



Numerical validation of periodic modeling and orientation-driven thermal behavior in branched-fin PCM thermal energy storage systems

Rawia Ahmed^a, Mohammad Hossein Heidarshenas^b, Hayder I. Mohammed^c, Hanene Guesmi^a, Hany Alalfy^d, Jehan Habib^d, Mohammad Ghalambaz^{e,*}

^a Computer Science Department, Applied College, University of Ha'il, PO Box 2440, Ha'il City 55476, Saudi Arabia

^b Department of Mechanical and Nuclear Engineering, Kansas State University, Manhattan, Kansas, USA

^c Department of Physics, College of Education, University of Garmian, Kalar 46021, Iraq

^d Management Information Systems Department, Applied College, University of Ha'il, PO Box 2440, Ha'il City 55476, Saudi Arabia

^e Department of Mathematical Sciences, Saveetha School of Engineering, SIMATS, Chennai, India

ARTICLE INFO

Keywords:

Branched fins
Heat transfer enhancement
Latent heat thermal energy storage
Melting and solidification
Natural convection
Phase change material

ABSTRACT

The low thermal conductivity of phase change materials limits the charging and discharging rates of latent heat thermal energy storage systems, necessitating effective heat transfer enhancement strategies and reliable modeling approaches. This study presents a numerical investigation of fin-assisted phase change material thermal storage, with particular emphasis on validating the use of a periodic representative elementary unit for modeling vertically extended finned configurations. The phase-change process is simulated using the enthalpy-porosity method with buoyancy-driven flow, and the periodic framework is assessed by comparing single- and multi-unit domains. The results show that the periodic model reproduces the thermal response of the extended domains with deviations below 0.1%, supporting its use as a computationally efficient reduced-domain modeling approach for the configurations considered. Within this validated framework, the effects of fin number, branched fin length, and branch orientation are systematically analyzed. Increasing the number of main fins enhances conductive heat spreading, reducing melting time from 134.55 to 69.85 min. In contrast, branch length provides only marginal improvement, whereas branch orientation has a more pronounced influence within the investigated range, reducing melting time from 125.03 to 66.70 min as the angle increases from 30° to 75°. This behavior indicates that alignment with buoyancy-driven convection influences thermal performance more strongly than geometric extension alone. The same configuration also improves discharge performance, reducing solidification time from 539.73 to 120.75 min through enhanced conductive heat extraction. Validation against published data yields mean deviations of 0.91% and 6.33% relative to numerical and experimental results, respectively.

1. Introduction

Thermal Energy Storage (TES) plays a crucial role in enhancing the efficiency, flexibility, and reliability of modern energy systems by enabling the temporal decoupling of energy generation and demand [1,2]. Among the various TES technologies, Latent Heat Thermal Energy Storage Systems (LHTES) based on Phase Change Material (PCM) have attracted considerable attention due to its high energy storage density and quasi-isothermal operation during phase transition [3–5]. These advantages make PCMs particularly attractive for applications ranging

from renewable energy integration and waste heat recovery to thermal management and cold energy storage [6–8]. However, despite their favorable thermodynamic characteristics, most PCMs suffer from inherently low thermal conductivity, which severely limits heat transfer rates and leads to prolonged charging and discharging times [9,10]. In addition to poor thermal conductivity, practical deployment of PCM-based LHTES is further constrained by issues such as supercooling, phase segregation, volume change, leakage during melting, and material compatibility with containment structures [11,12]. These intrinsic drawbacks significantly hinder the effective utilization of PCMs in high-power thermal storage systems and have motivated extensive research

* Corresponding author.

E-mail addresses: ri.ahmad@uoh.edu.sa (R. Ahmed), Heidarshenas@ksu.edu (M.H. Heidarshenas), hayder.i.mohammad@garmian.edu.krd (H.I. Mohammed), hs.guesmi@uoh.edu.sa (H. Guesmi), j.habib@uoh.edu.sa (J. Habib), m.ghalambaz@gmail.com (M. Ghalambaz).

<https://doi.org/10.1016/j.icheatmasstransfer.2026.111981>

Nomenclature		t	Time [s]
<i>Greek symbols</i>		t_f	Fin thickness [mm]
α	Branched fins angle [°]	t_m	Total melting time [s]
β	Thermal expansion coefficient [K ⁻¹]	$\vec{V}$	Velocity vector [m s ⁻¹]
λ	Liquid fraction [1]	<i>Subscripts</i>	
μ	Dynamic viscosity [Pa s]	eff	Effective value
ρ	Density [kg m ⁻³]	e	Equilibrium
φ	Main fins angle [°]	i	Initial
<i>Latin symbols</i>		L	Latent heat
A_m	Mushy zone Darcy coefficient [Pa s m ⁻²]	lq	Liquidus
C_p	Specific heat capacity [J kg ⁻¹ K ⁻¹]	m	Momentum
E	internal energy [J]	ref	Reference
g	Gravitational acceleration [m s ⁻²]	S	Solidus
H	Enthalpy [J kg ⁻¹]	<i>Acronyms</i>	
k	Thermal conductivity [W m ⁻¹ K ⁻¹]	HTF	Heat Transfer Fluid
L_f	Latent heat of fusion [J kg ⁻¹]	LHTES	Latent Heat Thermal Energy Storage
L	Length of branched fin [m]	PCM	Phase Change Material
P	Pressure [Pa]	REU	Representative Elementary Unit
S	source term [W m ⁻³]	TES	Thermal energy storage
T	Temperature [K]		

Table 1

Literature-supported comparison of representative fin-enhanced PCM/LHTES studies and the gap addressed by the present work.

Study group	Configuration	Process	Reported performance improvement	Remaining gap
Straight/twisted fins [31]	Conventional and twisted fins in tubular storage systems	Melting and solidification	Twisted fins increased the heat charging and heat recovery rates by approximately 10% and 14%, respectively, compared with straight fins.	Does not isolate branch length and branch orientation effects
Sunburst/radial fins [32]	Radially distributed fins in multi-tube storage systems	Energy storage and recovery	Sunburst-distributed radial fins reduced melting time by 40.5%, shortened solidification time by 48.1%, improved heat recovery by 91.6%, and increased overall storage capacity by 21.57% compared with conventional fin designs.	Focuses on radial distribution rather than branch-angle-controlled convection coupling
Staggered/inline fins [24,25]	Staggered, inline, and extended fin arrangements	Mainly discharge/solidification	Staggered circular fins reduced solidification time by about 52% and increased discharge rate by about 30% compared with inline fins; extended Y-fin designs reduced melting time by about 28% relative to the baseline Y-fin case.	Limited separation of topology, spacing, orientation, and fin-volume effects
Sine-shaped, triangular, wavy, and optimized fins [33–36]	Curved, oriented, wavy, and optimization-based fin structures	Mainly melting/thermal performance	Advanced curved/wavy/optimized fin designs substantially improved melting performance; for example, wavy-wall/finned multi-shell designs increased melting rate by up to 88.5%, while orientation-controlled triangular-shell fins showed that fin angle can significantly alter melting rate.	Several geometric parameters are changed simultaneously
Tree-like, fractal, Y-shaped, and bio-inspired fins [38–49]	Branched, hierarchical, biomimetic, vascular, and alveolar fin concepts	Mainly melting or overall thermal response	Hierarchical/fractal/bio-inspired fins produced large reductions in phase-change time; combined fractal fins reduced complete melting time by up to 68% compared with traditional fractal fins, and tree-like fins have been reported to shorten complete melting/solidification time by about 34.5%.	Independent role of branch orientation relative to branch length is not clearly quantified
Present study	Branched fins with controlled main-fin number, branch length, and branch orientation	Melting, solidification, and REU validation	The present branched-fin configuration reduced melting time by 48.1% relative to the unfinned case, from 134.55 to 69.85 min, and branch orientation reduced melting time by 46.7%, from 125.03 to 66.70 min. During discharge, the selected branched-fin case reduced solidification time by 77.6%, from 539.73 to 120.75 min.	Establishes the relative importance of geometric parameters and validates periodic modeling for branched-fin LHTES

into heat transfer enhancement strategies and high-performing storage configurations [13–15].

To overcome the low thermal conductivity of PCM-based LHTES, enhancement strategies can be broadly classified into active or actively assisted approaches, material-based passive enhancement, and structural passive enhancement. Recent studies have shown that heat transfer enhancement can be achieved by combining high-conductivity porous structures, forced or rotation-assisted motion, encapsulated nano-

enhanced PCMs, and cascaded PCM arrangements to improve heat diffusion, melting uniformity, and charging/discharging response [16–18]. Although these approaches can improve thermal performance, they often require additional material design, more complex storage architecture, rotational or flow-control conditions, or careful matching of PCM melting ranges. Material-based passive approaches, including nano-enhanced PCMs, metal foams, and cascaded PCM arrangements, have also been proposed to improve thermal response and temperature

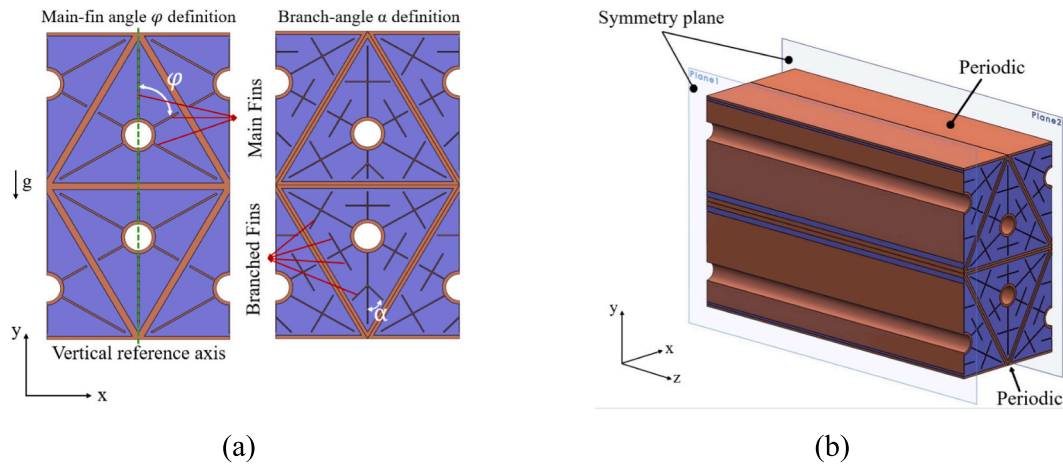


Fig. 1. Schematic definition of the geometric parameters used for the finned PCM storage unit: (a) main-fin angle ϕ and (b) branch angle α . Both angles are measured with respect to the vertical reference axis shown by the dashed line. The main fins and branched fins are identified, and the definitions are used consistently for all configurations listed in Table 2.

utilization [19]. Nevertheless, their practical implementation can be limited by cost, fabrication difficulty, long-term stability, leakage, or compatibility issues [20–23]. In contrast, fin-based passive enhancement provides a structurally simple and scalable route for reducing conduction length, increasing heat transfer area, and improving thermal penetration without external energy input. Fins are therefore among the most practical enhancement methods for compact and repeatedly cycled LHTES units, where reliability, manufacturability, and low parasitic energy consumption are important design requirements [24–27].

The importance of fin-based enhancement becomes more evident when both charging and discharging are considered. In practical LHTES operation, the thermal performance is governed not only by melting, but also by solidification, which determines heat-release rate, recovery time, and cyclic usability. Previous studies have shown that solidification is often slower than melting because buoyancy-driven convection is weakened as the liquid PCM disappears and heat transfer becomes increasingly conduction-dominated [28,29]. Inadequate solidification can therefore reduce the effective cyclic performance of PCM storage systems [30]. For this reason, fin geometry should be evaluated not only in terms of melting acceleration, but also in terms of its ability to provide conductive heat-extraction pathways during discharge.

Extensive efforts have been devoted to optimizing fin geometry, spacing, and topology in PCM-based LHTES. Comparative studies have shown that twisted fins can outperform straight fins in tubular storage systems [31], while radially distributed sunburst fins improve energy storage and recovery in multi-tube configurations [32]. Other studies have examined staggered and inline circular fins for discharge enhancement [24], sine-shaped fins [33], triangular-shell fins with orientation control [34], multi-shell PCM heat exchangers with wavy walls [35], and shell-tube structures optimized using artificial-intelligence-based methods [36]. More complex concepts, including petal-tube bundles embedded in metal foam [37], constructal tree-like networks [38], innovative fin topologies [39–42], non-uniform fin arrangements [43,44], Y-shaped fins [45], and biomimetic or vascular/alveolar fin concepts [46–49], have further confirmed that redistributing high-conductivity material within the PCM can improve phase-change performance. However, many of these studies modify several geometric features simultaneously, such as fin length, spacing, surface area, topology, orientation, and fin volume. As a result, the relative importance of individual geometric parameters remains difficult to identify from the existing literature.

To clarify the position of the present work relative to previous studies, Table 1 summarizes representative fin-enhanced PCM/LHTES configurations using the references reviewed above. The comparison

indicates that the literature has mainly focused on demonstrating the thermal benefit of advanced fin shapes relative to conventional or unfinned configurations. However, fewer studies have isolated the individual effects of branch length and branch orientation, and the validity of a periodic reduced-domain model has not been systematically assessed for branched-fin PCM storage systems.

LHTES systems are increasingly employed in applications where high energy density and fast thermal response are essential. Representative examples include solar TES for load shifting and power stabilization [50], waste heat recovery in industrial processes [51], thermal management of electronic devices subjected to transient heat loads [52,53], cold energy storage for refrigeration and cold-chain systems [54,55], and building energy systems for peak-load reduction and thermal comfort enhancement [56]. These applications require internal structures that can enhance both charging and discharging without excessive complexity. As summarized in Table 1, although previous fin-enhanced designs have achieved significant improvements, the literature still lacks a clear quantitative separation between branch extension and branch orientation. This distinction is physically important because branch length primarily increases conductive reach, whereas branch orientation also controls the alignment between conductive pathways and buoyancy-driven circulation in the molten PCM.

Despite extensive research on fin-enhanced PCM-based TES systems, several limitations remain. First, many studies evaluate complex fin shapes by changing several geometric features simultaneously, including fin length, spacing, surface area, topology, orientation, and fin volume. Therefore, the relative importance of individual geometric parameters remains difficult to determine. Second, although branched, tree-like, Y-shaped, and bio-inspired fins have been investigated [38–49], the independent role of branch orientation relative to branch length has not been clearly quantified. Third, many studies emphasize melting enhancement, while the corresponding solidification behavior receives comparatively less attention, even though discharge performance is essential for cyclic LHTES operation [28–30]. Finally, the use of periodic representative domains for modeling extended finned systems has not been rigorously validated for branched geometries, creating uncertainty regarding the accuracy of simplified computational domains.

The present study addresses these gaps by combining validated periodic modeling with a mechanism-based analysis of branched-fin geometries. The novelty of this work lies in four specific aspects. First, the effects of main-fin number, branch length, and branch orientation are examined separately to identify their relative influence on phase-change behavior. Second, the periodic Representative Elementary Unit (REU) is

Table 2

Geometric parameters of the simulated cases, including number of main fins, branched fin length, pipe-fine solid cross-sectional area, and orientation.

Cases	Number of fins	Thickness of fins t_f (mm)	Length of Branched fin L (mm)	Pipe-fin solid cross-sectional area (mm ²)	φ (°)	α (°)
0	-	-	-	-	-	-
1	3	1.5	-	3669	120	-
2	4	1.8	-	3630	90	-
3	5	1.5	-	3634	72	-
4	6	1	-	3651	60	-
5	6	0.8	4	3671	60	90
6	6	0.7	7	3671	60	90
7	6	0.56	12.5	3661	60	90
8	6	0.56	12.5	3671	60	30
9	6	0.56	12.5	3671	60	45
10	6	0.56	12.5	3671	60	60
11	6	0.56	12.5	3671	60	75

verified against multi-unit domains specifically for branched-fin configurations, providing a basis for computationally efficient modeling of vertically repeated LHTES structures. Third, the physical role of branch orientation is analyzed in terms of its effect on the coupling between conductive heat-spreading pathways and buoyancy-driven convection, rather than being treated only as a geometric surface-area modification. Fourth, the selected branched-fin configuration is also assessed during solidification to examine whether the geometry that enhances charging can also support heat extraction during discharge. Through this structure, the study provides design-oriented insight into branched-fin LHTES systems without relying solely on case-by-case geometric comparison.

2. Numerical methodology

2.1. Computational model and geometric configuration

A two-dimensional numerical model of a finned LHTES unit is considered to investigate the influence of geometric fin parameters on the melting and solidification behavior of the PCM. The storage unit

consists of a central cylindrical pipe carrying the Heat Transfer Fluid (HTF), surrounded by a PCM domain equipped with radial main fins and secondary branched fins. Copper is used as the material for both the pipe and fins, while RT35 is selected as the PCM.

The geometric definitions of the angular parameters are illustrated in Fig. 1. The main-fin angle φ defines the inclination of the primary fin with respect to the vertical reference axis, while the branch angle α

Table 3

Initial and boundary conditions used in the charging and discharging simulations.

Region/quantity	Charging condition	Discharging condition
Initial PCM phase	Completely solid PCM	Fully liquid PCM
Initial PCM temperature	$T_0 = 30^\circ\text{C}$	$T_0 = 40^\circ\text{C}$
Initial velocity	$\mathbf{u} = 0$	
Pipe wall / HTF boundary	$T_h = 60^\circ\text{C}$	$T_c = 20^\circ\text{C}$
Top and bottom REU boundaries	Periodic boundary condition	
Solid walls	No-slip condition, $u = v = 0$	
PCM-copper interfaces	Thermal continuity; perfect thermal contact	
Lateral cut boundaries	Symmetry condition: zero normal velocity and zero normal gradients of scalar variables	

Table 4

Thermophysical properties of RT35 PCM and copper used in the numerical simulations, including density, thermal conductivity, specific heat, latent heat, and melting temperature range.

Property	Copper [57]	PCM (RT35) [58,59]	Unit
Mean density (ρ)	8978	815	kg m^{-3}
Specific heat capacity (C_p)	381	2000	$\text{J kg}^{-1} \text{K}^{-1}$
Thermal conductivity (k)	387.6	0.2	$\text{W m}^{-1} \text{K}^{-1}$
Latent heat of fusion (L_f)	–	160,000	J kg^{-1}
Thermal expansion coefficient (β)	–	0.0006	K^{-1}
Dynamic viscosity (μ)	–	0.023	Pa s
Melting temperature range	–	32–38	$^\circ\text{C}$

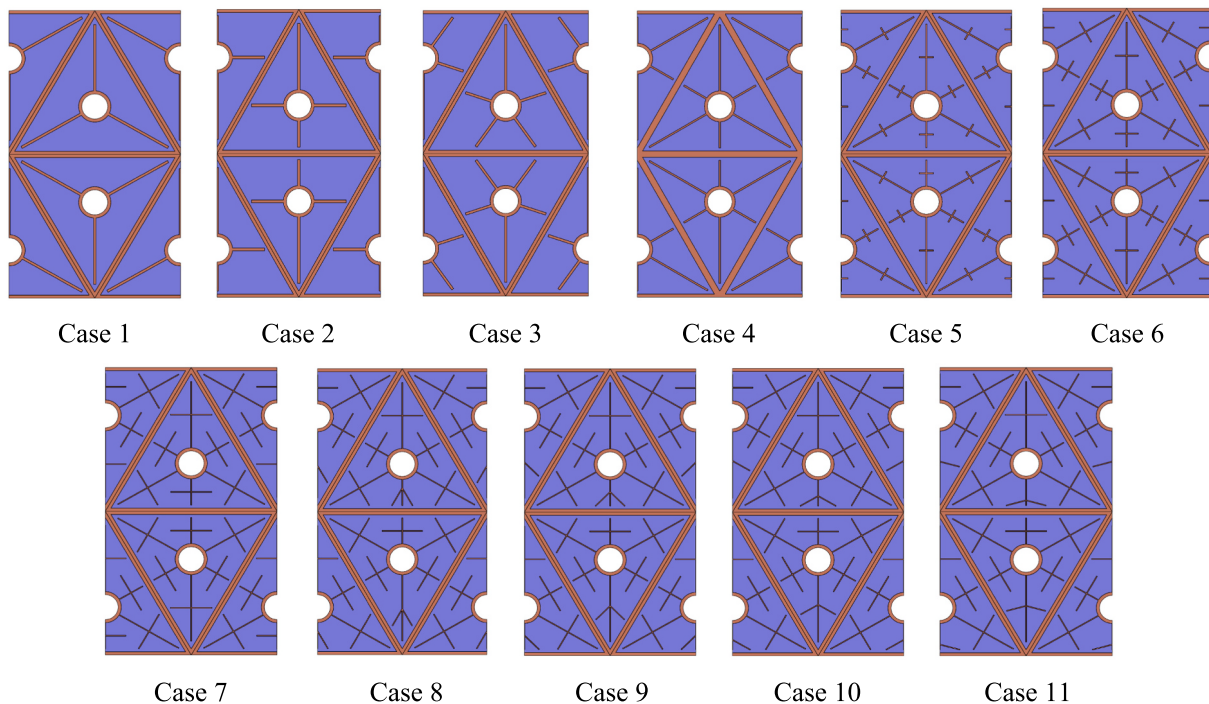


Fig. 2. Geometric configurations of the eleven simulated cases illustrating variations in the number of main fins, branched fin length, and branched fin orientation. These configurations define the parametric space used to assess the influence of fin topology on phase-change behavior.

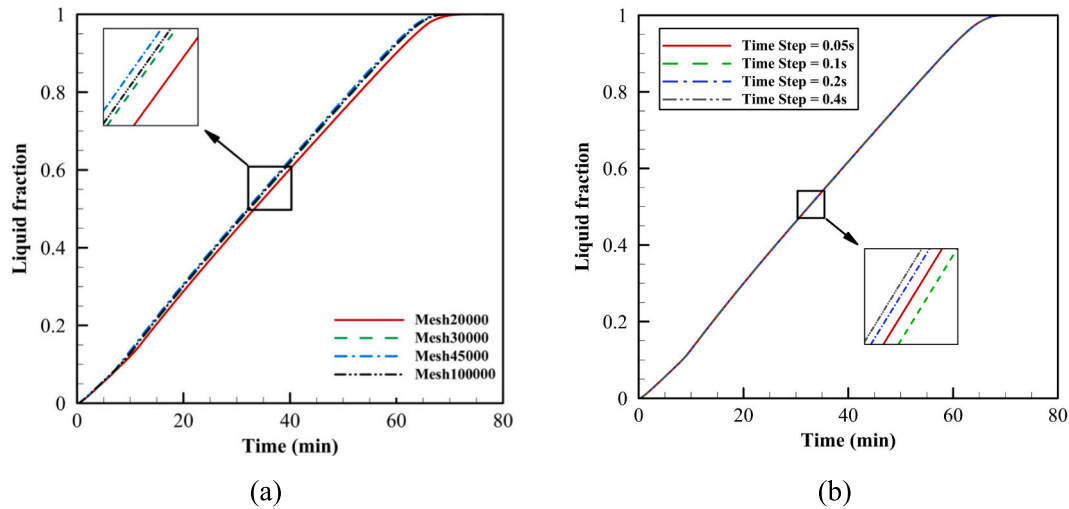


Fig. 3. Mesh and time-step independence analyses: (a) effect of mesh resolution (20,000–100,000 cells) on the predicted melting behavior, and (b) influence of time-step size (0.05–0.4 s).

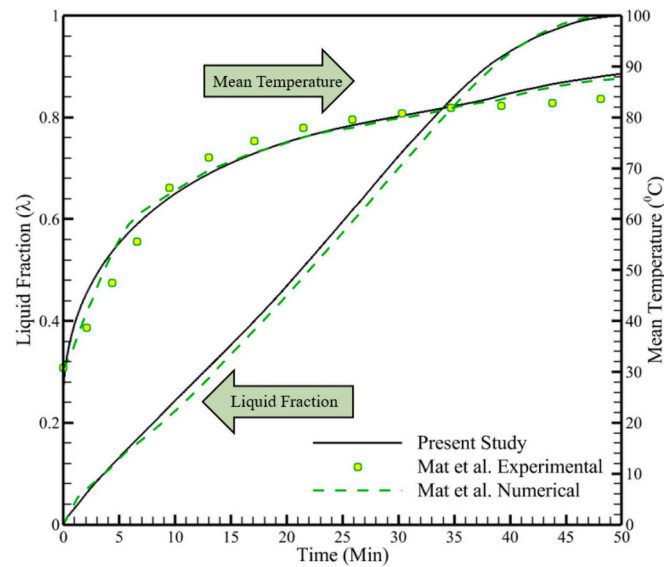


Fig. 4. Validation of the present model against the results of Mat et al. [69] in terms of (a) liquid fraction evolution and (b) mean PCM temperature during melting.

defines the orientation of the secondary branched fins with respect to the same reference axis. The Cartesian coordinate system used in the simulations is shown. The x-axis denotes the horizontal direction, the y-axis denotes the vertical direction, and gravity acts downward along the negative y-direction. The branch length L and fin thickness t_f are also used to define the geometric configurations. These definitions are applied consistently in Table 2 for all simulated cases.

The periodic REU representation is valid under the assumption that the finned structure is vertically repetitive, with uniform spacing,

identical fin geometry, and consistent thermal boundary conditions between adjacent units. It also assumes that axial end effects are negligible and that the dominant temperature and flow structures are generated locally within each repeated unit rather than by long-range vertical communication across the full storage height. Under these conditions, the top and bottom boundaries of the REU represent equivalent planes in an extended periodic system, allowing the single-unit model to reproduce the thermal response of the vertically extended configuration. This simplification is adopted because the

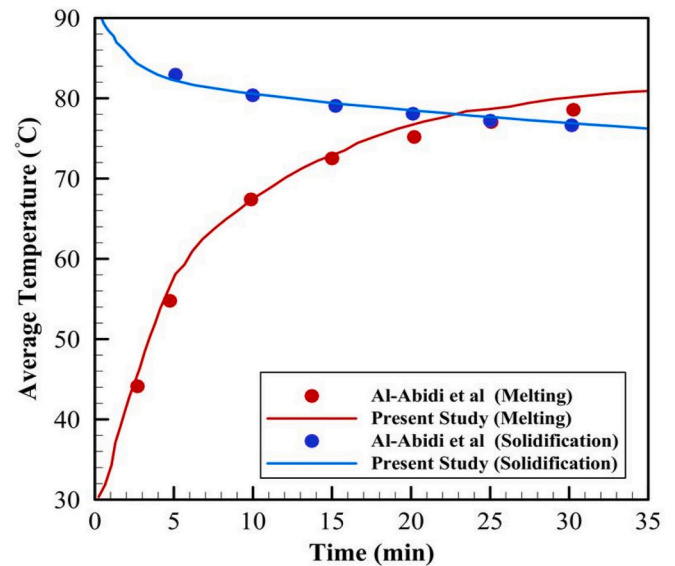


Fig. 5. Comparison of the predicted temporal evolution of the mean PCM temperature during solidification with the experimental data of Al-Abidi et al. [70].

Table 5

Quantitative comparison between the present predictions and the numerical and experimental results of Mat et al. [69] for mean PCM temperature at selected times.

Time (s)	Present study (°C)	Numerical (°C) [69]	Error vs numerical (°C / %) [69]	Experiment (°C) [69]	Error vs experimental (°C / %) [69]
300	55.34	56.00	0.66 (1.18)	49.74	5.60 (11.26)
600	64.98	65.60	0.62 (0.95)	67.61	2.63 (3.89)
900	71.00	71.42	0.42 (0.59)	73.84	2.84 (3.85)
Mean error	–	–	0.57 (0.91%)	–	3.69 (6.33%)

Table 6
Quantitative comparison between the present model and Al-Abidi et al. [70] based on the mean PCM temperature during melting and solidification.

Process	Time (min)	Present study (°C)	Al-Abidi et al. (°C) [70]	Absolute error (°C)	Relative error (%)
Melting	4.80	56.67	54.70	1.96	3.59
	9.92	67.08	67.33	0.25	0.37
	15.02	72.78	72.43	0.35	0.48
	20.21	76.75	75.11	1.64	2.18
	30.28	80.13	78.48	1.66	2.11
Mean error	–	–	–	1.17	1.75
Solidification	5.15	82.25	82.82	0.57	0.69
	10.05	80.54	80.30	0.23	0.29
	15.27	79.33	78.97	0.36	0.45
	20.13	78.39	78.01	0.37	0.48
	25.02	77.56	77.18	0.38	0.49
Mean error	–	–	–	0.36	0.45

studied geometry is periodically repeated in the vertical direction and the imposed thermal conditions are identical for adjacent units. Therefore, when end effects and inlet/outlet non-uniformities are absent, the dominant local melting-front evolution and buoyancy-driven recirculation can be represented within a single repeated unit.

To assess the combined effects of fin number, branch length, and branch orientation, a total of eleven distinct geometric configurations are examined, as illustrated in Fig. 2. The corresponding geometric parameters for each case are summarized in Table 2. The thickness of the pipe wall is maintained at 2 mm for all configurations. The geometries were designed to maintain comparable PCM and solid volumes as far as

possible; however, the fin volume fraction and effective heat transfer surface area are not strictly identical among all configurations because of geometric constraints associated with branching and thickness adjustment. Therefore, the reported performance differences should be interpreted as the combined outcome of fin topology, conductive-path redistribution, local surface-area variation, and coupling with buoyancy-driven convection. To ensure a fair comparison among the simulated configurations, the total solid area associated with the pipe and fins was maintained nearly constant across the cases. Because the present model is two-dimensional, the reported area corresponds to the solid volume per unit depth in the out-of-plane direction. The calculated pipe–fin solid area varied only from 3630 to 3671 mm², with an average value of approximately 3661 mm² and a maximum variation of about 1.12%. Therefore, the effect of fin material volume on the comparative trends is limited. In particular, the branch-orientation cases have the same pipe–fin solid area of 3671 mm², ensuring that their differences are primarily associated with branch orientation rather than changes in fin volume. Because the pipe geometry is identical in all cases, the variation in pipe–fin solid area reflects the variation in fin material per unit depth.

It should be noted that the present parametric design does not isolate the effect of surface area alone. Instead, it evaluates how changes in fin topology, branch length, and branch orientation modify the internal conductive pathways and their interaction with buoyancy-driven convection. For this reason, the performance trends should not be interpreted solely as a consequence of fin volume fraction or surface-area variation. In particular, the branch-orientation cases have identical branch length and thickness, and therefore the same fin volume fraction; their performance differences mainly reflect orientation-induced changes in heat-spreading direction and convection coupling.

The computational domain represents a two-dimensional REU of a

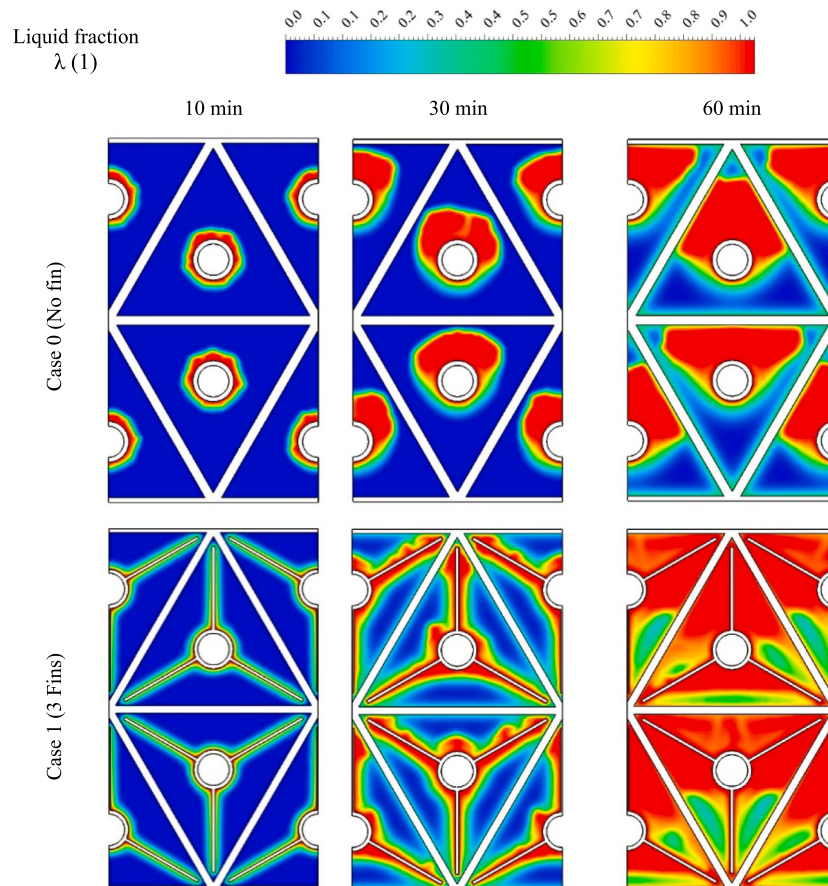


Fig. 6. Liquid fraction contours illustrating the evolution of the melting front for the unfinned configuration (Case 0) and finned configurations with different numbers of main fins at selected times ($t = 10, 30$, and 60 min).

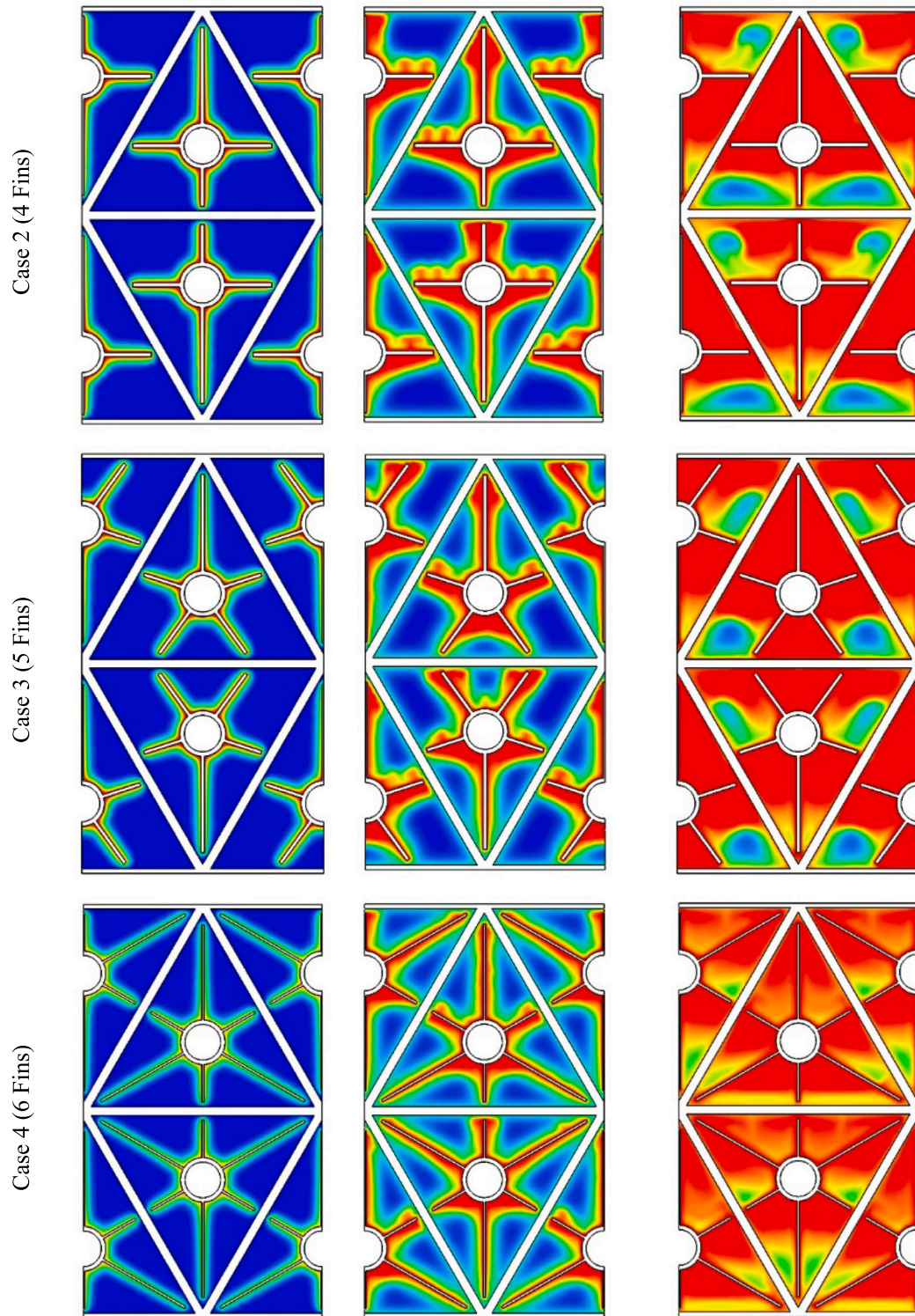


Fig. 6. (continued).

vertically repeated finned structure, enabling accurate representation of the dominant heat transfer and phase-change mechanisms within a reduced domain while significantly improving computational efficiency.

At the start of the charging process, the PCM is assumed to be completely solid and at a uniform initial temperature of $T_0 = 30^\circ\text{C}$, which is below the melting range of RT35. The initial velocity in the PCM domain is set to zero. During charging, the pipe wall in contact with the HTF is maintained at a constant hot-wall temperature of $T_h = 60^\circ\text{C}$,

while the remaining boundaries are treated according to the periodic and symmetry conditions of the representative elementary unit. For the discharging process, the PCM is initially assumed to be fully liquid at a uniform temperature of $T_0 = 40^\circ\text{C}$, which is above the liquidus temperature of RT35. The same geometric configuration is used, and the pipe wall temperature is changed to a constant cold-wall temperature of $T_c = 20^\circ\text{C}$, which is below the solidification range of the PCM. The top and bottom boundaries of the REU are assigned periodic boundary

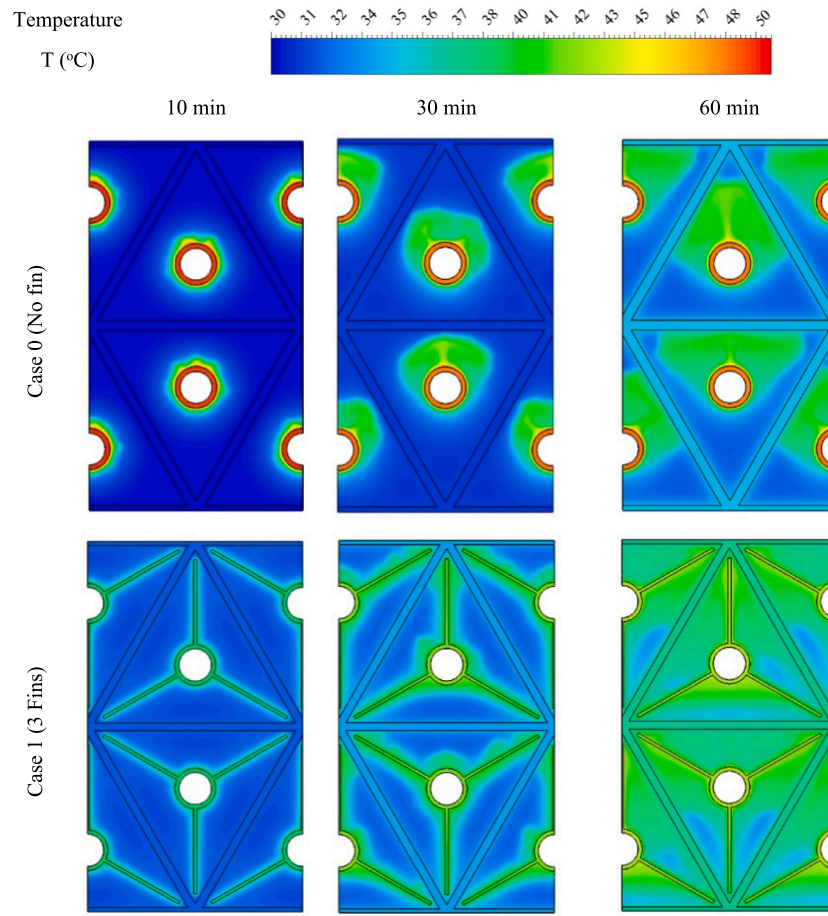


Fig. 7. Temperature contours during melting for configurations with different numbers of main fins at selected times ($t = 10, 30$, and 60 min).

conditions to represent the vertically repeated finned structure, while the lateral cut planes are treated as symmetry boundaries with zero normal velocity and zero normal gradients of scalar variables. No-slip velocity conditions are imposed at solid walls. Thermal continuity is applied at the interfaces between the PCM and the copper pipe/fins, and perfect thermal contact is assumed. For clarity, the initial and boundary conditions used in the charging and discharging simulations are summarized in Table 3.

The material properties of the PCM (RT35) and the solid components (copper) are listed in Table 4. The PCM is assumed to be homogeneous and isotropic, with phase change occurring over a finite temperature range defined by its solidus and liquidus temperatures. The solid components are treated as thermally conductive with constant thermophysical properties.

RT35 is selected as the PCM due to its melting temperature range of approximately $32\text{--}38^\circ\text{C}$, which is suitable for low- to medium-temperature TES applications such as solar thermal systems, building thermal regulation, and waste heat recovery. In addition, RT35 is widely used in the literature and exhibits stable and well-documented thermophysical properties, enabling reliable comparison with previous studies.

Copper is chosen as the material for the pipe and fins because of its high thermal conductivity, which facilitates rapid heat transfer between the HTF and the PCM. The use of copper ensures that the thermal resistance within the solid structure is minimized, allowing the analysis to focus on the influence of fin geometry and phase-change behavior. Moreover, copper is commonly employed in fin-assisted LHTES systems, providing a consistent basis for comparison with existing studies.

It is acknowledged that the fin volume fraction is not perfectly

identical across all configurations because of geometric constraints associated with fin branching and thickness adjustment. However, the geometries were designed to keep the PCM area and the pipe-fin solid area nearly constant, as reported in Table 2. The pipe-fin solid area varies only from 3630 to 3671 mm^2 , corresponding to a maximum variation of approximately 1.12% relative to the average value. Therefore, the comparative trends are not expected to be governed primarily by differences in the amount of solid material. In particular, the branch-orientation cases have the same pipe-fin solid area, branch length, and fin thickness; hence, differences among these cases can be attributed mainly to orientation-induced changes in heat-spreading direction and coupling with buoyancy-driven convection.

The validity of this assumption is assessed in the present study by comparing the thermal response of single-unit and multi-unit domains, as discussed in Section 4.1.4. This validation indicates that the periodic model captures the dominant heat transfer mechanisms and provides a reliable representation of the vertically repeated configuration considered in this study.

2.2. Governing equations

The unsteady melting and solidification of the PCM are modeled using a unified computational domain in which the solid, liquid, and mushy phases are treated simultaneously. The phase-change process is represented through the enthalpy-porosity approach, whereby the solid-liquid interface is resolved implicitly without explicit interface tracking [60,61]. Within this formulation, the liquid fraction, λ , is defined in each computational cell, varying from 0 for completely solid PCM to 1 for fully liquid PCM.

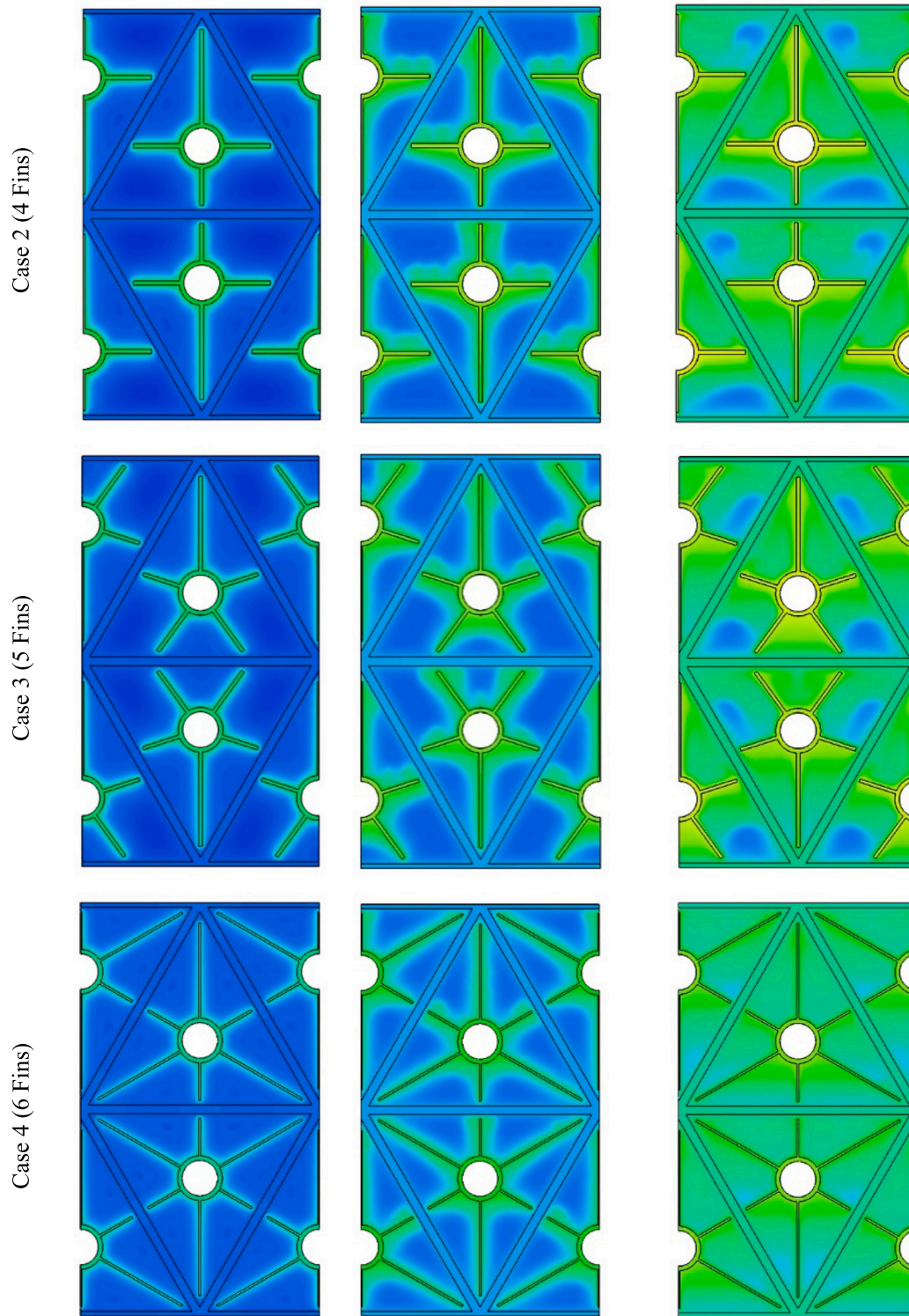


Fig. 7. (continued).

The governing equations are formulated based on the following assumptions:

1. The PCM is homogeneous and isotropic, and its thermophysical properties are taken as constant within the temperature range considered, except for density variation in the buoyancy term.
2. The PCM melt is Newtonian and incompressible, and the flow in the liquid region is laminar.
3. Density variation is neglected in all governing equations except in the buoyancy force, where the Boussinesq approximation is applied.
4. The solid phase of the PCM is assumed to remain stationary during phase change.
5. The mushy region is treated as an isotropic porous medium, and the flow resistance in this region is modeled using the Carman–Kozeny-type damping source term.

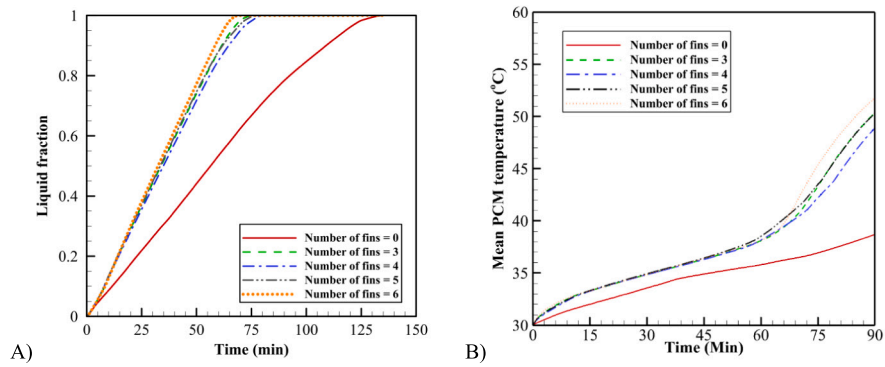


Fig. 8. Time evolution of (a) liquid fraction and (b) mean PCM temperature for different numbers of main fins during melting.

Table 7

Summary of melting performance for configurations with different numbers of main fins, including melting time and average charging power.

Cases	Melting time (min)	Average charging power (W)
Case 0 (fin = 0)	134.55	288.26
Case 1 (fin = 3)	75.21	505.22
Case 2 (fin = 4)	79.87	479.60
Case 3 (fin = 5)	76.88	499.28
Case 4 (fin = 6)	69.85	536.36

6. Local thermal equilibrium is assumed within each computational cell, so a single temperature field is used for the solid, liquid, and mushy phases.
7. Phase change occurs over a finite temperature interval between the solidus and liquidus temperatures, and the liquid fraction varies linearly within this interval.
8. Latent heat absorption and release are incorporated through the enthalpy formulation using a volumetric source term, without explicit tracking of the solid–liquid interface.
9. Viscous dissipation and radiation heat transfer are neglected because their contributions are small compared with conduction,

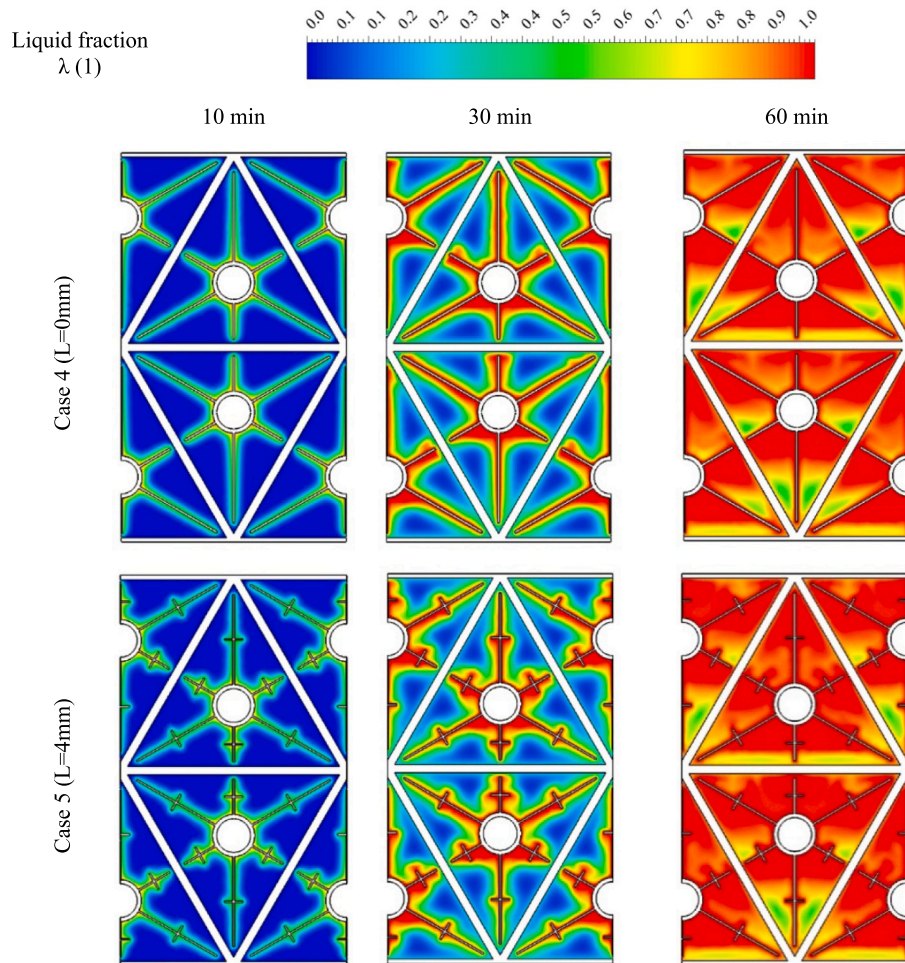


Fig. 9. Liquid fraction contours during melting for different branched fin lengths ($L = 0$ –12.5 mm) at selected times ($t = 10, 30$, and 60 min).

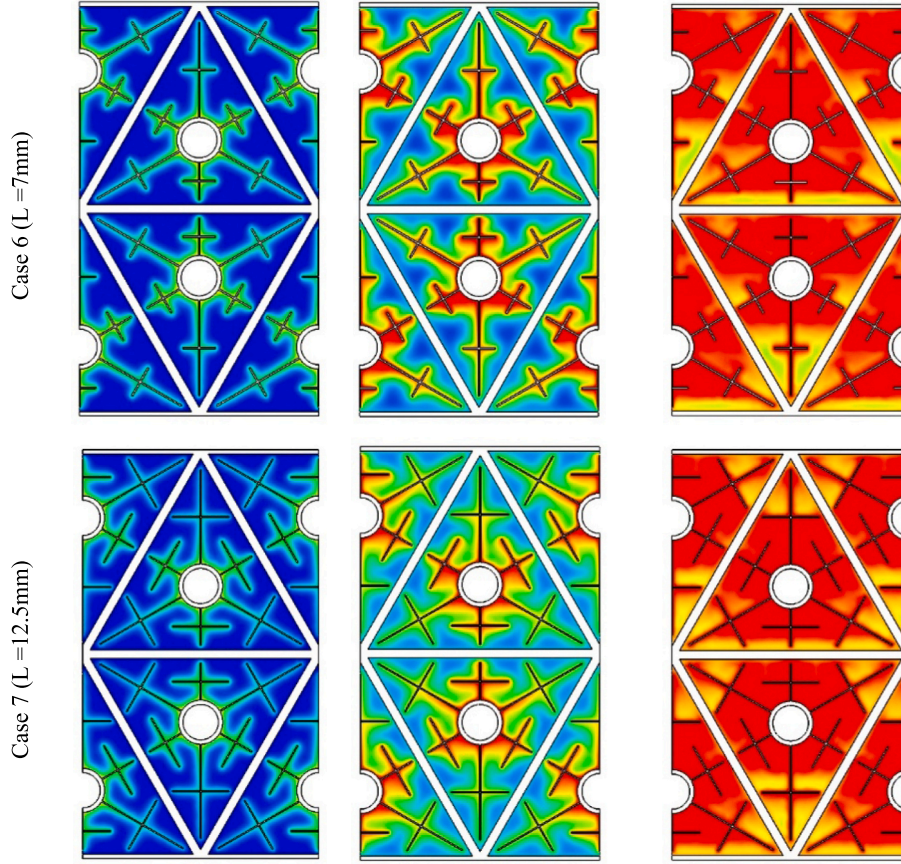


Fig. 9. (continued).

convection, and latent heat effects under the present operating conditions.

10. Heat transfer in the pipe and fins is modeled by conduction, and perfect thermal contact is assumed at the interfaces between the solid components and the PCM.

Based on these assumptions, the governing equations for mass, momentum, and energy conservation are written as follows.

The continuity equation for the incompressible PCM is written as Eq. (1):

$$\nabla \cdot \vec{V} = 0 \quad (1)$$

where $\vec{V}$ represents the velocity vector of the liquid phase of the PCM. The transport of momentum in the molten region is governed by Eq. (2) [62]:

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot (\nabla \vec{V}) = \frac{1}{\rho} \left[-\nabla P + \mu (\nabla^2 \vec{V}) - \rho \beta (T - T_{ref}) \vec{g} - \vec{S}_m \right] \quad (2)$$

In this formulation, ρ denotes the density of the PCM, P is the pressure, and μ represents the dynamic viscosity. Buoyancy effects are incorporated using the Boussinesq approximation, in which β is the coefficient of thermal expansion, T is the local temperature, and T_{ref} is a reference temperature. The term $\vec{S}_m$ accounts for the momentum sink in the mushy region and progressively reduces the velocity as the phase change proceeds toward solidification [63,64].

The resistance force is expressed Eq. (3) as:

$$\vec{S}_m = \frac{A_m}{\lambda^3 + \delta} (1 - \lambda)^2 \vec{V} \quad (3)$$

where A_m denotes the Darcy coefficient associated with the mushy region, λ is the liquid fraction, and $\delta = 10^{-5}$ is a small numerical constant introduced to avoid numerical singularity. This treatment enforces a gradual attenuation of fluid velocity as the PCM undergoes solidification. Consistent with commonly reported values in previous studies, the Darcy term for the mushy zone was specified using $A_m = 10^5 \text{ Pa s m}^{-2}$ [65].

The thermal response of the PCM throughout the melting and solidification processes is described by the energy balance equation (Eq. (4)), which incorporates both conductive heat transfer and energy advection resulting from liquid-phase motion. The formulation is written in terms of enthalpy so that sensible and latent heat contributions are combined within a single governing equation. Accordingly, the temporal variation of enthalpy is linked to convective transport induced by the molten PCM, whereas thermal diffusion is modeled using an effective thermal conductivity [66].

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T \right) = \nabla \cdot (k \nabla T) - S_L \quad (4)$$

where T denotes the temperature, C_p is the specific heat capacity, k represents the thermal conductivity, and S_L is the volumetric latent heat source term associated with phase-change energy transfer. In the enthalpy–porosity formulation, phase-change effects are incorporated into the governing equations by means of supplementary source terms added to the conservation laws. In particular, the energy equation includes a volumetric latent heat source term S_L (presented in Eq. (5)) to represent the heat absorbed or released during melting and solidification, thereby establishing a direct coupling between the thermal field and the phase-change process. This approach allows the solid–liquid transition to be resolved on a fixed computational grid without requiring explicit interface tracking, while preserving the thermodynamic consistency

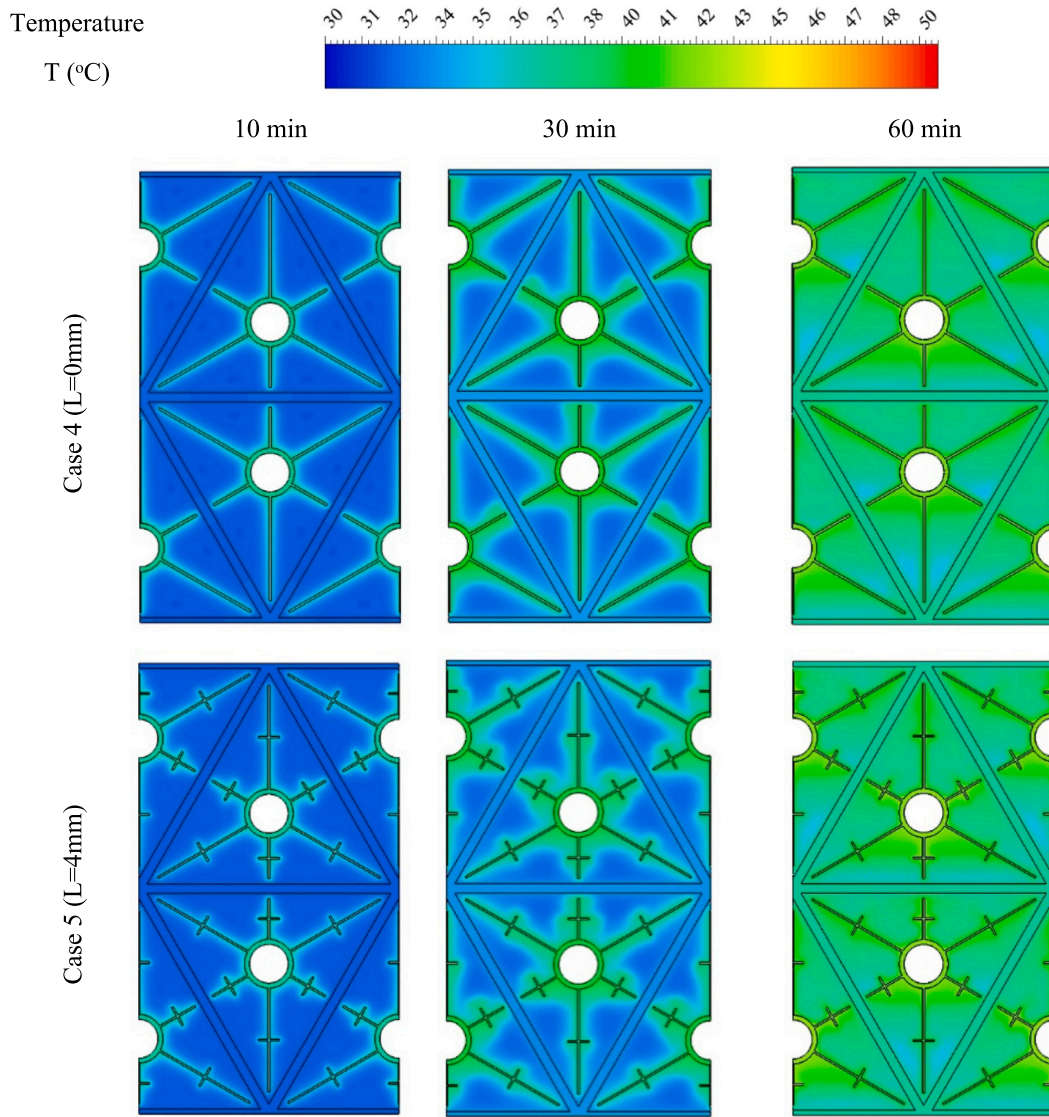


Fig. 10. Temperature contours during melting for different branched fin lengths at selected times ($t = 10, 30$, and 60 min).

inherent to the enthalpy–porosity method [67].

$$S_L = \rho L_f \left(\frac{\partial \lambda}{\partial t} + \nabla \cdot (\vec{V} \lambda) \right) \quad (5)$$

where L_f is the latent heat of fusion and λ is the liquid fraction, evaluated according to the PCM temperature relative to the solidus and liquidus temperatures by Eq. (6) as:

$$\lambda = \frac{\Delta H}{L_f} = \begin{cases} 0 & \text{if } T < T_s \\ 1 & \text{if } T > T_{lq} \\ \frac{T - T_s}{T_{lq} - T_s} & \text{if } T_s < T < T_{lq} \end{cases} \quad (6)$$

where T_s and T_{lq} correspond to the solidus and liquidus temperatures, respectively. This segmented formulation enables a smooth variation of the liquid fraction within the mushy zone, which enhances numerical robustness and provides a more accurate representation of the phase-transition behavior [68]. The total thermal energy stored in the PCM during the charging stage is determined from the variation of internal energy as:

$$E_{\text{stored}} = E_e - E_i \quad (7)$$

where E_i and E_e are the initial and final internal energies of the PCM, respectively.

In the present study, this stored energy is not reported directly; instead, it is used to define the average charging power, which serves as a performance indicator. Accordingly, the average charging power is calculated by Eq. (8):

$$\dot{E}_T = \frac{E_{\text{stored}}}{t_m} \quad (8)$$

where t_m is the total melting time. Similarly, during the solidification process, the average discharging power is defined based on the total released energy over the corresponding solidification time. In the present study, the stored or released energy is not reported as a separate cumulative energy curve; instead, it is used to define the average charging and discharging power. These average values are adopted as integral performance indicators because they provide a consistent basis for comparing different fin configurations using the total energy stored or released over the corresponding melting or solidification time. This

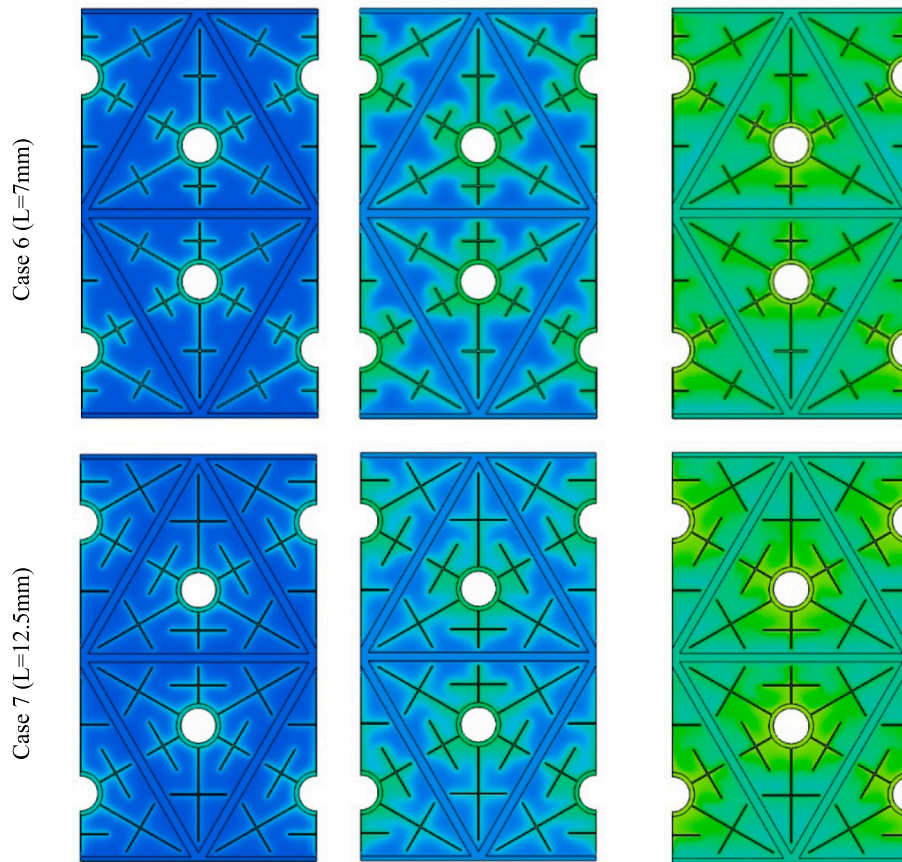


Fig. 10. (continued).

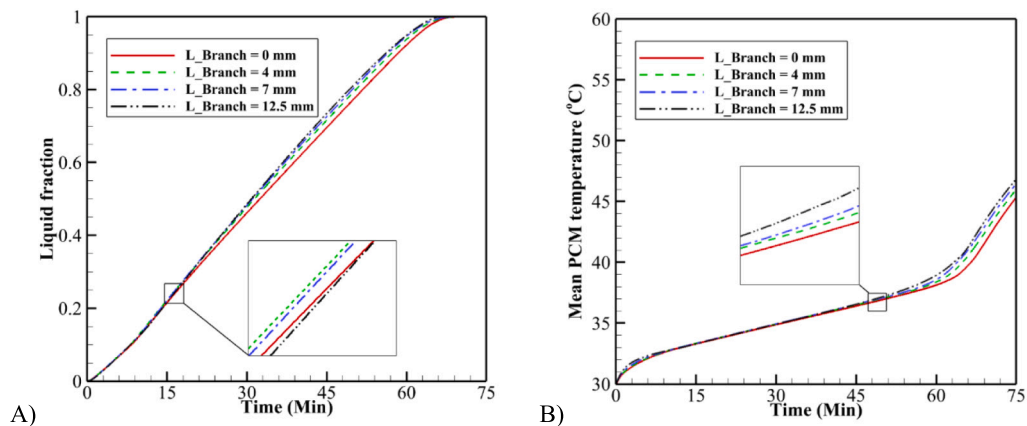


Fig. 11. Time variation of (A) liquid fraction and (B) mean PCM temperature for different branched-fin lengths. Magnified local regions are included in both panels to clarify the relatively small differences among the branch-length cases.

Table 8

Effect of branched fin length on melting performance, including melting time and average charging power for different branch lengths.

Cases	Melting time (min)	Average charging power (W)
Case 4 (L = 0 mm)	69.85	536.36
Case 5 (L = 4 mm)	69.67	541.72
Case 6 (L = 7 mm)	69.13	546.97
Case 7 (L = 12.5 mm)	67.62	555.69

choice is appropriate for the present objective, which is to rank the

relative effectiveness of different geometries rather than to optimize time-dependent system control. However, average power does not capture the instantaneous evolution of heat transfer rate during the phase-change process. In particular, it cannot distinguish between configurations that have similar total melting times but different early-stage heating rates, peak heat transfer rates, or late-stage thermal recovery behavior. Instantaneous power or cumulative energy curves would therefore be more informative for applications involving dynamic load matching, intermittent heat supply, cyclic operation, or time-dependent thermal management. These transient performance indicators are not included in the present work to keep the analysis

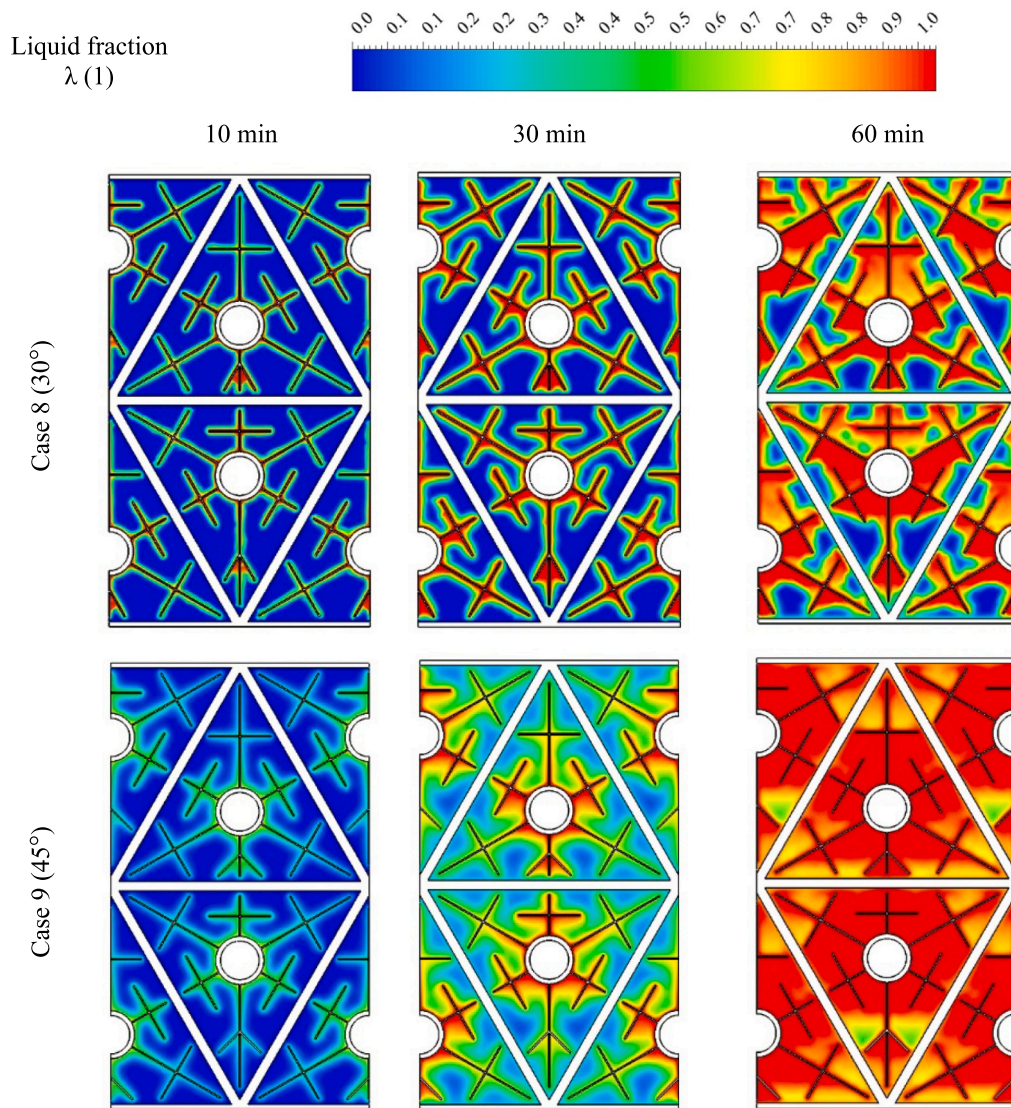


Fig. 12. Liquid fraction contours during melting for different branched fin orientations ($\alpha = 30^\circ$ – 90°) at selected times ($t = 10, 30$, and 60 min).

focused on geometry-driven phase-change enhancement, but they are identified as an important direction for future study.

It should be noted that the enthalpy–porosity method assumes the solid phase remains stationary and models the mushy region as a porous medium with high flow resistance. In reality, additional effects such as local detachment of solid fragments or density-driven motion of partially melted regions may occur, which can influence heat transfer and melting behavior. These effects are not captured in the present formulation, and therefore the model represents an approximation of the physical process. Nevertheless, the enthalpy–porosity approach is widely used and has been shown to provide reasonable accuracy for engineering-scale analysis of PCM systems.

3. Numerical implementation and validation

3.1. Numerical solution strategy

The numerical simulations were performed using ANSYS Fluent to model heat transfer coupled with phase-change phenomena. Thermal diffusion within the solid PCM and buoyancy-driven flow in the molten region were solved in a fully coupled manner, enabling the simultaneous

representation of conductive and convective heat transfer during melting. For the incompressible flow regime, the pressure–velocity linkage was treated using the SIMPLE procedure to ensure continuity satisfaction and numerical stability. A periodic boundary condition was imposed on the top and bottom boundaries of the computational domain, such that identical thermal and flow fields were enforced across these boundaries. This approach allowed the modeling of a repeating finned structure using a single representative unit, thereby significantly reducing computational cost. The validity of the periodic assumption was verified by comparing the results with simulations performed on domains composed of three and five repeated geometrical units.

The governing equations were discretized on an unstructured, cell-centered grid. Spatial gradients were evaluated using the Green–Gauss cell-based method to accurately capture variations in temperature and velocity fields. The advection terms in the momentum and energy equations were approximated using the QUICK scheme in order to limit numerical diffusion and enhance the resolution of steep thermal gradients near the phase-change interface. Pressure interpolation was performed with the PRESTO! scheme, which is well suited for buoyancy-dominated flows. Convergence of the numerical solution was ensured by imposing residual tolerances of 10^{-4} for the continuity and

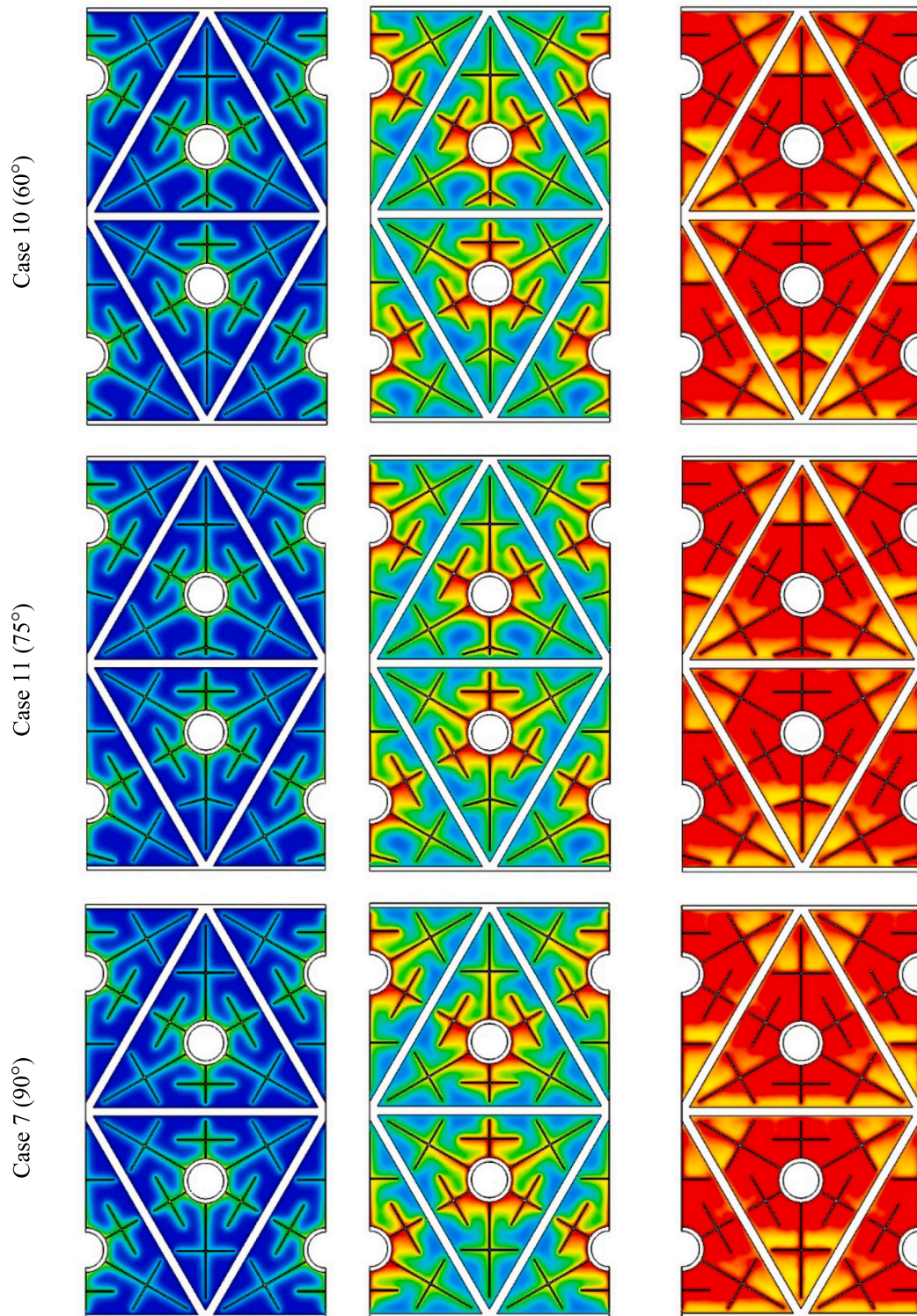


Fig. 12. (continued).

momentum equations and 10^{-6} for the energy equation, guaranteeing both numerical stability and physical consistency of the results.

Mesh and time-step independence were verified by monitoring the evolution of the liquid fraction. Four mesh sizes (approximately 20,000, 30,000, 45,000, and 100,000 cells) and four time steps (0.05, 0.1, 0.2, and 0.4 s) were examined (Fig. 3). The results showed negligible variation in the predicted melting behavior for all tested spatial and temporal resolutions, indicating that the solution is independent of both

mesh size and time step within the investigated ranges. Accordingly, a mesh with 20,000 cells and a time step of 0.4 s were adopted for all simulations to achieve an optimal compromise between numerical accuracy and computational cost. These tests confirm that the subsequent results are governed by physical phenomena rather than numerical discretization effects.

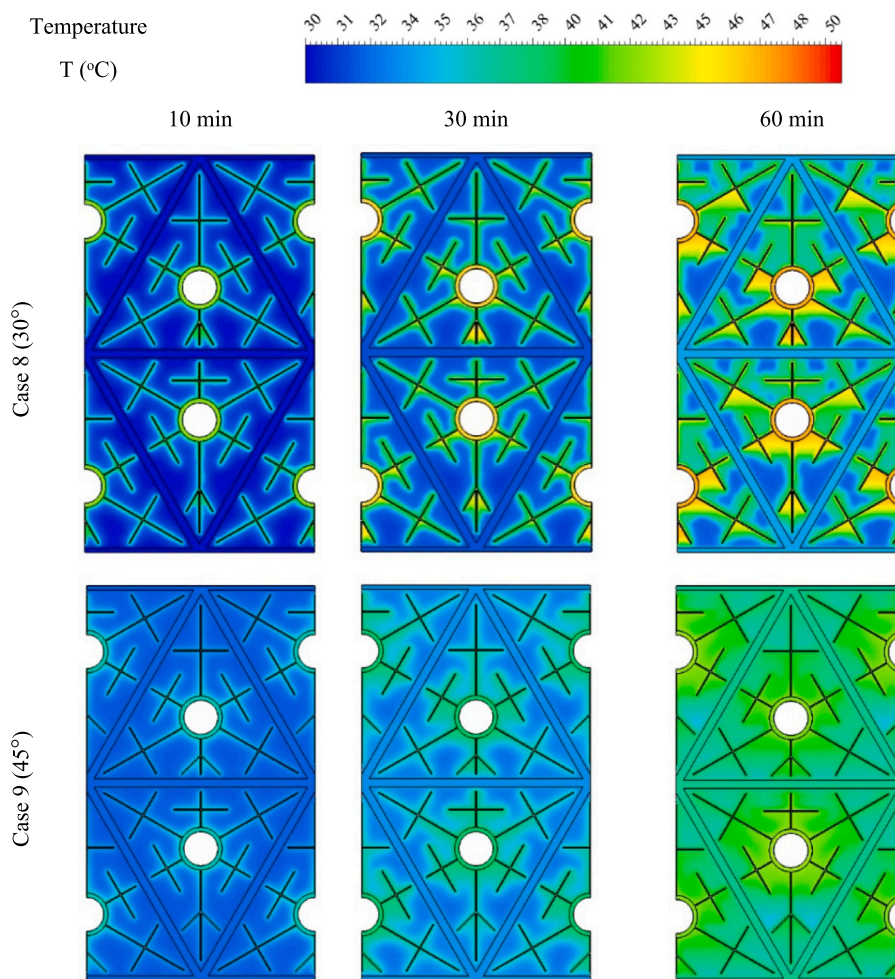


Fig. 13. Temperature contours during melting for different branched fin orientations at selected times ($t = 10, 30$, and 60 min).

3.2. Validation

The validation strategy was designed to assess both the governing phase-change physics and the applicability of the model to fin-assisted LHTES configurations. The numerical model is validated against the experimental study of Mat et al. [69], which investigates the melting behavior of a PCM in a two-dimensional rectangular enclosure. The validation case consists of a vertical rectangular cavity filled with PCM, where one vertical wall is maintained at a constant temperature above the melting point, while the remaining walls are thermally insulated. Specifically, the left wall is subjected to a constant temperature boundary condition, and the top, bottom, and right walls are considered adiabatic. The PCM is initially in a solid state at a uniform temperature below its melting point.

Natural convection is induced due to buoyancy effects arising from temperature gradients within the liquid phase, with gravity acting in the vertical direction. The melting process begins with conduction-dominated heat transfer near the heated wall, followed by convection-driven flow as the liquid region expands. The thermophysical properties of the PCM used in the validation case correspond to those reported in the reference study.

Fig. 4 presents the comparison between the present predictions and the numerical and experimental results of Mat et al. [69]. The close agreement between the present predictions and the reference data confirms that the numerical model can capture the coupled conduction–convection heat transfer behavior and phase-change evolution

during PCM melting. The predicted melting trend follows the same temporal evolution reported in the reference study, indicating that the present model correctly captures the coupled conduction–convection mechanisms governing PCM melting. Minor deviations can be attributed primarily to differences in geometric configuration and flow development between the present periodic finned structure and the triplex-tube geometry adopted in Ref. [69].

A quantitative comparison of the mean PCM temperature at selected time instants is provided in Table 5. The average relative deviation between the present results and the numerical data of Mat et al. [69] is approximately 0.9%, while the deviation with respect to the experimental measurements remains below 6.5%. These discrepancies are considered acceptable for phase-change simulations involving natural convection and complex melting fronts. Overall, the agreement confirms the accuracy and robustness of the present numerical framework for predicting melting behavior in fin-enhanced PCM systems.

Although the geometry and boundary conditions of the validation case differ from those of the present branched fin configuration, this benchmark problem is widely used for validating numerical models based on the enthalpy–porosity method. Therefore, agreement with this case confirms the ability of the present model to accurately capture the coupled heat transfer and phase-change phenomena.

A second validation is conducted against the experimental study of A. Al-Abidi et al. [70], which investigates the melting and solidification behavior of a PCM in a triplex-tube heat exchanger (TTHX) equipped with internal and external fins. The system consists of three concentric

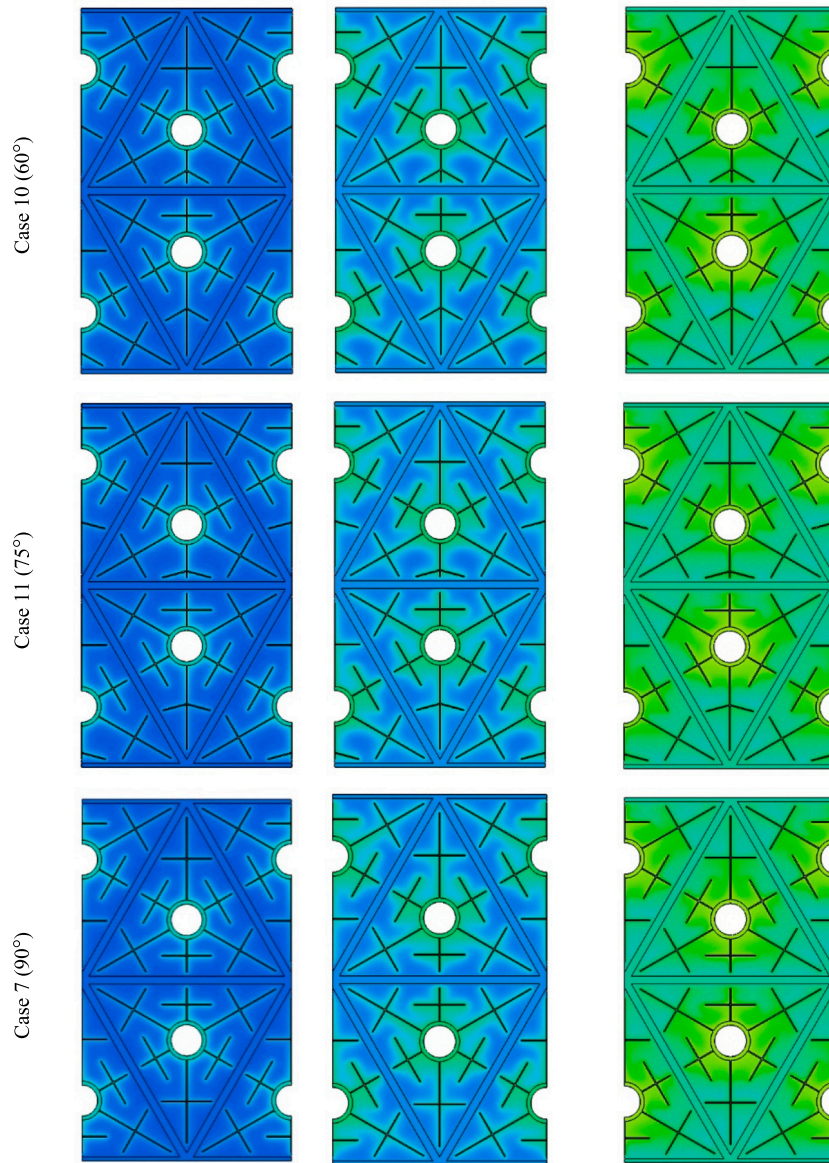


Fig. 13. (continued).

Table 9

Effect of branched fin orientation on melting performance, showing variations in melting time and average charging power for different branch angles.

Cases	Melting time (min)	Average charging power (W)
Case 8 (30°)	125.03	326.83
Case 9 (45°)	68.39	552.83
Case 10 (60°)	67.13	558.48
Case 11 (75°)	66.70	560.06
Case 7 (90°)	67.62	555.69

tubes, where the PCM is located in the annular region between the inner and outer tubes, and HTF flows through the inner and outer channels. During the charging process, hot water is circulated through the heat transfer channels at a constant inlet temperature (typically in the range of 85–100 °C), while during discharging, cooling water at a lower temperature is supplied.

The PCM is initially at a uniform temperature close to ambient conditions, below its melting point, and the melting process is initiated by the imposed HTF temperature. Heat transfer occurs through both conduction and natural convection within the liquid PCM, while the

presence of internal and external fins enhances thermal diffusion and accelerates phase change. The system includes thermocouples distributed along radial and angular positions to capture temperature evolution during both charging and discharging processes.

To provide a quantitative assessment of the second validation, the temperature values in Fig. 5 reported by Al-Abidi et al. [70], and the corresponding deviations are summarized in Table 6. The mean absolute error is approximately 1.17 °C for melting and 0.36 °C for solidification, corresponding to mean relative errors of 1.75% and 0.45%, respectively. Considering both processes together, the overall mean absolute error is approximately 0.73 °C, with an average relative deviation of 1.04%. These small deviations confirm that the present model reproduces the temperature evolution of the fin-assisted triplex-tube LHTES validation case with acceptable accuracy.

Although the geometrical configurations and boundary conditions of the validation cases are not identical to those of the present branched-fin REU, the selected benchmarks are appropriate because they validate the governing physical and numerical components required in the present model. The rectangular-cavity benchmark of Mat et al. [69] is used as a fundamental phase-change validation case because it directly tests the

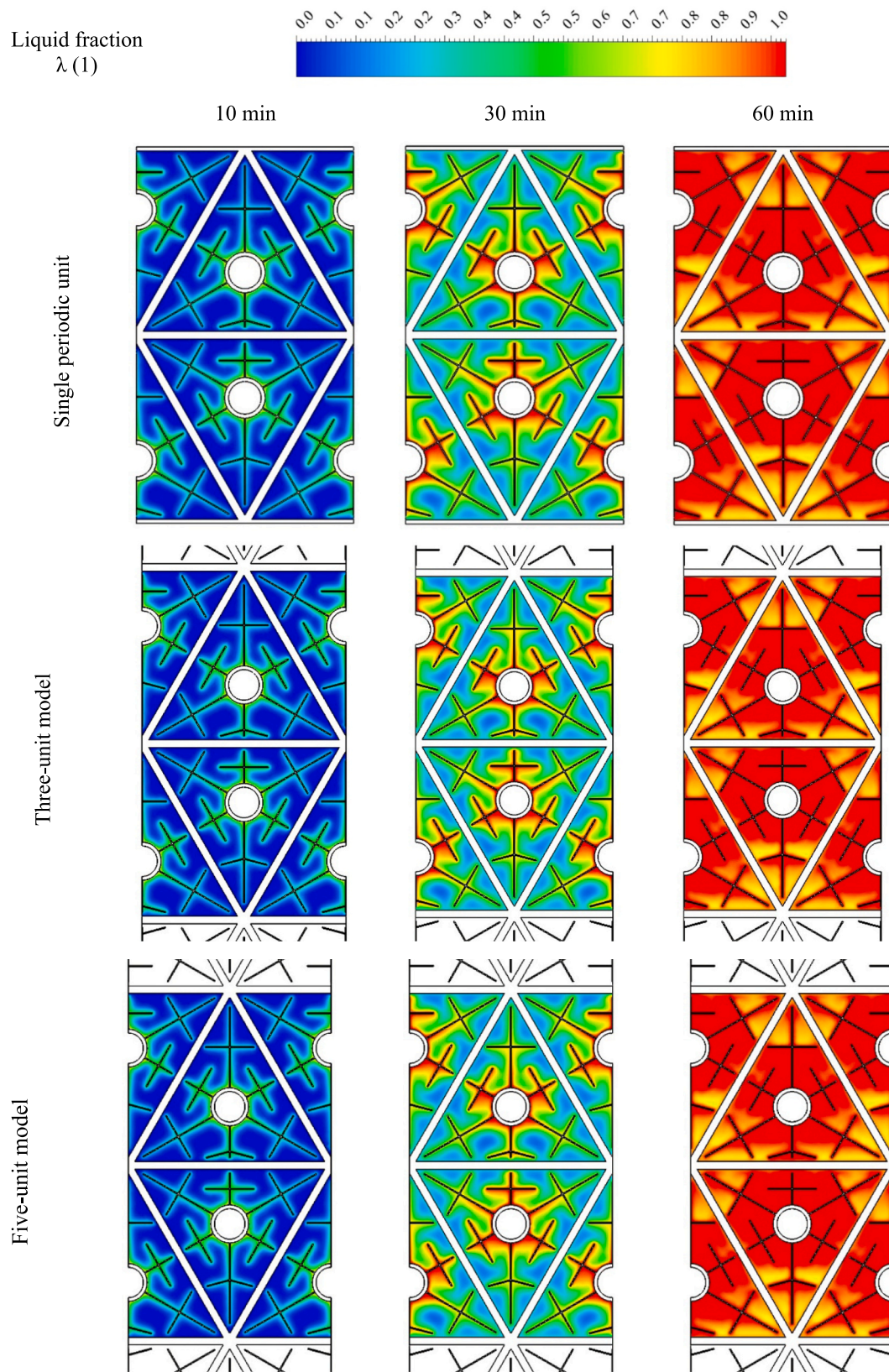


Fig. 14. Liquid fraction contours during melting for periodic models with different numbers of vertically repeated units (single-unit, three-unit, and five-unit configurations).

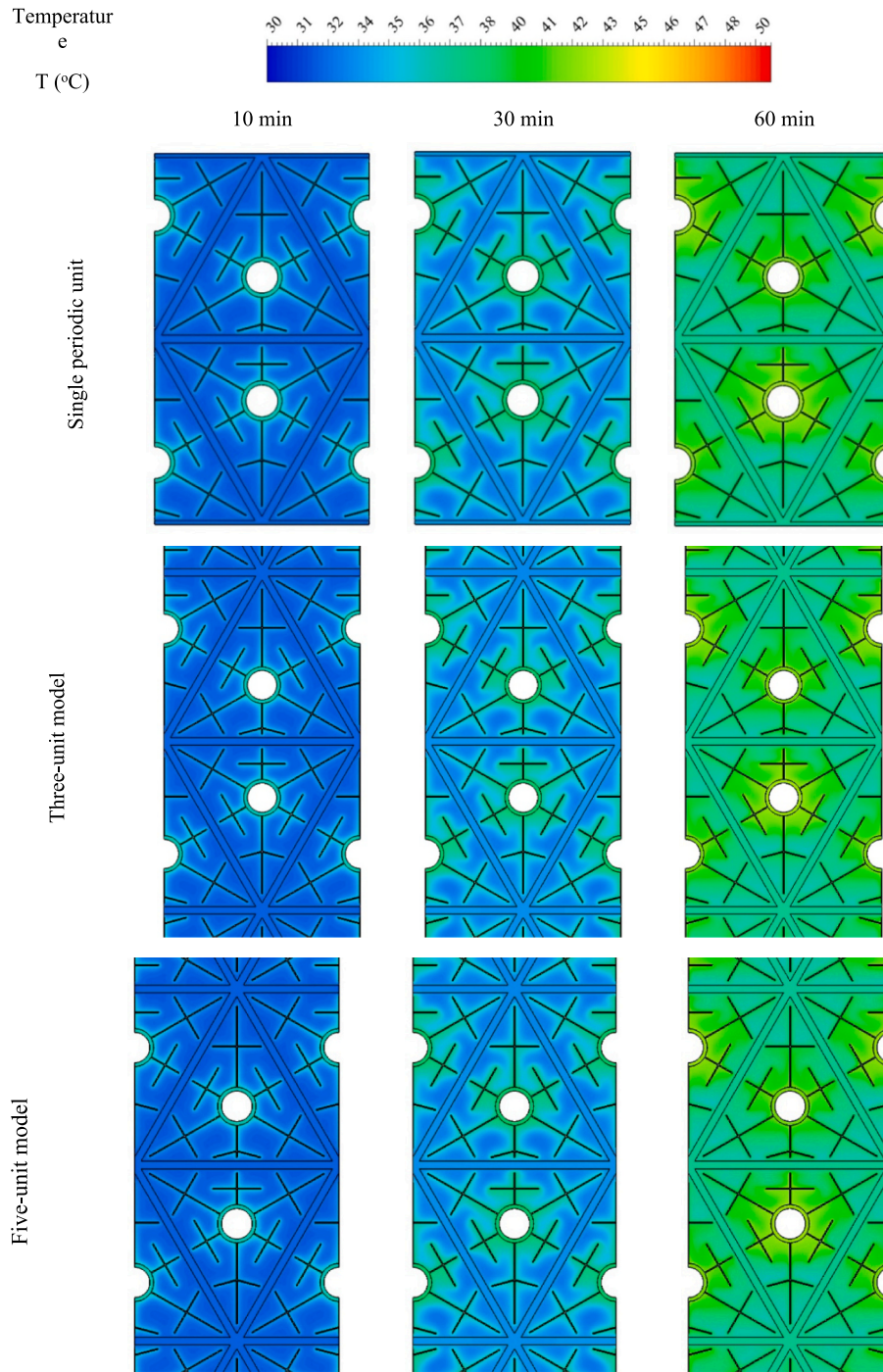


Fig. 15. Temperature contours during melting for periodic models with different numbers of vertically repeated units.

enthalpy–porosity formulation, liquid-fraction evolution, melting-front propagation, and buoyancy-driven natural convection in a two-dimensional PCM domain. These are the core mechanisms governing the present simulations. However, this benchmark is not intended to validate the branched-fin geometry itself. For this reason, a second validation is included using the finned triplex-tube LHTES experiment of Al-Abidi et al. [70], which involves conductive heat transfer through fins, melting and solidification of PCM, and temperature evolution in a fin-assisted thermal storage configuration. Therefore, the two external benchmarks provide complementary validation: Mat et al. [69] verifies the phase-change and natural-convection physics, while Al-Abidi et al. [70] verifies the model performance for a fin-assisted LHTES system. In addition, the geometry-specific validity of the present periodic

branched-fin representation is examined separately by comparing the REU model with three- and five-unit branched-fin domains. Thus, the validation strategy does not rely solely on a simple rectangular cavity; rather, it combines physics-level validation, finned-LHTES validation, and configuration-specific REU verification.

The importance of buoyancy-driven convection during melting was evaluated using the Rayleigh number, defined as $Ra = g\beta\Delta T L_c^3 / (\nu\alpha)$, where $g = 9.81 \text{ m s}^{-2}$, $\beta = 6.0 \times 10^{-4} \text{ K}^{-1}$, $\Delta T = T_h - T_0 = 60 - 30 = 30 \text{ K}$, $\nu = \mu/\rho$, and $\alpha = k/(\rho C_p)$. Using the RT35 properties listed in Table 4, $\rho = 815 \text{ kg m}^{-3}$, $\mu = 0.023 \text{ Pa s}$, $k = 0.2 \text{ W m}^{-1} \text{ K}^{-1}$, and $C_p = 2000 \text{ J kg}^{-1} \text{ K}^{-1}$, the kinematic viscosity and thermal diffusivity are $\nu = 2.82 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ and $\alpha = 1.23 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$, respectively. The characteristic length L_c was taken as the representative vertical dimension of the

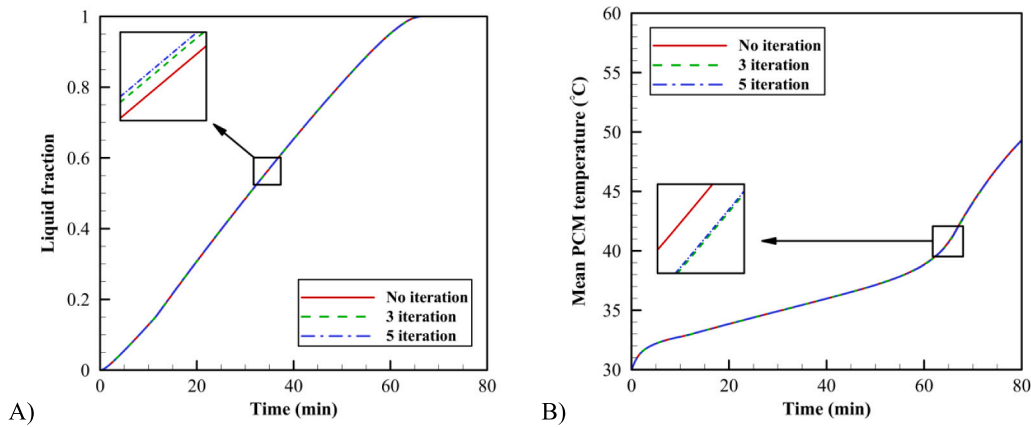


Fig. 16. Comparison of (A) liquid fraction and (B) mean PCM temperature histories for different periodic model sizes.

Table 10

Comparison of periodic model configurations with different numbers of vertically repeated units, including melting time and average charging power, used to assess the validity of the periodic assumption.

Cases	Melting time (min)	Average charging power (W)
Single periodic unit	66.70000	560.05
Three-unit model	66.76667	559.49
Five-unit model	66.76667	559.53

liquid PCM region between adjacent conducting boundaries. Because this length varies locally with the fin arrangement, L_c was estimated to be approximately 15–27 mm for the present configurations. This gives $Ra \approx 1.7 \times 10^5$ – 1.0×10^6 . Therefore, although the exact Rayleigh number is not identical for all fin configurations, all cases fall within a range where buoyancy-driven flow can significantly influence melting once a continuous liquid region is formed. Accordingly, melting is conduction-dominated at early times and becomes governed by coupled conduction and natural convection at later times.

4. Overview of melting and solidification behavior

The thermal behavior observed in this study is governed by the relative dominance of conduction and buoyancy-driven convection, which evolves during the phase-change process. At early times, heat transfer is limited by conduction through the solid PCM, whereas at later stages the formation of a continuous liquid region enables buoyancy-driven convection to contribute substantially to heat redistribution. Consequently, the effectiveness of each geometric parameter depends on how it modifies either conductive heat penetration or the structure of the convective flow field.

The results demonstrate that internal fin geometry plays a critical role in overcoming the low thermal conductivity of the PCM and improving both melting and solidification behavior. Increasing the number of fins enhances conductive heat spreading, while branched extensions improve spatial distribution of thermal energy within the PCM domain. In addition, branch orientation significantly influences heat transport pathways, with intermediate-to-high angles providing more effective coupling between conduction and natural convection. The periodic boundary approach is also validated, confirming that a single representative unit accurately captures the thermal response of vertically extended systems. These findings highlight the strong sensitivity of phase-change behavior to fin geometry and provide guidance for the design of fin-assisted LHTES systems.

4.1. Melting behavior and thermal performance

4.1.1. Role of main fin number in melting enhancement

As shown in Figs. 6–8, the effect of increasing the number of main fins is governed by two competing mechanisms: enhancement of conductive heat spreading and progressive restriction of the liquid flow space. When only a few fins are present, heat transfer from the pipe to the PCM remains highly localized, and melting proceeds slowly because a large fraction of the domain must still be heated through the low-conductivity PCM. Increasing the number of fins introduces additional conductive pathways that distribute thermal energy more uniformly into the PCM, thereby reducing the characteristic conduction distance and accelerating the formation of molten regions away from the pipe wall. This promotes earlier development of buoyancy-driven flow and shortens the conduction-dominated stage of melting.

The nonlinear trend observed with fin number indicates that the benefit of adding fins is not unlimited. At low fin counts, each additional fin significantly improves thermal penetration because it opens a new route for heat diffusion into previously poorly heated regions. However, as the PCM domain becomes increasingly partitioned, the available space for convective circulation between neighboring fins is reduced. Under these conditions, the gain from further increasing fin number becomes smaller because the conductive advantage of more fins begins to compete with the weakening of natural-convection transport. The six-fin configuration therefore performs best within the studied range because it provides strong conductive coverage without yet suppressing the buoyancy-driven motion to the extent that the net benefit is lost.

These qualitative observations are confirmed by the quantitative results in Fig. 8 and Table 7. The melting time decreases from 134.55 min for the no-fin case to 69.85 min for the six-fin configuration, while the average charging power increases from 288.26 W to 536.36 W. However, the improvement is nonlinear with respect to fin number: the performance gain obtained when increasing the fin count from three to four is larger than that obtained when increasing it from five to six. This behavior suggests that once the PCM domain becomes sufficiently partitioned by fins, further subdivision yields diminishing enhancement because convective transport becomes constrained by reduced flow space. This indicates that fin number should be selected to achieve effective thermal spreading without excessively obstructing natural convection pathways.

4.1.2. Geometric influence of branched fin length on melting performance

As illustrated in Figs. 9–11 and summarized in Table 8, the influence of branch length is primarily associated with how deeply the solid conductive network penetrates into the PCM domain. As the branch length increases, thermal energy is delivered more directly to regions that would otherwise be reached only through conduction across the

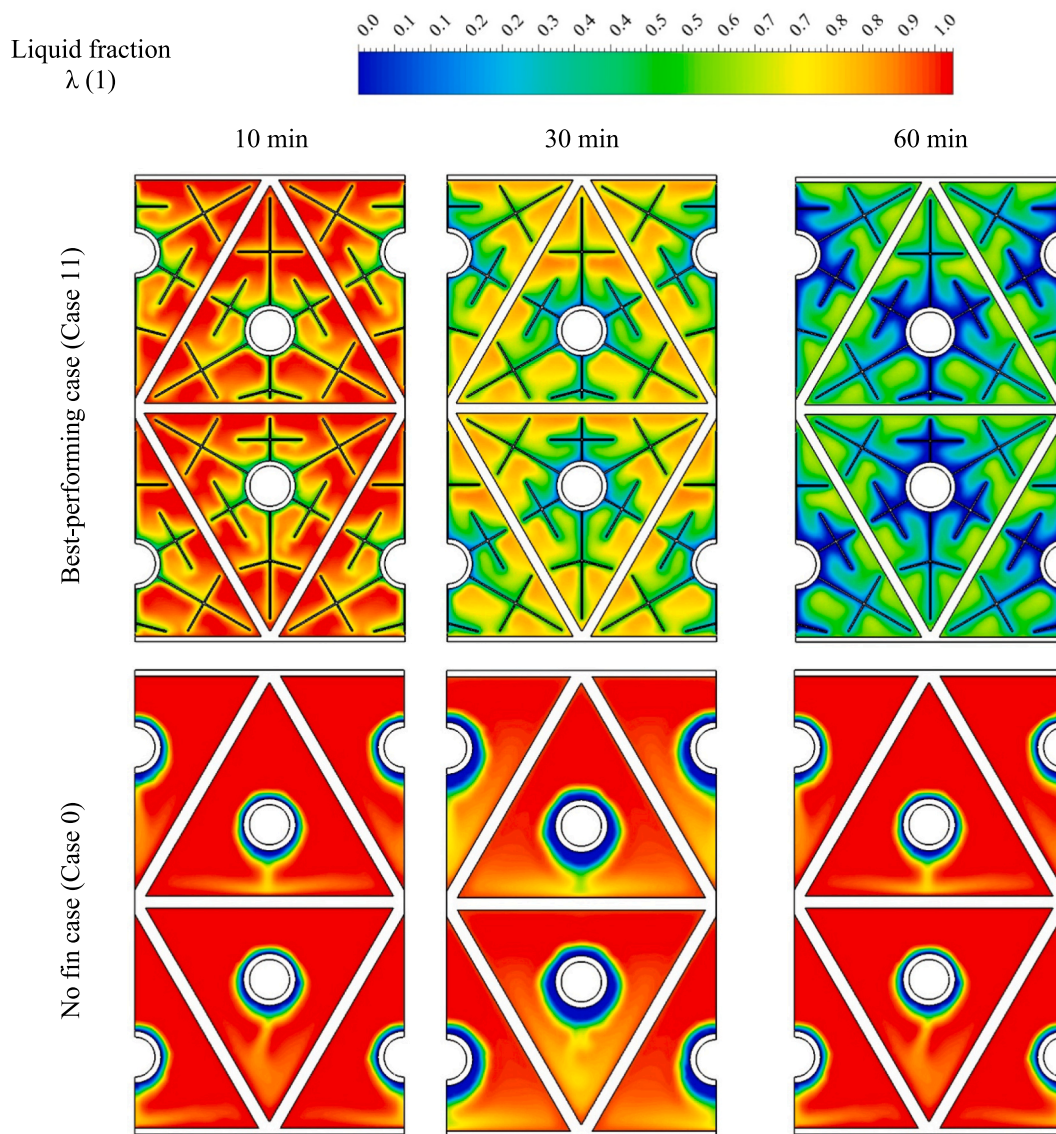


Fig. 17. Liquid fraction contours during solidification for the branched fin configuration (Case 11) and the unfinned reference case (Case 0) at selected times ($t = 10$, 30, and 60 min).

PCM. This reduces the thermal resistance between the heated pipe and the colder outer PCM regions and promotes a more distributed melting front. In physical terms, longer branches act as internal thermal bridges that expand the effective heated perimeter and shift heat delivery away from the pipe vicinity toward the bulk PCM.

Despite this beneficial role, the improvement associated with increasing branch length remains relatively modest because the governing bottleneck changes during melting. Once the branches become sufficiently long to reduce the dominant conduction distance, further extension does not produce a proportional reduction in melting time. At that stage, the limiting resistance is no longer primarily the delivery of heat through the solid network, but rather the redistribution of thermal energy within the molten PCM by convection. This explains why the reduction in melting time from 69.85 to 67.62 min is much smaller than the variation caused by branch angle. In other words, branch length improves geometric reach, but it does not strongly control the alignment between heat transfer and the buoyancy-driven transport mechanism.

The weak sensitivity to branch length also indicates that geometric extension alone is not sufficient to produce major enhancement once a minimum conductive coverage has been established. While longer branches increase the contact area between fin and PCM, the present

results suggest that simply enlarging this contact is less influential than controlling where and in which direction the thermal pathways are introduced. This distinction is important because it shows that surface-area increase and thermal effectiveness are not equivalent in branched fin configurations.

The quantitative results indicate that the effect of branch length is marginal rather than dominant. Increasing the branch length from 0 to 12.5 mm reduces the melting time from 69.85 to 67.62 min, corresponding to a reduction of only 3.19%, while the average charging power increases from 536.36 to 555.69 W, corresponding to an increase of 3.60%. Therefore, this difference should not be interpreted as a strong enhancement comparable to the effect of branch orientation. Instead, it indicates a weak but consistent trend: longer branches slightly extend the conductive heat transfer pathways and improve heat delivery to regions farther from the pipe. However, once the dominant conduction distance has been reduced, further branch extension provides diminishing returns because the later melting stage is increasingly controlled by thermal redistribution in the liquid PCM and by buoyancy-driven convection. The monotonic variation in both melting time and charging power suggests that the trend is physically consistent, but its small magnitude confirms that branch length is a secondary design

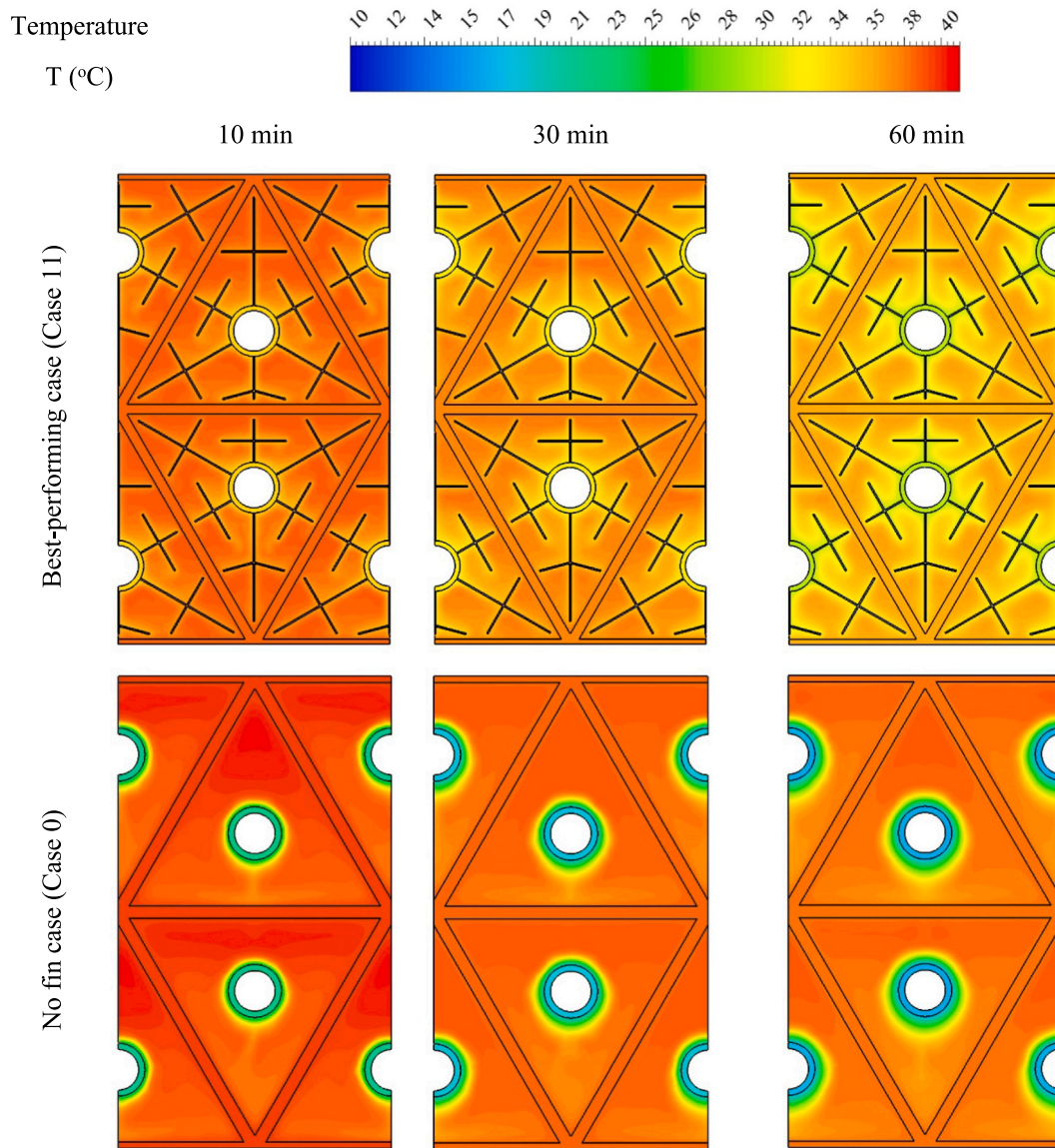


Fig. 18. Temperature contours during solidification for the branched fin configuration and the unfinned case.

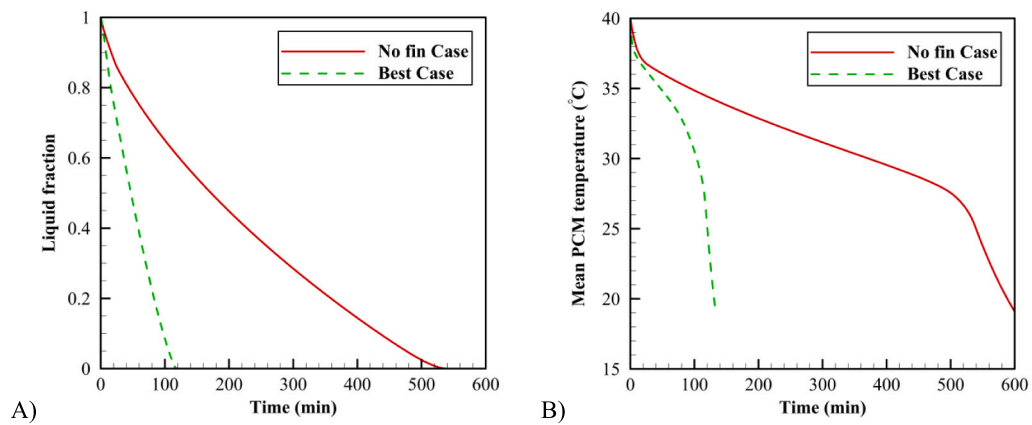


Fig. 19. Comparison of solidification histories in terms of (A) liquid fraction and (B) mean PCM temperature for the branched fin configuration (Case 11) and the unfinned case (Case 0).

parameter compared with branch orientation.

Table 11

Comparison of solidification performance between the branched fin configuration (Case 11) and the unfinned baseline case, including solidification time and average discharging power.

Cases	Solidification time (min)	Average discharging power (W)
Case 11 (shortest melting time among simulated cases)	120.75	320.92
Case 0 (No Fin)	539.73	71.58

4.1.3. Angular dependence of branched fins on melting performance

As observed in Figs. 12 and 13 and Table 9, branch orientation has the strongest influence on melting because it directly controls the interaction between fin-assisted conduction and buoyancy-driven convection. During melting, thermal energy absorbed near the pipe and fin surfaces is transported upward by the lighter, warmer liquid PCM. When the branches are oriented at larger angles, they extend in directions that are more favorably aligned with this upward transport, allowing the conductive heat pathways to support rather than oppose the dominant convective motion. As a result, the combined heat transfer process becomes more effective, and thermal energy penetrates the PCM domain more rapidly.

The poor performance of the 30° case can be interpreted as a consequence of unfavorable geometric alignment. At this shallow angle, the branches extend primarily in the lateral direction, whereas the dominant convective redistribution of heat occurs upward. This mismatch reduces the effectiveness of thermal penetration into the upper PCM region and delays the growth of a fully connected molten zone. The contour plots are consistent with this interpretation, as they show persistent unmelted regions in the upper part of the domain for the 30° configuration. Thus, the substantially longer melting time at low angles is not simply a geometric effect, but a consequence of weaker coupling between the conductive network and the natural-convection pathway.

The quantitative influence of branch angle is summarized in Table 9. The melting time decreases markedly from 125.03 min at 30° to 66.70 min at 75°, while the average charging power increases from 326.84 W to 560.06 W. These results demonstrate that angular orientation exerts a stronger influence on melting kinetics than branch length alone. Among the tested configurations, the 75° case achieves the shortest melting time and the highest average charging power, indicating that a near-vertical arrangement offers the most efficient heat transfer pathway for the present geometry.

The pronounced influence of branch orientation on melting performance can be explained by the interaction between fin-assisted conduction and buoyancy-driven natural convection in the molten PCM. During melting, the warm liquid PCM rises, and the effectiveness of the branched fins depends not only on their ability to conduct heat away from the pipe, but also on how well their orientation aligns with the dominant convective flow direction. At low branch angles, such as 30°, the branches extend mainly in the lateral direction, transferring heat into regions where natural convection is relatively weak. Under these conditions, the upper parts of the PCM domain remain less effectively heated and melting continues primarily through conduction. As the branch angle increases, the fins become more aligned with the upward convective motion, allowing the heat conducted through the fins to be delivered more directly into the path of the rising warm liquid. This improves the conduction–convection coupling and accelerates thermal redistribution throughout the PCM domain. Consequently, the melting time decreases markedly as the branch angle increases from 30° to 75°. For the near-vertical configuration, the convective alignment remains favorable, but the reduction in lateral heat spreading may slightly limit further improvement.

The superior performance at 75° suggests that there exists a favorable angular range in which the conductive branches support upward thermal transport without excessively sacrificing lateral heat distribution. At lower angles, the geometry underutilizes buoyancy-driven motion; at very steep orientations, the branches become more vertically aligned, which may slightly reduce their ability to spread heat laterally between neighboring sectors. The small difference between 75° and 90° indicates that once alignment with the convective direction becomes sufficiently strong, further increases in angle yield only marginal benefit. This explains why branch orientation produces a much larger performance variation than branch length: it controls not only where heat is conducted, but also how effectively that conducted heat couples with the dominant fluid motion.

It is noted that all branched fin configurations with varying orientation (Cases 8–11) have identical fin volume fractions, as only the branch angle is changed while keeping branch length and thickness constant. Therefore, the substantial performance variation observed across these cases (melting time ranging from 125.03 to 66.70 min) is primarily attributable to orientation effects, not to differences in fin material volume. This provides strong evidence that branch orientation influences phase-change performance independently of fin volume fraction.

These results indicate that branch orientation is the most influential geometric parameter for melting performance within the investigated

Table 12

Literature-supported qualitative comparison of representative fin configurations and the present branched-fin structure. The characteristics of previously reported straight, topology-optimized/optimized, tree-like/constructal, dendritic/fractal, bifurcated/Y-shaped, and leaf-vein/bionic fins are summarized from the literature, while the interpretation of the present configuration is supported by the numerical results of this study.

Fin type	Key characteristic	Heat transfer mechanism	Advantages	Limitations
Straight fins [31]	Uniform radial extension	Mainly conduction-dominated heat spreading	Simple design, low cost, easy fabrication	Limited thermal penetration and weak geometric adaptability
Topology-optimized / optimized fins [36,39–42]	Algorithmically or numerically optimized material distribution	Redistribution of conductive pathways according to thermal objective function	High thermal effectiveness and design flexibility	Geometry can be complex; fabrication and generalization may be difficult
Tree-like / constructal fins [38]	Hierarchical trunk–branch structure	Multi-level conduction pathway and distributed thermal penetration	Efficient heat spreading over different length scales	Complex branching network; difficult to isolate individual geometric effects
Dendritic / fractal fins [40,41]	Multi-scale recursive branching	Enhanced conduction and distributed heat diffusion	High surface area and improved spatial heat distribution	Increased geometric complexity and manufacturing cost
Bifurcated / Y-shaped fins [45]	Split or bifurcated branches from primary fins	Extended conduction paths with improved local thermal distribution	Better penetration than simple straight fins; moderate complexity	Coupled effects of branch length, angle, and surface area are difficult to separate
Leaf-vein / bionic fins [46]	Network-like bio-inspired distributed structure	Distributed heat transfer pathways similar to vascular networks	Efficient thermal spreading and improved coverage of PCM domain	Difficult to manufacture and may require complex optimization
Present branched fins	Single-level controlled branching	Coupled conduction and buoyancy-driven convection through adjustable branch orientation	Adjustable geometry; independent control of fin number, branch length, and branch orientation; directional heat spreading	Limited hierarchical distribution compared with fractal or biomimetic networks

range, whereas branch length plays a secondary role. This distinction suggests that effective thermal enhancement depends more strongly on the directional alignment of conductive pathways with buoyancy-driven flow than on geometric extension alone.

4.1.4. Assessment of periodic boundary modeling

As shown in Figs. 14–16 and Table 10, the applicability of the periodic representation can be explained by the local nature of the heat transfer processes governing melting in the present geometry. Heat enters the system through the pipe wall and is redistributed within each repeated unit through a combination of fin-assisted conduction and confined buoyancy-driven convection. Because the fin arrangement partitions the PCM into repeating thermal sectors, the characteristic flow and temperature structures tend to develop within each unit rather than across multiple stacked units. Consequently, increasing the modeled vertical extent produces negligible changes in the thermal response of the central unit under the present boundary conditions.

The small difference between the single-unit, three-unit, and five-unit models indicates that thermal and hydrodynamic interactions across the periodic interfaces are weak for the investigated configuration. This suggests that the characteristic convection cells are largely confined within the representative unit and do not strongly depend on long-range vertical communication between adjacent units. In practical terms, the periodic model is appropriate here because the dominant length scale of the melting dynamics is set primarily by the local fin geometry and pipe-to-PCM heat transfer structure, rather than by the total modeled height. The close overlap of liquid fraction and mean temperature histories therefore provides physical and numerical support for treating a single repeated unit as representative of the vertically extended system.

However, this conclusion is specific to geometries and operating conditions in which the repeated units are identical and the vertical boundary conditions remain periodic. The REU approximation may become less accurate for non-uniform fin spacing, axially varying HTF temperature, finite-length storage units with strong inlet/outlet effects, asymmetric heating/cooling, or configurations in which large-scale convection cells extend across multiple repeated units.

Physically, this behavior indicates that buoyancy-driven convection remains confined within each repeated unit because the fin structure suppresses the formation of large-scale vertical circulation. The flow cells generated during melting close locally within each unit and do not extend across the periodic interfaces. As a result, thermal and hydrodynamic coupling between stacked units is negligible, and increasing the number of repeated units does not introduce additional heat transfer resistance or enhancement beyond that already captured within a single unit.

A quantitative comparison further supports this conclusion. As shown in Fig. 16 and summarized in Table 10, the time evolution of liquid fraction and mean PCM temperature for the single-unit, three-unit, and five-unit configurations overlap closely. The resulting differences in melting time and average charging power are below 0.1%, which is within the numerical uncertainty of the discretization scheme and confirms convergence of the periodic representation. Such agreement demonstrates that the periodic boundary condition accurately reproduces the thermal behavior of a vertically repeated finned structure.

These results establish that a single periodic unit constitutes REU for the present LHTES configuration, capturing the essential heat transfer and phase-change physics of a vertically extended system. Therefore, the use of periodic boundary conditions provides a physically valid and computationally efficient means of modeling the melting process in vertically extended systems without compromising accuracy.

The validity of using a single periodic REU to represent vertically extended finned systems is assessed by comparing the melting behavior of single-unit, three-unit, and five-unit domains. As shown in Fig. 16, the liquid fraction and mean temperature histories for all three models

overlap nearly identically. Quantitatively, the maximum deviation in melting time and average charging power between the single-unit and multi-unit models is below 0.1% (Table 10). This negligible difference confirms that thermal and hydrodynamic interactions across periodic interfaces are insignificant, the characteristic convection cells close within each repeated unit and do not depend on the total modeled height. Physically, this occurs because the fin arrangement partitions the PCM into repeating thermal sectors, and buoyancy-driven circulation remains confined within each unit. Therefore, a single REU constitutes a physically consistent and computationally efficient representation of the vertically extended system.

The nearly identical results obtained for the single periodic unit, three-unit model, and five-unit model confirm the validity of the periodic-domain assumption. The melting time changes only from 66.70 min for the single periodic unit to 66.77 min for the three- and five-unit domains, corresponding to a deviation of less than 0.1%. Similarly, the average charging power varies only from 560.05 W to approximately 559.5 W. These negligible differences indicate that the imposed periodic/symmetry conditions do not artificially alter the thermal response of the system. Instead, they show that the dominant conduction pathways, melting-front development, and buoyancy-driven flow structures are generated locally within each repeated unit. Therefore, the single REU is sufficient to represent the vertically repeated branched-fin configuration while substantially reducing computational cost.

4.2. Analysis of solidification and discharge enhancement

The strong reduction in solidification time produced by the branched-fin configuration arises from a shift in the dominant heat transfer mechanism relative to melting, as shown in Figs. 17–19 and Table 11. During solidification, convective transport rapidly weakens as the liquid fraction decreases and the mushy region expands. Under these conditions, heat removal is governed mainly by conduction from the remaining liquid PCM toward the cold pipe and fin surfaces. The fins therefore act as an internal conductive network that shortens the distance over which latent heat must be transported before it can be extracted. This effect is significantly more pronounced than in the unfinned case, where large regions of PCM remain thermally remote from the pipe wall and can solidify only slowly through conduction across the low-conductivity medium.

The branched structure further improves this process by distributing the cold conductive network deeper into the PCM domain. Rather than allowing solidification to proceed primarily as a single inward-moving front from the pipe wall, the branches create multiple locations at which heat can be removed simultaneously. This leads to a more spatially distributed freezing process, reduces the persistence of isolated liquid pockets, and promotes a more uniform temperature decline throughout the domain. The resulting improvement in solidification time is therefore a direct consequence of geometric redistribution of the conductive paths, not of any enhancement in convective transport.

Solidification analysis is presented for the branched-fin configuration that produced the shortest melting time among the simulated cases (Case 11) and the unfinned baseline configuration (Case 0). The purpose of this comparison is to evaluate whether the selected shortest-melting configuration also provides a discharge benefit relative to the lower-bound no-fin case. A full solidification parametric study over all fin numbers, branch lengths, and branch angles would provide additional information, but it is beyond the intended scope of the present work, which focuses primarily on identifying the dominant geometric mechanisms during melting and then verifying the discharge capability of the selected design. This reduced comparison is physically motivated by the fact that solidification becomes increasingly conduction-dominated as the liquid fraction decreases and buoyancy-driven motion is suppressed. Therefore, the discharge behavior is mainly governed by the presence and spatial distribution of conductive heat-extraction pathways. The

Case 11–Case 0 comparison quantifies the discharge enhancement achieved by the selected branched-fin design, while a complete solidification-based parametric assessment of all geometric parameters is identified as a direction for future work [24,25].

The comparison between melting and solidification shows that the same geometry can improve both processes, but through different mechanisms. During melting, the branches are effective because they support the coupling between conduction and buoyancy-driven convection. During solidification, their role is different: they primarily reduce conduction distances and increase the number of heat-extraction routes available to the remaining liquid PCM. This distinction is important because it shows that the effectiveness of the present branched fin design is not limited to one phase-change mode. Instead, the same geometric configuration is beneficial under both charging and discharging conditions, even though the physical reasons for the improvement are not the same.

From a system-level perspective, the enhanced solidification performance directly translates into higher discharge power and shorter recovery times between successive operating cycles. These improvements are particularly important for applications involving frequent charging and discharging, such as solar thermal storage and waste heat recovery. The present results therefore indicate that fin-design assessment should not be guided solely by melting enhancement, but should also account for the solidification stage to achieve balanced cyclic performance. The improved discharge behavior observed for the selected branched-fin configuration suggests that geometric tailoring of fins can enhance both charging and discharging performance, although a complete solidification-based parametric assessment would be required to confirm whether the same hierarchy applies to all geometric parameters.

5. Comparison with existing branched and bio-inspired fin structures

The branched fin structure considered in the present study can be interpreted within the broader class of multi-branch heat transfer enhancement strategies, including dendritic, bifurcated/fractal, and bio-inspired (leaf-vein) fin configurations reported in the literature.

The main physical distinction between the present geometry and multi-scale dendritic or bio-inspired structures lies in how thermal transport is distributed. Fractal and leaf-vein-type networks rely on hierarchical branching to spread heat across multiple spatial scales, often emphasizing surface-area increase and distributed conduction. The present geometry, by contrast, does not attempt to replicate such hierarchy. Instead, it isolates a simpler branching architecture in which the principal geometric variables can be varied independently. This allows the role of branch length and branch orientation to be separated more clearly than in more complex recursive structures, where several geometric effects are coupled.

In contrast, the present branched fin configuration adopts a simpler, non-recursive branching structure, where the number, length, and orientation of branches are independently controlled. This allows systematic investigation of geometric parameters without introducing the additional complexity associated with fully fractal or biomimetic designs. While the present structure does not replicate hierarchical branching across multiple scales, it retains the key advantage of extending thermal pathways into the PCM domain and modifying the local heat transfer patterns.

An important outcome of the present comparison is that thermal effectiveness is shown to depend not only on how much branching is introduced, but also on how that branching is oriented relative to the dominant transport mechanism. In many branched or fractal geometries, the discussion focuses primarily on increased surface area and distributed conduction. The present results suggest that, for melting in fin-assisted PCM systems, directional alignment with buoyancy-driven heat transport may be more influential than geometric complexity alone. This is why branch orientation produces a much stronger

response than branch length in the present study. The value of the proposed configuration therefore lies not in mimicking a fully hierarchical network, but in revealing that directional control of heat transfer pathways can be a dominant design feature.

As indicated in Table 12, the present branched fin configuration differs from multi-scale and bio-inspired designs by allowing independent control of geometric parameters, particularly branch orientation.

Table 12 provides a literature-supported qualitative comparison rather than a direct quantitative ranking, because the reported fin configurations differ in geometry, PCM type, boundary conditions, operating temperature range, and storage-unit scale. The comparison includes conventional straight fins, topology-optimized/optimized fins, tree-like/constructal fins, dendritic/fractal fins, bifurcated/Y-shaped fins, leaf-vein/bionic fins, and the present branched-fin configuration. The literature-based entries summarize the dominant geometric characteristics, heat transfer mechanisms, advantages, and limitations reported for each fin category. In contrast, the interpretation of the present branched-fin configuration is based on the numerical results of this study. Specifically, the results show that increasing branch length produces only a limited reduction in melting time, from 69.85 to 67.62 min, whereas changing the branch orientation reduces the melting time from 125.03 to 66.70 min and increases the average charging power from 326.84 to 560.06 W. Therefore, the purpose of the comparison is not to claim that the present design is universally superior to all advanced fin types, but to clarify its distinct contribution: a controlled branched geometry that separates the effects of fin number, branch length, and branch orientation and highlights the importance of aligning conductive pathways with buoyancy-driven convection.

As summarized in Table 12, the present branched-fin configuration is positioned as a controlled single-level branching design that enables separate assessment of fin number, branch length, and branch orientation, rather than as a universally superior alternative to more complex hierarchical or biomimetic fin structures.

6. Conclusion

This study numerically investigated branched-fin configurations in PCM-based latent heat thermal energy storage systems, with emphasis on validating a periodic REU for vertically extended finned geometries and identifying the dominant geometric parameters governing phase-change performance. The main conclusions are summarized as follows:

- The periodic REU modeling approach was validated against multi-unit domains, with deviations in melting time and average charging power below 0.1%. This confirms that a single representative unit can accurately reproduce the thermal behavior of vertically extended branched-fin systems while substantially reducing computational cost.
- Branch orientation was identified as the dominant geometric parameter. Increasing the branch angle from 30° to 75° reduced the melting time by 47% from 125.03 to 66.70 min and increased the average charging power from 326.84 to 560.06 W. In contrast, increasing branch length from 0 to 12.5 mm produced only a limited improvement from 69.85 to 67.62 min. This demonstrates that orientation-controlled coupling between conductive fin pathways and buoyancy-driven convection is more influential than branch extension alone.
- Increasing the number of main fins from 0 to 6 reduced the melting time from 134.55 to 69.85 min and increased the average charging power from 288.26 to 536.36 W. However, the improvement became less pronounced at higher fin counts because additional fins restrict the available space for natural-convection circulation.
- The selected branched-fin configuration also enhanced discharge performance relative to the unfinned baseline. The solidification time decreased from 539.73 to 120.75 min. At the same time, the average discharging power increased from 71.58 to 320.92 W. This

indicates that the proposed fin arrangement improves both charging and discharging. However, the dominant mechanisms differ: melting is governed by conduction–convection coupling, whereas solidification is primarily controlled by conductive heat-extraction pathways.

The present study indicates that directional alignment of branched fins with buoyancy-driven flow is more influential than geometric extension or surface area increase alone, providing a physically grounded design guideline: prioritize orientation control over branch length extension, and select fin count to balance conductive spreading with convective space.

6.1. Scope and limitations of the present study

The present study is limited to RT35 PCM and copper fins; therefore, the quantitative melting and solidification times may vary for materials with different latent heat, viscosity, density, or thermal conductivity. The simulations are also based on a two-dimensional periodic REU, which was validated against multi-unit domains but assumes uniform vertical repetition and consistent thermal conditions between adjacent units; therefore, it does not resolve possible three-dimensional effects near fin tips, axial ends, inlet/outlet regions, or non-periodic geometries. In addition, the enthalpy–porosity model assumes a stationary solid phase and does not capture effects such as solid detachment, fragmentation, shrinkage-induced motion, or density-driven displacement of partially melted regions. Finally, the comparison is based mainly on total phase-change time and average charging/discharging power. While these integral metrics are suitable for ranking geometric configurations, they do not capture transient heat transfer behavior, such as peak power, early-stage response, or cyclic load-matching capability. Future work should therefore include instantaneous power analysis, cumulative energy curves, cyclic operation, three-dimensional simulations, and experimental validation. In addition, the solidification analysis is limited to the selected best-performing branched-fin configuration among the simulated cases and the unfinned baseline; future work should extend the parametric analysis of branch length, branch orientation, and fin number to the discharge process.

CRedit authorship contribution statement

Rawia Ahmed: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Funding acquisition, Conceptualization. **Mohammad Hossein Heidarshenas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Hayder I. Mohammed:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hanene Guesmi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Funding acquisition, Data curation, Conceptualization. **Hany Alalfy:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition. **Jehan Habib:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Data curation. **Mohammad Ghalambaz:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been funded by Scientific Research Deanship at

University of Ha'il - Saudi Arabia through project number “RG-25 100”.

Data availability

Data will be made available on request.

References

- [1] C.C. Kwasi-Effah, O. Okpako, Comprehensive review of emerging trends in thermal energy storage mechanisms, materials and applications, *Front. Energy Res.* 13 (2025) 1651471.
- [2] N.B. Khedher, K. Hosseinzadeh, A.M. Abed, K. Khosravi, J.M. Mahdi, H.S. Sultan, H.I. Mohammed, P. Talebizadehsardari, Accelerated charging of PCM in coil heat exchangers via central return tube and inlet positioning: a 3D analysis, *Int. Commun. Heat Mass Transf.* 152 (2024) 107275.
- [3] S. Mao, Y. Liu, X. Wu, L. Zhang, J. Chen, T. Zhou, Thermal energy storage performance, application and challenge of phase change materials: a review, *Energy Storage Sav* 4 (3) (2025) 300–322.
- [4] M. Abdullah, M. Obayedullah, S.A. Musfika, Recent advances in phase change energy storage materials: developments and applications, *Int. J. Energy Res.* 2025 (1) (2025) 6668430.
- [5] J. Shen, H.I. Mohammed, S. Chen, B. Alkali, M. Luo, J. Yang, Mechanical vibration's effect on thermal management module of Li-ion battery module based on phase change material (PCM) in a high-temperature environment, *Case Stud. Therm. Eng.* 60 (2024) 104752.
- [6] Z. Ouajoua, A. Ousegui, C. Toubal, O. Rouaud, M. Havet, Phase change materials for cold thermal energy storage applications: a critical review of conventional materials and the potential of bio-based alternatives, *J. Energy Storage* 110 (2025) 115339.
- [7] M. Ghufan, D. Huitink, Advances in encapsulated phase change materials for integration in thermal management applications, *Emerg. Mater.* 8 (2025) 1–32.
- [8] P. Talebizadehsardari, K. Hosseinzadeh, H.I. Mohammed, H.A. Maarof, F.L. Rashid, H. Togun, N. Biswas, A. Al Miaari, H.M. Ali, G. Wang, X. Zhang, L. Li, Enhanced thermal management of 3D-printed heat sinks with paraffin and low-melting-point alloy for electronic cooling, *Int. Commun. Heat Mass Transf.* 174 (2026) 110885.
- [9] M.A. Said, H. Togun, A.M. Abed, N. Biswas, H.I. Mohammed, H.S. Sultan, J. M. Mahdi, P. Talebizadehsardari, Evaluation of wavy wall configurations for accelerated heat recovery in triplex-tube energy storage units for building heating applications, *J. Build. Eng.* 94 (2024) 109762.
- [10] X. Hu, P. Chen, X. Zhang, X. Gong, Y. Shuai, Y. Wang, X. Xing, X. Zheng, G. Wang, Experimental and numerical study on thermal management performance of PCM-based heat sinks with various configurations fabricated by additive manufacturing, *Renew. Energy* 232 (2024) 121069.
- [11] K. Matuszek, M. Kar, J.M. Pringle, D.R. MacFarlane, Phase change materials for renewable energy storage at intermediate temperatures, *Chem. Rev.* 123 (1) (2022) 491–514.
- [12] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, *Renew. Sust. Energ. Rev.* 13 (2) (2009) 318–345.
- [13] M. Boujelbene, J.M. Mahdi, A.M. Abed, M.S. Ghanim, K.A. Hammoodi, H. I. Mohammed, H. Togun, P. Talebizadehsardari, The potential of arch-shaped fins for energy-charge enhancement in triplex-tube heat storage: comparative analysis and optimization, *J. Energy Storage* 79 (2024) 110188.
- [14] S. Mehryan, M.H. Heidarshenas, A. Hajjar, M. Ghalambaz, Numerical study of melting-process of a non-Newtonian fluid inside a metal foam, *Alex. Eng. J.* 59 (1) (2020) 191–207.
- [15] X. Hu, P. Chen, X. Guo, X. Zhang, Numerical investigation on thermal behavior of PCM embedded in structured porous fins (SPFs) with various configurations and materials, *Appl. Therm. Eng.* 274 (2025) 126617.
- [16] X. Dai, L. Zeng, Q. Zhang, H. Su, X. Li, C. Zhou, Y. Li, Thermal performance study of a cascaded heat storage device based on solid-liquid interface information of phase change materials, *J. Energy Storage* 135 (2025) 118363.
- [17] S.K. Gupta, S. Kumari, A.P. Singh, A review on recent development and applications of nano-enhanced phase change material in thermal management system, *Energy Storage Sav.* 5 (2) (2026) 100138.
- [18] X. Zhai, Z. Xu, W. Zhang, Q. Zhang, X. Yang, J. Qu, G. Liu, B. Yu, Phase change thermal energy storage: materials and heat transfer enhancement methods, *J. Energy Storage* 123 (2025) 116778.
- [19] B.K. Choure, T. Alam, R. Kumar, A review on heat transfer enhancement techniques for PCM based thermal energy storage system, *J. Energy Storage* 72 (2023) 108161.
- [20] X. Zhu, Y. Li, Q. Zhu, Heat transfer enhancement technology for fins in phase change energy storage, *J. Energy Storage* 55 (2022) 105833.
- [21] M.A. Rahman, R. Zairov, N. Akylbekov, R. Zhapparbergenov, S.M. Hasnain, Pioneering heat transfer enhancements in latent thermal energy storage: passive and active strategies unveiled, *Heliyon* 10 (19) (2024).

- [24] H.R. Mouziraji, M.E. Tiji, A.M. Abed, A.E. Tiji, H.I. Mohammed, J.M. Mahdi, P. Talebizadehsardari, A. Keshmiri, Boosting solidification rates in a triplex-tube thermal storage system using circular fins: novel staggered and inline fin arrangements, *Heat Transf. Eng.* 46 (12) (2025) 1024–1045.
- [25] A. Zaib, A.R. Mazhar, C. Zeng, T. Talha, H.A. Saeed, Performance enhancement of latent heat storage using extended-Y-fin designs, *Thermo* 6 (1) (2025) 1.
- [26] U. Srivastava, R.R. Sahoo, Advanced fin designs for enhancement in thermal management of eutectic phase change materials in a latent heat thermal energy storage system, *Int. Commun. Heat Mass Transf.* 170 (2026) 109932.
- [27] Z. Elleuch, A.A.H. Kadhum, M.H. Heidarshenas, H.I. Mohammed, M. Bouzidi, N. Ayari, Z. Raizah, M. Ghalambaz, Thermal performance enhancement of a flat-plate latent heat thermal energy storage system using plate-mounted fins: effects of fin length, number, and shape, *Appl. Therm. Eng.* 300 (3) (2026) 131402.
- [28] C. Bianqui, A. Viedma, A. Egea, A. García, Experimental analysis of the melting and solidification patterns in a PCM encapsulation for domestic hot water production, *Appl. Therm. Eng.* 272 (2025) 126313.
- [29] Z. Du, X. Huang, Y. Li, G. Liu, X. Yang, B. Sundén, Experimental study on melting and solidification cycle of a hybrid pin fin/metal foam energy storage tank, *ASME J. Heat Transf.* 146 (8) (2024) 082401.
- [30] S.A. Abdollahi, S. Faramarzi, B. Azizi Gheshlaghchaei, S.S. Amin, M. H. Heidarshenas, H. Majidi, F. Talati, Development of freezing process of phase change materials in cylindrical thermal energy storage tanks with various fin configurations, *Sci. Rep.* 15 (1) (2025) 17896.
- [31] M. Boujelbene, H.I. Mohammed, H.S. Sultan, M. Eisapour, Z. Chen, J.M. Mahdi, A. Cairns, P. Talebizadehsardari, A comparative study of twisted and straight fins in enhancing the melting and solidifying rates of PCM in horizontal double-tube heat exchangers, *Int. Commun. Heat Mass Transf.* 151 (2024) 107224.
- [32] M.A. Said, H.S.S. Aljibori, A.M. Abed, H. Togun, H.I. Mohammed, J.M. Mahdi, P. Talebizadehsardari, N.B. Khedher, Boosting energy storage and recovery in shell-and-multitube latent heat storage systems through sunburst-distributed radial fins, *Int. Commun. Heat Mass Transf.* 167 (2025) 109360.
- [33] O. Younis, J. Shafi, S. Tiari, M. Ghalambaz, Artificial intelligence–numerical study of a 3D model of latent heat thermal energy storage with sine-shaped fins, *J. Energy Storage* 139 (2025) 118798.
- [34] F. Alimi, N.H. Alrasheedi, M.H. Heidarshenas, M. Bouzidi, M. Mohamed, K. Hajlaoui, X. Hu, M. Ghalambaz, Triangular-shell finned latent heat storage: orientation and fin-design effects, *Case Stud. Therm. Eng.* 78 (2025) 107624.
- [35] F. Alimi, N.H. Alrasheedi, M.H. Heidarshenas, H.I. Mohammed, M. Bouzidi, M. Mohamed, M. Ghalambaz, K. Hajlaoui, Multi-shell PCM heat exchangers with wavy walls and fins: parametric analysis of melting dynamics and storage efficiency, *Int. Commun. Heat Mass Transf.* 175 (2026) 111074.
- [36] F. Alimi, N.H. Alrasheedi, M. Edalatfar, J. Shafi, K. Hajlaoui, S. Chebaane, M. Bouzidi, M. Ghalambaz, Artificial intelligence-computational fluid dynamics study close contact melting of phase change materials in a finned shell-tube energy storage, *Case Stud. Therm. Eng.* 75 (2025) 107015.
- [37] J. Shafi, O. Younis, S. Tiari, M. Ghalambaz, Artificial intelligence–numerical study of melting and solidification heat transfer in a bundle of petal tubes embedded in metal foam, *Appl. Therm. Eng.* 279 (2025) 127960.
- [38] A. Arshad, A phase change material-based structural design finned heat sink: an evolutionary design for thermal management, *Int. Commun. Heat Mass Transf.* 161 (2025) 108379.
- [39] S. Marzouk, A. Aljabr, F.A. Almeahmadi, M.A. Sharaf, T. Alam, D. Dobrotă, Thermal performance enhancement of phase change material melting using innovative fins, *Therm. Sci. Eng. Prog.* 61 (2025) 103585.
- [40] T. Mills, K. Venkateshwar, S.H. Tasnim, S. Mahmud, Numerical and experimental investigation of the melting of a PCM in an enclosure having a tree-shaped internal fin, *Therm. Sci. Eng. Prog.* 48 (2024) 102434.
- [41] X. Luo, J. Gu, H. Ma, Y. Xie, A. Li, J. Wang, R. Ding, Numerical study on enhanced melting heat transfer of PCM by the combined fractal fins, *J. Energy Storage* 45 (2022) 103780.
- [42] Z. Liu, C. Li, Optimizing the geometric parameters of double branched fins for improving the melting performance of PCM, *J. Energy Storage* 118 (2025) 116284.
- [43] N.S. Dhaidan, F.N. Al-Mousawi, H.A. Al-Salami, R.Z. Homod, Melting of phase change materials in thermal storage unit with uniform and non-uniform distribution of fins, *Sol. Energy* 302 (2025) 114073.
- [44] A. Uniyal, Y.K. Prajapati, Impact of fin arrangement on heat transfer and melting characteristics of phase change material, *J. Therm. Sci.* 33 (2) (2024) 435–456.
- [45] H. Al Ali, A. Radwan, A.S. Soliman, M.A. Abdelkareem, A.G. Olabi, Melting and solidification of phase change material in a cylindrical container with Y-shaped fins, *Case Stud. Therm. Eng.* 72 (2025) 106347.
- [46] Z. Fang, C. Zhao, Thermal performance analysis of novel bionic fins in a concentric three-tube latent heat storage system, *Renew. Energy* 243 (2025) 122607.
- [47] F. Ren, L. Xin, Q. Li, Investigation on enhanced heat storage characteristics of a bio-inspired alveolar vascular fins assisted by inner-tube annular fins, *Int. Commun. Heat Mass Transf.* 175 (2026) 111206.
- [48] F. Ren, Z. Song, Q. Li, J. Wang, S. Halilovic, A combined strategy of copper foam and topology-optimized fins for latent heat storage: thermal analysis and multi-objective optimization, *Int. J. Heat Mass Transf.* 264 (2026) 128791.
- [49] F. Ren, Y. Pan, Q. Li, L. Shi, Bionic vascular fin latent heat system synergistically enhances heat transfer: parameter optimization and prediction of pulsating flow and nanofluid based on machine learning, *Energy* 337 (2025) 138452.
- [50] D. Jayathunga, H. Karunathilake, M. Narayana, S. Witharana, Phase change material (PCM) candidates for latent heat thermal energy storage (LHTES) in concentrated solar power (CSP) based thermal applications-a review, *Renew. Sust. Energ. Rev.* 189 (2024) 113904.
- [51] S. Sokakini, J.V.S. Tala, L. Nadau, A. Ilinca, D. Bougeard, Heat transfer enhancement in shell and tube latent heat thermal energy storage units for waste heat recovery applications: a 3D numerical study on melting-solidification kinetics, *Appl. Therm. Eng.* 274 (2025) 126564.
- [52] X. Zhang, C. Yu, C. Zhang, Advances in latent heat storage technology for electronic cooling, *Renew. Sust. Energ. Rev.* 215 (2025) 115614.
- [53] V. Bianco, M. De Rosa, K. Vafai, Phase-change materials for thermal management of electronic devices, *Appl. Therm. Eng.* 214 (2022) 118839.
- [54] H. Selvnes, Y. Allouche, R.I. Manescu, A. Hafner, Review on cold thermal energy storage applied to refrigeration systems using phase change materials, *Therm. Sci. Eng. Prog.* 22 (2021) 100807.
- [55] A. Ilangoan, S. Hamdane, P.D. Silva, P.D. Gaspar, L. Pires, Promising and potential applications of phase change materials in the cold chain: a systematic review, *Energies* 15 (20) (2022) 7683.
- [56] K. Merlin, D. Delaunay, J. Soto, L. Traonvouez, Heat transfer enhancement in latent heat thermal storage systems: comparative study of different solutions and thermal contact investigation between the exchanger and the PCM, *Appl. Energy* 166 (2016) 107–116.
- [57] F.P. Incropera, D.P. DeWitt, T.L. Bergman, A.S. Lavine, *Fundamentals of Heat and Mass Transfer*, Wiley, New York, 1996.
- [58] M. Bouzidi, M.H. Heidarshenas, M.H. Ali, T. Anwar, M. Mohamed, H. Khmissi, Z. Raizah, B.S. Chauhan, M. Ghalamba, Systematic design and evaluation of a shell-based latent heat thermal energy storage system with a petal shape tube, *Appl. Therm. Eng.* 290 (2026) 129905.
- [59] R. GmbH, RT35 Phase Change Material Datasheet, Rubitherm GmbH, 2024.
- [60] P. Talebizadeh Sardari, G.S. Walker, M. Gillott, D. Grant, D. Giddings, Numerical modelling of phase change material melting process embedded in porous media: effect of heat storage size, *Proc. Inst. Mech. Eng. A: J. Power Energy* 234 (3) (2020) 365–383.
- [61] J.M. Mahdi, E.C. Nsofor, Melting enhancement in triplex-tube latent heat energy storage system using nanoparticles-metal foam combination, *Appl. Energy* 191 (2017) 22–34.
- [62] A. Shahsavari, A. Goodarzi, H.I. Mohammed, A. Shirneshan, P. Talebizadehsardari, Thermal performance evaluation of non-uniform fin array in a finned double-pipe latent heat storage system, *Energy* 193 (2020) 116800.
- [63] A. Shahsavari, A. Shaham, P. Talebizadehsardari, Wavy channels triple-tube LHS unit with sinusoidal variable wavelength in charging/discharging mechanism, *Int. Commun. Heat Mass Transf.* 107 (2019) 93–105.
- [64] P. Wang, X. Wang, Y. Huang, C. Li, Z. Peng, Y. Ding, Thermal energy charging behaviour of a heat exchange device with a zigzag plate configuration containing multi-phase-change-materials (m-PCMs), *Appl. Energy* 142 (2015) 328–336.
- [65] A.A. Al-Abidi, S. Mat, K. Sopian, M. Sulaiman, A.T. Mohammad, Internal and external fin heat transfer enhancement technique for latent heat thermal energy storage in triplex tube heat exchangers, *Appl. Therm. Eng.* 53 (1) (2013) 147–156.
- [66] W.-B. Ye, D.-S. Zhu, N. Wang, Numerical simulation on phase-change thermal storage/release in a plate-fin unit, *Appl. Therm. Eng.* 31 (17–18) (2011) 3871–3884.
- [67] M. Esapour, M. Hosseini, A. Ranjbar, Y. Pahamli, R. Bahrapoury, Phase change in multi-tube heat exchangers, *Renew. Energy* 85 (2016) 1017–1025.
- [68] E. Assis, L. Katsman, G. Ziskind, R. Letan, Numerical and experimental study of melting in a spherical shell, *Int. J. Heat Mass Transf.* 50 (9–10) (2007) 1790–1804.
- [69] S. Mat, A.A. Al-Abidi, K. Sopian, M.Y. Sulaiman, A.T. Mohammad, Enhance heat transfer for PCM melting in triplex tube with internal-external fins, *Energy Convers. Manag.* 74 (2013) 223–236.
- [70] A.A. Al-Abidi, S. Mat, K. Sopian, M. Sulaiman, A.T. Mohammad, Experimental study of melting and solidification of PCM in a triplex tube heat exchanger with fins, *Energy Buildings* 68 (2014) 33–41.