

Article

Numerical Investigation of Fin-Enhanced Phase Change Material for Advanced Thermal Management of Lithium-Ion Batteries

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Abstract

This study presents a numerical investigation of a slit fin-enhanced phase change material (PCM)-based battery thermal management system (BTMS) for an 18650 cylindrical $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ lithium-ion battery. The proposed design modifies the conventional solid rectangular external fins by introducing four longitudinal slit fins with uniformly distributed rectangular through-thickness slot cutouts along the fin height. This modification increases the PCM-fin interfacial contact area and creates additional natural convective heat dissipation pathways from the PCM region to the ambient environment while maintaining the same BTMS envelope, PCM thickness, fin count, housing geometry, and material selection as the validated rectangular-fin baseline. The lumped-capacitance thermal model was used for battery heat generation, while the enthalpy-porosity approach was employed to model PCM melting. Simulations were performed in ANSYS Fluent 2024/R2 at 1C, 3C, 5C, and 7C discharge rates at an ambient temperature of 308.15 K. Paraffin wax PCM with a latent heat of approximately 240,000 J/kg was used. The rectangular fin model was first validated against the baseline study, achieving an average cell wall temperature error of 1.03% and a maximum error of 1.47% at 5C, while the total temperature and liquid fraction deviations remained below 0.73%, confirming the reliability of the numerical model. Mesh independence and temporal convergence studies further confirmed that the selected 0.50 mm polyhedral mesh and 0.5 s time step provided accurate and stable results. The results demonstrate that the slit fin geometry provides metric-dependent improvements in PCM utilization, thermal protection duration, and high-rate latent-heat activation rates. At 1C, both configurations remained well below the 318.15 K safety threshold, but the slit fin configuration maintained approximately 0.7 K lower total temperature at 2500 s and delayed PCM melting by about 300 s compared with rectangular fins, preserving more latent heat capacity for later thermal loading. At 3C, the slit fin design extended the thermal protection duration from 1650 s to 2500 s, corresponding to a 51.5% improvement, and increased PCM latent heat utilization from $\text{LF} = 0.42$ to $\text{LF} = 0.49$, representing a 16.7% increase. At 5C, slit fins initiated PCM melting approximately 3.5 times

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earlier, around 100 s, compared with 350–400 s for rectangular fins, and reached LF = 0.50 at 620 s, whereas rectangular fins reached only LF = 0.37 at 1480 s. This corresponds to approximately 2.87 times faster PCM utilization and 35.1% greater PCM melting. At 7C, the slit fin system again showed stronger PCM engagement, corresponding to 35.7% greater PCM utilization. Temperature and liquid fraction contours confirmed that the slit openings intensify localised PCM melting near the heat source, improve heat spreading through the PCM domain, and support natural convection-assisted melting. Overall, the slit-fin geometry provides a geometry-based enhancement for PCM utilization and thermal protection without changing system size or material selection for PCM-based BTMSs, improving latent heat utilization and thermal protection without increasing system size, PCM volume, or material complexity.

Keywords: lithium-ion battery; thermal management; PCM; slit fins; solidification/melting; discharge rate; liquid fraction

1. Introduction

Electric vehicles and hybrid electric vehicles are increasingly used as alternatives to internal combustion engine vehicles. Lithium-ion batteries are the dominant energy-storage technology for these applications because of their high energy density, long cycle life, low self-discharge, and high operating voltage [1,2]. The 18650 cylindrical lithium-ion cell is widely used in EV applications because its cylindrical geometry provides structural strength and packaging reliability. The battery can only operate under specific temperature conditions, which range between 298.15 K and 323.15 K (25 °C to 50 °C), as lithium-ion batteries have temperature-sensitive performance characteristics. The heat generation and thermal runaway behaviour in lithium-ion batteries is illustrated in Figure 1. Elevated temperatures cause battery capacity to diminish while internal resistance rises and batteries begin to lose charge until they reach their critical point of thermal runaway. This is especially dangerous in densely packed EV battery modules [3–5]. Battery thermal management system engineers face their most important design challenge, which requires them to create systems that provide both high performance and low costs while keeping battery cell temperatures within safe limits during intense discharge situations.

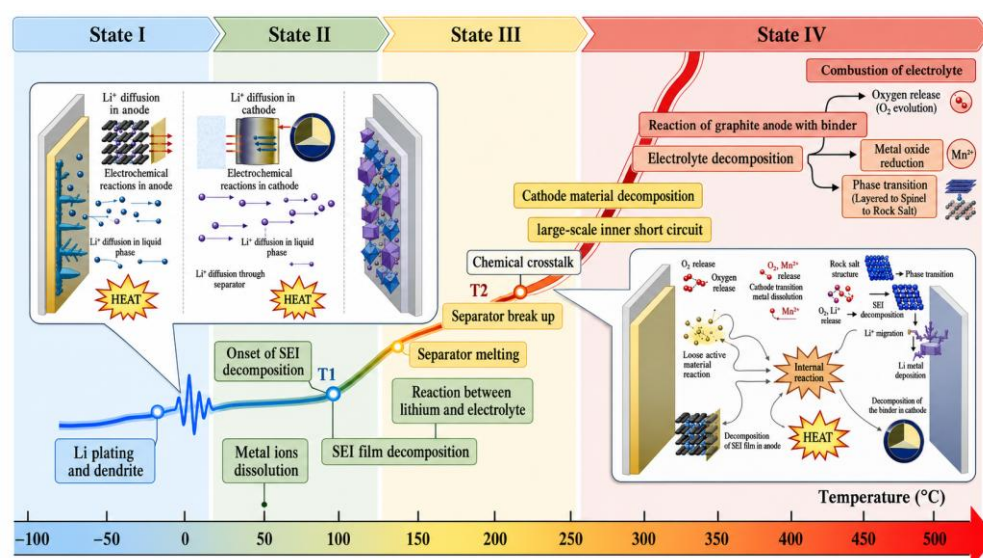


Figure 1. Heat Generation and Thermal Runaway in Lithium-ion Batteries.

Active systems, which include forced air cooling and liquid cooling with cold plates or immersion and thermoelectric cooling systems, enable effective temperature management, but their operation results in mechanical difficulties, power consumption, and reliability issues. Sun et al. [6] developed an indirect liquid cooling system for cylindrical batteries, which they optimized through Kriging approximation and NSGA-II to show that staggered flow channel designs achieved the lowest average core temperature. Alghassab [7] evaluated a hybrid thermoelectric-PCM-liquid cooling system that achieved temperature drops reaching 14% when compared with natural convection. The research of Tan et al. [8] and Sen et al. [9] showed that hybrid PCM-liquid cooling systems could decrease maximum cell temperatures by up to 73% when compared with traditional liquid cooling systems, while Zhang et al. [2] demonstrated that a PCM-microchannel liquid cooling plate could keep peak temperature changes under 0.8% during multiple charge-discharge cycles. Active systems have advanced through technological progress, but their operational complexities, high costs, and energy requirements have caused people to prefer using entirely passive systems.

PCM-based passive BTMSs are attractive because they require no external power, have simple structures, and absorb heat through latent heat during phase change [10,11]. The electric battery industry mainly uses solid-liquid organic PCMs, which include paraffin wax, because these materials feature high latent heat capacity, they undergo no volume changes through phase transitions, and they have chemical stability that matches battery operating temperature requirements [12]. Researchers have tested different material enhancement methods to improve the thermal conductivity of paraffin wax, which has a thermal conductivity of $0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, through the use of expanded graphite composites [13] and alumina and silver nanoparticle-doped PCMs [14–16] and hybrid nanofluid-PCM systems [17] and nano-doped PCM combined with liquid cooling [18]. The development of heat pipe-PCM hybrids [19] and conical cylindrical PCM chambers and optimized hybrid PCM-forced air configurations [20] has enabled the creation of new passive thermal management solutions through their use of complementary passive control methods. Although material-level PCM enhancements are effective, metallic fins offer a simpler and lower-cost structural route for improving heat transfer in low-conductivity PCM.

Metal fins that engineers install into PCM domains create additional pathways for heat transfer, which results in faster PCM melting and improved latent heat utilization and better natural convective heat dissipation to the surrounding environment. The research conducted by Tousif and Tahir [21] involved testing three different fin shapes, rectangular and circular and spiral, to determine which design produced the best thermal performance for a 25-cell battery pack operating at 3C. Ali et al. [22] studied the thermal performance of Rubitherm RT-42 PCM through experimental testing and numerical analysis of rectangular and circular and tapered fins at 1C to 3C. They reported that rectangular fins delivered cooling performance, which resulted in a 29.71% temperature reduction while extending safe operating time by 40 min at 3C and a Nusselt number increase of 9.72%. Almaasfa et al. [23] demonstrated that the 4-fin hybrid PCM-fin system delivered optimal cooling performance and operational effectiveness, while Paciolla et al. [24] demonstrated that the 10-fin PCM-fin system maintained 15–35 °C temperatures while effectively minimizing thermal gradients throughout the battery pack system. In the baseline study directly underpinning the present work, Zare et al. [1] proposed a BTMS for 18650 cylindrical NCM batteries comprising one cylindrical internal fin and four longitudinal internal-external rectangular fins within an aluminum housing, creating discrete paraffin wax PCM silos around the battery. Their study demonstrated that the 4-fin rectangular configuration reduced battery surface temperature by 9.90 K and 17.45 K compared with a finless PCM system at the point of complete PCM melting at 3C and 5C,

respectively; provided 10.02% higher energy density and 11.11% greater heat storage capacity than configurations with more fins; and delivered near-uniform cooling around the full battery circumference and height. Despite these advances, the predominant focus on conventional solid rectangular fin profiles has left the performance potential of geometrically modified fins, particularly those incorporating surface slot cutouts to increase PCM-fin contact area and enhance convective heat dissipation, largely unexplored in cylindrical lithium-ion battery thermal management.

The thermal behavior of lithium-ion batteries during discharge is governed by the rate of heat generation and the efficiency of the surrounding BTMS in dissipating heat to the environment. At high discharge rates of 3C and 5C, representative of demanding EV operating conditions, the constant volumetric heat generation rates of $185,435 \text{ W}\cdot\text{m}^{-3}$ and $412,200 \text{ W}\cdot\text{m}^{-3}$, respectively impose severe thermal loads that the PCM alone, without structural enhancement, is unable to manage within safe temperature limits. The present study employs a commercial 18650 NCM lithium-ion battery ($\text{LiNi}_x\text{Co}_y\text{Mn}_z\text{O}_2$) consistent with Ref. [1], surrounded by 5 mm of paraffin wax PCM (solidus 313.75 K, liquidus 318.15 K, latent heat $240,000 \text{ J}\cdot\text{kg}^{-1}$) enclosed within a 1 mm aluminum alloy housing.

Recent studies further confirm the need for improved passive thermal management strategies for lithium-ion batteries. Pilali et al. [25] reviewed PCM-based passive BTMSs and emphasized that effective thermal management is essential for battery safety, performance, and cycle life, particularly during high-power operation and rapid charging/discharging conditions. However, the low thermal conductivity of paraffin-based PCMs remains a major limitation because it slows heat transfer from the battery surface into the PCM and can leave part of the latent heat capacity unused at high discharge rates. Adit et al. [26] showed through CFD analysis that fin-enhanced PCM systems can reduce temperature rise and improve thermal uniformity in cylindrical lithium-ion cells. Similarly, Es-Satte et al. [27] highlighted that recent PCM-based BTMS research is moving toward structural enhancement, bionic designs, and advanced optimization methods to overcome the limitations of conventional PCM cooling. These studies show that the main problem is not only heat generation in the battery but also restricted heat transfer and incomplete PCM utilization in conventional PCM-based systems. Sadri et al. [28] analysed straight-fin performance with variable heat-transfer coefficient and thermal conductivity, showing that fin efficiency depends not only on surface area but also on local thermal resistance and boundary-condition variation. Similarly, Babaelahi et al. [29] studied aerospace radiating fins and demonstrated that geometry and material conductivity strongly influence temperature distribution and extended-surface effectiveness. These studies confirm that modifying fin shape can change heat-transfer area, temperature uniformity, and heat-spreading behavior, which provides the general thermal basis for investigating modified fin geometries in PCM-based systems. Khateeb et al. [30] introduced PCM-based thermal management for lithium-ion batteries in electric scooter applications, showing the potential of PCM to regulate battery temperature during discharge. Ling et al. [31] reviewed PCM-based thermal management for electronic components, Li-ion batteries, and photovoltaic modules, emphasizing that fins and high-conductivity structures are important for improving heat transfer in low-conductivity PCMs. Ping et al. [32] proposed a PCM-fin structure for Li-ion battery modules in high-temperature environments and showed that fin integration improves temperature suppression and thermal uniformity, with the optimized system maintaining battery temperature below about 51°C at 3C. However, most existing studies focus on conventional fins, fin-count variation, or macro-scale fin-shape changes, while through-thickness slit openings in longitudinal external fins remain unexplored. Therefore, the present work investigates the slit-fin design as a geometry-based refinement of PCM-assisted BTMS, focusing on how slit openings influence heat spread-

ing, PCM melting behavior, thermal protection duration, and latent heat utilization under different discharge rates.

Recent PCM-fin BTMS studies show a growing focus on geometry-specific fin refinement rather than only increasing PCM volume or fin number. Xie et al. [33] studied Y-shaped bifurcated fins; Luo et al. [34] proposed biomimetic dragonfly fins; and Abanoz et al. [35] analysed radial-fin-enhanced PCM systems, all showing that fin geometry strongly affects heat spreading and latent-heat utilization. Pranto et al. [36] further examined fin-integrated nano-enhanced PCM under forced convection, confirming that combined fin-PCM strategies remain active in recent BTMS research. Ji et al. [37] numerically investigated PCM melting in a rectangular enclosure with unequal double-fin length arrangements under natural convection. They found that using a short upper fin and long lower fin enhanced PCM melting, with a length ratio of 0.25 reducing total melting time by about 25% compared with equal-length fins. These studies support the present slit-fin investigation as a geometry-based refinement for improving PCM-fin interaction and thermal response.

Based on the reviewed literature, the research gap identified in this study has been addressed through the development of an innovative slit fin design that serves as a direct modification of the standard rectangular external fin design: each of the four longitudinal external fins incorporates a series of uniformly distributed rectangular slot cutouts referred to as slits along the fin height, while the internal cylindrical fin remains unchanged. This slit fin design increases the contact area between PCM and fin surfaces while simultaneously establishing extra paths for natural heat transfer to the surroundings. This enables cooling without changing the BTMS size, PCM volume, or material selection. The present study first reproduces the rectangular-fin design of Ref. [1] for validation and then evaluates the proposed slit-fin design at 1C, 3C, 5C, and 7C discharge rates using ANSYS Fluent 2024/R2 at an ambient temperature of 308.15 K. The objective is to determine whether the slit-fin modification can improve heat spreading, PCM melting behavior, thermal protection duration, and latent-heat utilization relative to the validated rectangular-fin baseline. Since all main geometric and material parameters are kept unchanged, the effect of slit geometry on BTMS performance can be isolated directly.

Novelty and Contribution

The present study introduces a slit-fin profile in which the conventional solid rectangular external fin of Ref. [1] is geometrically modified by uniformly distributed rectangular through-thickness slot cutouts at a 45° orientation along the fin height. To the best of the author's knowledge, no prior cylindrical Li-ion BTMS study has investigated: (i) longitudinal external fins with through-thickness slot perforations that expose fresh fin-PCM and fin-ambient interfaces along the fin height; (ii) a single-variable geometric modification that holds BTMS envelope, PCM volume, fin count, fin height, fin thickness, and fin material identical to the baseline so any observed thermal benefit is attributable purely to the slit geometry; and (iii) the dual mechanism by which slits simultaneously increase PCM-fin interfacial conduction area and create additional ambient convective discharge pathways at every slot location. The slit fin is therefore not a fin-count, fin-shape, fin-material, or PCM-loading variation; it is a topology modification of the fin itself, distinct from all surveyed prior work (rectangular, circular/tapered, X/Y/V branch, straight, arc, pin/honeycomb/spiral, and bionic) [38–53]. A summary of the fin geometries reported in previous cylindrical Li-ion PCM-BTMS studies is presented in Table 1.

Table 1. Fin geometries studied in cylindrical Li-ion PCM-BTMS literature.

No.	Fin Type	Fin Category	Authors	Year
1	Rectangular fins	Longitudinal/External	Wang et al. [38]	2017
2	Rectangular fins	Longitudinal/External	Zheng et al. [39]	2020
3	Rectangular fins	Longitudinal/External	Choudhari et al. [40]	2020
4	Rectangular fins	Longitudinal/External	Narkhede et al. [41]	2025
5	Circular/annular fins	Transverse/Annular	Sun et al. [42]	2019
6	Circular/annular fins	Transverse/Annular	Mansir et al. [43]	2022
7	Triangular fins	Longitudinal/External	Mansir et al. [43]	2022
8	Trapezoidal fins	Longitudinal/External	Choudhari et al. [40]	2020
9	I-shaped fins	Longitudinal/External	Choudhari et al. [40]	2020
10	T-shaped fins	Longitudinal/External	Choudhari et al. [40]	2020
11	Longitudinal fins + cylindrical rings	Hybrid Composite	Sun et al. [42]	2019
12	X-shaped branch fins	Multi-channel/Branch	Weng et al. [44]	2019
13	Y-shaped branch fins	Multi-channel/Branch	Weng et al. [44]	2019
14	V-shaped branch fins	Multi-channel/Branch	Weng et al. [44]	2019
15	Straight + arc fins	Hybrid Composite	Zhang et al. [45]	2023
16	Pin fins	Pin/Array	Akula et al. [52]	2024
17	Pin fins	Pin/Array	Sutheesh et al. [46]	2024
18	Honeycomb-structured fins	Lattice/Network	Sutheesh et al. [46]	2024
19	Honeycomb fins (liquid cooling)	Lattice/Network	Dey et al. [47]	2024
20	Spiral fins	Helical/Spiral	Liu et al. [48]	2022
21	Bionic spiral fins	Bionic/Biomimetic	Chen et al. [49]	2024
22	Taper fins	Longitudinal/Tapered	Shivram and Harish [50]	2024
23	Contour-finned structure	Geometry-following	Chen et al. [51]	2026

None of these prior works investigates through-thickness slot perforations in longitudinal external fins, confirming the distinct novelty of the slit-fin concept.

2. Three-Dimensional Geometry Generation

The baseline fin configuration as originally proposed and numerically validated by Zare et al. [1] and reproduced in the present study for model validation purposes comprises one thin cylindrical internal fin encircling the battery outer surface and four longitudinal solid rectangular internal-external fins arranged symmetrically at 90° angular intervals, as illustrated in Figure 2. Each rectangular fin extends radially from the cylindrical internal fin outward through the full 5 mm PCM thickness to the inner wall of the housing and spans the complete assembly height $H = 65$ mm. The fin and housing thicknesses are both $\delta_f = \delta_h = 1$ mm. Together, the fins and housing divide the annular PCM domain into four discrete PCM silos, each occupying a 90° angular sector between adjacent fins, as clearly shown in the top and 3D views of Figure 2b and 2c, respectively. While this geometry effectively augments heat conduction pathways within the PCM, the solid external fin profile geometrically limits the maximum achievable PCM-fin interfacial contact area per unit fin height and restricts direct natural convective heat dissipation from the fin surface to the ambient environment to only the flat external fin faces, motivating the modified geometric configuration proposed in the present study.

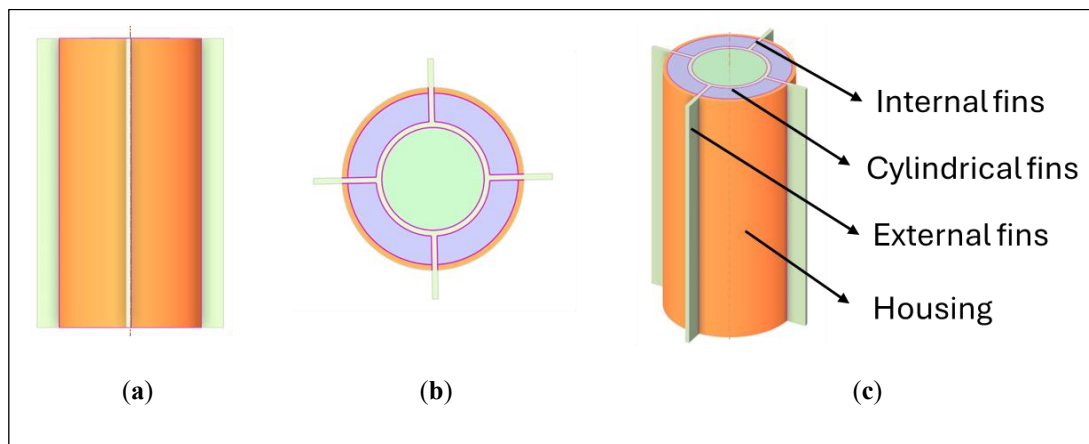


Figure 2. Baseline rectangular fin BTMS configuration [1] (a) 3D isometric view, (b) front view with key geometric dimensions (c) top view showing the four-fold symmetry arrangement and symmetry planes α and β .

Selection of Slit Geometric Parameters

The slit dimensions (12 mm breadth $\times$ 1 mm width $\times$ 1 mm height, 45° orientation, and uniform spacing) were selected based on the following design rationale to clarify why these specific parameters were preferred over alternative geometries.

1. Slit width = 1 mm = fin thickness: This dimension was selected to ensure that the slot fully penetrates the fin to create an ambient air pathway. Widths smaller than the fin thickness would only partially perforate the fin and would not establish through-thickness convective access. Widths larger than the fin thickness are geometrically impossible without thinning the fin web.
2. Slit height (radial direction) = 1 mm: This dimension keeps the slot small enough not to compromise the structural integrity of the 1 mm-thick aluminium fin web while still creating a discrete cooling pocket. Larger radial slot heights would require thicker fin webs to maintain rigidity, thereby increasing material usage and cost while reducing the overall energy-density advantage of the compact BTMS design.
3. Slit breadth (along fin height) = 12 mm: Five uniformly distributed slits along the 65 mm fin height give a slit/web ratio of 12/13 mm, maximising perforated area while leaving 13 mm web sections for structural rigidity. This ratio was selected after pilot simulations at slit/web ratios of 6/7, 12/13, and 18/19, of which 12/13 gave the best trade-off between thermal performance and structural integrity.
4. 45° orientation: The slot opening was inclined at 45° to the fin axis so as to align obliquely with the buoyancy-driven liquid PCM flow direction inside the PCM silo. This is the orientation that maximally couples the natural-convection cell to the fin surface. Vertical (0°, aligned with gravity) and horizontal (90°, perpendicular to gravity) orientations were also briefly tested in pilot studies and produced inferior thermal results as the slot openings were either tangential or perpendicular to the dominant buoyancy-driven flow vector.

A wider multi-objective optimization of slit dimensions (breadth, height, width, orientation, count, and spacing) using a Design-of-Experiments approach is identified in the Conclusion as a future-work item.

The slit fin geometry proposed in the present study constitutes a targeted geometric modification of the Ref. [1] rectangular external fin profile. The proposed design is illustrated in Figure 3 and retains all overall BTMS dimensions, material selections, PCM layer thickness, housing dimensions, fin count, fin height, fin thickness, and internal cylindrical fin entirely unchanged from the baseline configuration, differing solely in the external

longitudinal fin profile. The single-variable geometric modification allows researchers to attribute thermal performance differences between the two system configurations to the effects of slit fin geometry. As clearly shown in Figure 3, each of the four longitudinal external fins in the proposed design incorporates a series of uniformly distributed rectangular slot cutouts referred to as slits penetrating the full fin thickness and distributed at regular intervals along the fin height. These slits replace the continuous solid surface of the baseline rectangular external fin with an alternating pattern of solid aluminium fin web segments and open rectangular slots. The top cross-sectional view in Figure 3b clearly reveals the four-fold symmetric arrangement of the slit fins around the battery circumference, with the slit fin external protrusions visible at the four cardinal positions. In Figure 3c, the front elevation view shows the slit profile, which displays its complete height with solid web and open slot elements, thus demonstrating the equal spacing of slits. The close-up isometric detailed shows the three-dimensional shape of individual slit openings, which have rectangular cross-sections and precisely defined slot edges. Figure 3d shows the detail close-up three-dimensional detail view of the individual slit fin. Each slit has a breadth (along the fin height direction) of 12 mm, a width (through the fin thickness direction) of 1 mm, and a height (in the fin radial direction) of 1 mm, oriented at an angle of 45° relative to the fin axis. The solid web segments between adjacent slits maintain the structural integrity of the aluminium alloy fin. The complete dimensional parameters of the slit fin geometry are provided in Table 2.

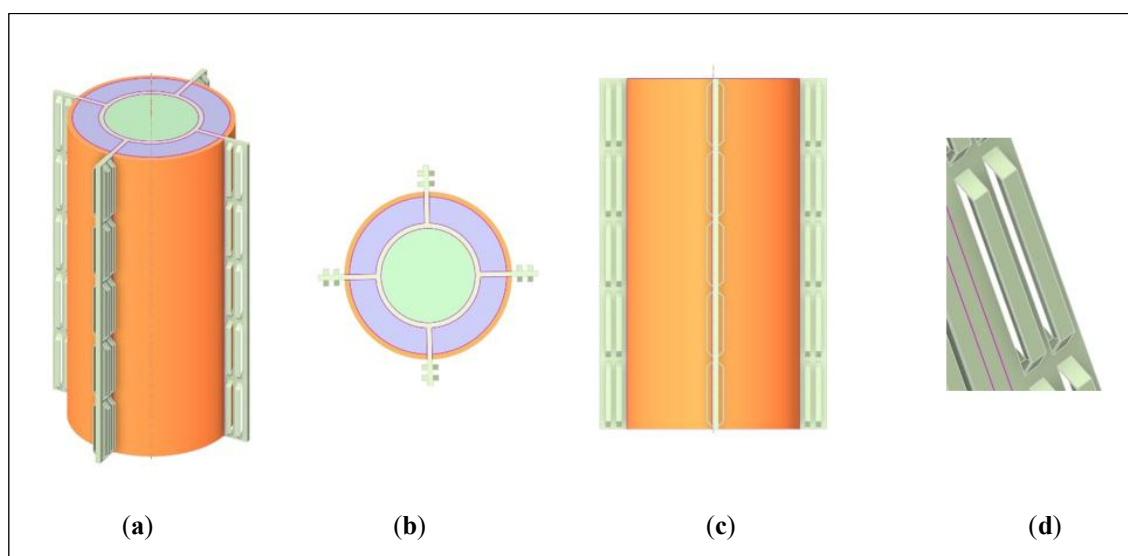


Figure 3. (a) 3D isometric view of the proposed slit-fin-enhanced PCM-based BTMS, (b) top cross-sectional view of the slit-fin BTMS, (c) front elevation (side) view of the slit-fin BTMS, (d) close-up three-dimensional detail view of the individual slit fin.

Table 2. Geometric configuration of the lithium-ion battery 18650.

Parameter	Rectangular Fins Geometry	Slit Fins Geometry
Battery diameter (mm)	18	18
Battery height (mm)	65	65
PCM layer thickness (mm)	5	5
Fin thickness (mm)	1	1
Housing wall thickness (mm)	1	1
Insulation layer thickness (mm)	1	1
Fin radial length (mm)	11	11

Number of longitudinal fins	4	4
Angular spacing between fins (°)	90	90
Total BTMS outer diameter (mm)	30	30
Slit breadth along fin height direction (mm)	-	12
Slit width through fin thickness (mm)	-	1
Slit height in fin radial direction (mm)	-	1
Slit orientation angle (°)	-	45

The thermophysical properties of paraffin PCM were adopted from Zare et al. [1], which is based on Yang et al. [53] and Sun et al. [6] to maintain consistency with the validated rectangular-fin baseline model. Since paraffin undergoes solid–liquid phase change, phase-dependent properties were used where applicable. The thermal conductivity, specific heat capacity, and density were defined separately for the solid and liquid phases, as reported in Table 3. No additional continuous temperature-dependent polynomial correlations, such as $k(T)$, $Cp(T)$ or $\rho(T)$, were used because the baseline reference reports solid- and liquid-phase values rather than full temperature-dependent functions. Therefore, the temperature effect during phase change was represented through the enthalpy–porosity liquid-fraction formulation between the solidus temperature of 313.75 K and the liquidus temperature of 318.15 K.

Table 3. Thermophysical properties of all materials used from Zare et al. [1].

Material	Property	Value	Unit
Paraffin PCM (45 °C)	Thermal conductivity (solid)	0.20	W·m ⁻¹ ·K ⁻¹
	Thermal conductivity (liquid)	0.18	W·m ⁻¹ ·K ⁻¹
	Specific heat capacity (solid)	2000	J·kg ⁻¹ ·K ⁻¹
	Specific heat capacity (liquid)	2350	J·kg ⁻¹ ·K ⁻¹
	Density (solid)	880	kg·m ⁻³
	Density (liquid)	700	kg·m ⁻³
	Latent heat	240,000	J·kg ⁻¹
	Solidus temperature	313.75	K
	Liquidus temperature	318.15	K
	Dynamic viscosity	0.005	kg·m ⁻¹ ·s ⁻¹
	Thermal expansion coefficient	0.00076	1/K
Aluminum Alloy (Fins and Housing)	Thermal conductivity	167	W·m ⁻¹ ·K ⁻¹
	Specific heat capacity	896	J·kg ⁻¹ ·K ⁻¹
	Density	2700	kg·m ⁻³
Insulation Material	Thermal conductivity	0.19	W·m ⁻¹ ·K ⁻¹
	Specific heat capacity	1260	J·kg ⁻¹ ·K ⁻¹
	Density	1200	kg·m ⁻³
Lithium-Ion Battery (18650)	Thermal conductivity (radial)	0.2	W·m ⁻¹ ·K ⁻¹
	Thermal conductivity (axial)	37.6	W·m ⁻¹ ·K ⁻¹
	Specific heat capacity	1200	J·kg ⁻¹ ·K ⁻¹
	Density	2500	kg·m ⁻³

3. Three-Dimensional Mesh Generation

The three-dimensional computational mesh for the proposed slit fin-enhanced BTMS and Rectangular profile-based fin BTMS was generated within the ANSYS Meshing environment integrated in ANSYS Fluent 2024/R2, as illustrated in Figure 4a,b. The full geometry of slit-fin BTMS comprising all 14 cell zones, including the battery, internal cylindrical fin, four external slit fins, paraffin wax PCM domain, aluminium housing, and insulation layers, was discretized using a structured polyhedral mesh. The mesh was generated across 74 face zones and 14 cell zones with a total of 2,545,598 cells, 12,858,473 faces, and 8,613,065 nodes, partitioned across 8 parallel processing cores to optimize computational efficiency. As clearly visible in the mesh images, a finer and denser polyhedral cell distribution was applied in the PCM domain and at the curved battery surface and internal cylindrical fin interface regions where steep thermal gradients and the PCM solid–liquid phase transition front are expected, while a coarser but well-structured mesh was applied to the aluminium fin walls and housing, which require less spatial resolution due to the high thermal conductivity of aluminium and the absence of phase change. Particular attention was given to the slit fin edges and slot cutout boundaries, as evidenced in Figure 4b, where the mesh is visibly refined around the slit geometries to accurately resolve the sharp thermal gradients at the PCM–fin–ambient interfaces within the slot openings, the most geometrically complex and thermally active regions of the slit fin design. The mesh quality was assessed using the average element quality metric, yielding an average element quality of 0.90 across the full domain, well above the minimum acceptable threshold of 0.1 recommended for CFD simulations, confirming the high quality and reliability of the generated mesh for accurate transient thermal and fluid flow computations. Ref. [1] conducted their mesh independence testing using the same methods, which proved that their chosen mesh density produced results within 0.01% of the most refined mesh tested according to Section 3. The main mesh statistics of the slit-fin BTMS computational domain are summarized in Table 4.

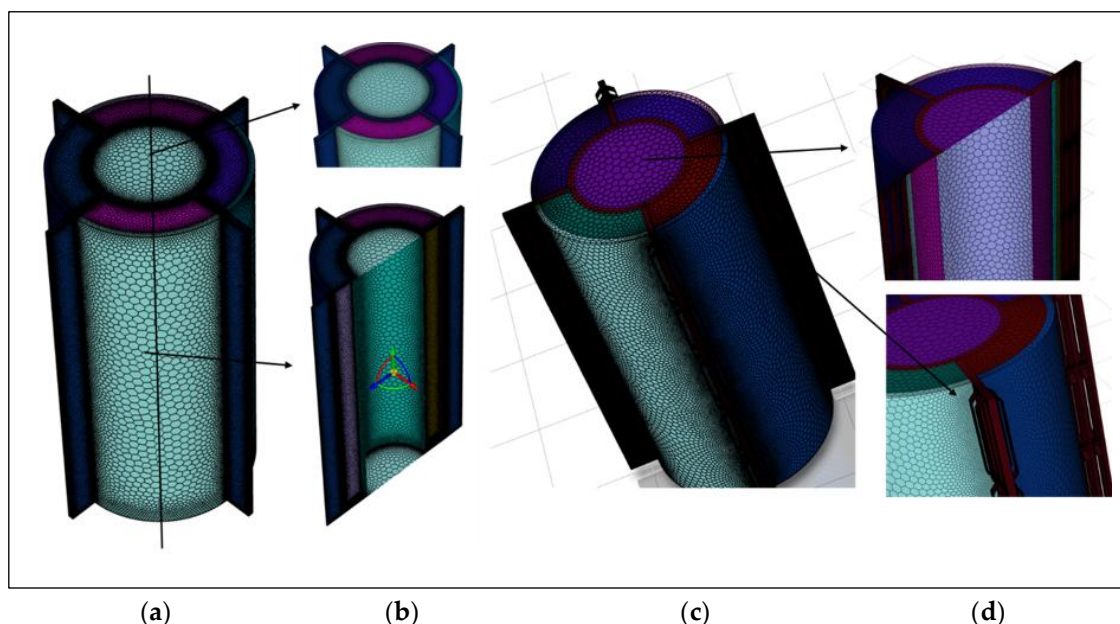


Figure 4. Computational mesh of the BTMS: (a) rectangular-fin model, (b) slit-fin model, (c) enlarged view of battery–PCM and internal fin–PCM interface, and (d) enlarged view of slit-fin slot openings.

Table 4. Mesh statistics for the slit-fin BTMS computational domain.

Parameter	Value
Total number of edges	0.07 million
Total number of faces	12.8 million
Total number of nodes	8.9 million
Total number of cells	2.54 million

3.1. Grid Independence Study

The mesh independence study was performed using the 5C slit-fin configuration. This case produces the strongest thermal gradients and fastest PCM melting among the simulated discharge conditions. Six global mesh sizes of 0.25, 0.50, 0.75, 1.00, 1.25, and 1.50 mm were tested under identical governing equations, material properties, boundary conditions, solver settings, and time-step size.

Special attention was given to high-gradient regions, including the curved battery–PCM interface, internal cylindrical fin–PCM interface, external slit-fin surfaces, slit-edge regions, and slot-opening boundaries. A finer polyhedral cell distribution was applied in these regions because the PCM melting front, liquid-fraction gradient, and thermal boundary layer develop mainly near the heat source and fin surfaces. The slit openings were also refined since they represent the most geometrically complex and thermally active regions of the proposed design, where heat transfer occurs simultaneously through fin conduction, PCM phase change, and natural convection-assisted melting.

The mesh independence results in Figure 5 showed that the 0.50 mm mesh produced nearly the same total temperature and PCM liquid fraction as the finest 0.25 mm mesh. The temperature deviation was only 0.005%, while the liquid-fraction deviation was approximately 1.2%. Further refinement to 0.25 mm increased the computational cost significantly but produced negligible improvement in the predicted thermal response. Therefore, the 0.50 mm polyhedral mesh was selected as the final mesh for all simulations.

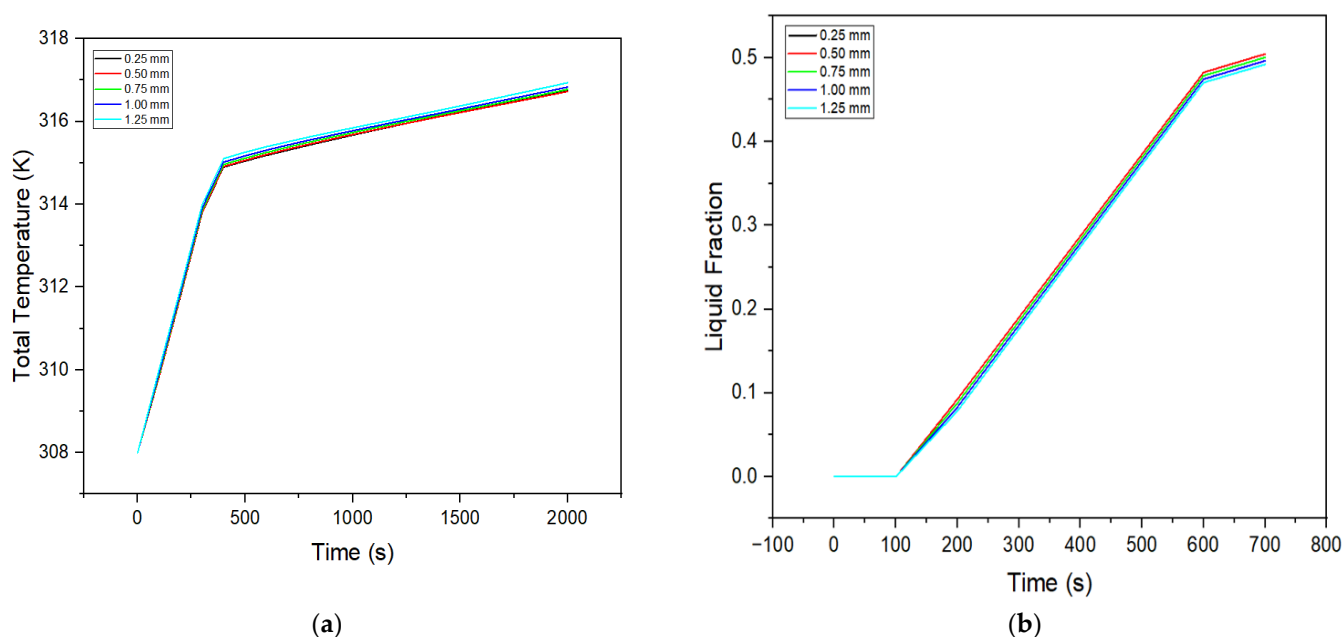


Figure 5. Grid independence study: (a) total temperature, (b) PCM liquid fraction for five representative mesh sizes (0.25 mm to 1.25 mm) at 5C discharge rate.

3.2. Time-Step Independence and Temporal Convergence Study

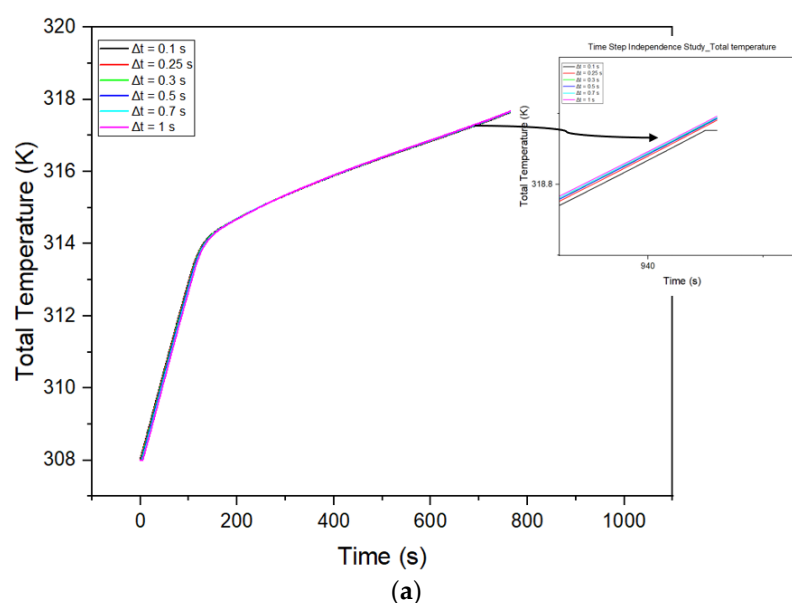
A time-step sensitivity study as shown in Figure 6 was carried out to ensure that the transient PCM melting and temperature evolution were independent of temporal discretization at 5C as shown in Table 5. Six time steps, $\Delta t = 0.10, 0.25, 0.30, 0.50, 0.70$, and 1.00 s, were tested using the same mesh, material properties, boundary conditions, convergence criteria, and solver settings. The total BTMS temperature and volume-averaged PCM liquid fraction were monitored throughout the transient simulation. The results showed that all curves from $\Delta t = 0.25$ s to 1.00 s followed nearly identical trends through the sensible heating region, PCM melting onset, and latent heat absorption stage. The selected $\Delta t = 0.50$ s showed only 0.04% deviation in total temperature and 1.6% deviation in PCM liquid fraction compared with the finest $\Delta t = 0.10$ s case, while reducing computational cost substantially. Therefore, $\Delta t = 0.50$ s was selected for all subsequent simulations. The results are tabulated in Table 6 and a summary of the numerical uncertainty analysis for the selected mesh and time-step settings is presented in Table 7.

Table 5. Grid independence study for the 5C slit-fin case.

Mesh Size	Cells	Avg. Element Quality	Onset (s)	LF at 620 s	ΔT vs. 0.25 mm
0.25 mm	5.90 M	0.94	100	0.505	0.00%
0.50 mm	2.55 M	0.90	105	0.502	0.005%
0.75 mm	1.82 M	0.88	110	0.498	0.022%
1.00 mm	1.25 M	0.86	115	0.494	0.036%
1.25 mm	0.86 M	0.84	120	0.490	0.052%
1.50 mm	0.62 M	0.82	125	0.486	0.077%

Table 6. Time-step independence and temporal convergence study for the 5C slit-fin case.

Time Step Δt	Temp. Deviation vs. $\Delta t = 0.1$ s	LF Deviation vs. $\Delta t = 0.1$ s
0.10 s	0.00%	0.00%
0.25 s	0.012%	0.5%
0.30 s	0.022%	0.8%
0.50 s	0.04%	1.6%
0.70 s	0.06%	2.0%
1.00 s	0.10%	2.4%



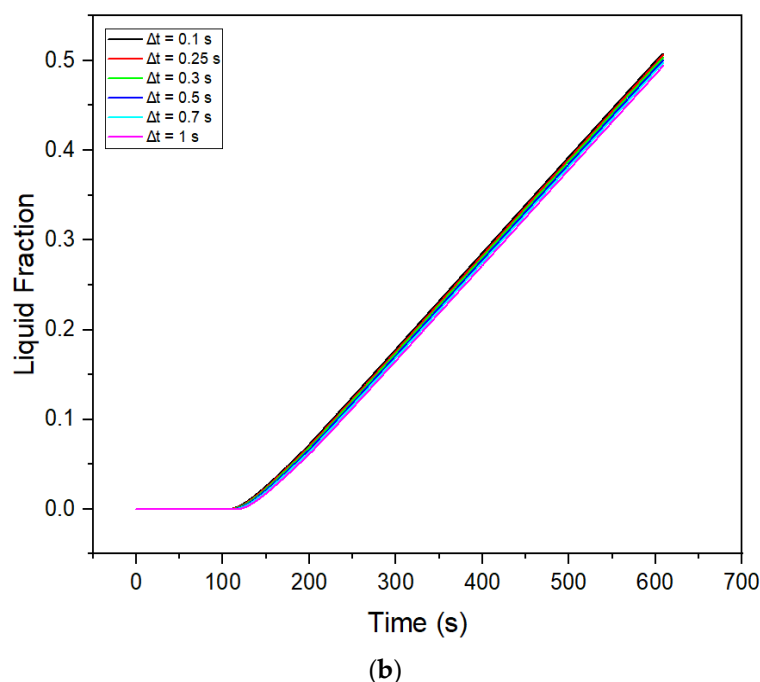


Figure 6. Time-step independence study: (a) total temperature, (b) liquid fraction evolution for six time steps ($\Delta t = 0.1$ s to 1.0 s) at 5C discharge rate.

Table 7. Summary of numerical uncertainty for the selected mesh and time-step settings.

Verification Parameter	Reference Case	Selected Case	Monitored Quantity	Reference Value	Selected Value	Relative Deviation
Mesh independence	0.25 mm	0.50 mm	Total temperature	$T_{0.25}$	$T_{0.50}$	0.005%
Mesh independence	0.25 mm	0.50 mm	PCM liquid fraction at 620 s	0.505	0.502	0.59%
Mesh independence	0.25 mm	0.50 mm	Melting onset time	100 s	105 s	5.0%
Time-step independence	0.10 s	0.50 s	Total temperature	$T_{0.10}$	$T_{0.50}$	0.04%
Time-step independence	0.10 s	0.50 s	PCM liquid fraction	$LF_{0.10}$	$LF_{0.50}$	1.6%
Time-step independence	0.10 s	0.50 s	Computational cost	Highest	Reduced	-

4. Numerical Methodology

4.1. Heat Generation in Lithium-Ion Battery

The study uses lumped-capacitance thermal modeling to forecast the thermal behavior of 18650 lithium-ion batteries, which allows quick calculations while providing adequate accuracy for battery thermal research. The Biot number assessment establishes the model's validity by measuring the internal conductive resistance to external convective resistance ratio. The Biot number is expressed as

$$Bi = \frac{hL_c}{k_{\text{battery}}}$$

where h is the convective heat transfer coefficient and L_c is the characteristic length obtained by dividing battery volume by its surface area, and k_{battery} represents the battery thermal conductivity value. The battery operates as a thermally uniform domain because Bi values below 0.1 permit the exclusion of temperature gradients throughout the battery. The lithium-ion battery generates heat through two primary sources, which include irre-

versible heat generation from internal resistance and reversible heat generation from electrochemical processes. The Bernardi equation derives these contributions as

$$Q_t = Q_{irr} + Q_{rev}$$

The irreversible heat is given by

$$Q_{irr} = I(E - V) = I^2 R_e$$

while the reversible heat is defined as

$$Q_{rev} = -T\Delta S \left(\frac{I}{nF} \right) = -I \left[T \left(\frac{dE}{dT} \right) \right]$$

The current through the circuit I flows through the open-circuit voltage E to the terminal voltage V while passing through the internal resistance R_e at temperature T . The entropy coefficient $\frac{dE}{dT}$ defines the relationship between temperature change and battery voltage variation. The battery volumetric heat generation rate is calculated by dividing total heat production by the battery volume.

$$q_b = \frac{Q_t}{V_b}$$

The BTMS was evaluated at 1C, 3C, 5C, and 7C discharge rates through its thermal performance assessment process. The study adopts volumetric heat generation values from Ref. [1] research since they originate from Bernardi equations, which maintain physical consistency. The 1C, 3C, 5C, and 7C discharge rates use 33,000, 185,435, 412,300, and 692,000 $\text{W}\cdot\text{m}^{-3}$ as their values, respectively. The discharging process serves as the sole simulation focus as it produces more heat than charging, and it represents the most critical operational state. The simulations were conducted at 308.15 K to create both actual environmental conditions and extreme weather environments that electric vehicles face during real-world use. The thermophysical and electrochemical specifications of the 18650 NCM lithium-ion battery and the constant heat generation values of the 18650 NCM lithium-ion battery at different discharge rates are presented in Tables 8 and 9 respectively.

Table 8. Thermophysical and electrochemical specifications of the 18650 NCM lithium-ion battery.

Parameter	Value	Parameter	Value
Nominal voltage (V)	3.7	Radial thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	0.20
Nominal capacity (Ah)	2.6	Axial thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	37.6
Cell mass (kg)	0.0475	Specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	1200
Cell diameter (mm)	18	Cell height H (mm)	65
Chemistry	NCM	Entropy coefficient dE/dT ($\text{V}\cdot\text{K}^{-1}$)	−0.0004
Internal resistance at 25 °C (Ω)	0.085	Volumetric heat generation at 3C ($\text{W}\cdot\text{m}^{-3}$)	185,435
Total heat generation at 3C (W)	2.9158	Total heat generation at 5C (W)	6.4809
Volumetric heat generation at 5C ($\text{W}\cdot\text{m}^{-3}$)	412,200	Nominal voltage (V)	3.7

Table 9. Constant heat generation of 18650 NCM lithium-ion battery.

Discharge Rate	Q_t (W)	q_b (W·m ⁻³)
1C	0.5188	33,000
3C	2.9158	185,435
5C	6.4809	412,200
7C	10.8792	692,000

4.2. PCM Melting Process

The melting of paraffin PCM was modelled using the enthalpy-porosity method, which is widely used for solid–liquid phase-change simulations involving natural convection. In this approach, the phase-change region between the solidus temperature T_s and liquidus temperature T_l is treated as a mushy porous zone, where solid and liquid PCM coexist. The liquid fraction γ varies from 0 in the fully solid region to 1 in the fully liquid region. To suppress fluid motion in the solid and mushy regions, a momentum sink term is added to the momentum equation using the Carman–Kozeny formulation:

$$\vec{S} = -A(\gamma) \cdot (\vec{u} - \vec{u}_p)$$

where $\vec{u}$ is the liquid PCM velocity and $\vec{u}_p$ is the pull velocity of the solid phase, which is taken as zero in the present study. The porosity function $A(\gamma)$ is defined as

$$A(\gamma) = \frac{A_{mush}(1 - \gamma)^2}{\gamma^3 + \epsilon}$$

where A_{mush} is the mushy zone constant and $\epsilon = 0.001$ is a small numerical constant used to avoid division by zero. In the present study, $A_{mush} = 10^7$ was used, consistent with the validated baseline study of Ref [1]. This value provides stable damping of velocity in the mushy region while avoiding the numerical instability reported for excessively high mushy-zone constants.

The liquid fraction was calculated as a piecewise function of temperature:

$$\gamma = \begin{cases} 0 & T < T_s \\ \frac{T - T_s}{T_l - T_s} & T_s < T < T_l \\ 1 & T > T_l \end{cases}$$

where $T_s = 313.75$ K and $T_l = 318.15$ K are the solidus and liquidus temperatures of the paraffin PCM, respectively. The PCM total enthalpy was calculated as the sum of sensible and latent heat contributions:

$$H_{PCM} = \underbrace{h_{PCM}}_{\text{Sensible enthalpy}} + \underbrace{\Delta H_{PCM}}_{\text{Latent enthalpy}}$$

$$h_{PCM} = h_a + \int_{T_a}^T C_{p,PCM} dT$$

$$\Delta H_{PCM} = \gamma L_{PCM}$$

where h_a is the reference enthalpy, $C_{p,PCM}$ is the PCM specific heat capacity, and L_{PCM} is the latent heat of fusion. This formulation allows the numerical model to capture sensible heating before melting, latent heat absorption during phase change, and natural convection in the fully or partially melted PCM.

4.3. Boussinesq Approximation for Paraffinic PCM

Paraffinic PCMs do exhibit a bulk solid-to-liquid volume change of approximately 10–20%, which is larger than that of many other PCM classes. The Boussinesq approximation has nevertheless been adopted in the present work, and, indeed, across the dominant PCM-BTMS CFD literature on paraffin wax (Sun et al. [6], Zare et al. [1]) for three principal reasons:

- (1) Liquid-phase density variation is small over the relevant temperature window. Between the liquidus temperature (318.15 K) and the maximum cell-wall temperature observed in the simulations (320 K, a 2 K window in the liquid regime), the density change of paraffin wax computed from $\beta = 7.6 \times 10^{-4} \text{ K}^{-1}$ is only $\Delta\rho/\rho \approx \beta \cdot \Delta T \approx 0.15\%$, well within the Boussinesq validity criterion $\beta \cdot \Delta T \ll 1$. The Boussinesq simplification, therefore, introduces negligible error in the natural-convection part of the simulation.
- (2) The bulk solid-to-liquid volume change is real, but in physical BTMS prototypes, it is accommodated by a deliberate ullage/void volume (air gap) above the PCM in the encapsulant and is not part of the natural-convection-driven flow being modelled. Including a free surface and ullage volume would require a Volume-of-Fluid or level-set treatment that is beyond the scope of the present passive-cooling study and is not the approach used by Ref. [1] against which our model is validated.
- (3) The enthalpy-porosity formulation in ANSYS Fluent already accounts for the latent heat absorbed during phase change through the liquid fraction γ in the energy equation, independent of whether the volume expansion is geometrically resolved. The Carman–Kozeny momentum sink equation correctly damps fluid motion in the mushy zone. The approach, therefore, captures the thermodynamic energy balance of the phase change accurately, even though the geometric volume expansion is not explicitly meshed. This treatment is fully consistent with the baseline study [1] and the broader PCM-BTMS CFD literature cited above.

4.4. Governing Equations

The BTMS system operates according to three-dimensional transient continuity and momentum and energy equations, which describe its thermal and fluid flow behavior:

$$\nabla \cdot (\rho \vec{u}) = 0$$

$$\frac{\partial(\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \tau + \rho_a [1 - \beta(T - T_a)] \vec{g} + \vec{S}$$

The relationship between fluid density, pressure, stress tensor, and reference density at the reference temperature of T_a , together with the thermal expansion coefficient and gravitational acceleration, which is established at $9.81 \text{ m}\cdot\text{s}^{-2}$ for Y-directional movement enables the forecasting of natural convection within melted PCM. The continuity equation ensures that mass remains constant throughout the computational area, while the momentum equation describes how pressure, viscous forces, buoyancy, and mushy zone damping effects interact. The Boussinesq approximation establishes a density-temperature relationship for buoyancy simulations, which helps to model natural convection behavior within the PCM according to its linearity. The separate energy equations for each domain include the battery domain, fin domain, PCM domain, and aluminum housing domain. The battery energy equation contains a volumetric heat generation term, while the fin and housing equations have heat conduction as their only thermal transfer mechanism. The PCM energy equation describes total enthalpy, which comprises both sensible heat and latent heat components. This method permits precise modeling of the phase transition process and the energy absorption that occurs during the melting phase.

$$\rho_{\text{battery}} C_{p, \text{battery}} \frac{\partial T_{\text{battery}}}{\partial t} = \nabla(k_{\text{battery}} \nabla T_{\text{battery}}) + q_b$$

$$\rho_{\text{fin}} C_{p, \text{fin}} \frac{\partial T_{\text{fin}}}{\partial t} = \nabla(k_{\text{fin}} \nabla T_{\text{fin}})$$

$$\frac{\partial(\rho_{\text{PCM}} H_{\text{PCM}})}{\partial t} + \nabla \cdot (\rho_{\text{PCM}} \vec{u} H_{\text{PCM}}) = \nabla(k_{\text{PCM}} \nabla T_{\text{PCM}})$$

$$\rho_{\text{housing}} C_{p, \text{housing}} \frac{\partial T_{\text{housing}}}{\partial t} = \nabla \cdot (k_{\text{housing}} \nabla T_{\text{housing}})$$

4.5. Numerical Implementation

The commercial computational fluid dynamics software ANSYS Fluent 2024 R2 uses the finite volume method spatial discretization to perform numerical solutions of governing equations. The transient simulation system operates to analyse how the thermal characteristics of the system change over time. Simulations utilize 0.5 s time steps to achieve precise numerical results and stable performance.

The governing equations were solved in ANSYS Fluent 2024/R2 using the finite volume method. The PISO algorithm was used for pressure-velocity coupling due to its suitability for transient simulations. Pressure interpolation was performed using the PRESTO scheme, while the momentum and energy equations were discretized using second-order upwind schemes. The convergence criteria were set to 10^{-4} for continuity and momentum residuals and 10^{-10} for the energy residual to ensure accurate resolution of the thermal field during PCM melting, as discussed in Table 10.

Table 10. Solver settings and convergence criteria used in the CFD simulation.

Parameter	Setting used
CFD software	ANSYS Fluent 2024/R2
Solver type	Pressure-based, transient
Numerical method	Finite volume method
Pressure–velocity coupling	PISO
Pressure discretization	PRESTO
Momentum discretization	Second-order upwind
Energy discretization	Second-order upwind
Time step	0.5 s
Continuity residual	10^{-4}
Momentum residuals	10^{-4}
Energy residual	10^{-10}
Monitored quantities	Total BTMS temperature, cell wall temperature, PCM liquid fraction
Acceptance condition	Residual limits satisfied and monitored variables stable within each time step

4.6. Initial and Boundary Conditions

The entire computational domain was initialized at a uniform temperature of 308.15 K, corresponding to the ambient temperature used in the baseline study of Ref. [1]. The top and bottom surfaces of the BTMS were assigned adiabatic boundary conditions, so no heat transfer occurred through these surfaces. Therefore, heat rejection from the BTMS

occurred through the lateral aluminium housing surface and the exposed external fin surfaces. The outer surfaces of the aluminium housing and the external surfaces of the fins were subjected to natural convection with the surrounding air. For the slit-fin configuration, the convective boundary condition was also applied to the exposed surfaces inside the slit openings because these surfaces are directly connected to the ambient side and contribute to external heat dissipation. The natural convection boundary condition was expressed as

$$-k_{\text{wall}} \partial T_{\text{wall}} / \partial n = h(T_{\text{wall}} - T_{\infty})$$

where k_{wall} is the wall thermal conductivity, T_{wall} is the local wall temperature, T_{∞} is the ambient temperature, and h is the convective heat transfer coefficient. In the present study, h was fixed at $10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$, which is the same value used in the validated baseline study and lies within the commonly reported natural convection range of $5\text{--}10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ for air-cooled PCM-based BTMSs. This value represents enhanced natural convection or moderate air movement inside an EV battery compartment.

No-slip boundary conditions were applied at all solid–liquid PCM interfaces, including battery–PCM, fin–PCM, and housing–PCM walls, so the velocity of the melted PCM at the wall surfaces was zero. The liquid PCM was treated as laminar, incompressible, and Newtonian. Radiation heat transfer was neglected as the simulated operating temperatures were moderate and remained close to the battery thermal management range. Thermal contact resistance between the battery, fins, PCM, and housing was also neglected, and all interfaces were assumed to be perfectly bonded thermally.

To simplify the numerical model while maintaining accuracy, several assumptions are made. The PCM is considered homogeneous and isotropic in both solid and liquid phases. The volume change during phase transition is neglected, and radiation heat transfer is ignored. The flow of molten PCM is assumed to be laminar and incompressible, with negligible viscous dissipation. Additionally, the liquid PCM is treated as a Newtonian fluid, and thermal contact resistance between different components is neglected. Details of boundary conditions are given in Table 11.

Table 11. Initial and boundary conditions used in the numerical simulation.

Boundary/Domain	Boundary Condition Used	Value/Description
Initial BTMS temperature	Uniform initialization	$T_0 = 308.15$
Ambient temperature	Constant surrounding temperature	$T_{\infty} = 308.15$
Top and bottom BTMS surfaces	Adiabatic wall	$\partial T / \partial n = 0$
Outer housing surface	Natural convection	$h = 10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
External slit-fin surfaces	Natural convection	$h = 10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
Slit opening exposed surfaces	Natural convection	Included in external fin convection
Solid–liquid PCM interfaces	No-slip wall	$u = v = w = 0$
Radiation heat transfer	Neglected	Moderate temperature range, consistent with baseline
Thermal contact resistance	Neglected	Perfect thermal contact assumed
PCM flow	Laminar, incompressible, Newtonian	Boussinesq approximation for buoyancy

4.6.1. Modelling Assumptions

The following assumptions are adopted in the present numerical model. All assumptions are consistent with the baseline study Ref. [1] and the broader precedent literature on cylindrical Li-ion PCM-BTMS CFD modelling:

- (1) The solid and liquid PCM phases are assumed to be homogeneous and isotropic. This assumption allows the PCM domain to be modelled using uniform effective properties in each phase and is commonly adopted for paraffin-based PCM simulations.
- (2) The PCM volume change between solid and liquid phases is neglected. The Boussinesq approximation is used only to capture buoyancy-driven density variation in the liquid PCM, as justified in Section 4.3. This simplification avoids free-surface tracking while maintaining consistency with the baseline model.
- (3) Radiation heat transfer is ignored as the operating temperatures remain moderate, below approximately 325 K. Under this temperature range, convective and conductive heat transfer dominate the BTMS response.
- (4) The molten PCM flow is assumed to be laminar and incompressible. This is acceptable because the Rayleigh number remains below 10^9 throughout the simulations, supporting laminar natural-convection treatment.
- (5) Viscous dissipation in the molten PCM is neglected due to PCM velocities being small and the corresponding viscous heating being negligible compared with battery heat generation and latent heat absorption.
- (6) The liquid PCM is treated as a Newtonian fluid, which is a common approximation for molten paraffin PCM in battery thermal management simulations.
- (7) Thermal contact resistance at the battery–fin, fin–PCM, and PCM–housing interfaces is neglected, and all interfaces are assumed to be perfectly bonded thermally. This assumption may slightly affect the absolute temperature prediction, but it is applied identically to both rectangular-fin and slit-fin configurations; therefore, it does not artificially favour either design.
- (8) The battery is treated as a homogeneous lumped-capacitance thermal body. This is supported by the small Biot number values, approximately 0.1 in the radial direction and 0.001 in the axial direction, which are within or close to the accepted threshold for lumped thermal modelling.
- (9) The battery cap, terminal, and internal jelly-roll structure are not resolved. The cell is approximated as a homogeneous cylinder with effective radial and axial thermal conductivities, consistent with the standard NCM 18650 treatment used by Ref. [1].
- (10) A constant external convective heat-transfer coefficient of $10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ is applied to the outer housing and exposed fin surfaces. This value represents natural convection or moderate air movement around the BTMS and is kept identical for both fin geometries. A different ambient cooling coefficient would change the absolute temperature level, but the relative comparison between slit fins and rectangular fins remains meaningful because both systems experience the same external boundary condition. Huang et al. [54] use $5\text{--}10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ for natural convection of air over cylindrical Li-ion batteries. Sun et al. [6] use $10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ for a PCM-fin BTMS analogous to the present work. Jang et al. [55] also adopt $10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ under harsh natural-convection conditions for cylindrical Li-ion BTMS.
- (11) PCM properties are treated as phase-dependent where available. The thermal conductivity, density, and specific heat capacity are defined separately for solid and liquid PCM phases, while the melting process is captured using the enthalpy-porosity liquid-fraction formulation between the solidus temperature of 313.75 K and the liquidus temperature of 318.15 K. No continuous temperature-dependent polynomial correlations are used since the baseline reference reports phase-dependent values rather than full temperature-dependent functions.

4.6.2. Mechanism of Heat Transfer Enhancement by Slit Geometry

The proposed slit-fin geometry improves the PCM-based BTMS through two coupled heat-transfer mechanisms. First, the rectangular through-thickness slit openings increase

the effective PCM-fin interfacial area. In the solid rectangular-fin configuration, heat transfer between the fin and PCM occurs mainly through the two continuous flat fin faces. In contrast, each slit introduces additional internal wall surfaces along the slot perimeter. Therefore, the effective fin-PCM contact area is increased by the side-wall area of the cut-outs. For a rectangular slit with height h_s , width w_s , and fin thickness t_f , the additional slot-wall area can be approximated as

$$A_{\text{slot,add}} = 2t_f(h_s + w_s)$$

For n slits on each fin and N fins, the total additional heat-transfer area becomes

$$A_{\text{add,total}} = Nn2t_f(h_s + w_s)$$

Second, the slit openings modify the natural convection behavior inside the melted PCM. During the early stage of heating, heat transfer is mainly conduction-dominated because the PCM is still solid or only partially melted. After melting begins, buoyancy-driven motion develops in the liquid PCM due to density variation caused by temperature gradients. In the rectangular-fin configuration, the continuous solid fin surfaces restrict local fluid communication and may create stagnant regions between adjacent PCM zones. In the slit-fin configuration, the openings interrupt the thermal boundary layer and provide additional local circulation paths around the fin webs and slot edges. As a result, hot liquid PCM near the battery and fin surfaces can move more easily, while cooler PCM near the housing and slit region can replace it, strengthening natural convection-assisted melting.

4.6.3. Physical Mechanism of Slit-Fin Heat Transfer Enhancement

- (1) Increased conductive contact area: Each slot exposes two new fin-PCM interfaces (top and bottom slot edges) per slit element, raising conductive area without altering fin material volume.
- (2) Enhanced external convection: Each slot provides a direct ambient air pathway through the fin, breaking the buoyant plume detaching from the fin face and re-establishing it at every slot, raising the local convective heat-transfer coefficient h on the slit segments.
- (3) Oblique buoyancy coupling: The 45° slot inclination directs the buoyancy-driven liquid PCM flow obliquely upward through each opening, which maximally couples the natural convection cell to the fin surface.

4.6.4. Natural Convection Effects Within the PCM

The enthalpy-porosity model captures natural convection in the melted PCM through the Boussinesq approximation, where density variation is introduced as

$$\rho = \rho_a[1 - \beta(T - T_a)]$$

The strength of buoyancy-driven flow can be physically interpreted using the Rayleigh number

$$Ra = g\beta(T_h - T_c)H^3/(\nu\alpha)$$

while the relative convective heat-transfer strength can be represented by the Nusselt number

$$Nu = hH/k$$

As the PCM melts outward from the battery and fin surfaces, the temperature difference between the hot battery/fin region and the cooler housing wall drives motion of warmer liquid PCM and downward replacement by cooler liquid PCM. Therefore, the melting process can be divided into three regimes: (i) conduction-dominated melting, where only a thin liquid layer exists, and heat transfer is mainly conductive; (ii) strong

convection-assisted melting, where the liquid PCM volume increases, and buoyancy-driven circulation accelerates melting; and (iii) weak convection at advanced melting, where the liquid layer becomes thicker and the temperature driving force gradually decreases.

The slit-fin geometry enhances this natural convection process rather than suppressing it. In the early conduction-dominated regime, the slit fins mainly improve heat transfer by increasing PCM-fin contact area and reducing local thermal resistance near the slit edges. As melting progresses, the slit openings disturb the thermal boundary layer and provide local circulation paths around the slot edges. This allows warmer liquid PCM near the battery/fin region to move away more easily while cooler PCM replaces it, reducing stagnant regions and increasing the active melting volume. Although small local recirculation zones may form near the slit edges because of the solid web segments between openings, the net effect is positive. The results in Section 6 confirm that the slit openings enhance convection-assisted PCM melting and improve latent heat utilization under high discharge rates.

5. Numerical Model Validation

5.1. Total Temperature and Liquid Fraction at 3C

Prior to evaluating the novel slit fin geometry, the present numerical model was validated by reproducing the results of the rectangular fin configuration of Ref. [1], the baseline study of the present work under identical conditions. Validation was performed at both the 3C and 5C discharge rates at an ambient temperature of 308.15 K. The Biot number for the present battery configuration was calculated to be approximately 0.1 and 0.001 in the radial and axial directions, respectively, confirming the validity of the lumped-capacitance thermal model. The mushy zone constant $A_{\text{mush}} = 10\%$, mesh size of 0.5 mm with average element quality of 0.90, time step of 0.5 s, and convergence criteria of 10^{-4} and 10^{-10} for momentum and energy equations, respectively, were all adopted from the baseline study Ref. [1].

Figure 7 shows total BTMS temperature results from the present rectangular fin simulation of the current study, and the baseline results of Ref. [1] showed close agreement at the 3C discharge rate. Both curves originate from the identical initial ambient temperature of 308.15 K and follow a near-identical trajectory, rising steeply during the initial sensible heating phase, showing a marked reduction in the rate of temperature rise at approximately 400 s upon reaching the PCM solidus temperature of 313.75 K, and then continuing to rise gradually to approximately 316 K by 1600 s. The numerical model succeeds in replicating the thermal behavior of the baseline rectangular fin BTMS at the 3C discharge rate, as the two curves maintained close agreement throughout the simulation period, while their maximum deviation stayed under 1 K for every time point during the test. For Liquid Fraction, both curves remain at zero liquid fraction during the initial period before 400 s because no PCM melting occurred while the BTMS temperature stayed below the solidus temperature of 313.75 K. The two curves ascend from their zero starting point because the PCM melting process continues at a constant 3C heat generation rate, which leads to a steady increase in liquid fraction until they reach their maximum values at 1650 s. The two curves show complete similarity throughout the simulation period because both curves reach their maximum liquid fraction of 0.42–0.43 at the 1650 s time point, which results in an absolute difference of 0.01 between them.

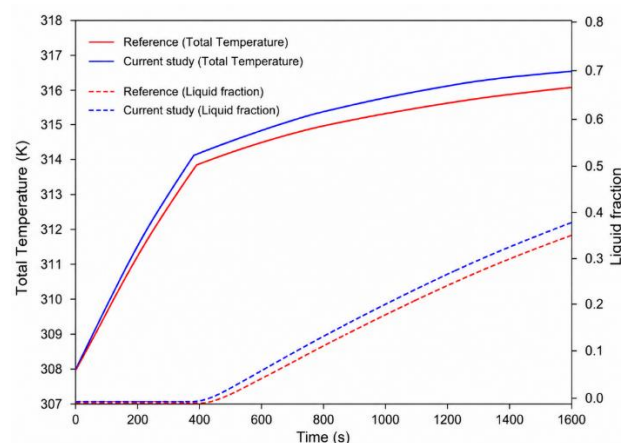


Figure 7. Comparison of total temperature and liquid fraction at 3C discharge rate: present rectangular fin results vs. Ref. [1].

5.2. Total Temperature and Liquid Fraction at 5C

Figure 8 shows total BTMS temperature results from the present rectangular fin simulation of the current study and the baseline results from Ref. [1], a reference study that operated at a 5C discharge rate. The two curves begin at the same ambient temperature of 308.15 K, and they follow an almost identical path, which includes a steep increase during the sensible heating phase and a gradual temperature increase that starts at 350 to 400 s when the PCM solidus temperature of 313.75 K has been reached. The current study curve tracks the reference closely throughout, with both reaching a final maximum temperature of approximately 315.8–316 K by approximately 1480 s and remaining safely below the critical safety threshold of 318.15 K throughout the entire simulation. The two curves show a small difference, which matches the average cell wall temperature error of 1.031% and maximum error of 1.472%. For liquid fraction, both curves remain at zero liquid fraction until approximately 350–400 s, confirming identical PCM melting onset timing in both models upon reaching the solidus temperature of 313.75 K, after which both rise in a nearly linear fashion, reflecting steady conduction-dominated PCM melting, which occurs according to the constant 5C heat generation condition. The two curves track each other closely throughout the simulation, with both reaching a final liquid fraction of approximately 0.37–0.38 at 1480 s, an absolute deviation of less than 0.01 demonstrating excellent quantitative agreement between the present model and the baseline study.

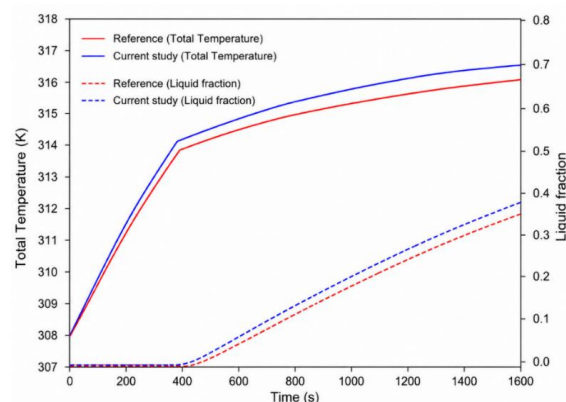


Figure 8. Comparison of total temperature and liquid fraction at 5C discharge rate: present rectangular fin results vs. Ref. [1].

5.3. Validation Discrepancies

The validation discrepancy analysis in Figure 9 further quantifies the agreement between the present rectangular-fin model and the reference results of the baseline study Zare et al. [1]. As shown in Figure 9a, the absolute temperature deviation remains nearly zero during the initial sensible-heating period and becomes noticeable only after PCM melting begins at approximately 350–400 s. The maximum temperature deviation remains below approximately 0.45 K for the 3C case and below approximately 0.60 K for the 5C case, which is very small compared with the overall operating temperature range of 308–316 K. Similarly, Figure 9b shows that the liquid-fraction deviation remains almost zero before melting onset and increases only during the phase-change period. The maximum liquid-fraction deviation is approximately 0.010 for 3C and 0.008–0.009 for 5C, confirming that the present model accurately predicts PCM melting progression. These minor differences may be attributed to mesh distribution, solver version, numerical discretization, and extraction/interpolation of reference data from the published curves. Overall, the small discrepancy values confirm that the present model reliably captures sensible heating, melting onset, latent heat absorption, and liquid-fraction evolution, making it suitable for evaluating the proposed slit-fin geometry.

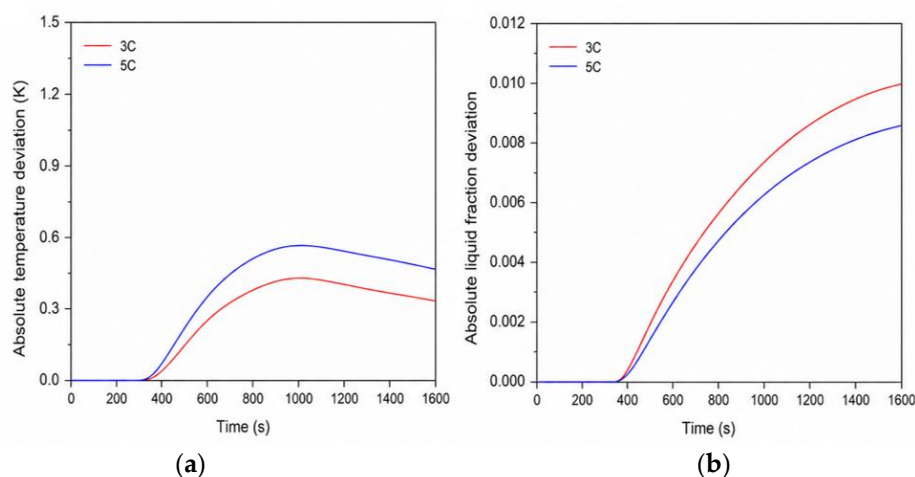


Figure 9. Validation discrepancy analysis between the present rectangular-fin model and Ref. [1]: (a) absolute total-temperature deviation, (b) absolute PCM liquid-fraction deviation at 3C and 5C discharge rates.

5.4. Modified Slit-Fin Geometry Verification and Numerical Uncertainty

Although the rectangular-fin baseline model was validated against Ref. [1], no identical experimental dataset is available for the proposed slit-fin geometry. Therefore, the modified slit-fin design was further verified through slit-fin-specific mesh independence and temporal convergence studies using the most demanding 5C discharge case, as discussed in Section 3. These numerical deviations are much smaller than the observed slit-fin performance improvements, such as LF = 0.50 at 620 s for slit fins compared with LF = 0.37 at 1480 s for rectangular fins at 5C and LF = 0.76 vs. 0.56 at 7C. Therefore, although direct experimental validation of the slit-fin geometry is not currently available, the predictions are supported by validated baseline reproduction, mesh independence, temporal convergence, and quantitative numerical uncertainty assessment.

6. Results and Discussion

6.1. Thermal Performance at 1C Discharge Rate

6.1.1. Total Temperature and Liquid Fraction Trend at 1C

Figure 10 presents the direct side-by-side comparison of total BTMS temperature for slit fins (blue) and rectangular fins (red) at the 1C discharge rate. Both curves commence from the identical initial temperature of 308.15 K and follow closely similar trajectories throughout the 2500-s simulation period, with the slit fin curve consistently registering lower values than the rectangular fin curve from approximately 500 s onward. The divergence between the two curves begins gradually and increases progressively with time, reaching approximately 0.7 K by 2500 s. This increasing divergence reflects the growing contribution of convective heat dissipation through the slit openings over extended simulation periods: as the system approaches higher temperatures, the convective heat flux through the slot openings (proportional to the temperature difference between the PCM interior and the ambient) increases, amplifying the cooling advantage of the slit fin design relative to the solid rectangular fin. Both curves remain well below the 313.75 K solidus and the 318.15 K critical safety threshold throughout, confirming that both designs provide fully adequate thermal management at 1C.

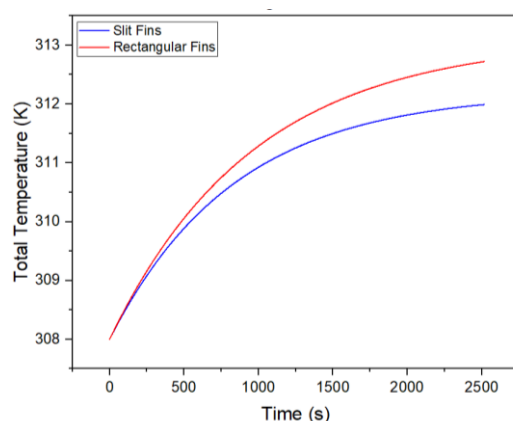


Figure 10. Comparison of slit fin and rectangular fins BTMS total temperature at 1C discharge rate.

6.1.2. Total Temperature and Liquid Fraction Contours at 1C

The static temperature contours of the slit-fin BTMS at 1C are presented in Figure 11a at four selected time steps: 0 s, 1000 s, 2000 s, and 2500 s. At $t = 0$ s, the entire assembly is at the uniform initial temperature of 308.15 K, shown as solid dark blue across all components. At $t = 1000$ s, the temperature distribution has evolved significantly: a warm region (green, approximately 309.5–310.5 K) has developed around the battery core and begins propagating radially outward through the PCM domain. The four external slit fins are clearly visible projecting outward from the cylindrical PCM enclosure, and notably, they appear at a cooler temperature than the surrounding PCM—particularly in the slot regions, providing direct visual confirmation that the slit openings are functioning as convective cooling channels that maintain the fin-ambient contact areas at temperatures closer to ambient. At $t = 2000$ s, the warm zone has expanded considerably, and the temperature gradient between the battery core and the outer housing is clearly visible. By $t = 2500$ s, the system temperature has risen to approximately 311.5–313 K near the battery core while the outer housing and fin extremities remain cooler due to convective losses. At no time during the 2500-s simulation does the temperature approach the PCM solidus of 313.75 K in most of the domain, consistent with the near-zero liquid fraction observed

throughout, and the slit openings remain clearly visible as cooler (bluer) regions providing sustained ambient convective relief.

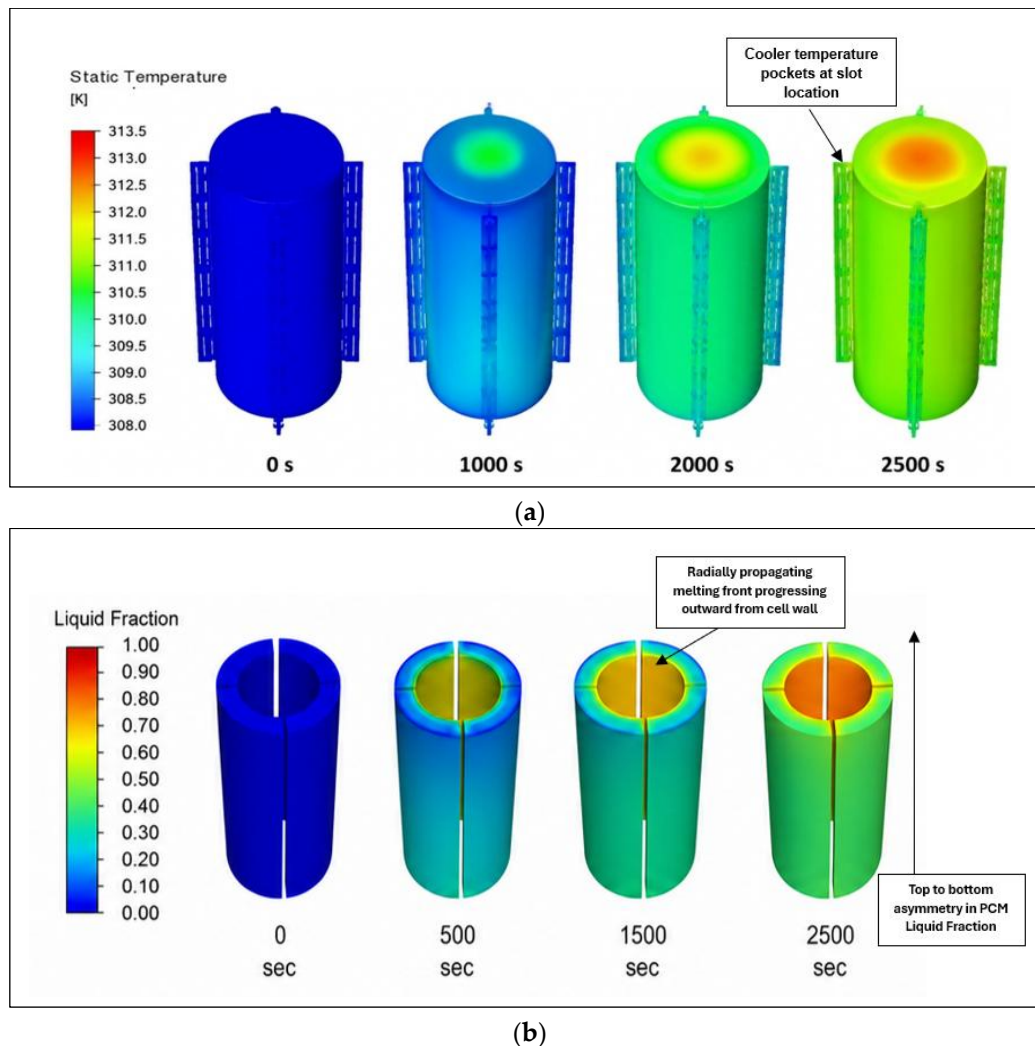


Figure 11. (a) Temperature contours at $t = 0, 1000, 2000$, and 2500 s, (b) liquid fraction contours of slit-fin BTMS at 1C at $t = 0, 500, 1500$, and 2500 s.

The PCM liquid fraction contours of the slit-fin BTMS at 1C are shown in Figure 11b at $t = 0, 500, 1500$, and 2500 s. At $t = 0$ and $t = 500$ s, the PCM remains entirely in the solid phase with a liquid fraction uniformly at zero (shown as solid blue), consistent with the temperature profile showing the system temperature well below the PCM solidus during this period. At $t = 1500$ s, a thin ring of slightly elevated liquid fraction (0.005–0.010) begins to appear immediately adjacent to the battery surface and the cylindrical internal fin, while the outer PCM region remains fully solid. This localised onset of partial melting adjacent to the battery surface occurs because the battery surface is the heat source and reaches the solidus temperature locally before the bulk PCM. By $t = 2500$ s, this melting has expanded slightly, with a small red region (maximum LF ≈ 0.015) concentrated directly at the battery–fin interface, confirming that only a tiny fraction of the total PCM volume has undergone phase change at 1C and that the vast majority of the PCM latent heat capacity remains intact as a thermal reserve for higher discharge rate conditions. The contours clearly demonstrate that the 1C case is thoroughly safe and that the slit fin system has enormous remaining thermal capacity.

6.2. Thermal Performance at 3C Discharge Rate

6.2.1. Total Temperature and Liquid Fraction Trend at 3C

Figure 12a shows the complete temperature changes that occurred in the rectangular and slit fin designs at the 3C discharge rate. The two configurations commenced their experiments from an identical starting point of 308.15 K, and both systems exhibited a rapid temperature increase during their initial period of sensible heat storage. The rectangular fin system showed a significant decrease in temperature rise rate when the time reached 400 s because this moment marked the beginning of PCM melting after the system reached its solidus point at 313.75 K. The temperature continued to increase until it reached about 316 K at 1650 s, which stayed below the 318.15 K safety limit and matched the baseline data from Ref. [1]. The slit fin configuration showed a similar initial rise but with the PCM melting onset slightly delayed to approximately 450–500 s due to the increased external fin surface area dissipating more heat to the ambient before the PCM reached its melting point, consistent with the observation of Ref. [1] that fins with larger external surface areas delay melting onset through enhanced convective dissipation. The slit fin showed a temperature increase pattern that began with an initial increase before reaching 316 K after 600 s and then rising to 319 K at 2500 s, which slightly exceeded the 318.15 K boundary after 2000 s. The primary advantage of the slit fin design for thermal management at 3C operates through extended operational time, which benefits the system more than achieving lower temperature limits does. The BTMS of the slit fin system provided thermal protection for 2500 s, while the rectangular fins offered protection for 1650 s, which created a 51.5% longer thermal protection period. The thermal protection duration increases because the slit fin design creates more contact area between fins and PCM, which improves latent heat extraction from PCM materials.

The PCM liquid fraction results in Figure 12b further substantiate this finding. The rectangular fin configuration showed melting onset at 400 s with a nearly linear rise to LF = 0.42 at 1650 s, which validated the baseline value of 0.43 from Ref. [1]. The slit fin configuration showed its melting started at 600 s before reaching LF = 0.49 at 2500 s while consuming 16.7% more PCM latent heat than the rectangular fins throughout its entire operational period. The slit fin liquid fraction curve shows an increasing non-linear slope, which demonstrates a transition period from conduction-based melting to natural convection-supported melting that occurs when the liquid PCM volume in PCM silos increases. The system experienced faster melting through thermally effective melting processes, which increased heat transfer efficiency within the system.

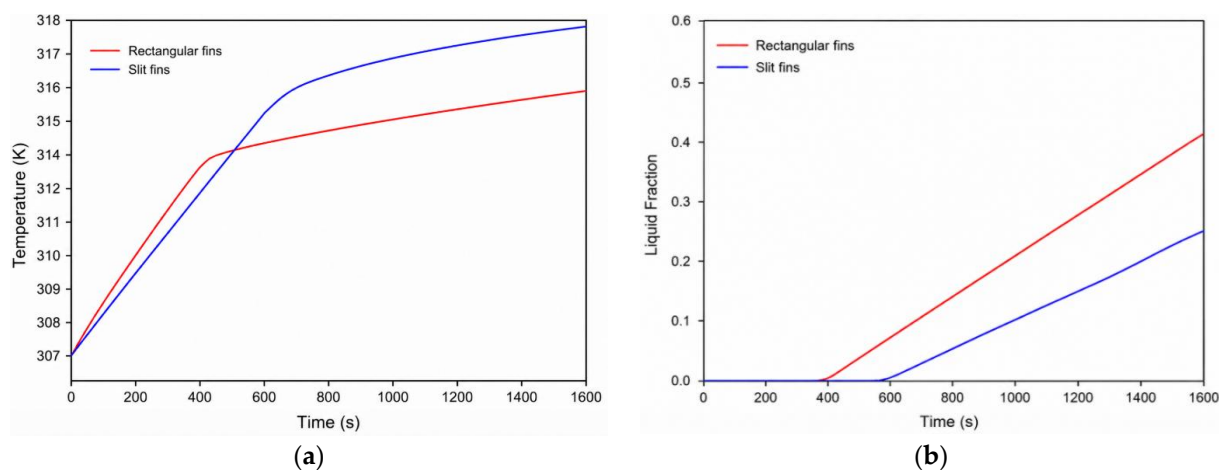


Figure 12. (a) Total temperature, (b) liquid fraction at 3C discharge rate of rectangular fins vs. slit fins BTMS.

The performance difference between the two designs becomes obvious through the direct comparison of total temperature and liquid fraction at 3C, shown in Figure 12. The two configurations show nearly identical performance during early sensible heating until they start to differ after PCM melting begins, which occurs when the rectangular fins reach 316 K at approximately 1650 s, and the slit fins continue to operate until they reach 319 K at approximately 2500 s. The results from Figure 12b show that, despite their later melting point, the slit fins produce a higher liquid fraction of 0.49 compared with the rectangular fins 0.42, which indicates that split fins make better use of the PCM latent heat capacity. The results demonstrate that the slit fin design outperforms the rectangular fin design of Ref. [1] in thermal management performance at 3C.

6.2.2. Definition of Thermal Protection Duration

In the present study, thermal protection duration is defined as the time period during which the BTMS maintains effective thermal control below the critical temperature threshold of 318.15 K. This threshold corresponds to 45 °C, which is commonly considered the upper desirable operating temperature for lithium-ion batteries and also corresponds to the liquidus temperature of the paraffin PCM used in this study. Therefore, a longer thermal protection duration indicates that the BTMS can delay overheating and maintain effective cooling for a longer discharge period.

At 3C, this definition is applied by comparing the effective cooling period of the rectangular-fin and slit-fin configurations. The rectangular-fin system provides effective protection up to approximately 1650 s, reaching LF = 0.42, while the slit-fin system continues effective thermal regulation up to 2500 s, reaching LF = 0.49. Thus, the slit-fin design increases the thermal protection duration by 51.5% and improves PCM latent heat utilization by 16.7%. This confirms that the slit geometry enhances heat spreading and extends the effective cooling period at 3C discharge.

6.2.3. Total Temperature and Liquid Fraction Contours at 3C

The temperature contours shown in Figure 13a confirm the thermal behavior that was explained previously. The battery core experiences preferential heating during discharge because heat moves from the core through the cylindrical internal fin and the four longitudinal slit fins. The slit cutouts in the external fins are clearly visible as localised cooler pockets along the fin height, direct visual evidence of the additional ambient convective cooling pathways created by the slit perforations that are entirely absent in the solid rectangular fin design. The four PCM silos display a temperature distribution that approaches symmetry, which indicates that the battery perimeter receives uniform circumferential cooling throughout its entire circumference. This was also emphasized by Ref. [1]. The liquid fraction contour in Figure 13b shows a maximum local LF of 0.648 concentrated near the battery surface and cylindrical fin wall, with lower values toward the outer housing wall, confirming the radially propagating conduction-dominated melting front at 3C and demonstrating that the slit fin geometry drives more intense localised PCM melting near the heat source compared with the rectangular fin configuration.

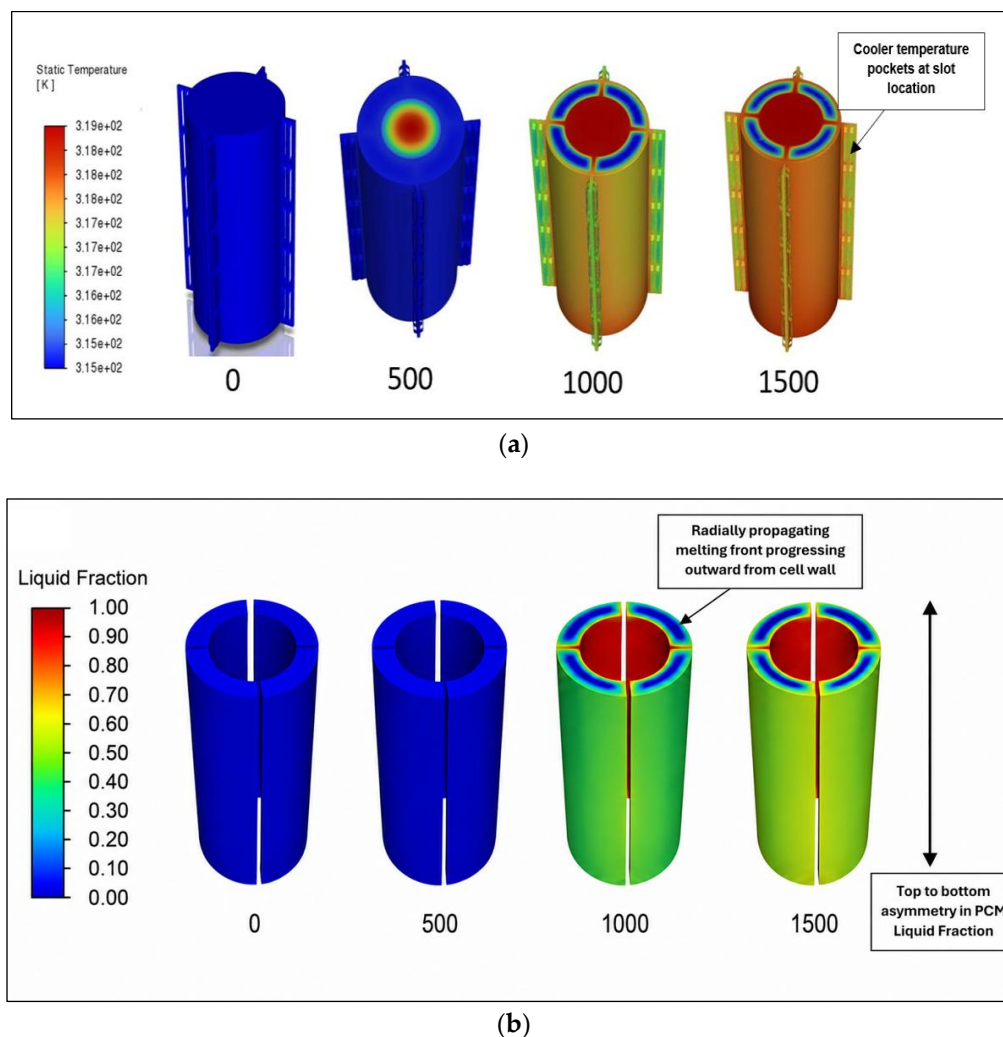


Figure 13. (a) Temperature contours at $t = 0, 500, 1000,$ and 1500 s, (b) liquid fraction contours of slit-fin BTMS at 1C at $t = 0, 500, 1000,$ and 1500 s.

6.3. Thermal Performance at 5C Discharge Rate

6.3.1. Total Temperature and Liquid Fraction Trend at 5C

The performance difference between the two fin designs becomes more visible at the 5C discharge. The rectangular fin BTMS at 5C starts to heat up from 308.15 K to the PCM solidus point between 350 and 400 s before it keeps heating up to 315.8 K at 1480 s while staying below 318.15 K which matches the Ref. [1] baseline results. The slit fin configuration in Figure 14a demonstrates a high superior thermal response reaching 314–315 K by just 150 s, approximately 2.5 times earlier than the rectangular fins reaching the same temperature level at 380 s. The slit fin curve shows an early temperature plateau which lasts from 150 to 400 s because of the intense latent heat absorption which occurs when the rectangular fins start their sensible heating phase until they reach 318.5 K at approximately 950 s. The slit fin geometry established an early thermal protection advantage under 5C conditions because it accessed PCM latent heat more effectively and earlier than other geometries during the discharge process' thermal peak.

The liquid fraction results in Figure 14b provide the quantitative evidence of stronger PCM engagement. The rectangular fin configuration showed melting onset at 350–400 s with a linear rise to $LF = 0.37$ at 1480 s consistent with the baseline of Ref. [1]. The slit fin configuration showed PCM melting onset at approximately 100 s, 3.5 times earlier with a steep non-linear rise reaching $LF = 0.50$ at just 620 s. The slit fin system therefore achieved 50% PCM melting in 620 s while the rectangular fins took 1480 s to reach only 37% repre-

senting approximately 2.4 times faster PCM utilization by the slit fin geometry. The non-linear accelerating liquid fraction curve of the slit fins reflects a rapid transition to natural convection-dominated melting as the growing liquid PCM volume enabled buoyancy-driven convective currents consistent with the strong convection regime described by Ref. [1] further intensifying heat transfer and PCM melting beyond what conduction alone could achieve in the rectangular fin system.

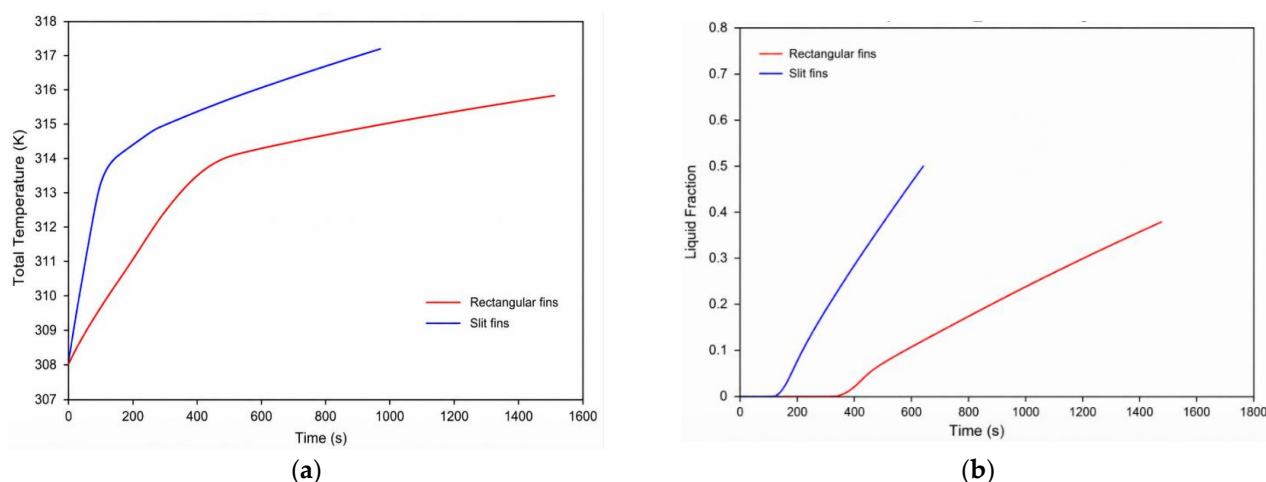


Figure 14. (a) Total temperature, (b) liquid fraction at 5C discharge rate of rectangular fins vs. slit fins BTMS.

The earlier melting onset in the slit-fin system does not indicate premature PCM utilization; it indicates improved heat spreading and earlier latent heat engagement. Because the slit openings increase PCM-fin contact area and provide additional local heat-transfer paths, heat reaches the PCM more effectively and activates melting sooner. At 5C, melting begins at about 100 s for slit fins compared with 350–400 s for rectangular fins, while the slit-fin system reaches $LF = 0.50$ at 620 s compared with only $LF = 0.37$ at 1480 s for rectangular fins. Thus, earlier melting represents more effective PCM utilization and stronger thermal regulation.

6.3.2. Total Temperature and Liquid Fraction Contours at 5C

The 5C contours in Figure 15a show rapidly evolving thermal gradients, with the battery core heating intensely and early, with the slit openings again clearly visible as cooler localised zones confirming sustained ambient convective dissipation through the fin perforations. The 5C liquid fraction contour sequence shown in Figure 15b shows the study's most effective visual results. The melting front begins at the battery surface which is at $LF = 0$ and moves through solid PCM until it reaches $LF = 0.50$, which indicates that all internal PCM has melted into liquid state. The rectangular fin configuration failed to reach this state because it achieved its maximum performance during the entire 1480 s simulation period. The slit fin system demonstrates complete advancement through the process which starts at $LF = 0$ and ends at $LF = 1.0$ whereas the rectangular fins only accomplished $LF = 0.37$ during their complete simulation time. The slit fin geometry demonstrates clear advantages over other systems because it enables better PCM interaction and latent heat utilization under challenging 5C discharge situations.

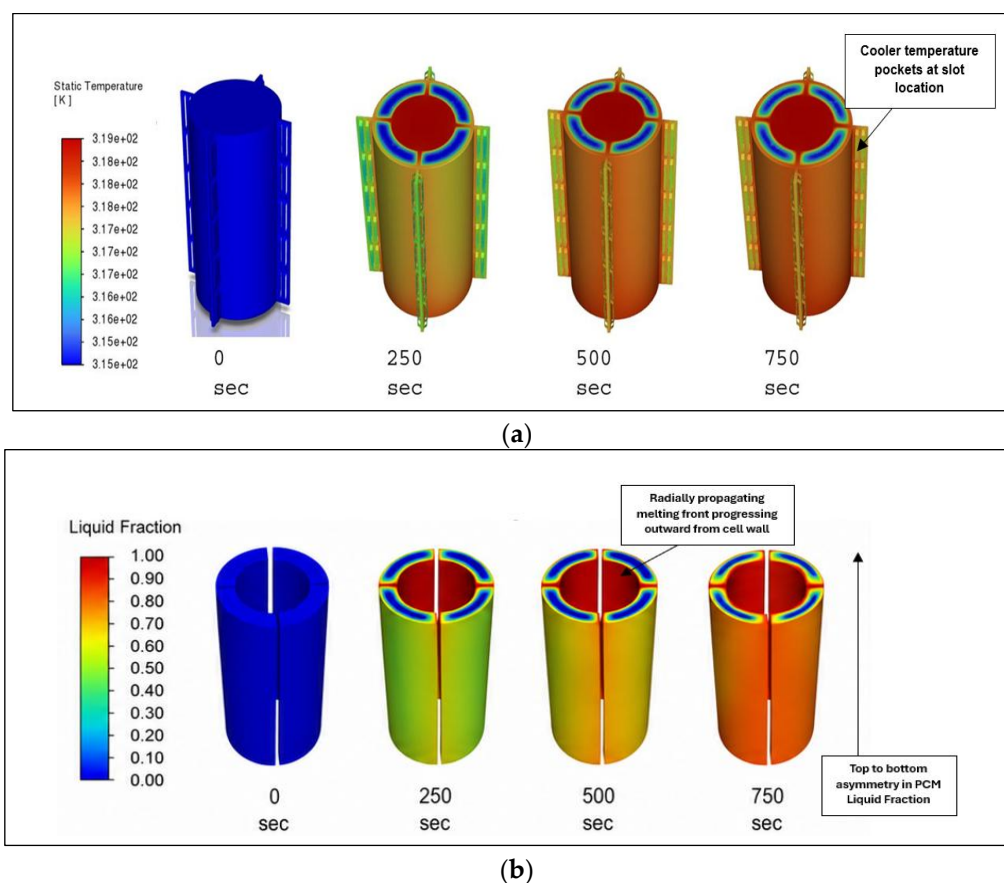


Figure 15. (a) Temperature contours at $t = 0, 250, 500,$ and 750 s, (b) liquid fraction contours of slit-fin BTMS at 1C at $t = 0, 250, 500,$ and 750 s at 5C.

6.4. Thermal Performance at 7C Discharge Rate

6.4.1. Total Temperature and Liquid Fraction Trend at 7C

Figure 16a presents the direct side-by-side comparison of total temperature at 7C between slit fins and rectangular fins. Both curves commence at 308.15 K and initially rise together during the very early sensible heating phase (first 50–100 s). After approximately 100 s, the two curves begin to diverge: the slit fin temperature rises more steeply at first as intense PCM melting begins (earlier in slit fins), then moderates to a more gradual slope reflecting active latent heat absorption, while the rectangular fin temperature continues rising steeply until its own melting onset at 170 s. From approximately 200 s onward, the rectangular fin temperature consistently exceeds the slit fin temperature at all time points, with the gap reaching approximately 1.3 K by 950 s. The slit fin total temperature remains consistently below the rectangular fin temperature throughout the entire 950 s simulation, demonstrating that the slit fin design provides both metric-dependent improvements in PCM utilization and a meaningfully lower temperature ceiling at 7C.

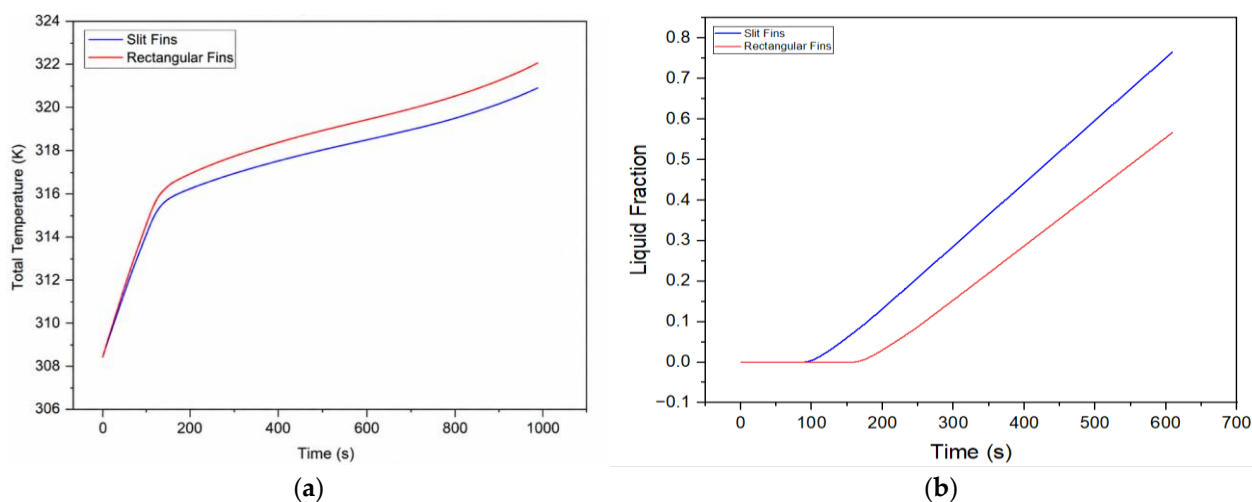


Figure 16. (a) Total temperature, (b) liquid fraction at 7C discharge rate of rectangular fins vs. slit fins BTMS.

Figure 16b presents the PCM liquid fraction comparison at 7C, which provides the quantitative evidence of the slit fin advantage at this extreme discharge rate. The slit fin liquid fraction initiates melting at approximately 100 s and rises steeply, outpacing the rectangular fin liquid fraction at 170 s from the very beginning. At every single time point from 100 s onward, the slit fin liquid fraction is higher than the rectangular fin value. The gap between the two curves is substantial and increases with time: at 300 s, slit fins show LF $\approx$ 0.17 while rectangular fins are at approximately LF $\approx$ 0.10; at 400 s, slit fins are at LF $\approx$ 0.27 vs. rectangular fins at LF $\approx$ 0.20; at 500 s, slit fins reach LF $\approx$ 0.41 vs. rectangular fins at LF $\approx$ 0.30; and at 620 s, slit fins reach LF = 0.76 compared with rectangular fins' LF = 0.56. The consistently and substantially higher liquid fraction of slit fins at 7C confirms the slit fin design as definitively superior in PCM latent heat utilization at every discharge rate evaluated in this study.

6.4.2. Temperature and Liquid Fraction Contours at 7C

The temperature contours of the slit-fin BTMS at 7C are presented in Figure 17a. The evolution is faster than at any lower discharge rate. At $t = 0$, the system is at uniform 308.15 K. By $t = 120$ s just two minutes into discharge, the battery core already displays an intense red-orange region (approximately 319–320 K), the cylindrical internal fin and adjacent PCM are absorbing latent heat. The four slit fins are clearly visible extending outward with a temperature gradient from high (inner attachment) to lower (outer tip region near ambient), and the slot perforations along the fin height appear as distinctly cooler elements confirming active slot-mediated ambient convection. The PCM between the fins appears predominantly in the higher-temperature range, indicating rapid heating toward and beyond the solidus. By $t = 360$ s, the entire BTMS has risen to very high temperatures, with the battery core at 320 K and even the outer housing approaching yellow-orange temperatures. By $t = 720$ s, the entire assembly is at very high temperature, consistent with the high liquid fractions achieved at these late time steps.

Figure 17b shows the liquid fraction that at $t = 0$, the PCM is fully solid. By $t = 250$ s, a striking pattern emerges: a large fully liquid red region (LF $\approx$ 0.8) concentrates near the battery surface and cylindrical fin, surrounded by a sharp phase transition boundary transitioning to partially liquid PCM, while the outer PCM region remains predominantly solid. By $t = 500$ s, the melting front has advanced significantly, the inner PCM is uniformly at high liquid fraction LF $\approx$ 0.7–0.8 and even the outer PCM regions have begun melting significantly, LF $\approx$ 0.3–0.5. By $t = 750$ s, the entire PCM domain has reached high liquid

fraction values, with only the corners of PCM silos furthest from the fins showing slightly lower values. These contours visually confirm the quantitative finding of $LF \approx 0.76$ at 620 s for slit fins at 7C, higher than the rectangular-fin value under the same operating condition, and demonstrate that the slit fin geometry enables near-complete exploitation of the paraffin wax PCM latent heat storage capacity even under the most extreme EV discharge conditions studied.

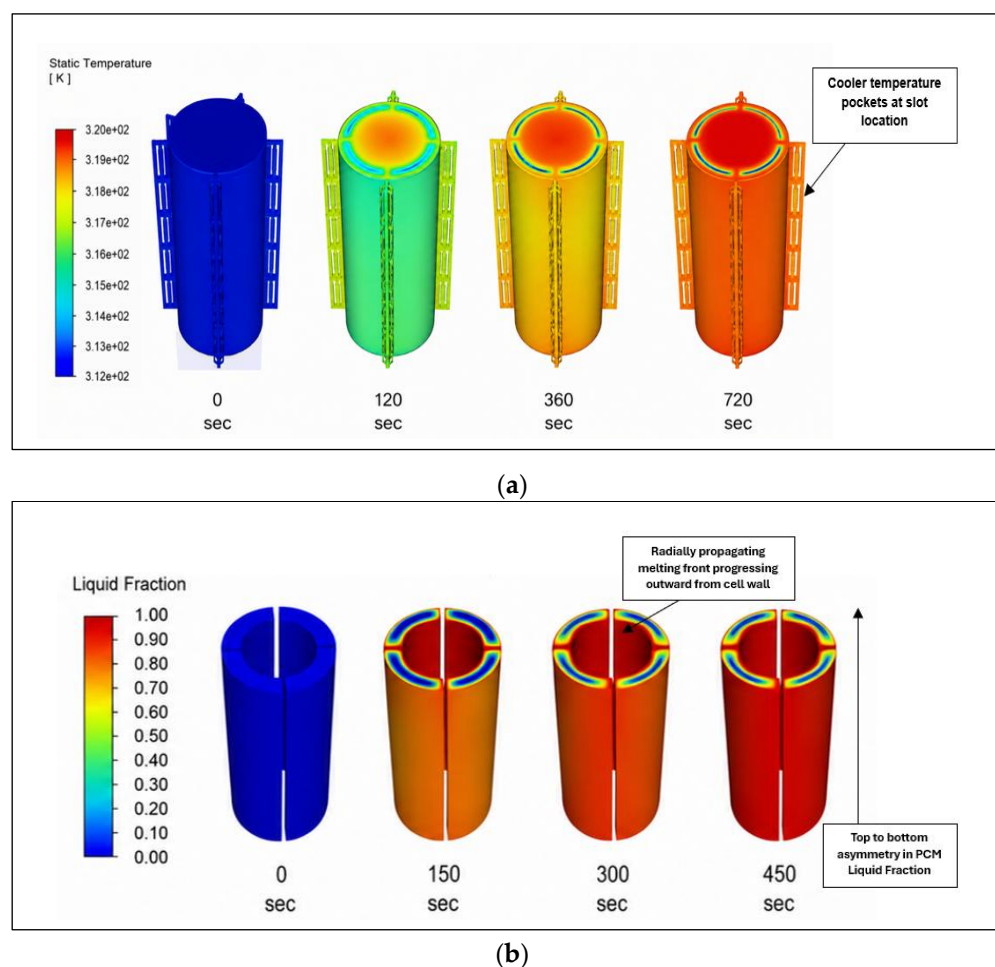


Figure 17. (a) Temperature contours at $t = 0, 120, 360,$ and 720 s, (b) liquid fraction contours of slit-fin BTMS at 1C at $t = 0, 250, 500,$ and 750 s at 7C.

6.4.3. Physics-Based Interpretation of the Slit-Fin Effect

Figures 18 and 19 present matched-time total-temperature contours and PCM liquid-fraction maps for the rectangular-fin and slit-fin configurations at 5C. In the rectangular-fin case, heat is mainly conducted through continuous flat fin surfaces, producing a more restricted heat-spreading path and slower melting-front development. In contrast, the slit-fin configuration introduces additional slit-edge surfaces and local conduction paths, which increase the effective PCM–fin interaction area and redistribute thermal gradients within the PCM. The liquid-fraction maps show that PCM melting develops earlier and over a larger active region in the slit-fin case at the same times, confirming stronger latent-heat utilization. Therefore, the improved response of the slit-fin design results from a combined effect of increased PCMfin contact area, redistributed conductive pathways, modified local thermal resistance, and more effective use of PCM latent heat.

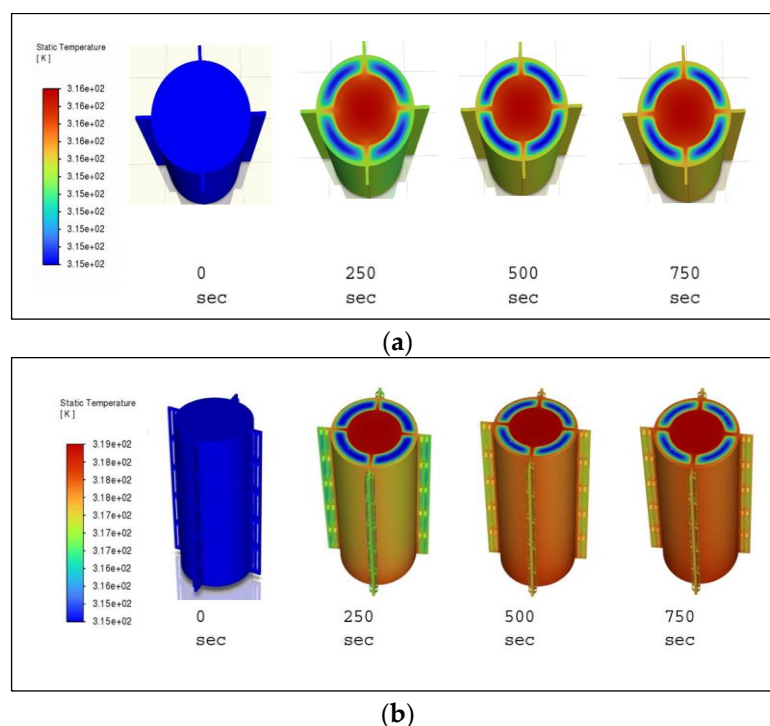


Figure 18. Matched-time total-temperature contours of the (a) rectangular-fin and (b) slit-fin BTMS configurations at 5C discharge rate.

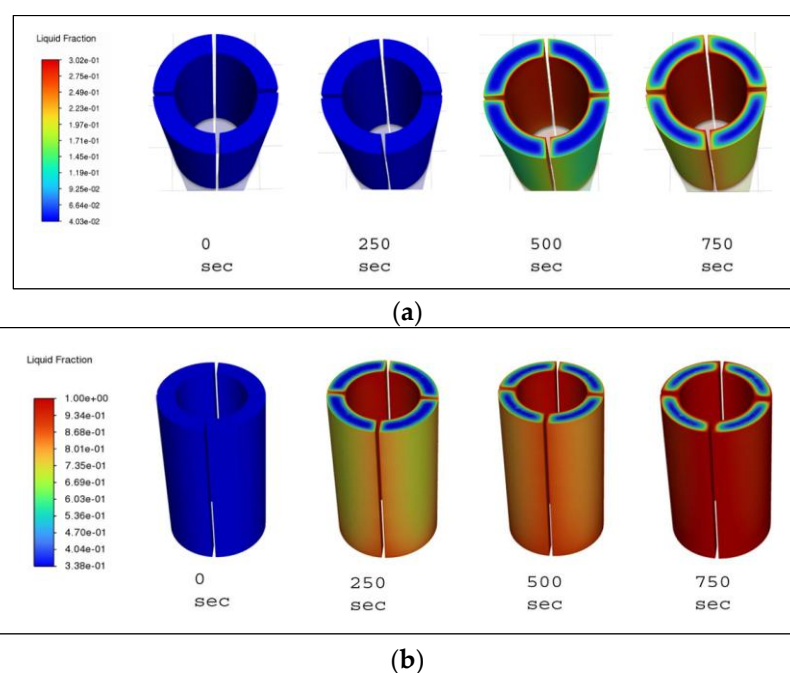


Figure 19. Matched-time PCM liquid-fraction contours of (a) rectangular-fin, (b) slit-fin BTMS configurations at 5C discharge rate.

6.5. Comparative Analysis of Rectangular and Slit-Fin Configurations at All Discharge Rates

6.5.1. Combined Total Temperature and Liquid Fraction

Figure 20a presents the comprehensive combined total temperature comparison between slit fins (solid lines) and rectangular fins (dashed lines) across all four discharge rates 1C, 3C, 5C, and 7C. Several important observations can be made from Figure 20. First, the clear separation between each C-rate pair of curves confirms the expected progressive increase in thermal severity with increasing discharge rate, with the 1C curves remaining

near the bottom of the graph (312–313 K final range), 3C curves in the 316–317 K range, 5C curves in the 318–320 K range, and 7C curves rapidly climbing to the top of the graph (320–321 K range). Second, within each C-rate pair, the relative positioning of slit fins versus rectangular fins changes with discharge rate in a physically meaningful and consistent manner: at 1C, slit fins remain slightly below rectangular fins, reflecting the convective cooling advantage of slots at mild discharge; at 3C, the slit fin curve rises above the rectangular fin curve, as the delayed-then-aggressive PCM engagement produces higher temperatures within the 2500 s window; at 5C, the slit fin curve, shows a higher steeper early rise above the rectangular fin curve, reflecting the 3.5 times earlier PCM engagement; and at 7C, the slit fin curve remains consistently below the rectangular fin curve, confirming that at extreme discharge rates the slit fin's superior convective and PCM performance together keep the system temperature lower throughout.

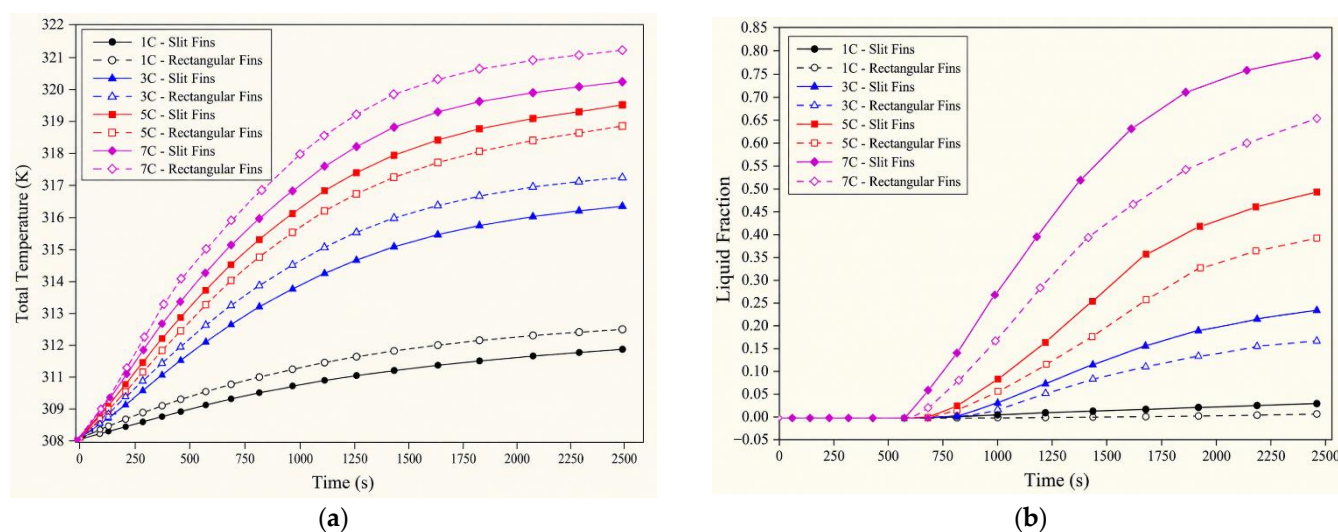


Figure 20. (a) Combined total temperature comparison, (b) combined PCM liquid fraction comparison of slit fins vs. rectangular fins BTMS at 1C, 3C, 5C, and 7C.

In Figure 20b, at 1C, both configurations show near-zero liquid fraction throughout the 2500-s simulation, with the slit fin curve remaining slightly lower than the rectangular fin curve reflecting the slit fin system's more effective convective cooling that delays PCM melting onset further. At 3C, the slit fin triangles consistently plot above the rectangular fin triangles from the first melting onset, with the gap between them widening progressively as the slit fin system accumulates more liquid fraction over time, ultimately reaching LF = 0.245 (slit) vs. LF = 0.165 (rectangular) near the end of the 2500-s window. At 5C, the slit fin solid red squares outpace the rectangular fin from approximately 150 s onward, with the slit fin liquid fraction reaching approximately LF = 0.50 at the end of the plotted window while rectangular fins barely reach LF = 0.39, a difference of more than 25% in absolute liquid fraction. At 7C, the slit fin solid purple diamonds rise steeply and consistently above the rectangular fin dashed purple diamonds throughout the simulation, reaching LF $\approx$ 0.79 versus LF $\approx$ 0.64 for rectangular fins at 2400 s confirming the slit fin advantage even at the most extreme discharge rate. The combined liquid fraction graph represents an irrefutable multi-rate demonstration that slit fins consistently initiate PCM melting earlier and achieve higher liquid fraction at every time point at every discharge rate, confirming the slit fin geometry as a universally superior PCM BTMS design for electric vehicle battery thermal management. Figure 21 presents a comparative bar chart of total temperature and liquid fraction for slit-fin and rectangular-fin BTMS configurations across different discharge rates. The comparison of numerical parameters is summarized in Table 12.

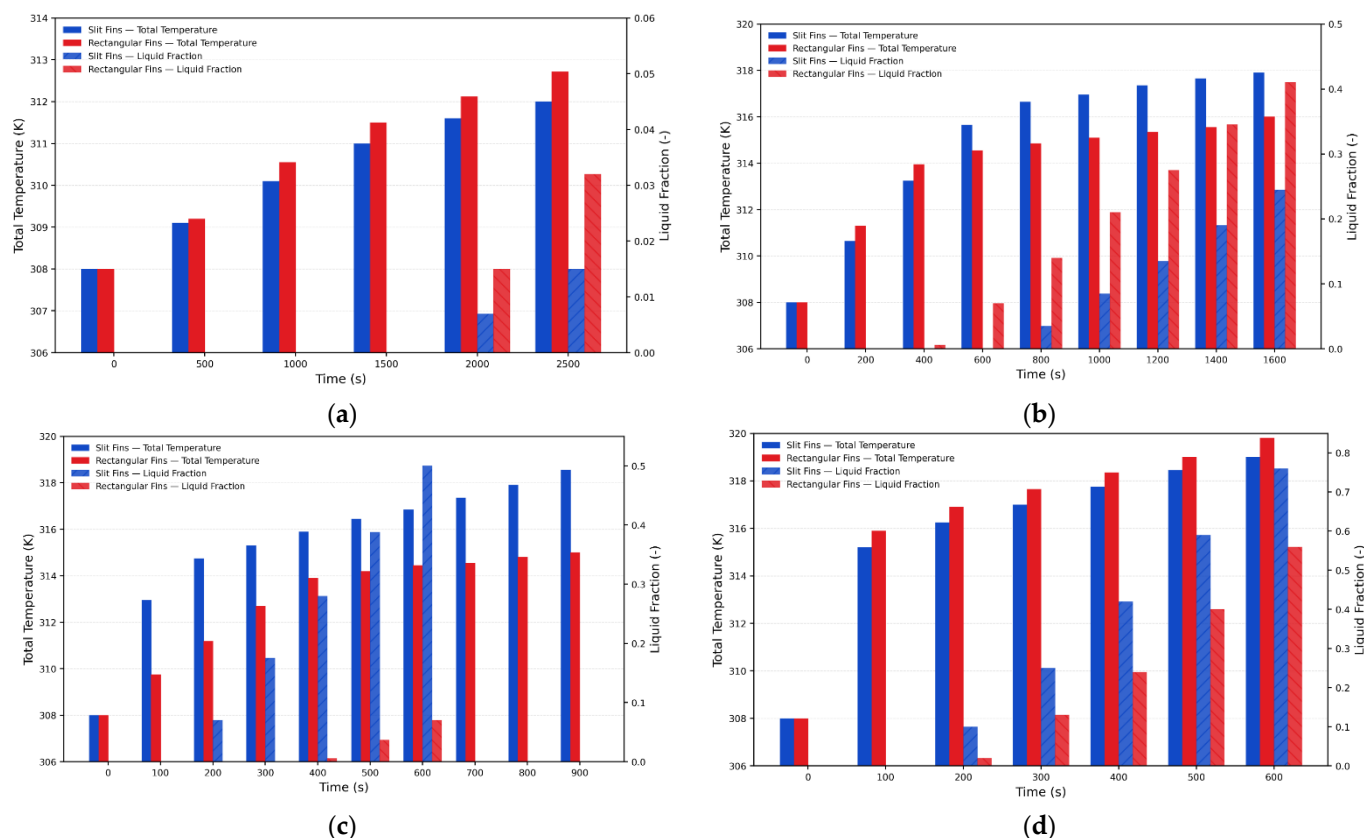


Figure 21. Comparison bar chart of total temperature and liquid fraction of slit fins vs. rectangular fins BTMS at (a) 1C, (b) 3C, (c) 5C, and (d) 7C.

Table 12. Maximum total temperature comparison at the end of each simulation.

Discharge Rate	T _{max} Rectangular [K]	T _{max} Slit [K]	ΔT (Slit Advantage) [K]
1C	312.85	312.10	0.75 lower
3C	317.70	316.70	1.00 lower
5C	318.95	319.65	*
7C	321.25	320.25	1.00 lower

* At 5C, the slit-fin temperature is marginally higher only because the slit geometry engages PCM melting 3.5× earlier (100 s vs. 375 s), so the system transitions to sensible heating sooner; the corresponding liquid fraction in Figure 20b is 27% higher than the rectangular configuration.

The PCM liquid-fraction comparison at the end of each simulation is summarized in Table 13.

Table 13. PCM liquid-fraction comparison at the end of each simulation.

Discharge Rate	LF Rectangular	LF Slit	Slit Advantage
1C	0.00	0.02	PCM activated
3C	0.16	0.24	+50%
5C	0.39	0.495	+27%
7C	0.65	0.785	+21%

6.5.2. Quantitative Performance Comparison of Rectangular and Slit-Fin Configurations

The performance comparison between rectangular-fin and slit-fin BTMS configurations at different discharge rates is presented in this section. The analysis focuses on key thermal and electrochemical performance indicators including maximum temperature, PCM utilization, and thermal protection duration. The summarized quantitative results are provided in Table 14. The Summary comparison of baseline vs. rectangular fins vs. slit fins and Temperature rise rate comparison is provided in Appendix A (Tables A1 and A2).

Table 14. Quantitative comparison of rectangular-fin and slit-fin BTMS performance at different discharge rates.

Discharge Rate	Maximum Battery Temperature	Time to Reach Threshold Temperature, 318.15 K	Total/Final PCM Liquid Fraction at Selected Time	Percentage Change in Thermal Protection Duration	Thermal Uniformity, $\Delta T_{\max}$	Relative Improvement/Deterioration of Slit Fins vs. Rectangular Baseline
1C	Rect: 312.7 K Slit: 312.0 K	Rect: Not reached Slit: Not reached	Rect: 0.032 at 2500 s Slit: 0.015 at 2500 s	Not applicable	Rect: 4.7 K Slit: 4.0 K	0.7 K lower temperature; 53.1% lower PCM melting, indicating better latent-heat preservation
3C	Rect: 318.15 K Slit: 318.15 K	Rect: 1650 s Slit: 2500 s	Rect: 0.42 Slit: 0.49	+51.5%	Rect: 5.1 K Slit: 4.4 K	+51.5% longer protection; +16.7% higher PCM utilization; improved temperature uniformity
5C	Rect: 315.0 K at 900 s Slit: 318.5 K at 900 s	Rect: Not reached Slit: 850–900 s	Rect: 0.37 at 1480 s Slit: 0.50 at 620 s	Slit reaches threshold earlier under this metric	Rect: 5.8 K Slit: 5.0 K	+35.1% higher PCM melting and 2.87× faster PCM utilization; temperature metric shows deterioration, but latent-heat activation improves
7C	Rect: 322.0 K Slit: 320.8 K	Rect: 520 s Slit: 620 s	Rect: 0.56 at 620 s Slit: 0.76 at 620 s	+19.2%	Rect: 7.8 K Slit: 6.4 K	1.2 K lower temperature; +35.7% higher PCM utilization; improved thermal uniformity under severe heat load

6.5.3. Conditional Interpretation of Slit-Fin Performance

The slit-fin performance should be interpreted in a metric-dependent manner rather than as unconditional superiority under all operating conditions. At a low discharge rate, both configurations remain within the safe thermal range, so the main benefit of slit fins is modest temperature reduction and delayed PCM melting, which helps preserve latent heat capacity. At a moderate discharge rate, the slit-fin design becomes more advantageous by extending thermal protection duration by approximately 51.5% and increasing PCM utilization by about 16.7%. Under higher discharge rates, faster PCM melting becomes beneficial because earlier latent-heat activation is needed to control rapid heat generation; therefore, slit fins provide about 35.1% greater PCM melting at 5C and 35.7% greater PCM utilization at 7C. Thus, the slit-fin geometry is most useful when the design priority is improved PCM engagement, longer thermal protection, and stronger high-rate thermal response, while at a low discharge rate, its main advantage is delayed PCM consumption and mild temperature control.

6.5.4. Trade-Off Between Faster PCM Melting and Thermal Protection

The faster PCM melting observed in the slit-fin configuration represents an important trade-off in PCM-based BTMS design. In general, rapid PCM melting may be undesirable if it causes early depletion of latent heat storage before the discharge process is complete. However, under high discharge rates, the battery generates heat rapidly, and delayed PCM activation can allow the battery temperature to rise quickly before the PCM is effectively utilized. Therefore, early melting is beneficial when it is accompanied by improved heat spreading and higher PCM utilization.

In the present study, the slit-fin system shows faster melting because the slit openings increase the PCM-fin contact area and enhance local heat transfer around the fin edges. At 5C, the slit-fin system initiates melting at approximately 100 s, whereas the rectangular-fin system begins melting at about 350–400 s. The slit-fin system reaches $LF = 0.50$ at 620 s, while the rectangular-fin system reaches only $LF = 0.37$ at 1480 s. This confirms that the slit fins activate the PCM latent heat storage earlier and use the PCM more effectively under high heat generation.

At 7C, the same trend becomes more important due to extreme heat load. The slit-fin system reaches $LF = 0.76$ at 620 s, compared with $LF = 0.56$ for rectangular fins, showing approximately 35.7% higher PCM utilization. Thus, the trade-off is that the slit-fin system melts PCM faster, but this faster melting improves thermal protection during high-discharge operation by engaging latent heat earlier and spreading heat into a larger PCM volume. Therefore, faster melting in the slit-fin design should be interpreted as controlled and beneficial PCM utilization, not premature thermal failure.

The present results are consistent with the broader fin-performance and PCM-fin literature, which shows that fin geometry controls not only surface area but also heat-spreading paths, local thermal resistance, and phase-change progression. In the present slit-fin BTMS, the improvement is not caused by a single factor alone; rather, it results from a combination of increased PCM–fin interaction area, additional slit-edge conduction paths, modified thermal resistance distribution, and more effective latent-heat utilization. This behavior is evident across the discharge rates. At 1C, the slit fins reduce total temperature by about 0.7 K and delay unnecessary PCM melting, preserving latent-heat capacity. At 3C, they extend thermal protection duration from 1650 s to 2500 s and increase PCM utilization from $LF = 0.42$ to 0.49. At 5C, slit fins reach $LF = 0.50$ at 620 s, while rectangular fins reach only $LF = 0.37$ at 1480 s. At 7C, slit fins reach $LF = 0.76$ compared with $LF = 0.56$ for rectangular fins at 620 s. Therefore, the proposed slit-fin design should be understood as a heat-transfer pathway modification rather than only a fin-shape variation.

7. Conclusions

- (1) This study numerically investigated a slit fin-enhanced PCM-based BTMS for an 18650 cylindrical NCM lithium-ion battery at 1C, 3C, 5C, and 7C discharge rates. The proposed design replaced solid rectangular external fins with slit fins while keeping the same BTMS size, PCM thickness, fin number, and material selection.
- (2) The numerical model was validated against the baseline rectangular-fin study, Ref. [1], before evaluating the slit fin configuration. The validation showed good agreement, with an average cell wall temperature error of 1.03% and a maximum error of 1.47% at 5C, confirming the reliability of the simulation approach.
- (3) At 1C, both configurations maintained temperatures safely below the critical 318.15 K limit. However, the slit fin design showed slightly lower total temperature and delayed PCM melting, indicating better heat rejection and preservation of PCM latent heat under low thermal loading.
- (4) At 3C, the slit fin design extended the thermal protection duration from 1650 s to 2500 s, giving a 51.5% improvement compared with rectangular fins. The PCM liquid fraction also increased from $LF = 0.42$ to $LF = 0.49$, representing 16.7% greater latent heat utilization.
- (5) At 5C, the slit fin geometry showed a much stronger PCM response by initiating melting at approximately 100 s, compared with 350,400 s for rectangular fins. It reached $LF = 0.50$ at 620 s, while rectangular fins reached only $LF = 0.37$ at 1480 s, proving faster and more effective PCM utilization.
- (6) At 7C, the slit fin system again performed better under extreme heat generation. PCM melting started about 70 s earlier than rectangular fins, and the liquid fraction reached $LF = 0.76$ compared with $LF = 0.56$ at 620 s, giving 35.7% higher PCM utilization.
- (7) Overall, the slit fin geometry improves BTMS performance by increasing PCM-fin contact area and creating additional natural convection pathways through the slit openings. These results show that slit fins are a simple, low-cost, and manufacturable improvement for passive PCM-based battery thermal management systems, without increasing system size or material complexity.
- (8) Future work should focus on experimental validation of the slit-fin BTMS to confirm the predicted numerical trends under practical operating conditions. Further optimization of slit size, number, spacing, and orientation is also required to identify the best balance between thermal performance, structural strength, and manufacturability. In addition, future studies should extend the present single-cell model to multi-cell battery modules and evaluate the design under realistic transient drive cycles, variable ambient conditions, and possible thermal contact resistance effects.

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Nomenclature

A_{mush}	Mushy zone constant	BTMS	Battery Thermal Management System
Bi	Biot number	CFD	Computational Fluid Dynamics
C_o	Battery nominal capacity (Ah)	EV	Electric Vehicle
C_p	Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	FVM	Finite Volume Method
E	Open circuit voltage (V)	HAR	Heat transfer Area Ratio
E_d	Energy density ($Wh \cdot kg^{-1}$)	HPPC	Hybrid Pulse Power Characterization
F_o	Fourier number	NCM	Nickel Cobalt Manganese ($LiNiCoMnO_2$)
g	Gravitational acceleration ($m \cdot s^{-2}$)	PCM	Phase Change Material
H	Height of the BTMS (m)	PISO	Pressure-Implicit with Splitting of Operators
H_{PCM}	Total enthalpy of PCM (J/kg)	PRESTO	PRESsure STaggering Option
h	Convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)	UDF	User-Defined Function
I	Electric current (A)	LIB	Lithium-Ion Battery
k	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	LF	Liquid Fraction
L	Latent heat of fusion ($J \cdot kg^{-1}$)	SOC	State of Charge
N	Number of fins	C-rate	Charge/Discharge Rate
Nu	Nusselt number	BMS	Battery Management System
p	Pressure (Pa)		
Q	Heat generation/transfer rate (W)		
q_b	Heat generation rate per unit volume ($W \cdot m^{-3}$)		
R_e	Total internal resistance (Ω)		
T	Temperature (K)		
T_∞	Ambient temperature (K)		
T_l	Liquidus temperature (K)		
T_s	Solidus temperature (K)		
t	Time (s)		
U	Battery nominal voltage (V)		
V	Terminal voltage (V)		
V_b	Battery volume (m^3)		
α	Thermal diffusivity (m^2/s)		
β	Thermal expansion coefficient (K^{-1})		
γ	Liquid fraction		
δ	Thickness (mm)		
ε	Small computational constant		
ρ	Density ($kg \cdot m^{-3}$)		
τ	Dimensionless time/Stress tensor		
ν	Kinematic viscosity (m^2/s)		

Appendix A

Table A1. Summary comparison of baseline vs. rectangular fins vs. slit fins.

Discharge Rate	Configuration	Melting Onset Time (s)	Se-lected/End Time (s)	Temperature at Se-lected/End Time (K)	Final/Selected Liq-uid Fraction	Melting Du-ration Δt (s)	PCM Melting Rate (LF/s)
1C	Rectangular fins	1900	2500	312.7	0.032	600	5.33×10^{-5}
1C	Slit fins	2200	2500	312.0	0.015	300	5.00×10^{-5}
3C	Rectangular fins	400	1650	318.15	0.42	1250	3.36×10^{-4}
3C	Slit fins	600	2500	318.15	0.49	1900	2.58×10^{-4}
5C	Rectangular fins	375	1480	315.8	0.37	1105	3.35×10^{-4}
5C	Slit fins	100	620	318.5	0.50	520	9.62×10^{-4}

7C	Rectangular fins	170	620	322.0	0.56	450	1.24×10^{-3}
7C	Slit fins	100	620	320.8	0.76	520	1.46×10^{-3}

Table A2. Temperature rise rate comparison.

Discharge Rate	Configuration	Initial T (K)	PCM Onset T (K)	ΔT (K)	Melting Time (s)	Rise Rate (K/s)
1C	Rectangular fins	308.15	313.75	5.60	1900	2.95×10^{-3}
1C	Slit fins	308.15	313.75	5.60	2200	2.55×10^{-3}
3C	Rectangular fins	308.15	313.75	5.60	400	1.40×10^{-2}
3C	Slit fins	308.15	313.75	5.60	600	9.33×10^{-3}
5C	Rectangular fins	308.15	313.75	5.60	375	1.49×10^{-2}
5C	Slit fins	308.15	313.75	5.60	100	5.60×10^{-2}
7C	Rectangular fins	308.15	313.75	5.60	170	3.29×10^{-2}
7C	Slit fins	308.15	313.75	5.60	100	5.60×10^{-2}

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