

Article

Influence of Fin Geometry on Enhancement of Phase Change Material Melting in a Finned Double-Pipe Heat Exchanger

Amr Owes Elsayed

Mechanical and Energy Engineering Department, College of Engineering, Imam Abdulrahman Bin Faisal University, Dammam P.O. Box 1982, Saudi Arabia; aowes@iau.edu.sa

Abstract

Low thermal conductivity of phase change materials (PCMs) remains a major limitation in the design of efficient thermal energy storage systems. Enhancing the thermal performance of PCM storage units is therefore a critical design consideration. Fin geometry plays a pivotal role in improving the heat charging and discharging rates by influencing heat transfer mechanisms, particularly natural convection during melting. This study presents a two-dimensional numerical investigation of novel fin geometries aimed at accelerating the melting process of PCM in a double-pipe heat exchanger. Four fin designs are examined: single-step thickness reduction, double-step thickness reduction, stepwise thickness reduction/expansion, and smooth thickness reduction fins. These configurations are specifically developed to promote natural convection currents in the molten PCM regions adjacent to the fin's surfaces. The enthalpy–porosity method is employed using ANSYS Fluent 19 to simulate the phase change process. The COUPLED algorithm is used for pressure–velocity coupling, with the PRESTO! scheme applied for pressure interpolation and a second-order upwind scheme adopted for the discretization of transport equations. The results demonstrate that the proposed thickness reduction fins significantly enhance the PCM melting rate by intensifying natural convection currents, driven by localized temperature gradients along the fin surfaces.

Keywords: influence of fin geometry; enhancement of PCM melting; double-pipe heat exchanger; numerical simulation of melting process



Academic Editor: Luca Molinaroli

Received: 18 July 2025

Revised: 6 August 2025

Accepted: 8 August 2025

Published: 15 August 2025

Citation: Elsayed, A.O. Influence of Fin Geometry on Enhancement of Phase Change Material Melting in a Finned Double-Pipe Heat Exchanger. *Energies* **2025**, *18*, 4355. <https://doi.org/10.3390/en18164355>

Copyright: © 2025 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Double-pipe heat exchanger is one of the most commonly utilized types of heat exchangers due to its structural simplicity, operational efficiency, and great number of engineering applications. For enhancing the thermal efficiency of double-pipe heat exchanger, longitudinal fins within the annular space are installed to increase the contact surface area. In recent years, the importance of thermal energy storage systems has significantly grown, emphasizing the energy sustainability target. The integration of phase change materials (PCM) within the annular gap of double-pipe heat exchangers has considerable attention from researchers (e.g., [1–3]). This approach improves the thermal efficiency of energy storage systems, through which enhancing the heat transfer rate is essential for reducing charging/discharging times and supporting the sustainable energy solutions.

Dukhana et al. [4] experimentally investigated the melting characteristics of phase change material within the annular space between an externally insulated cylinder and a heated inner pipe. The study focused on paraffin wax RT-42 contained in a horizontal, concentric double-pipe heat exchanger. They used the water as the heat transfer fluid

(HTF) at various inlet temperatures. Their findings showed that the melting time was significantly affected by the HTF temperature, with reductions in time by about 27% and 46% as the HTF temperature increased from 60 °C to 70 °C and from 60 °C to 80 °C, respectively. Motevali et al. [5] numerically analyzed the melting behavior of RT82 as a phase change material in double-tube heat exchangers. They employed a combination of nanoparticles with PCM to improve the phase change process. Their results indicated that at the beginning of melting, the heat conduction mechanism is recognized as the dominant phenomenon; with the progress of melting, the heat convection mechanism becomes the superior mechanism. Furthermore, the effective enhancement of PCM melting was achieved by using finned tubes and a simultaneous combination of nano-enhanced PCM and nano-heat transfer fluid. Paroutoglou et al. [6] performed a numerical investigation into the use of organic paraffin RT18, both in its pure and fiber-enhanced forms, as a phase change material encapsulated in the annular space in a latent heat thermal energy storage system with various geometric configurations. The study showed the influence of both external and internal fins by analyzing ten configurations of a double-tube heat exchanger and one single-tube latent heat energy storage system. The results demonstrated that the incorporation of fins significantly accelerated the melting process by 99.97% and the solidification by 31.12%, compared to the configuration without fins for the same external pipe diameter. Şimşek [7] investigated the effect of inner pipe material on the melting characteristics of phase change materials placed in the annular gap of a double-pipe heat exchanger. Two different salt hydrates, calcium chloride hexahydrate ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$) and sodium sulfate decahydrate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), were employed as PCMs. It was observed that using copper and aluminum inner pipes led to significant melting time reductions for $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$: 19.2% and 17.8%, respectively. This significantly showed the impact of both PCM type and thermal conductivity of pipe material on the melting efficiency.

Fin geometry is a critical and important factor in enhancing heat transfer and, consequently, improving the phase change process. As a result, many researchers have focused on studying the effect of fin geometry on the melting and solidification behaviors of phase change materials (e.g., [8–10]). Al-Mudhafar et al. [11] conducted a numerical investigation for enhancing the thermal performance of phase change materials (PCMs) within a shell-and-tube heat exchanger. The study offered the use of T-shaped fins as an innovative geometry to accelerate the PCM melting process. A comparison was made with the traditional longitudinal fins to evaluate the thermal performance of T-shaped fins. The results showed that the melting time of the PCM was reduced by approximately 33% when using T-shaped fins, compared to utilizing the longitudinal fins. Fang et al. [12] conducted a numerical investigation to examine the heat transfer characteristics of a shell-and-tube phase change heat exchanger filled with paraffin wax (RT50). The shell had a rectangular cross-section with side lengths of 50 × 50 mm and enclosed a concentric inner tube with an outer diameter of 14 mm. Two fin configurations were analyzed: longitudinal straight fins and annular fins spaced 17 mm apart, both with a fin length of 9 mm. The results indicated that, in the straight-fin configuration, natural convection was significantly enhanced during the melting process, which primarily governed the total melting duration. In contrast, by using the annular fins, the conduction in the initial melting period was improved. However, the annular fins had a limited effect on enhancing the natural convection. The study concluded that the straight-fin design reduced the total melting time by 42.1%, compared to the finless configuration, due to the combined enhancement of both heat conduction and natural convection. Mao et al. [13] offered a numerical investigation on the heat transfer performance of paraffin melting and the structural optimization of a fan-shaped finned-tube heat exchanger. The system consists of two vertical cylinders, each with a height of 350 mm. The outer shell, made of acrylic, has a diameter of 200 mm,

while the heat exchange tube is made of copper, with an inner diameter of 25 mm and a wall thickness of 2 mm. Five longitudinal fan-shaped fins are symmetrically arranged around the inner copper tube with an adjacent angle of 36° . Each fin has a height of 350 mm and a length of 51.3 mm, with a thickness of 1 mm. The results indicated that the PCM adjacent to the fins exhibited a significantly higher local melting fraction, regardless of fin shape. The melting rate was consistently greater near the fins, compared to regions farther away, confirming the fins' effectiveness in accelerating the melting process. Moreover, the presence of localized eddy currents and natural convection led to an uneven melting front, resulting in a characteristic wave-like profile during the phase change process. A comprehensive review on heat transfer enhancement of phase change materials using finned-tube designs was presented by Fei Ma et al. [14]. The article evaluated and compared various fin configurations, including rectangular, annular, and spiral fins, to show the influence of geometry on the thermal performance of the exchanger. The study concluded that rectangular fins show better thermal performance than annular fins, while complex fin geometries tend to offer superior heat transfer performance compared to conventional rectangular fins. Moreover, it was observed that increasing the number and length of fins significantly reduces the phase change duration time. The review also highlighted that the integration of nanoparticles offers further enhancement of PCM thermal conductivity, which leads to the improvement of heat transfer performance. Zhang et al. [15] proposed a novel enhancement strategy for the solidification performance of phase change materials in a triplex tube heat exchanger by integrating branch-structured fins combined with Al_2O_3 nanoparticles. A two-dimensional computational fluid dynamics model was developed for simulating the thermal conduction and natural convection of liquid PCM supported with Brownian motion of nanoparticles. The simulation results indicated that solidification time is reduced by 8.5%, 9.3%, and 10.3% for nanoparticle volume fractions of 2%, 5%, and 8%, respectively, compared to a base case without enhancements. Zaib et al. [16] numerically investigated the heat transfer enhancement techniques for the melting and solidification of phase change material using external and combined internal–external fins in both duplex and triplex tube heat exchangers. Four configurations were analyzed: two involving duplex tube arrangements and two involving triplex tube systems. In each case, two fin geometries were offered as Y-shaped fins and λ -shaped fins. The results revealed that increasing the number of fins and utilizing a double-sided heat transfer fluid supply significantly accelerated the melting process. In the duplex tube configuration, the Y-shaped fins demonstrated a superior thermal performance by reducing the melting time by 48.76%, compared to the λ -shaped fin configuration. Recently, Waqas et al. [17] explored the effectiveness of novel eccentric and concentric arc fin geometries combined with traditional fins to enhance PCM melting. The study also evaluated the role of nanoparticles such as aluminum oxide (Al_2O_3) and multi-walled carbon nanotubes, dispersed within a molten salt-based PCM. The results demonstrated that the combined use of advanced-configuration fins and nanoparticles yielded a melting time reduction of up to 87.03% over baseline designs.

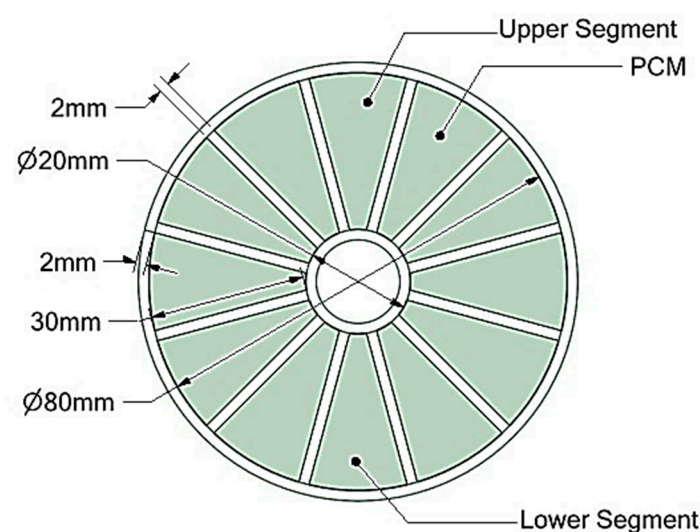
While many fin geometries have been investigated in literature, seeking more effective designs for enhancing phase change heat transfer remains an active area of research. The current study proposes a simple yet innovative fin configuration aimed at accelerating the natural convection currents within the molten region adjacent to the fin surfaces. A numerical analysis is carried out under thermal boundary conditions, with a constant temperature difference maintained between the outer hot pipe and the inner cold pipe in a double-pipe heat exchanger. ANSYS Fluent is employed to simulate the phase change process, due to its extensive capabilities in handling complex and sophisticated numerical analyses. ANSYS Fluent software utilizes a robust Finite Volume Method solver, which is particularly well-suited for simulations involving phase change materials, multi-physics

coupling, and conjugate heat transfer. It has a reliable solver framework that helps to minimize convergence risk and stability issues. It is well-established in literature (e.g., Ref. [18]) that ANSYS Fluent is one of the most widely adopted CFD platforms for simulating melting and solidification of PCMs. Its built-in melting/solidification model, based on the enthalpy–porosity method, has been extensively validated against experimental data and is known for its robustness in handling natural convection-dominated melting phenomena.

The main objective of this study is to improve the melting efficiency of the phase change material through geometric optimization of the fin structure. Four fin configurations are investigated in this study; the chosen geometries include simple, straight fins with a step reduction in thickness. Straight longitudinal fins are widely used in heat exchanger applications due to their ease of fabrication and predictable heat transfer enhancement. By comparing these four configurations under identical boundary conditions, the study provides a comprehensive evaluation of how fin geometry influences melting rates, temperature gradients, and natural convection patterns in the PCM domain.

2. Physical Model

The system under investigation is a finned double-pipe heat exchanger, in which the annular gap is divided into 12 segments by longitudinal fins. Each segment is filled with phase change material, and the volume of these segments remains constant across different fin configurations (segment face area equals 332.5 mm^2). The depth of the annular gap, corresponding to the fin length, is 30 mm. The outer pipe is maintained at a constant wall temperature of 65°C , while the inner pipe is held at 48°C . The detailed dimensions of the double-pipe heat exchanger are illustrated in Figure 1.



Outer diameter of inner pipe = 20 mm

Inner diameter of outer pipe = 80 mm

Pipe thickness = 2 mm

Fin length = 30 mm

Uniform fin thickness = 2 mm

Annular gap depth = 30 mm

Segment face area = 332.5 mm^2 (constant for various fin geometries)

Figure 1. Detailed double-pipe heat exchanger.

Four fin geometries, incorporating both stepped and smooth thickness variations, are investigated to enhance heat transfer within the segments of the heat exchanger. The first geometry features a single-step reduction in thickness located at the midpoint of the fin, transitioning from 3 mm to 1 mm. The second geometry includes two stepwise reductions along the fin length: the first occurs at one-third of the fin length (from 3 mm to 2 mm) and the second at two-thirds of the length (from 2 mm to 1 mm), both measured from the outer pipe. The third geometry also involves two thickness transitions: a reduction from 2.5 mm to 1 mm at one-third of the fin length, followed by an expansion from 1 mm to 2.5 mm at two-thirds of the length, again measured from the outer pipe. The fourth geometry consists of a smooth, continuous reduction in fin thickness, decreasing from 3 mm at the outer pipe to 1 mm at the inner pipe. These configurations are illustrated in Figure 2.

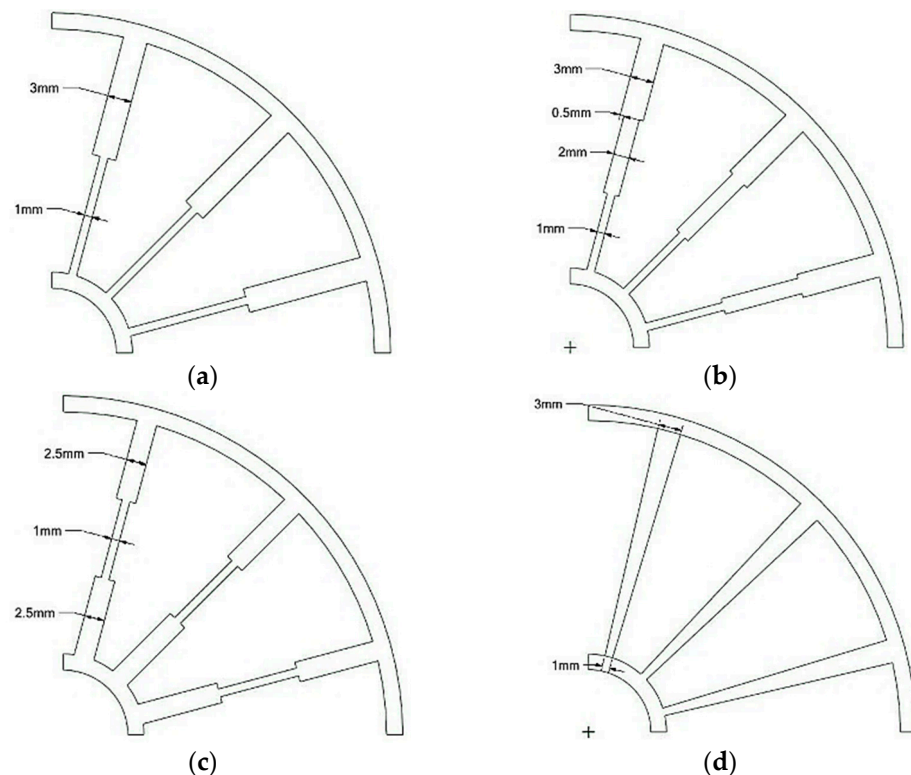


Figure 2. Different configurations of fin geometries. (a) Single-step thickness reduction fin; (b) smooth thickness reduction fin; (c) step thickness reduction/expansion fin; (d) smooth thickness reduction fin.

3. Mathematical Model

ANSYS Fluent is employed to simulate the phase change process. In this approach, the mushy region is treated as a pseudo-porous medium. The liquid fraction of each computational cell (f) is updated at each iteration. As melting progresses, the porosity of the cell increases from 0 to 1 (fully liquid).

The liquid fraction (f) can be defined as follows:

$$f = \begin{cases} 0 & T < T_{Solidus} \\ 1 & T \geq T_{Liquidus} \\ \frac{T - T_{Solidus}}{T_{Liquidus} - T_{Solidus}} & T_{Solidus} < T < T_{Liquidus} \end{cases} \quad (1)$$

where

$T_{Solidus}$ and $T_{Liquidus}$ are solid and liquid phase change temperatures, respectively.

In the enthalpy method, the total enthalpy of phase change material (H) is calculated as the sum of the sensible enthalpy (h) and latent heat content (ΔH). The latent heat component is treated as a source term in the energy equation to account for the energy absorbed or released during the phase change process. The latent heat content (ΔH) in each computational cell could be expressed in terms of the material's latent heat of fusion (L) as follows:

$$\Delta H = fL \quad (2)$$

where

f = the liquid fraction. This formulation allows the energy equation to accommodate both sensible heat transfer and the latent heat effects associated with phase change.

The relationship between temperature and total enthalpy of phase change material can be described as follows [19]:

$$(T) = \begin{cases} c_s T & T \leq T_{Solidus} \\ c_s T_{Solidus} + fL & T_{Solidus} < T < T_{Liquidus} \\ c_s T_{Solidus} + L + c_l (T - T_{Liquidus}) & T \geq T_{Liquidus} \end{cases} \quad (3)$$

The energy equation can be written as follows:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho \vec{V} h) = \nabla \cdot (k \nabla T) + S_{\Delta H} \quad (4)$$

where

$\vec{V}$ = fluid velocity;

$S_{\Delta H}$ = source term.

The source term can be expressed as follows:

$$S_{\Delta H} = \frac{\partial(\rho \Delta H)}{\partial t} + \nabla \cdot (\rho \vec{V} \Delta H) \quad (5)$$

In the melt region, the conservation of mass and momentum can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (6)$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho \vec{V} u) = - \frac{\partial p}{\partial x} + \mu \nabla^2 u + S_u \quad (7)$$

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho \vec{V} v) = - \frac{\partial p}{\partial y} + \mu \nabla^2 v + S_v \quad (8)$$

S_u and S_v are source terms and are defined as follows:

$$S_u = \frac{(1-f)^2}{f^3 + \epsilon} A_{mush} u \quad (9)$$

$$S_v = \frac{(1-f)^2}{f^3 + \epsilon} A_{mush} v + \rho g \beta (T - T_m) \quad (10)$$

where

ϵ = a small number (0.001) to prevent division by zero;

A_{mush} = the mushy zone constant (10^5).

In this study, Boussinesq approximation is employed to account for natural convection effects within the molten regions of the PCM. This assumption allows density variations

to be considered only in the buoyancy term of the momentum equation, through which the treatment of convection-driven flow can be simplified. In this work, the temperature difference between the hot wall (65 °C) and the PCM melting point (48 °C) is 17 °C, which is within the commonly accepted range (typically less than 20–30 °C [20]) for applying the Boussinesq approximation in liquid-phase flow simulations. Further details regarding the mathematical formulation of the model can be found in Ref. [21].

Commercial paraffin wax is used as a PCM, with a melting temperature range of 48–50 °C. For simplicity, the thermophysical properties of the PCM [22] are assumed to be constant throughout the simulation. At the initial time ($t = 0$), the temperatures of both the PCM and the cylinder walls are assumed to be uniform and equal to the solidus temperature of the material.

4. Numerical Method and Validation

4.1. Numerical Simulations

The numerical simulations for all investigated cases were performed using ANSYS Fluent 19. A transient, two-dimensional model was employed to simulate the phase change process occurring within the finned double-pipe heat exchanger. The governing equations were solved using a pressure-based solver, with the COUPLED algorithm applied for pressure–velocity coupling. The PRESTO! scheme was used for pressure interpolation at control volume faces, while a second-order upwind scheme was adopted for the discretization of all transport variables.

The convergence criteria for continuity, momentum, and energy equations were set to a residual $\leq 10^{-6}$. A high-resolution mesh was used to accurately simulate the thermal and flow fields for the various fin geometries.

A comprehensive mesh sensitivity analysis was conducted using three different grid resolutions: first (27,650 elements), medium (31,920 elements), and fine (34,250 elements). The corresponding melt volume fractions at a selected time instant were found to be 0.282, 0.2845, and 0.2847, respectively. The difference in melt fraction between the medium and fine meshes was less than 0.1%, indicating that further mesh refinement has a negligible effect on the simulation results. Therefore, the medium mesh was selected for all subsequent simulations, providing a balanced compromise between computational accuracy and efficiency. In addition, a time step independence study was performed using time steps of 0.1 s, 0.05 s, and 0.025 s. The results revealed that the change in melt fraction between 0.05 s and 0.025 s was less than 0.024%, thereby confirming that the numerical solution is temporally converged. Based on this, a time step of 0.05 s was adopted for all simulations.

4.2. Initial and Boundary Conditions

The initial temperature of PCM was set uniformly to 48 °C, corresponding to the solidus temperature. This ensured that the PCM was entirely in the solid phase at the start of the simulation. For the thermal boundary conditions, the outer pipe wall was maintained at a constant temperature of 65 °C to provide the heat input driving the melting process. The inner pipe wall was held at a constant temperature of 48 °C throughout the simulation, matching the initial PCM temperature. All other surfaces were assumed to be adiabatic, with no heat losses to the surroundings.

Regarding flow conditions, the PCM domain was treated as initially stationary. Natural convection effects during melting were captured through the enthalpy–porosity method. No-slip boundary conditions were applied along all solid surfaces in contact with the PCM.

4.3. Validation of the Numerical Model

To validate the present numerical model, a λ -shaped fin configuration within a double-pipe heat exchanger was selected for comparison with the results reported by Zaib et al. [16]. The annular space between the inner copper tube and the outer steel shell was filled with stearic acid as a PCM. The inner pipe wall was maintained at a constant temperature of 358 K (isothermal boundary), while the outer shell was treated as adiabatic. The PCM was initially at a uniform temperature of 300 K. As shown in Figure 3, the simulation results from the current study closely match with those reported in Ref. [16], with the deviation in the melt volume fraction within about 5%. This good agreement confirms the accuracy and reliability of the developed numerical model. The discrepancy in the melt volume fraction may be attributed to the value of the mushy zone constant (typically ranging from 10^4 to 10^7) used in the enthalpy–porosity method. This parameter significantly influences the damping of the velocity field in partially melted regions, thereby affecting the accuracy of the predicted melting front and melt fraction distribution. To further validate and enhance confidence in the robustness of the numerical model, a comparison between mushy zone constants 10^5 and 10^6 was conducted. The model showed best agreement with the reported results in Ref. [16] when using a mushy constant of 10^6 , as shown in Figure 3.

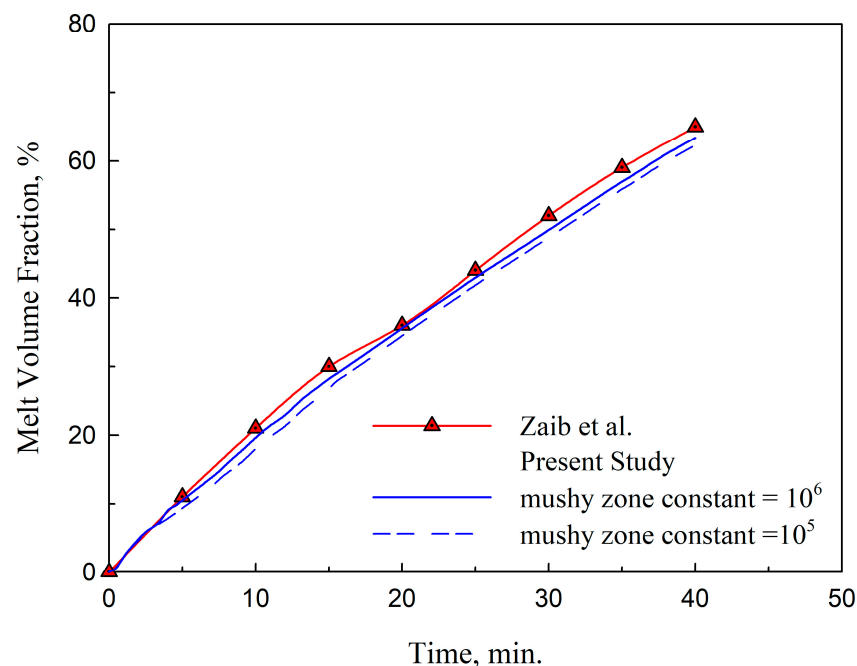


Figure 3. Variation of melt volume fraction with time for numerical validation [16].

5. Results and Discussion

5.1. Mechanism of PCM Melting in Various Segments of Heat Exchanger

The melting behavior of PCM in different segments of the heat exchanger can be detected through the temperature and melt volume fraction contours shown in Figure 4. At the beginning of the heat charging process (30 s), the molten region is approximately the same across all segments, since the heat transfer from the outer hot pipe is primarily governed by the conduction mechanism. As the time increases, the molten region expands more significantly in the lower segment and at the corners of the middle segment, compared to the upper segment. This is due to the natural convection currents that develop in the thicker molten layers.

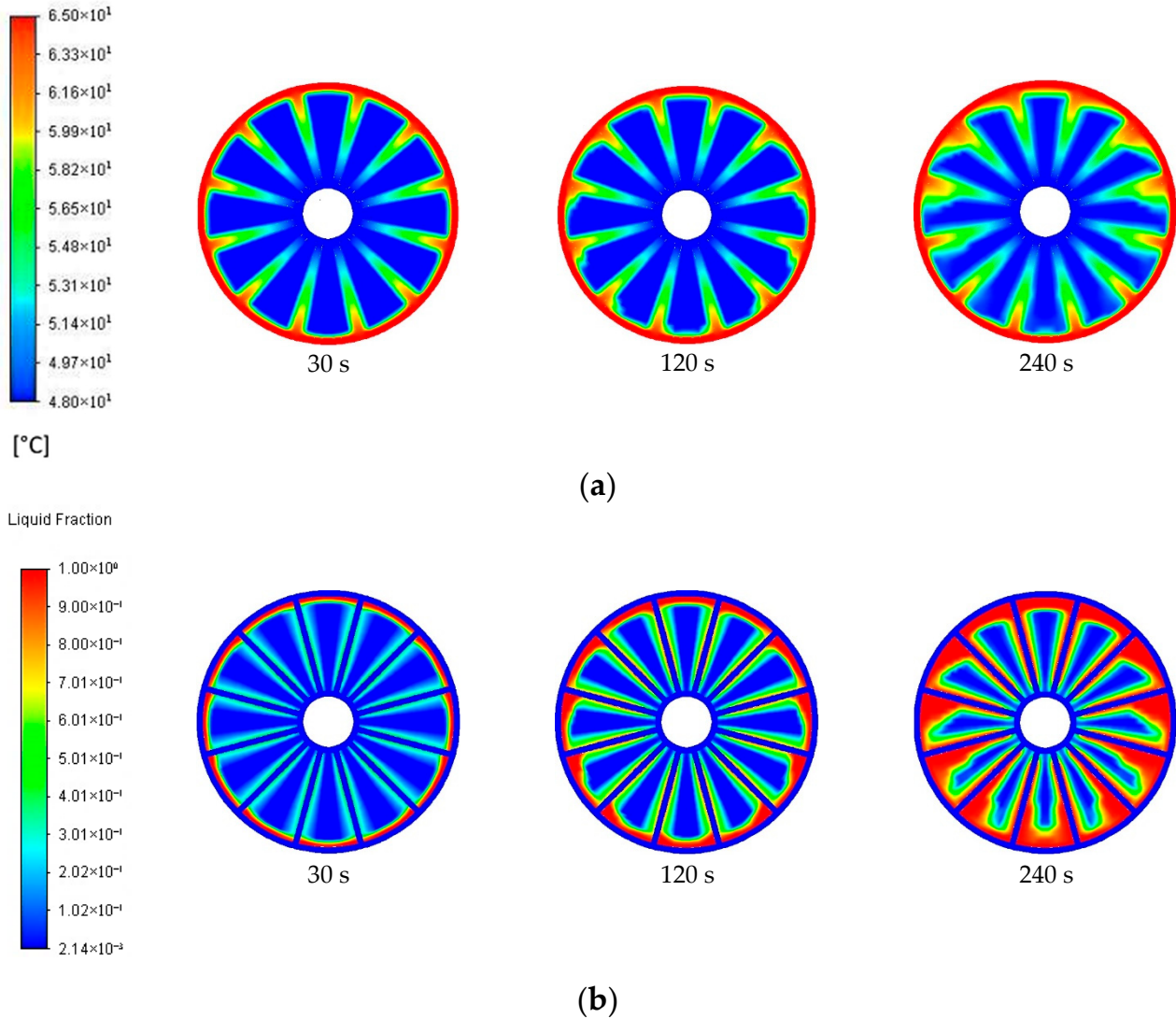


Figure 4. Melting behavior of PCM in a double-pipe heat exchanger with uniform-thickness fins. (a) Temperature contour lines. (b) Melt volume fraction contours.

The progress of PCM melt volume fraction over time in upper, middle, and lower segments is presented in Figure 5. The complete melting of PCM occurs at approximately 420 s in the lower segment and 500 s in the middle segment, while 12% of the PCM remains solid in the upper segment after 700 s of heat charging. This highlights the influence of free convection currents within the melt layer.

Figure 6 illustrates the velocity vectors in the melt layers across different heat exchanger segments. This figure reveals two convection vortices in the lower segment and one vortex at the corner of the middle segment, which enhance the melting rate in these regions due to the buoyancy force effect. In the upper segment, the free convection current appears weak in the molten zone.

Figure 7 presents the total melt volume fraction across all segments. The melting rate of solid PCM follows a consistent slope until 450 s, after which the slope decreases, indicating a reduction in melting rate at the upper segments where convection currents are weak in the molten zones. Approximately 3% of the solid phase remains un-melted in the upper segments, as illustrated in Figure 7b.

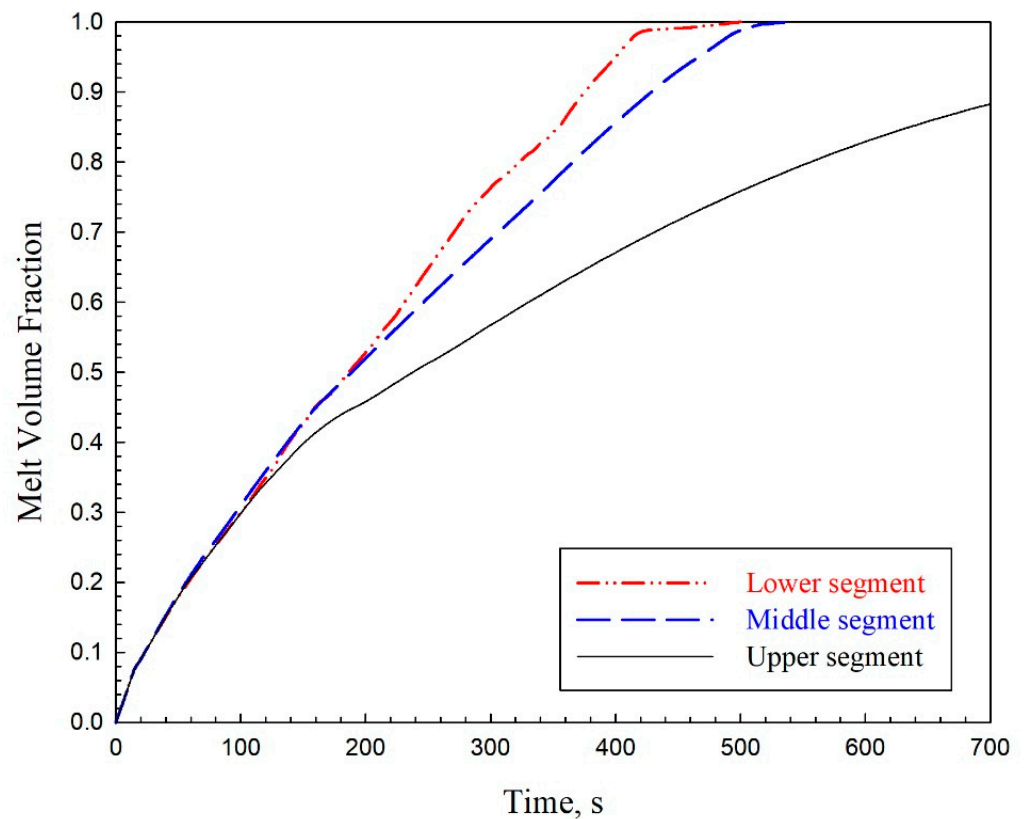


Figure 5. Melt volume fraction over the time in upper, middle, and lower segments.

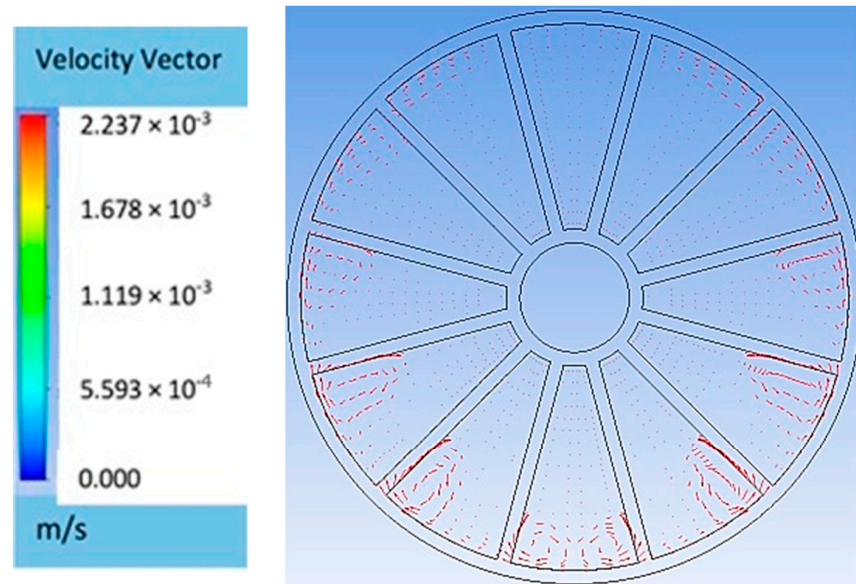


Figure 6. Velocity vectors in the melt layers at various heat exchanger segments.

5.2. Enhancement of Melting Rate Through Sudden Step Reduction in Fin Thickness

As previously mentioned, three geometries of fins with stepped thickness reductions were investigated to enhance the heat transfer and improve the melting rate within the segments of a heat exchanger. The first geometry is a single-step reduction in thickness located at the midpoint of the fin. The second geometry includes two-step reductions along the fin length. The third geometry also includes two steps of thickness change, which represent reduction/expansion of the thickness along the fin length. All of these

configurations maintain the same volume of PCM within each segment to ensure a fair comparison. Figure 8 illustrates the temperature variation along the fin length for different fin geometries. As shown in Figure 8, a sudden reduction in fin thickness extends the high-temperature region along the fin length, despite having the same temperature difference between the inner and outer pipes. This effect is more clearly demonstrated in Figure 9, which shows the detailed temperature distribution along the fin length. At a distance of 10 mm from the hot pipe, the temperatures of fins with a sudden thickness reduction increased by approximately 5% (a 3 °C rise), compared to the fin with uniform thickness. At the midpoint of the fin length, the fin with a single-step reduction reached a temperature 4 °C higher (a 7% increase), while the fin with a two-step reduction showed a 3.25 °C increase, compared to the uniform-thickness fin. These two fin geometries showed a higher temperature rise along the fin length.

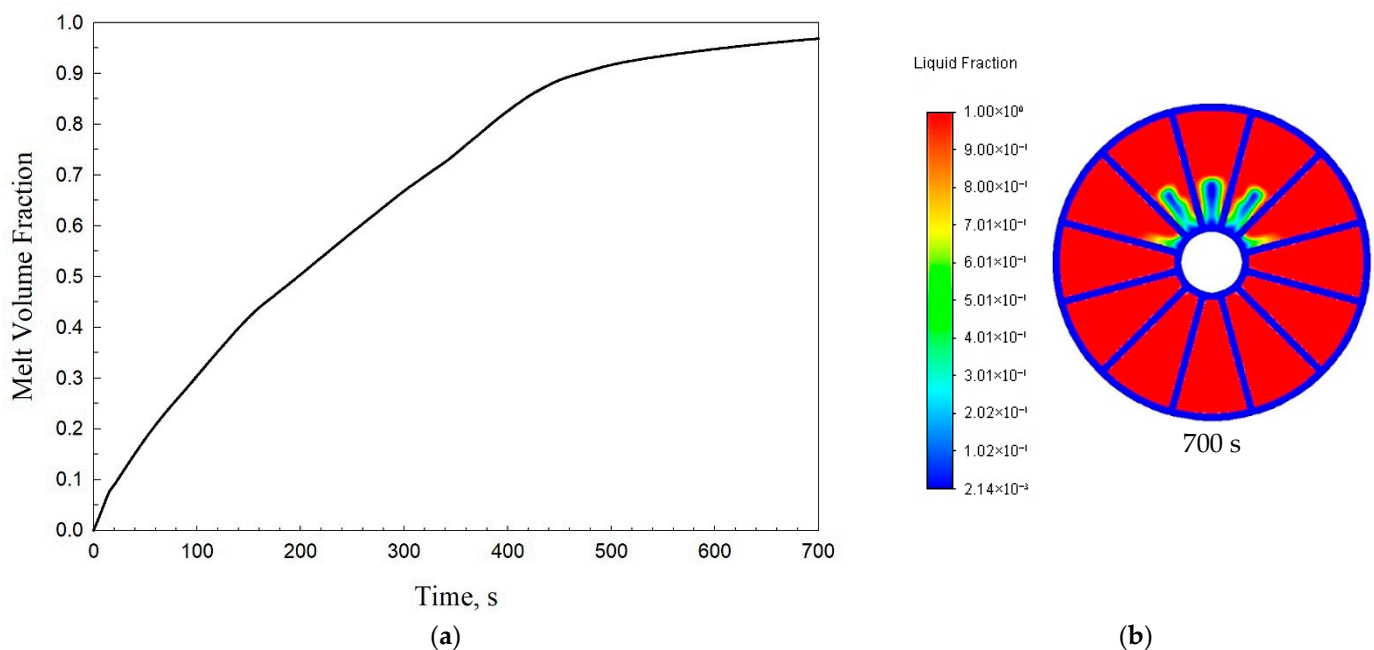


Figure 7. Total melt volume fraction across all segments. (a) Variation of melt volume fraction with time. (b) Melt volume fraction contours.

This is due to the increased thermal resistance in the thinner sections, which leads to obstruction of heat flow and the rising of temperature. However, in the case of the reduction/expansion fin geometry, at a distance of 16 mm from the hot pipe, the temperature trend reverses. The fin temperature becomes lower than that of the uniform-thickness fin due to the increase in thickness, which facilitates greater heat flow. It is important to highlight that the increase in fin temperature enhances natural convection currents within the melted layers of PCM, thereby accelerating the overall melting process. This phenomenon is depicted in Figure 10, which presents the melt volume fraction for various fin geometries after 300 s of heat charging. It is evident that a greater melt volume is achieved, with fins featuring stepped thickness reduction, attributed to the enhanced convection currents at the fin edges, since the temperature is relatively high.

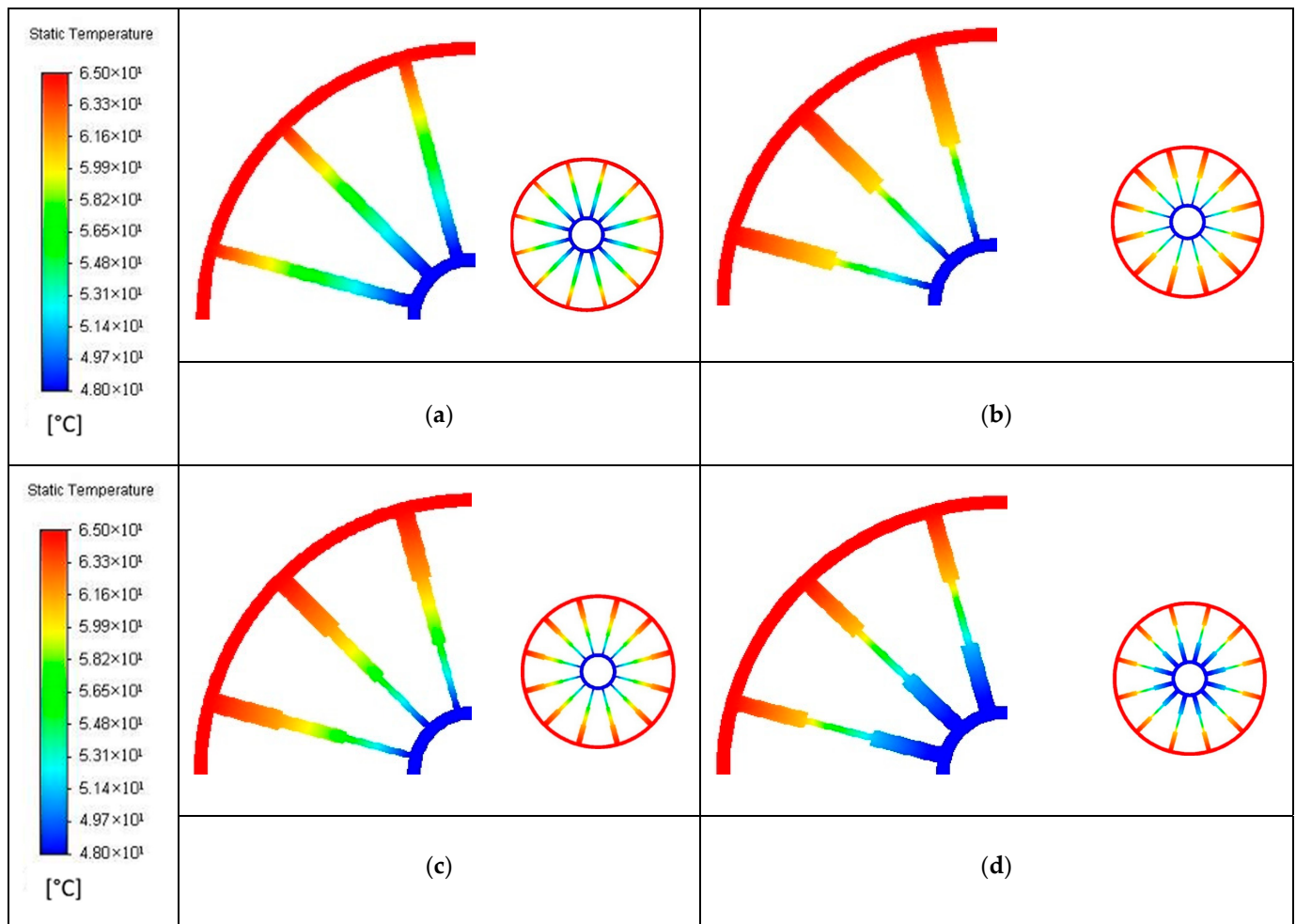


Figure 8. Temperature contours for various fin geometries. (a) Uniform-thickness fin. (b) Single-step thickness reduction fin. (c) Double-step thickness reduction fin. (d) Step reduction/expansion fin.

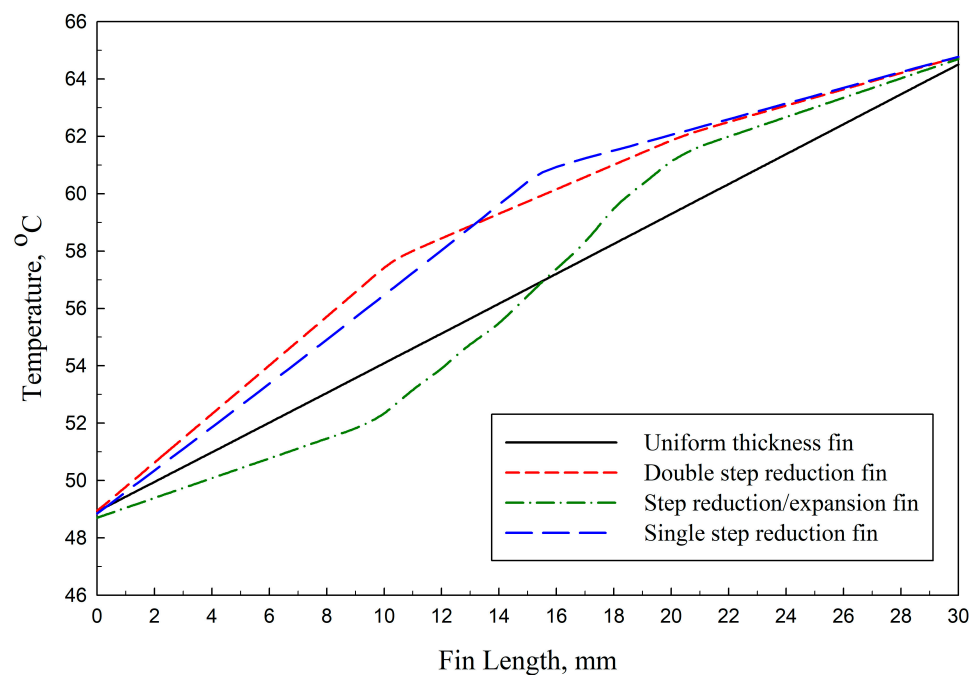


Figure 9. Temperature distribution along the fin length for various geometries.

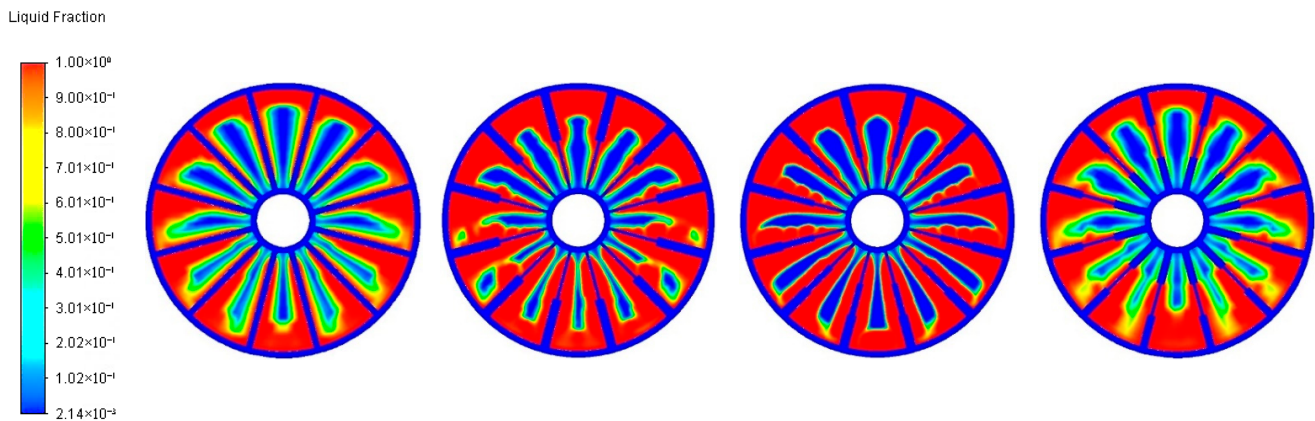


Figure 10. Melt volume fraction contour lines at 300 s of heat charging.

Further details regarding the total melt volume fraction throughout the heat charging period are presented in Figure 11. It is observed that fins with single- and double-thickness reductions exhibit higher melting rates, compared to the other configurations. Specifically, the single-thickness reduction fin achieves approximately a 12% higher melting rate relative to the uniform-thickness fin, while the double-thickness reduction fin demonstrates an improvement of about 9% over the uniform-thickness configuration. Moreover, it is observed that the step reduction/expansion fin exhibits a melting rate performance approximately comparable to that of the uniform-thickness fin. After 450 s of heat charging, most of the solid PCM in the lower and middle segments is melted, while a significant amount of solid PCM remains in the upper three segments. Consequently, the melting rate decreases due to the weakening of convection currents.

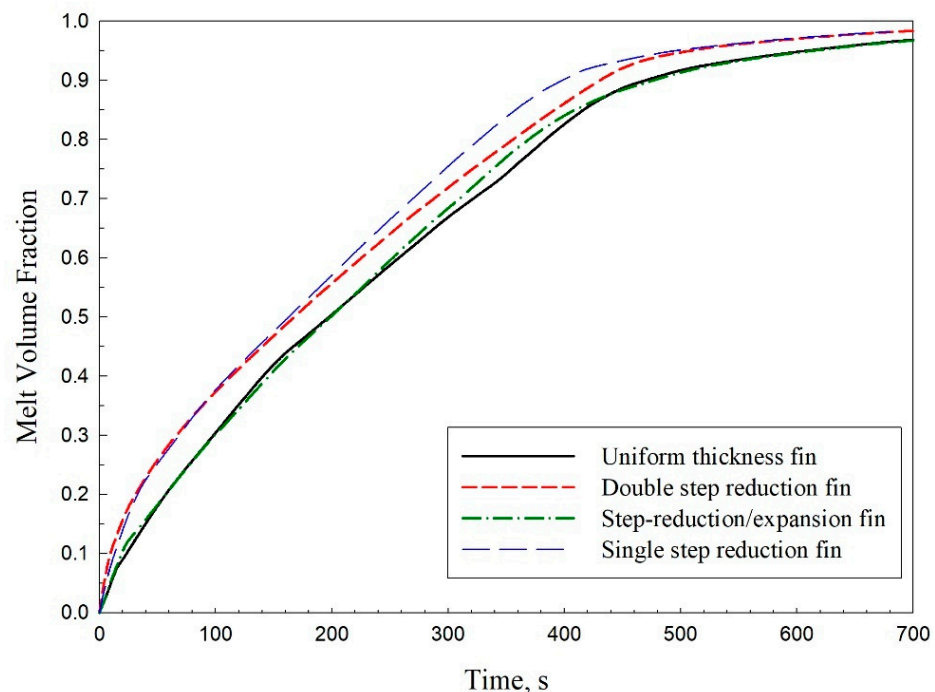


Figure 11. Total melt volume fraction for various fin geometries.

To further investigate the melting behavior in the upper region, Figure 12 illustrates the melting rate in the upper segment for various fin geometries. As observed, fins with single- and double-thickness reductions exhibit improvements in the melting rate by approximately 16% and 12%, respectively, compared to the other geometries.

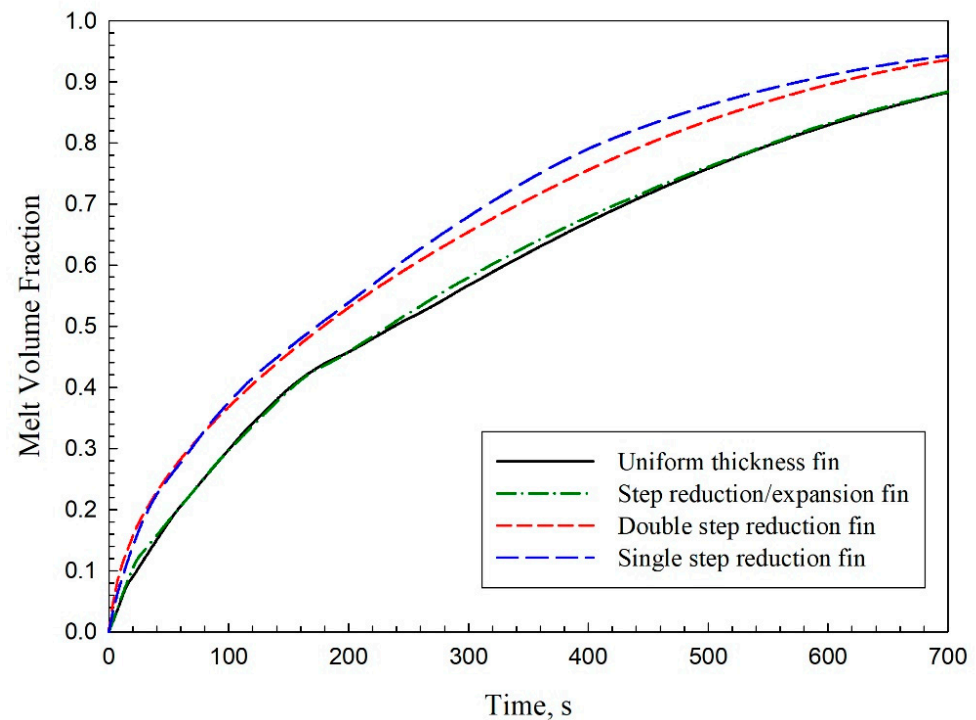


Figure 12. Melt volume fraction at the upper segment for various fin geometries.

5.3. Comparison of Influence of Smooth and Stepwise Fin Thickness Reduction on the Melting Rate

The study is extended to investigate the effects of smooth and stepwise fin thickness reductions on the melting rate. Figure 13 presents the temperature distribution along the fin length for fins with single-thickness reduction, smooth thickness reduction, and uniform thickness. As shown in the figure, heat propagation along the single-reduction fin is more pronounced than that along the smooth reduction fin, extending from the hot pipe to approximately the midpoint of the fin. Beyond this point, the temperature along the single-reduction fin decreases toward the inner pipe.

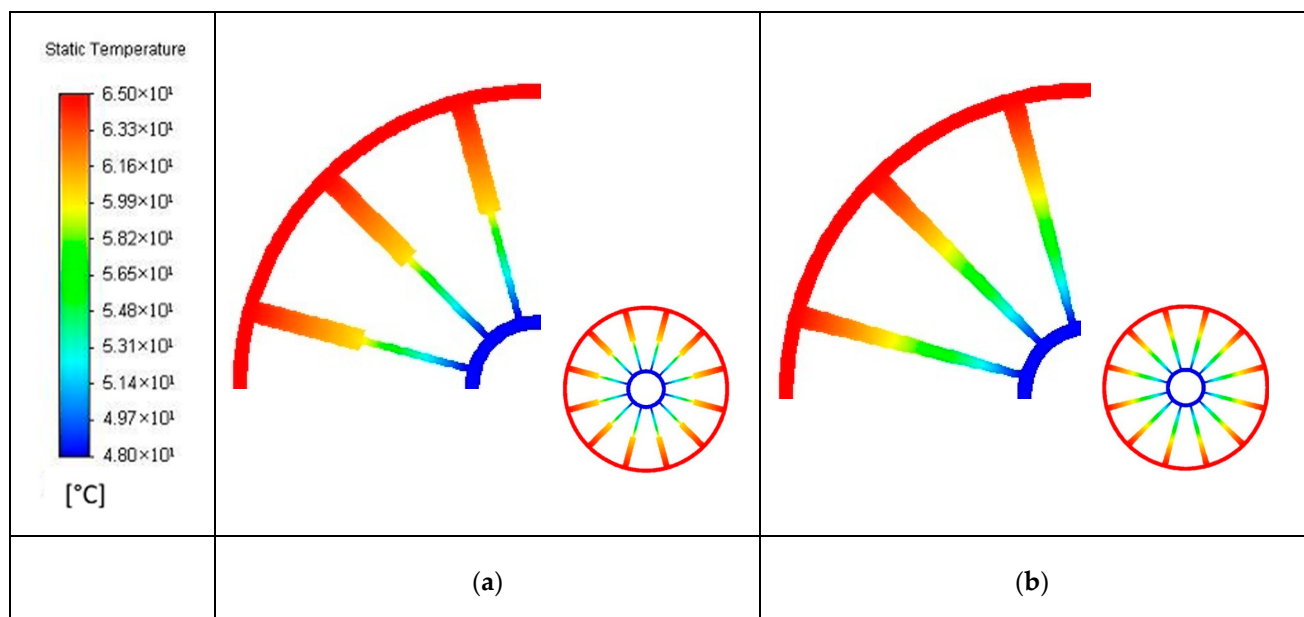


Figure 13. Temperature contours of smooth and stepwise fin thickness reductions. (a) Single-step thickness reduction fin. (b) Smooth thickness reduction fin.

The total melt volume fraction for these fins is presented in Figure 14. As illustrated, the single-thickness reduction fin continues to exhibit superior melting performance compared to the smooth thickness reduction fin, with an improvement of approximately 4%. Additionally, the melting rate achieved with the smooth reduction fin is about 9% higher than that of the uniform-thickness fin.

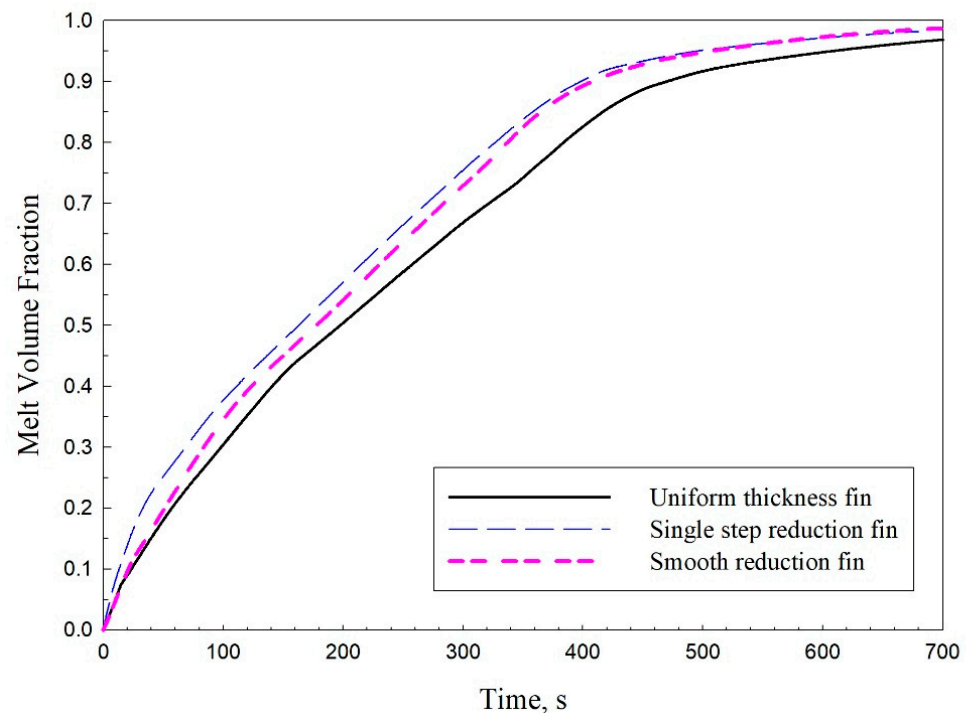


Figure 14. Total melt volume fraction for smooth- and single-stepwise thickness reduction fins.

6. Conclusions

The enhancement of PCM melting within a finned double-pipe heat exchanger was numerically investigated through the implementation of four distinct fin geometries. A series of innovative and practical fin designs were proposed with the objective of accelerating the melting process. The core concept was to elevate the fin temperature positioned between the hot and cold pipes under a constant temperature difference in order to promote stronger natural convection currents within the molten regions, thereby improving the overall melting rate. For consistency, the volume of the solid PCM contained within each segment was maintained at a constant across all configurations. Based on the numerical investigation, the following conclusions can be drawn:

- The single-thickness reduction fin achieves approximately a 12% higher melting rate compared to the uniform-thickness fin, while the double-thickness reduction fin demonstrates an improvement of about 9% over the uniform-thickness configuration.
- The smooth-thickness reduction fin also exhibits an approximately 9% enhancement in the melting rate relative to the uniform-thickness fin.
- The temperature distribution along the fin length revealed that single-thickness reduction fins maintain higher temperatures over a greater length compared to smooth reduction fins, promoting more effective heat transfer in the melting process.
- In the upper segments of the PCM domain, where natural convection is weak, fins with single- and double-thickness reductions improved the local melting rate by approximately 16% and 12%, respectively, compared to uniform-thickness fins.

- The performance of the stepwise-thickness reduction/expansion fin is approximately similar to that of the uniform-thickness fin.

These results suggest that although all thickness reduction strategies improve the melting performance compared to the uniform fin, the stepwise single-reduction configuration is more effective in promoting heat transfer and accelerating the phase change process.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The author declares no conflict of interest.

Nomenclature

A	area, m^2
c	specific heat at constant pressure, $kJ/kg\ ^\circ C$
d	diameter, m
f	liquid fraction
g	gravitational acceleration, m/s^2
h	specific enthalpy, kJ/kg
H	total enthalpy, kJ/kg
ΔH	latent heat content, kJ/kg
k	thermal conductivity, $W/m\ ^\circ C$
T	temperature, K or $^\circ C$
T_m	melting temperature of PCM, $^\circ C$
t	time, s
p	pressure, Pa
u	velocity in x direction, m/s
v	velocity in y direction, m/s
x, y	space coordinates
β	coefficient of thermal expansion
μ	viscosity, $Pa\cdot s$
ρ	density, kg/m^3
<i>Subscript</i>	
l	liquid
s	solid

References

1. Alhamdo, M.H.; Theeb, M.A.; Golam, A.S. Finned double-tube PCM system as a waste heat storage. *IOP Conf. Ser. Mater. Sci. Eng.* **2015**, *95*, 012033. [\[CrossRef\]](#)
2. Geete, P.; Kumar, N.; Somani, S.K.; Gangele, A. Simulation of double pipe heat exchanger with implementation of PCM. *Int. J. Innov. Technol. Explor. Eng. (IJITEE)* **2019**, *8*, 658–663. [\[CrossRef\]](#)
3. Fong, M.; Kurnia, J.; Sasmito, A.P. Application of phase change material-based thermal capacitor in double tube heat exchanger: A Numerical Investigation. *Energies* **2020**, *13*, 4327. [\[CrossRef\]](#)
4. Dukhana, W.A.; Dhaidana, N.S.; Al-Hattabb, T.A. Experimental investigation of the horizontal double pipe heat exchanger utilized phase change material. *Mater. Sci. Eng.* **2020**, *671*, 012148. [\[CrossRef\]](#)
5. Motevali, A.; Rostami, M.H.; Najafi, G.; Yan, W.-M. Evaluation and improvement of PCM melting in double tube heat exchangers using different combinations of nanoparticles and PCM (The Case of Renewable Energy Systems). *Sustainability* **2021**, *13*, 10675. [\[CrossRef\]](#)
6. Paroutoglou, E.; Fojan, P.; Gurevich, L.; Furbo, S.; Fan, J.; Medrano, M.; Afshari, A. A numerical parametric study of a double-pipe LHTES unit with PCM encapsulated in the annular space. *Sustainability* **2022**, *14*, 13317. [\[CrossRef\]](#)
7. Şimşek, F. Numerical analysis of double pipe heat exchanger using different internal pipe material in the melting Process of PCM. *Int. J. Innov. Res. Rev.* **2024**, *8*, 25–34.
8. Tiari, S.; Hockins, A.; Mahdavi, M. Numerical study of a latent heat thermal energy storage system enhanced by varying fin configurations. *Case Stud. Therm. Eng.* **2021**, *25*, 100999. [\[CrossRef\]](#)

9. Bondareva, N.S.; Ghalambaz, M.; Sheremet, M.A. Influence of the fin shape on heat transport in phase change material heat sink with constant heat loads. *Energies* **2021**, *14*, 1389. [\[CrossRef\]](#)
10. Cheriet, N.; Benlekkam, M.; Kherris, S. Influence of fin shape design on thermal efficiency of phase change material-based thermal energy storage unit. *Arch. Mech. Eng.* **2024**, *71*, 189–211. [\[CrossRef\]](#)
11. Al-Mudhafara, A.H.N.; Nowakowskib, A.F.; Nicolleau, F.C.G.A. Enhancing the thermal performance of PCM in a shell and tube latent heat energy storage system by utilizing innovative fins. *Energy Rep.* **2021**, *7*, 20–126. [\[CrossRef\]](#)
12. Fang, J.; Han, T.; Bi, Y.; Yan, H.; Wei, J. Numerical study on heat transfer and enhancement mechanism in PCM-filled shell-and-tube heat exchangers. *Front. Energy Res.* **2022**, *10*, 885564. [\[CrossRef\]](#)
13. Mao, Q.; Hu, X.; Zhu, Y. Numerical investigation of heat transfer performance and structural optimization of fan-shaped finned tube heat exchanger. *Energies* **2022**, *15*, 5682. [\[CrossRef\]](#)
14. Ma, F.; Zhu, T.; Zhang, Y.; Lu, X.; Zhang, W.; Feng, M. A review on heat transfer enhancement of phase change materials using fin tubes. *Energies* **2023**, *16*, 10545. [\[CrossRef\]](#)
15. Zhang, J.; Cao, Z.; Huang, S.; Huang, X.; Han, Y.; Wen, C.; Walther, J.H.; Yang, Y. Solidification performance improvement of phase change materials for latent heat thermal energy storage using novel branch-structured fins and nanoparticles. *Appl. Energy* **2023**, *342*, 121158. [\[CrossRef\]](#)
16. Zaib, A.; Mazhar, A.R.; Aziz, S.; Talha, T.; Jung, D.-W. Heat transfer augmentation using duplex and triplex tube phase change material (PCM) heat exchanger configurations. *Energies* **2023**, *16*, 4037. [\[CrossRef\]](#)
17. Waqas, H.; Hussain, M.; Ahmad, S.; Al-Mdallal, Q.M.; Abdelmohimen, M.A.H. Enhancing thermal storage performance: A combined approach using nano-integrated phase change material and arc fins. *Int. Commun. Heat Mass Transf.* **2025**, *161*, 108549. [\[CrossRef\]](#)
18. Vanaga, R.; Narbutis, J.; Zundāns, Z.; Gušča, J. Systematic literature review of software tools for modeling heat transfer in phase change materials for building applications. *Int. Conf. Sustain. Energy Green Technol.* **2023**, *1372*, 012017. [\[CrossRef\]](#)
19. Nedjar, B. An enthalpy-based finite element method for nonlinear heat problems involving phase change. *Comput. Struct.* **2002**, *80*, 9–21. [\[CrossRef\]](#)
20. Bejan, A. *Convection Heat Transfer*, 4th ed.; Wiley: Hoboken, NJ, USA, 2013.
21. ANSYS Fluent Theory Guide. Available online: <https://www.afs.enea.it/project/neptunius/docs/fluent/html/th/node349.htm> (accessed on 3 May 2025).
22. Elsayed, A.O. Numerical investigation on PCM melting in triangular cylinders. *Alex. Eng. J.* **2018**, *57*, 2819–2828. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.