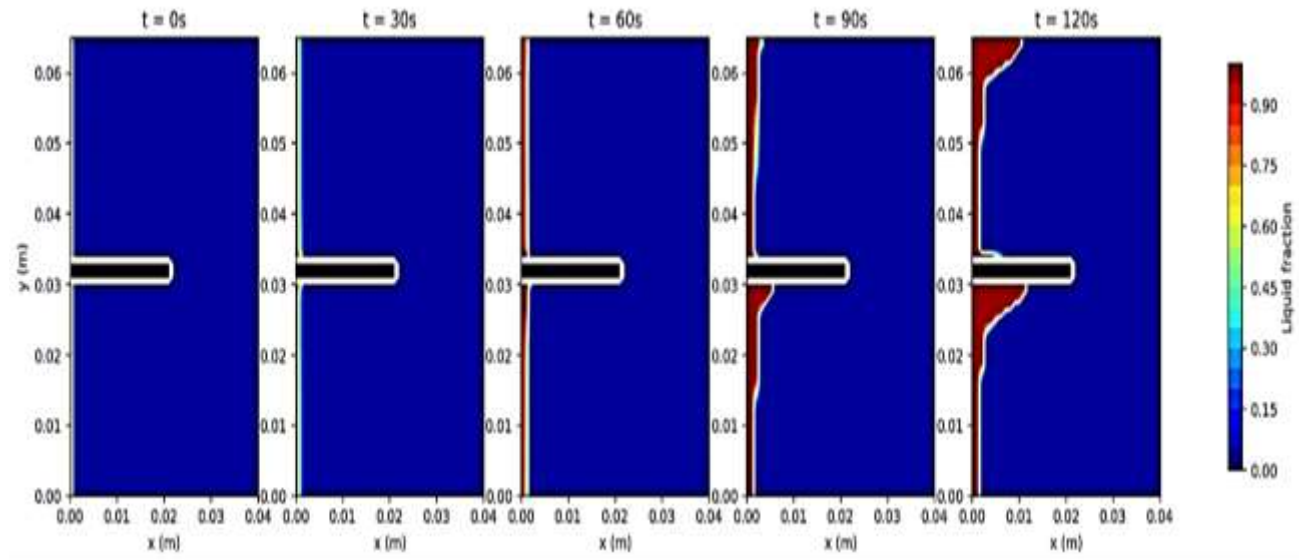


Figure 3. Transient liquid-fraction distribution during PCM melting for a single fin positioned at mid-height (0.50H) at different time intervals.

4.2 Transient Velocity Field and Natural Convection During PCM Melting with a Mid-Height Fin

To evaluate the transient velocity-field distribution in the PCM enclosure at the mid-height (0.50H) corresponding to evolution of the liquid-fraction, one of the fins is placed at the same location as shown in figure X. The velocity magnitude is very small at the beginning of the simulation, $t = 0$ s, due to the fact that the PCM is initially solid and there is no natural convection. The contours of the liquid-fraction show the formation of a thin liquid layer close to the heated wall at $t = 30$ s, allowing fluid motion to be initialised but with relatively small velocity magnitude. When t approaches 60 s, the melting process is underway up to a certain region and the region available for fluid motion increases, so that the weak buoyancy driven circulation starts to develop. The velocity field is more prominent above and below the mid-height fin in the areas of the melted PCM, as seen in the liquid-fraction contours, and is more prominent near the heated wall at $t = 90$ s. These density variations between the heated liquid and the relatively cooler liquid result in buoyancy forces, which drive natural-convection circulation in the liquid PCM. The velocity magnitude further increases at $t = 120$ s, the highest velocities are now mostly concentrated in the vicinity of the heated wall, and into the upper part of the enclosure. This is in line with the liquid-fraction distribution, where large melting in the vicinity of the heated wall is observed and the melting front is further advanced upward. The mid-height fin has a different flow regimes around it as it has an effect on the local flow field by blocking the flow of the fluid and also it introduces another conductive pathway into the PCM, which also affects the flow field. Therefore, the evolution of velocity field shows that natural convection is significant as the liquid fraction increases, further supporting the conduction-dominated heat transfer during the initial melting period, and its contribution to the gradual increase in melting velocity of PCM at later times.

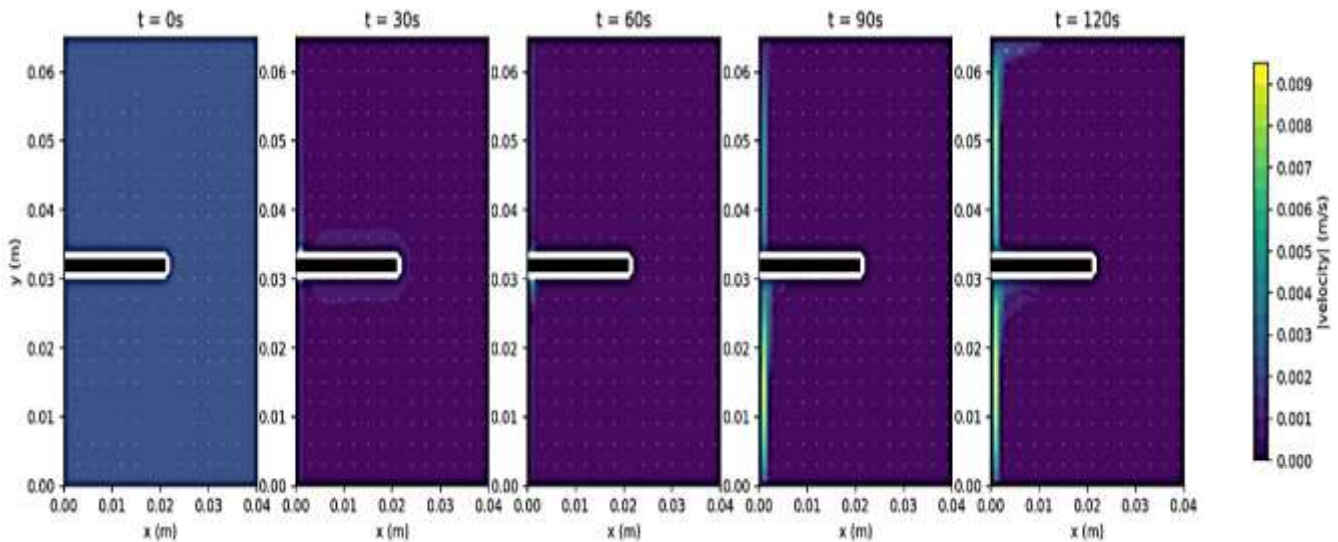


Figure 4: Transient velocity-field distribution during PCM melting for a single fin positioned at mid-height (0.50H).

4.3 Comparative Analysis of Liquid Fraction Evolution for Different Fin Configurations

The results of the transient evolution of the liquid fraction in the PCM enclosure for three different fin configurations (one fin at 0.50H, one fin at 0.25H and 0.30H, 0.70H) have been evaluated at $t = 0$ s, 30 s, 60 s, 90 s and 120 s and presented in figure X. The contour lines of the liquid-fraction range from 0 (solid PCM) to 1 (full liquid phase). All of the configurations start with a solid PCM with a very thin molten interface near the heated left wall, so heat transfer is initially driven by conduction. As time goes on, at $t = 30$ s melting is advancing along the heated wall, while the solid region of the PCM is still predominant, but the effect of fins can be seen and the liquid portion is not large enough to significantly affect the natural convection. The thickness of the liquid layer increases with time as the liquid penetrates further from the heated wall, and the positions of the fins start to create identifiable melting patterns as these act as additional conductive heat transfer paths. In the single fin configuration, at 0.50H, melting occurs around the central fin, while with 0.25H, the melting is mainly in the lower part of the enclosure. At 0.30H and 0.70H the two fins add extra heat transfer pathways at the vertical positions of the two fins, and therefore melting regions at both positions of the two fins. The melting fronts are not uniform and curved at $t = 90$ s, which shows the increasing importance of buoyancy driven natural convection in the liquid PCM. Circulation in the melted region, and thus heat transport, occurs due to the relatively cooler liquid moving down and the heated liquid moving up next to the wall. This is especially seen in the upward expansion of the liquid region. At $t = 120$ s, significant melting is observed in the region close to the heated wall in all configurations, and the farthest region of the PCM is mostly solid in all cases. There are severe melting below and above the single fin in the 0.50H configuration, and the natural convection causes the fin to extend upward. Single fin - 0.25H configuration: The lower fin changes the melting pattern in the lower part of the enclosure and the buoyancy induced flow carries heat upwards into the upper part. The two-fin configuration has two separate conductive heat-transfer pathways (at $H/0.30H$ and $H/0.70H$) and affects the melting fronts at different heights. Overall the results show the early stage being conduction dominated melting and the later stage being coupled conduction and buoyancy-driven natural convective melting. The distribution of the liquid fraction is greatly changed by the position and number of fins, both by changing the conductive heat-transfer pathway and by changing the natural-convection flow structure. Hence, the liquid fraction contours give further evidence that suitable placement of fins can redistribute thermal energy within the PCM and can affect the melting progress and uniformity, which is crucial in designing and optimising fin-assisted latent heat thermal energy storage systems.

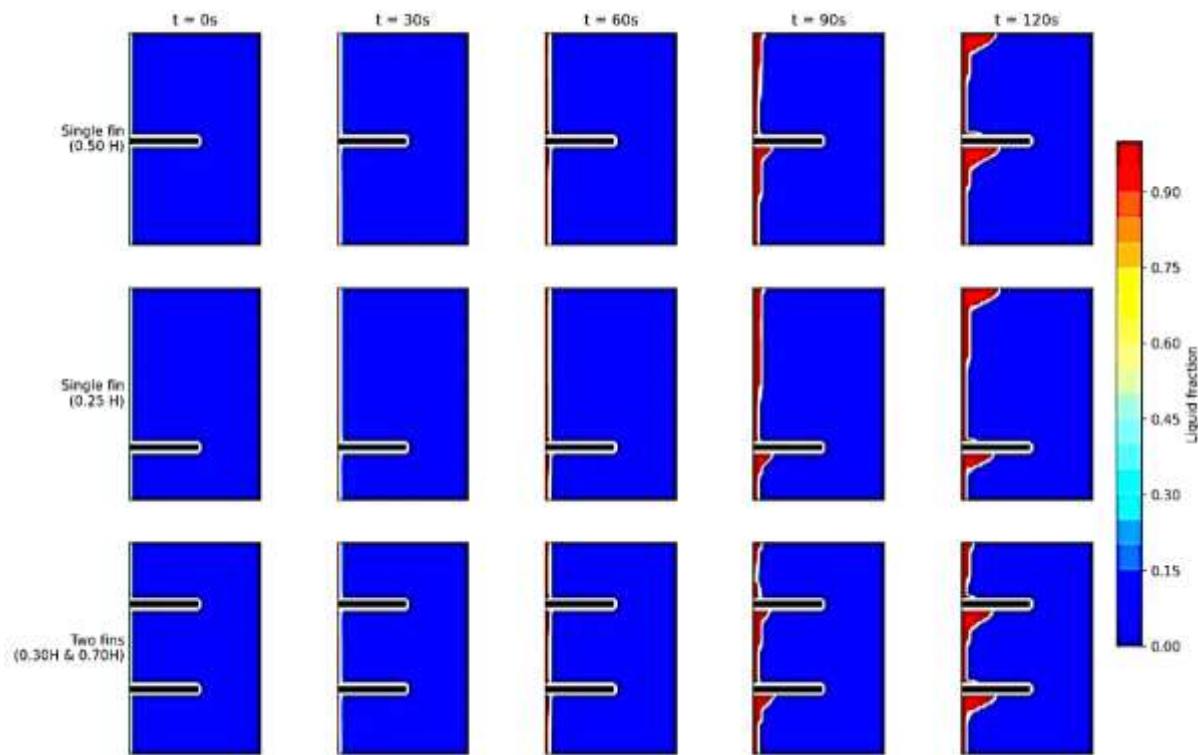


Figure 5: Comparative analysis of liquid fraction evolution for different fin configurations

5. Conclusion

The current numerical study focused on the influence of the location of the fin and the arrangement of the fins on the transient phase change characteristics of the phase change material (PCM) in a rectangular enclosure. The development of the liquid fraction and velocity field showed that the melting of PCM is initially conducted from the heated wall and as the liquid fraction grows, buoyancy-driven natural convection plays an increasing role. The contours of the liquid-fraction indicated that the melting started near the heated wall and gradually moved toward the bulk of the PCM as a function of time; and the melting front became more irregular as the natural-convection transport progressed. The velocity-field results also showed the development of buoyancy-induced circulation, where the heated liquid moving upwards along the heated wall, and relatively cooler liquid moving downwards enhancing heat transfer inside the melted region. The presence of the fins introduced an extra conductive pathway for heat transfer and changed the local convection pattern, leading to the formation of different melting features for the various fin configurations. A single fin at 0.50H caused a hot distribution above and below the fin, and led to a melting around the central region, while a single fin at 0.25H moved the heat transfer enhancement towards the lower part of the enclosure. The two fin configuration at 0.30H and 0.70H spread the enhancement in the conductive heat transfer over two vertical positions and thus modified the spatial evolution of the melting fronts. The comparison shows the fin location and number also has significant effect on the interaction of conduction and natural convection during PCM melting. The overall results illustrate that the proper placement of the fins can change the melting pattern, enhance thermal transport in the PCM, and eventually minimize the melting time by fins, which can serve as a guideline for the thermal design and optimization of fin-assisted latent heat thermal energy storage systems.

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