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Research papers

Uniform temperature distribution, prolonged temperature regulation, and accelerated recovery of battery thermal management system using a novel fin design

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ARTICLE INFO	A B S T R A C T		
Keywords: Thermal management Temperature distribution Solidification heat transfer Fin design Heat transfer enhancement	This study proposed a battery thermal management system (BTMS) integrating phase change material (PCM) with novel interior-exterior fins to address the low heat conduction properties of PCM. The battery heat generation and PCM liquefaction were analysed using the lumped model and enthalpy-porosity technique. The irreversible, reversible, and total battery heat generation were investigated. The BTMS was investigated under 1C, 2C, 3C, and 5C current rates. The Interior-Exterior Fin-PCM-Air-Cooled BTMS outperformed the Air-Cooled BTMS, PCM-Air-Cooled BTMS, Interior Fin-PCM-Air-Cooled BTMS, and Exterior Fin-PCM-Air-Cooled BTMS before, during, and after the PCM melting process, providing a superior uniform cooling effect to the battery. Different heat transfer mechanisms were identified throughout the PCM phase transition. During PCM melting and solidification cycles at 5C, the variation in the maximum battery surface temperature in the Interior-Exterior Fin-PCM-Air-Cooled BTMS, buffering the effects of the temperature change. In the first cycle at 5C, the interior-exterior fins extended the duration for which the battery's temperature remained within the optimal range by 6.91 % and decreased the recovery period of the thermal management system by 37.56 % compared to the PCM-Air-Cooled BTMS. These results provided new horizons for the development of effective BTMSs.		

1. Introduction

Nowadays, fossil fuels provide almost 80 % of the global energy demands, which causes the prevailing environmental pollution and deteriorates human health. Additionally, as fossil fuels are depleted, researchers are motivated to explore more efficient, economical, and environmentally sustainable power sources in the form of energy storage technologies. Electrical energy storage technologies powered by renewable energy sources can be a viable alternative to fossil fuels [1]. Replacing internal combustion engine vehicles with electric vehicles reduces gas emissions by 20 % and produces less noise and air pollution [2]. However, the electric vehicle industry continues to encounter significant obstacles in reaching its full potential due to the challenges related to electric batteries, the main power source in electric vehicles [2].

Lithium-ion batteries, known for their substantial specific capacity, elevated energy density, and extended lifespan, are the predominant type of commercially available rechargeable batteries [3]. The operating

temperature affects lithium-ion batteries' capacity, lifespan, and resistance, with 298.15–318.15 K (25–45 °C) being the optimal range for their cycle life and safety [2,4,5]. Hence, a robust battery thermal management system (BTMS) is crucial [6]. The non-uniform temperature distribution in the battery can adversely affect the battery's functionality. Hence, it is essential to minimise temperature gradients within a battery [7]. However, providing a uniform cooling effect for the battery has been largely neglected [28–30].

Phase change materials (PCMs) have become popular thermal management systems within the research community due to their simple structures, affordability, outstanding cooling capabilities, and significant latent heat properties, with no requirement for an external energy source [8–10]. A primary technical obstacle associated with PCMs is their low heat conduction properties, hindering heat distribution within the materials and decreasing their ability to dissipate heat [11]. Furthermore, PCMs have limited latent heat capacity due to their reduced surface heat transfer coefficient. The surface heat transfer coefficient is the rate of heat transfer per unit area between a surface and

https://doi.org/10.1016/j.est.2024.115054

Received 6 June 2024; Received in revised form 21 November 2024; Accepted 14 December 2024 Available online 23 December 2024

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its surroundings. A low surface heat transfer coefficient limits the PCM's ability to efficiently exchange heat with its environment, hindering the effective utilisation of its latent heat during phase transitions. This can slow down the solidification process, reduce cooling performance, and create temperature gradients within the PCM, further diminishing its efficiency. Thus, the battery temperature will increase after the PCM completely melts. Therefore, the solidification process has to be conducted in time to recover the PCM latent heat. This is achieved by dissipating the heat absorbed by the PCM to its surroundings, highlighting the importance of employing heat transfer enhancement techniques within the PCM [12,13]. Various techniques [14–16] have been proposed to enhance heat transfer within the PCMs, including using metallic and carbon-based materials. Incorporating metal fins into the PCM is an effective method for improving heat transfer, attributed to their simple configuration and the simplicity of their fabrication process [11]. When PCM melts, the natural convection of the liquid PCM can enhance the heat transfer rate. This factor should be carefully considered in the design of metal fin inserts [17]. Consequently, comprehensive research into PCM-based BTMSs with fins is essential.

Metal fins are used in various shapes, including pin, radial, longitudinal, and triangular. Longitudinal fins have been more popular than radial fins due to the enhancement of heat conduction and natural convection of liquid PCM [18]. Researchers integrated fins into the PCM to improve its conductive heat transfer capabilities [12,19] and placed fins on the PCM surface to enhance the convective heat transfer to the surroundings [20,21]. Previous research investigated the thermal management of batteries using fin-enhanced PCM within nylon [22–24], acrylic [25], and plastic casings [21], which prevented heat dissipation to the surrounding environment through the casing walls.

In addition to passive cooling techniques, such as PCMs, hybrid BTMSs that combine PCM with active cooling techniques, such as liquid cooling, have been investigated to address the limitations of standalone PCM-based BTMSs. These hybrid BTMSs utilise the high latent heat capacity of PCM for effective thermal regulation while employing liquid cooling to dissipate excess heat and accelerate PCM solidification [26]. For instance, dynamic liquid cooling enhanced cooling performance and energy efficiency by optimising liquid cooling activation times [27], highlighting the potential of combining passive and active cooling techniques for improved thermal management.

Currently, most studies on PCM-based BTMSs [19,28,29] have focused on enhancing thermal conductivity by incorporating various types of metal fins. However, they often fail to achieve uniform temperature distribution on the battery surface and rapid recovery after the PCM has melted entirely. Furthermore, while previous research has investigated the use of either interior fins [12,19] or exterior fins

[20,21] individually, there is a notable gap in the literature regarding the integration of both interior and exterior fins within PCM-based BTMSs to simultaneously improve heat distribution within the PCM and heat dissipation to the surroundings. Additionally, existing studies have not sufficiently explored the challenges of maintaining effective temperature regulation throughout the complete PCM melting and solidification cycles. These cycles are crucial for ensuring consistent thermal performance and durability of BTMSs under repeated operation. The novelty of this study lies in proposing a hybrid fin design that leverages the complementary advantages of interior and exterior fins, enabling effective thermal management of lithium-ion batteries under demanding conditions, such as high current rates and prolonged operation. This study investigated a BTMS with a metal casing and metal fins comprised of a tubular fin covering the battery surface, accompanied by 4 rectangular fins submerged within the PCM and extended to the outside of the casing (Interior-Exterior Fin-PCM-Air-Cooled BTMS), as shown in Fig. 1 (e). The rationale behind the proposed BTMS was to increase the heat transfer area to enhance the conductive and buoyancydriven heat transfer within the PCM, plus the natural air convective heat transfer to the ambient. All the simulations in this study were conducted for one lithium-ion battery. Its purpose was to evaluate the effects of the fin design on the battery temperature without the complications of heat energy interactions among batteries in a battery pack.

The battery's heat generation was investigated under discharging with 1C, 2C, 3C, and 5C current rates. Furthermore, the temperature regulation performance of the Interior-Exterior Fin-PCM-Air-Cooled BTMS was compared to the battery thermally regulated by natural air convection (Air-Cooled BTMS) (shown in Fig. 1 (a)), PCM without fins (PCM-Air-Cooled BTMS) (shown in Fig. 1 (b)), PCM with a tubular and 4 rectangular interior fins (Interior Fin-PCM-Air-Cooled BTMS) (shown in Fig. 1 (c)), and PCM with a tubular and 4 rectangular exterior fins (Exterior Fin-PCM-Air-Cooled BTMS) (shown in Fig. 1 (d)). Non-dimensional analyses were conducted during the PCM phase transition in the BTMSs with different fin designs. This study also presented a detailed investigation of the dependability of the various BTMSs over three cycles of the PCM undergoing complete liquefaction and resolidification.

2. Problem statement and physical model

The present study used an 18,650 cylindrical lithium-ion battery ($\text{LiNi}_x\text{Co}_y\text{Mn}_z\text{O}_2$) [30,31]. The properties of the selected battery are detailed in Table 1 [32]. Since the temperature regulation performance of a cylindrical battery is not significantly impacted by its detailed structure in the lumped model, explained in Subsection 3.1, the battery



Fig. 1. The diagrams of the (a) Air-Cooled BTMS, (b) PCM-Air-Cooled BTMS, (c) Interior Fin-PCM-Air-Cooled BTMS, (d) Exterior Fin-PCM-Air-Cooled BTMS, and (e) Interior-Exterior Fin-PCM-Air-Cooled BTMS.

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Table 1

Specification of the selected lithium-ion battery [32].

1				
	Parameter	Value	Parameter	Value
	Nominal voltage (V)	3.7	Thermal conductivity in the radial direction $(W \cdot m^{-1} \cdot K^{-1})$	0.2
	Nominal capacity (Ah)	2.6	Thermal conductivity in the axial direction $(W \cdot m^{-1} \cdot K^{-1})$	37.6
	Cell mass (kg)	0.0475	Specific heat capacity (J·kg ⁻¹ ·K ⁻¹)	1200

was modelled as a uniform cylindrical entity to simplify the model while maintaining result accuracy [32].

Fig. 2 shows the engineering drawing of the proposed BTMS, comprising a casing, fins, and an insulating layer. The dimensions of the BTMS were chosen following standard practices within the research community [22–24,33]. The battery was placed at the core of the tubular casing. The battery surface was covered with metal fins, including a tubular and 4 rectangular interior-exterior fins. Each interior-exterior fin, measuring 11 mm in length, extended perpendicularly from the outer surface of the tubular fin to the outside of the casing. The fin and battery measured the same height, reaching 65 mm. The thickness of the fins, casing, and insulating layer was 1 mm. Paraffin wax filled the gaps between the fins and the casing, maintaining a consistent 5 mm thickness across the four PCM-based BTMSs.



Fig. 2. The engineering drawing of the Interior-Exterior Fin-PCM-Air-Cooled BTMS.

Copper and aluminium are commonly utilised in fin construction because of their superior thermal conductivity, which minimises conductive thermal resistance, high heat capacity for greater thermal storage per volume unit, and low density, enhancing thermal storage capacity per mass unit [34]. For the BTMS casing and fins in this study, an aluminium alloy was chosen over copper and pure aluminium because it is lighter, has greater thermal conductivity, and offers superior heat capacity. Furthermore, aluminium alloy benefits from excellent corrosion resistance, widespread availability, and affordability [35]. Paraffin wax was selected for its significant latent heat, suitable melting temperature, minimal volume change during phase transition, and favourable chemical and thermal stability, all at a cost-effective price. Detailed thermo-physical characteristics of the selected PCM, aluminium alloy, and insulating material are listed in Table 2 [22,36,37].

3. Governing equations

3.1. Battery heat generation

The heat generation in lithium-ion batteries is affected by factors such as the battery nominal capacity, electrode materials (battery chemistry), charge and discharge rates, battery size, battery type (cylindrical, pouch, or prismatic), depth of discharge (*DOD*), state of charge (*SOC*), and ambient temperature [38,39]. The lumped model was utilised in this study to characterise heat generation in lithium-ion batteries due to its low computational cost [40].

Bernardi et al. [41] showed that the entire heat generation of lithium-ion batteries consists of irreversible joule heat and reversible entropic heat, which are caused due to internal resistance and a change in the entropy of batteries, respectively [40]. The battery heat generation is mathematically expressed as [32]:

$$Q_{\rm t} = Q_{\rm irr} + Q_{\rm rev} \tag{1}$$

$$Q_{\rm irr} = I^2 R_{\rm e} \tag{2}$$

$$\Omega_{\rm rev} = -I \left[T \left(\frac{dE}{dT} \right) \right] \tag{3}$$

$$q_{\rm b} = \frac{Q_{\rm t}}{V_{\rm b}} \tag{4}$$

The total heat generation (Q_t), irreversible heat generation (Q_{irr}), reversible heat generation (Q_{rev}), electric current (I), total internal resistance (R_e), temperature (T), entropy coefficient (dE/dT), and q_b which is the heat generation per unit of the battery volume (V_b) are identified. Jiaqiang et al. [32] developed the equations for R_e and dE/dT for the selected battery as:

Table 2	
The thermo-physical properties of the materials [2	22,36,37].

Properties	Value
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$), solid	0.20
Thermal conductivity (W·m ⁻¹ ·K ⁻¹), liquid	0.18
Specific heat capacity (J·kg ⁻¹ ·K ⁻¹), solid	2000
Specific heat capacity (J·kg ⁻¹ ·K ⁻¹), liquid	2350
Density (kg⋅m ⁻³), solid	880
Density (kg⋅m ⁻³), liquid	700
Melting temperature (K)	313.75-317.85
Latent heat (J·kg ⁻¹)	240,800
Dynamic viscosity, $(kg \cdot m^{-1} \cdot s^{-1})$	0.005
Thermal expansion coefficient (K ⁻¹)	0.00076
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	167
Specific heat capacity (J·kg ⁻¹ ·K ⁻¹)	896
Density (kg⋅m ⁻³)	2700
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.19
Specific heat capacity $(J \cdot kg^{-1} \cdot K^{-1})$	1260
Density (kg⋅m ⁻³)	1200
	Properties Thermal conductivity $(W \cdot m^{-1} \cdot K^{-1})$, solid Thermal conductivity $(W \cdot m^{-1} \cdot K^{-1})$, liquid Specific heat capacity $(J \cdot kg^{-1} \cdot K^{-1})$, solid Specific heat capacity $(J \cdot kg^{-1} \cdot K^{-1})$, liquid Density $(kg \cdot m^{-3})$, solid Density $(kg \cdot m^{-3})$, liquid Melting temperature (K) Latent heat $(J \cdot kg^{-1})$ Dynamic viscosity, $(kg \cdot m^{-1} \cdot s^{-1})$ Thermal expansion coefficient (K^{-1}) Thermal conductivity $(W \cdot m^{-1} \cdot K^{-1})$ Specific heat capacity $(J \cdot kg^{-1} \cdot K^{-1})$ Density $(kg \cdot m^{-3})$ Thermal conductivity $(W \cdot m^{-1} \cdot K^{-1})$ Specific heat capacity $(J \cdot kg^{-1} \cdot K^{-1})$ Density $(kg \cdot m^{-3})$

C

$$\begin{aligned} R_{\rm e} &= \left(-112 \times SOC^3 - 0.203 \times SOC^2 \times T + 0.000737 \times SOC \times T^2 \right. \\ &+ 0.00000753 \times T^3 + 301 \times SOC^2 - 0.144 \times SOC \times T - 0.0061 \\ &\times T^2 - 188 \times SOC + 1.28 \times T + 23.6 \right) \times 10^{-3} \end{aligned}$$

$$(5)$$

$$\frac{dE}{dT} = (-0.342 + 0.979 \times SOC - 1.49 \times SOC^2 + 0.741 \times SOC^3) \times 10^{-3}$$
(6)

$$SOC = 1 - x \bullet t = 1 - DOD \tag{7}$$

where *t* is time. Under a constant discharge rate (current rate) of *x* C, the current rate is determined by dividing the discharging current by the nominal capacity of the battery [42].

The transient battery heat generation and actual thermal performance of the BTMSs were investigated using Eqs. (1)–(7) under discharging with 1C, 2C, 3C, and 5C current rates. The current rates ranging from 1C to 5C are commonly employed in experimental research [43] to investigate the performance of the selected battery under different load requirements, ensuring the battery remains undamaged. Furthermore, the BTMSs were investigated under constant averaged heat generation of 185,435 and 412,200 W·m⁻³ during discharging at 3C and 5C current rates, respectively [43]. This aimed to examine the temperature regulation performance of the BTMSs under a specific level of heat generation. Table 3 shows a detailed description of the various scenarios examined in this study.

3.2. PCM liquefaction

Various techniques are employed to model the process of solid-liquid phase change. The enthalpy-porosity technique [37] is widely utilised to precisely characterise the natural convection within the melting zone and predict the location and shape of the melting front while demanding \vec{x}

comparatively low computational cost. Therefore, a sink term, \vec{S} , is integrated into the Navier-Stokes equations, which is expressed as [44]:

$\vec{S} = -A(\gamma) \bullet \left(\vec{u} - \vec{u}_{p}\right)$ (8)

where \vec{u} is the velocity and \vec{u}_p , the pull velocity, is 0. The porosity function, $A(\gamma)$, is expressed as [45]:

$$\mathbf{A}(\gamma) = \frac{A_{\text{mush}}(1-\gamma)^2}{\gamma^3 + \varepsilon} \tag{9}$$

$$\gamma = \begin{cases} 0 \ T < T_{\rm s} \\ \frac{T - T_{\rm s}}{T_{\rm l} - T_{\rm s}} \ T_{\rm s} < T < T_{\rm l} \\ 1 \ T > T_{\rm l} \end{cases}$$
(10)

where γ is the liquid fraction, ε equals 0.001 to avoid 0 in the denominator, $T_{\rm s}$ is the PCM solidus temperature, and $T_{\rm l}$ is the PCM liquidus temperature. The constant for the mushy zone, $A_{\rm mush}$, indicates the melting front's structure and the rate at which the fluid's velocity nears zero during solidification. Since the effect of the value of $A_{\rm mush}$ on the heat transfer characteristics can be significant [44,46], a sensitivity study of the mushy zone constant was conducted by the authors with $A_{\rm mush}$ being 10⁴, 10⁵, 10⁶, 10⁷, and 10⁸ kg·m⁻³·s⁻¹ [37]. The simulations with $A_{\rm mush}$ values above 10⁸ kg·m⁻³·s⁻¹ were also conducted, which resulted in the divergence and oscillation of the solution. This divergence and oscillation of the solution. This divergence and oscillation of the solution. This study.

3.3. Continuity and momentum equations

The governing equations for continuity and momentum are detailed as follows [11]:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \, \vec{u}) = 0 \tag{11}$$

Table 3

Detailed description of the various scenarios examined in this study.

Scenario description	Initial conditions	Termination conditions	Current rates	BTMS configurations
Transient battery heat generation	The initial temperature was set to 308.15 K.	The simulations concluded at the end of the discharging process.	1C, 2C, 3C, 5C	Air-Cooled BTMS PCM-Air-Cooled BTMS Interior Fin-PCM- Air-Cooled BTMS Exterior Fin-PCM- Air-Cooled BTMS Interior-Exterior Fin- PCM-Air-Cooled BTMS
Constant averaged battery heat generation	The initial temperature was set to 298.15 K.	The simulations stopped after $t = 6000 \text{ s}$ at the 3C current rate and after $t = 2500 \text{ s}$ at the 5C current rate.	3C, 5C	PCM-Air-Cooled BTMS Interior Fin-PCM- Air-Cooled BTMS Exterior Fin-PCM- Air-Cooled BTMS Interior-Exterior Fin- PCM-Air-Cooled BTMS
Three cycles of the PCM undergoing complete liquefaction and re- solidification	The initial temperature for Cycle 1 was set to 298.15 K.	 Cycle specific: Cycle 1: The simulations stopped when the PCM melted completely (γ = 1). Then, the heat generation was removed, and the simulations stopped when the PCM solidified completely (γ = 0). Cycle 2: The simulations started when the PCM was solid (γ = 0) and stopped when the PCM melted completely (γ = 1). With the heat source removed, the simulations restarted and stopped when the PCM returned to solid (γ = 0). Cycle 3: The process of Cycle 2 was repeated 	The constant averaged battery heat generation was applied at 3C and 5C current rates.	PCM-Air-Cooled BTMS Interior Fin-PCM- Air-Cooled BTMS Exterior Fin-PCM- Air-Cooled BTMS Interior-Exterior Fin- PCM-Air-Cooled BTMS

$$\frac{\partial(\rho \vec{u})}{\partial t} + \nabla \bullet (\rho \vec{u} \vec{u}) = -\nabla p + \mu \nabla^2 \vec{u} + \rho_{\rm a} [1 - \beta (T - T_{\rm a})] \vec{g} + \vec{S}$$
(12)

where ρ represents density, *p* stands for pressure, μ is the dynamic viscosity, ρ_a is the density at T_a , β indicates the coefficient of thermal expansion, T_a is the ambient temperature, and \vec{g} signifies the gravitational acceleration. The effect of natural convection during the PCM phase change was included using the Boussinesq approximation. The energy equations for the battery (b), fins (f), PCM, and casing (c) can be written as [11]:

$$\rho_{\rm b}C_{\rm p,b}\frac{\partial T_{\rm b}}{\partial t} = \nabla(k_{\rm b}\nabla T_{\rm b}) + q_{\rm b} \tag{13}$$

$$\rho_{\rm f} C_{\rm p,f} \frac{\partial T_{\rm f}}{\partial t} = \nabla \left(k_{\rm f} \nabla T_{\rm f} \right) \tag{14}$$

$$\frac{\partial(\rho_{\rm PCM}H_{\rm PCM})}{\partial t} + \nabla \bullet (\rho_{\rm PCM}\vec{u}H_{\rm PCM}) = \nabla(k_{\rm PCM}\nabla T_{\rm PCM})$$
(15)

$$\rho_{\rm c} C_{\rm p,c} \frac{\partial T_{\rm c}}{\partial t} = \nabla (k_{\rm c} \nabla T_{\rm c}) \tag{16}$$

where k is the thermal conductivity and H_{PCM} , representing the specific enthalpy, is calculated as:

$$H_{\rm PCM} = \underbrace{h_{\rm PCM}}_{\rm Sensible \ enthalpy} + \underbrace{\Delta H_{\rm PCM}}_{\rm Latent \ enthalpy}$$
(17)

$$h_{\rm PCM} = h_{\rm a} + \int_{T_{\rm a}}^{T} C_{\rm p, PCM} dT \tag{18}$$

$$\Delta H_{\rm PCM} = \gamma L_{\rm PCM} \tag{19}$$

where h_a is the enthalpy at T_a , $C_{p,PCM}$ denotes the specific heat of the PCM at constant pressure, and L_{PCM} refers to the latent heat of PCM. The equations were numerically solved using ANSYS FLUENT 2023/R2. User-defined functions (UDFs) were developed for the transient heat generation of the battery using Eqs. (1)–(7) to serve as the heat source for the battery domain. The PISO scheme was used for transient simulations to couple the pressure and velocity. The PRESTO and second-order upwind algorithms were also utilised to discretise the pressure correction and the remaining equations, respectively. The convergence criteria for the continuity, momentum, and energy equations were 10^{-4} , 10^{-4} , and 10^{-10} , respectively. The initial condition of the system was:

$$t = 0; T(x, y, z) = T_a \tag{20}$$

The top and bottom of the BTMSs were insulated. The no-slip boundary condition was set at the fins and casing walls. No thermal contact resistance was specified for the thermal boundary conditions for PCM-fin, PCM-casing, and fin-battery interfaces. The boundary condition between the casing and ambient was:

$$-k_{\rm c}\frac{\partial T_{\rm c}}{\partial n} = h(T_{\rm c} - T_{\rm a}) \tag{21}$$

where *h* represents the convective heat transfer coefficient, set at 10 $W \cdot m^{-2} \cdot K^{-1}$ [22,47]. To simplify the simulations, (a) the PCM were considered isotropic and homogenous; (b) the PCM volumetric change during its phase transition was ignored; (c) heat transfer through radiation was overlooked; (d) the flow of liquid PCM was presumed to be laminar and incompressible, with minor viscous dissipation; and (e) the liquid phase of the PCM behaved as a Newtonian fluid.



Fig. 3. Validation of the transient heat generation of the battery compared to the results in [32].

4. Validation of the model

4.1. Battery heat generation

The transient thermal model of the battery under discharging with 0.5C and 1C current rates was compared to the numerical and experimental results reported in [32], where the battery's surface was subject to natural air convection. Fig. 3 shows the temperature at the central point along the battery's height, as reported in [32], and the temperature derived from the present numerical results. The current results exhibited a maximum discrepancy of approximately 0.5 %, demonstrating their accuracy in reproducing the battery heat generation.

4.2. PCM liquefaction

Sun et al. [22] conducted experimental and numerical studies on the effectiveness of thermal management using PCM integrated with straight and curved fins. To mimic the battery discharging, a heater generating 16 W of heat was used, elevating the battery's temperature from an initial 293.15 K to a maximum allowable limit of 333.15 K. Then, the heater was turned off to replicate the battery's cooling phase, allowing the temperature to drop from 333.15 K back to 313.15 K. Fig. 4 compares the current numerical findings with the results reported in [22], focusing on the PCM's transition to the liquid phase until complete melting and the mean battery surface temperature throughout the BTMS operational cycles. The PCM liquid fraction and battery temperature closely mirrored those reported in [22], with the greatest differences being 0.04, observed at t = 349 s, and 3.96 %, recorded at t = 1090 s, respectively. These results provided additional validation for the numerical model used in this study. The differences between numerical research and experimental study can be ascribed to the simplified simulations. Specifically, the simulations assumed constant thermo-physical properties for the PCM, whereas these properties may vary during experimental conditions due to various factors, such as the change in temperature. As shown in Fig. 4 (b), the time lapse between the numerical and experimental results can be attributed to the constant convective heat transfer coefficient used in the simulations. Experimentally, the convective heat transfer coefficient might be higher due to the fluctuations in the ambient temperature or changes in the airflow dynamics. Such conditions could lead to quicker thermal energy release from the BTMS into the environment and a more gradual rise in the temperature during the experiments.



Fig. 4. Validation of the current numerical findings through comparison with the results reported in [22] regarding (a) the PCM liquid fraction and (b) the mean battery surface temperature.



Fig. 5. (a) Grid and (b) time step dependency tests at the highest current rate of 5C.

4.3. Grid and time step dependency tests and symmetric model validation

The effects of grid and time step size on the results can be significant. Therefore, strict grid and time step dependency tests were conducted to guarantee the accuracy of the results, as shown in Fig. 5. The dependency tests were conducted for the Interior-Exterior Fin-PCM-Air-Cooled BTMS at the highest current rate of 5C. ANSYS Meshing generated the 3D structured grid to discretise the computational domain. Five grid sizes of 0.4 mm, 0.5 mm, 0.8 mm, 1 mm, and 1.5 mm were selected, which included 1,203,235, 573,820, 151,146, 91,344, and 28,035 elements, respectively. The grid size of 0.5 mm was selected, with a maximum error of 0.01 % in the maximum battery surface temperature ($T_{max,b.sur.}$) compared to the smallest grid size.

The dependency test was conducted for the time step sizes of 0.1, 0.25, 0.5, and 1 s, as shown in Fig. 5 (b). The time step size of 0.5 s was used in this study, with a maximum deviation of 0.0002 % in $T_{max,b,sur}$,

when compared to the time step size of 1 s.

The Interior-Exterior Fin-PCM-Air-Cooled BTMS model was simplified to a 1/8 model due to the symmetry in the geometry and physics of the BTMS. The maximum discrepancy in $T_{max,b.sur.}$ was 0.009 % compared to the whole BTMS model, which verified the accuracy of the 1/8 model. Hence, the 1/8 model was employed in the following research, reducing computational costs and time.

5. Results and discussion

5.1. Q_{irr} , Q_{rev} , and Q_t of the battery

Fig. 6 presents a comparison of the volume-averaged and transient battery heat generation, including Q_{irr} , Q_{rev} , and Q_t under natural air convection cooling during the battery discharging at 1C, 2C, 3C, and 5C current rates. Increasing the current rate resulted in higher Q_{irr} , Q_{rev} , and



Fig. 6. The comparison of (a) Q_{irr}, (b) Q_{rev}, and (c) Q_t under discharging with 1C, 2C, 3C, and 5C current rates.

 $Q_{\rm t}$. This might be because $Q_{\rm irr}$ had a quadratic relation with the electric current and Q_{rev} was linearly proportional to the electric current, indicating that Q_t was significantly affected by the operating current (as expressed in Eqs. (1)–(3)). Regardless of the current rate, Q_{irr} caused by the battery's internal resistance was higher than $Q_{\rm rev}$ due to the entropy changes, implying that the internal resistance played a crucial role in battery heat generation during discharging. Furthermore, higher current rates exhibited a greater dominance of Q_{irr} in Q_t, consistent with findings in a previous study [48]. The Q_{irr} ranged from 1.33 to 1.77, 2.43 to 3.49, 3.34 to 5.24, and 4.81 to 8.73 times higher than $Q_{\rm rev}$ under discharging with 1C, 2C, 3C, and 5C current rates, respectively. This indicated that the impact of the internal resistance on the battery heat generation became more pronounced at higher current rates. As outlined in Eq. (5), the overall internal resistance was a function of SOC and the temperature, and in Eq. (6), the entropy coefficient was a function of the SOC. Hence, as expressed in Eqs. (2) and (3), Q_{irr} and Q_{rev} were influenced by the SOC and temperature during the discharging of the battery at a constant current. Throughout the discharging process, Q_{irr}, Q_{rev}, and Q_t initially increased, slightly decreased in the mid-DOD range, and then increased again to their maximum values towards the end of the discharging process. More specifically, when DOD was approximately between 0.1 and 0.5, Q_{irr} showed a declining trend for all current rates. Similarly, Q_{rev} exhibited a downward trend within the DOD range of around 0.3 to 0.4. Consequently, Q_t decreased within the DOD range of about 0.1 to 0.5, as shown in Fig. 6 (c). This reduction in Q_t could be attributed to the predominant influence of SOC reduction over temperature increase, as described in Eqs. (1)-(7). These findings contribute to a better understanding of the heat generation characteristics of 18,650 lithium-ion batteries during the discharging process, shedding light on the factors that influence Q_{irr} and Q_{rev} and their relationship with the current rate, SOC, and temperature.

5.2. Various BTMSs' performance under the transient battery heat generation

Fig. 7 shows $T_{max,b,sur.}$ in the five BTMSs depicted in Fig. 1 during the transient battery heat generation under discharging with 1C, 2C, 3C, and 5C current rates. The change in $T_{max,b,sur.}$ of the Air-Cooled BTMS exhibited nonlinear behaviour throughout the discharging process, which was influenced by the nonlinear heat generation characteristics of the battery. This nonlinear battery heat generation was previously reported by Huang et al. [49] and was observed in Subsection 5.1 in this study. Consequently, as depicted in Fig. 7, $T_{max,b,sur.}$ rapidly increased at the beginning of the discharging process, followed by a gradual increase and another sharp rise at the end.

The thermal behaviour of the BTMSs highly depended on the current rate. Increasing the current rate resulted in a higher $T_{max,b,sur.}$ in all BTMSs due to the higher battery heat generation. The rise in $T_{max,b,sur.}$ was particularly pronounced in the Air-Cooled BTMS, indicating the effectiveness of the PCM-based thermal management systems in reducing $T_{max,b,sur.}$, especially at higher current rates. At a lower current rate of 1C, all BTMSs succeeded in keeping $T_{max,b,sur.}$ under the critical threshold of 318.15 K, essential for ensuring the battery's safety and longevity. However, at current rates of 2C, 3C, and 5C, $T_{max,b,sur.}$ in the Air-Cooled BTMS exceeded this optimum temperature limit, reaching 327.17, 336.67, and 354.13 K at the end of the discharging process, respectively.

The PCM-Air-Cooled BTMS significantly reduced the rate of temperature rise compared to the Air-Cooled BTMS, especially at higher current rates. This reduction in the temperature rise can be attributed to



Fig. 7. T_{max.b.sur} in various BTMSs during the transient battery heat generation at the current rates of (a) 1C, (b) 2C, (c) 3C, and (d) 5C.

the high heat absorption by the PCM during the phase transition. However, $T_{max,b,sur}$, in the PCM-Air-Cooled BTMS exceeded the optimum limit of 318.15 K, reaching 318.32 and 325.43 K at the end of 3C and 5C discharging, respectively. Therefore, a more effective BTMS was required at higher current rates.

The Exterior Fin-PCM-Air-Cooled BTMS further reduced the rate of temperature rise and maintained $T_{max,b,sur.}$ within the optimum limit at the current rates below 5C. However, $T_{max,b,sur.}$ was 321 K at the end of the 5C current rate, exceeding the temperature limit.

At a low current rate of 1C, the lower $T_{max,b,sur.}$ in the Interior-Exterior Fin-PCM-Air-Cooled BTMS, compared to the other four BTMSs, demonstrated the superior cooling performance achieved by the proposed fin design. At higher current rates of 2C, 3C, and 5C, the Interior-Exterior Fin-PCM-Air-Cooled BTMS and the Interior Fin-PCM-Air-Cooled BTMS, with almost similar temperature regulation performance, outperformed the other three BTMSs in effectively controlling $T_{max,b,sur.}$ below 318.15 K. At 5C current rate, $T_{max,b,sur.}$ increased by 45.98, 17.28, 12.85, 8.89, and 8.74 K in the Air-Cooled BTMS, PCM-Air-Cooled BTMS, Exterior Fin-PCM-Air-Cooled BTMS, Interior Fin-PCM-Air-Cooled BTMS, and Interior-Exterior Fin-PCM-Air-Cooled BTMS, respectively.

5.3. Various BTMSs' performance under the constant averaged battery heat generation and non-dimensional analysis

This study examined the temperature regulation performance of the different BTMSs under constant averaged battery heat generation to investigate these systems' long-term performance and reliability. Fig. 8 shows the variations in $T_{max,b,sur}$. (Sur.) and the maximum temperature inside the volume of the battery ($T_{max,b,vol}$.) (Vol.) at 3C and 5C current rates. The combined presentation of surface and volume temperatures allows for a direct comparison, illustrating how the cooling effect propagates from the battery surface into its core. The inclusion of vertical lines in the figure indicates the time points when the PCM phase



Fig. 8. Comparison of $T_{max,b,sur}$ and $T_{max,b,vol}$ in PCM-based BTMSs under constant averaged battery heat generation at the current rates of (a) 3C and (b) 5C (the vertical lines for the time shown on this graph represent the time at which the PCM phase transition started or ended in the respective BTMSs).

transition begins and ends, providing additional clarity on the impact of phase change on temperature regulation. The $T_{max,b,vol.}$ followed a similar trend to $T_{max,b,sur.}$, albeit with a delay. This delay occurred because it took time for the cooling effect to reach the central area of the battery. Thus, the central area of the battery showed the highest temperature due to the low thermal conductivity in the radial direction of the battery.

Before the PCM melting process started, the heat transfer and heat storage within the PCM relied on heat conduction and sensible heat capacity, respectively. Therefore, $T_{max,b,sur}$ rapidly increased in all BTMSs until the PCM phase transition started. The interior and interior-exterior fins provided additional pathways for the heat conduction from the battery surface to the PCM, further utilising the PCM's sensible heat storage capacity. This enhancement in the conductive heat transfer in the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS reduced $T_{max,b,sur}$ in comparison to the Exterior Fin-PCM-Air-Cooled BTMS and the PCM-Air-Cooled BTMS.

When the PCM temperature reached its melting point range of 313.75 to 317.85 K, the PCM changed its phase from solid to liquid. As the PCM started to melt, the remaining solid PCM was changing its phase along the radial direction in the PCM-Air-Cooled BTMS and the Exterior Fin-PCM-Air-Cooled BTMS. In the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS, the PCM phase change occurred along the radial and tangential directions until the PCM melted completely. Throughout the phase transition of the PCM, the heat transfer within the PCM relied on conductive and convective heat transfer, while the heat storage within the PCM relied on the latent heat storage capacity. Consequently, the PCM experienced an increase in the thermal energy intake through the latent heat storage, which significantly decreased the rate of the maximum temperature rise. The reduction in the rate of the maximum temperature rise was more significant in the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS compared to the Exterior Fin-PCM-Air-Cooled BTMS and PCM-Air-Cooled BTMS, especially at the current rate of 5C. This was due to the increased contact surface area between the heat-conducting surfaces and the PCM and the exploitation of the PCM latent heat along the radial and tangential directions in these BTMSs. As the liquid PCM region around the battery surface expanded in the PCM-Air-Cooled BTMS and the Exterior Fin-PCM-Air-Cooled BTMS,

the absorbed heat by the liquid PCM could not be dissipated effectively to the surrounding environment. This was because of the PCM's low thermal conductivity, resulting in the battery having a higher maximum temperature. When the PCM was fully melted at 5C current rate, $T_{max,b,sur}$ reached 342.00 K in the PCM-Air-Cooled BTMS at t = 1656.25 s, 329.90 K in the Exterior Fin-PCM-Air-Cooled BTMS at t = 1808.5 s, 325.28 K in the Interior Fin-PCM-Air-Cooled BTMS at t = 1637.75 s, and 324.56 K in the Interior-Exterior Fin-PCM-Air-Cooled BTMS at t = 1770.75 s.

After the PCM melted completely, the rate of the maximum temperature rise increased again in all the BTMSs due to the reliance only on the PCM's sensible heat storage capacity. In the PCM liquid phase, the heat transfer occurred primarily through convection. The maximum temperature in the Interior Fin-PCM-Air-Cooled BTMS exceeded that of the Exterior Fin-PCM-Air-Cooled BTMS due to the increased area for heat transfer using exterior fins. This highlighted the importance of exterior fins in reducing the battery temperature when the PCM completely melted. The temperature regulation performance of the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS was almost identical before and during the PCM phase change process. However, after the PCM melted entirely, the fins on the casing outer wall surface in the Interior-Exterior Fin-PCM-Air-Cooled BTMS facilitated the effective dissipation of heat trapped in the melted PCM to the surrounding environment. This led to the lower maximum battery temperature in the Interior-Exterior Fin-PCM-Air-Cooled BTMS compared to the Interior Fin-PCM-Air-Cooled BTMS. Therefore, the difference between the results for the maximum temperature in the Interior Fin-PCM-Air-Cooled BTMS and the Interior-Exterior Fin-PCM-Air-Cooled BTMS demonstrated the improved natural convection through the exterior fins in the Interior-Exterior Fin-PCM-Air-Cooled BTMS.

Fig. 9 presents the temperature and PCM liquid fraction contour plots in the 1/8 models of the different BTMSs during the PCM melting process at t = 1200 s, with a constant averaged battery heat generation at the current rate of 5C. In Fig. 9 (a), it is evident that the heat generated within the battery was transferred to the PCM layer around the battery surface in the PCM-Air-Cooled BTMS. During the PCM phase transition, the PCM absorbed a significant amount of heat by utilising its latent heat capacity. However, due to the inherently low thermal conductivity of



Fig. 9. Temperature and PCM liquid fraction contour plots in the 1/8 models of different BTMSs during the PCM melting process at t = 1200 s, with a constant averaged battery heat generation at the current rate of 5C.

the liquid PCM, the melted PCM around the battery surface acted as a thermal insulator. This insulating effect limited the temperature rise of the surrounding PCM and prevented rapid heat dissipation from the battery surface to the surrounding environment, thus increasing the battery temperature.

As shown in Fig. 9 (c), the generated heat was transferred to the casing and exterior fins through the tubular fin and the PCM. Adding exterior fins increased the heat transfer area and facilitated heat dissipation to the surrounding environment, reducing the thickness of the liquid PCM formed around the battery surface compared to the PCM-Air-Cooled BTMS. As a result, less heat was accumulated in the liquid PCM layer around the battery surface compared to the PCM-Air-Cooled BTMS, leading to a lower battery surface temperature.

As shown in Fig. 9 (b) and (d), inserting interior and interior-exterior fins with high thermal conductivity within the PCM offered several advantages in heat dissipation and temperature regulation. These fins enhanced the heat transfer in the radial direction of the BTMSs, thereby improving the cooling effect of the BTMSs. These fins mitigated the heat accumulation near the battery surface, facilitated more uniform PCM melting, and effectively utilised the PCM's heat storage capacity.

Furthermore, the fins on the outer wall surface of the casing in the Interior-Exterior Fin-PCM-Air-Cooled BTMS further increased the heat transfer area and augmented the heat dissipation performance compared to the interior fins. Therefore, employing interior-exterior fins led to a noticeable reduction in the temperature on the surface and in the core region of the battery compared to the PCM-Air-Cooled BTMS.

Fig. 10 presents the temperature profiles along horizontal I-I lines, depicted in Fig. 9, at three specific time points: t = 300 s (before the phase transition of the PCM), t = 1200 s (during the PCM phase change process), and t = 2400 s (after the PCM phase change process). These profiles were obtained for different PCM-based BTMSs while the battery experienced constant averaged heat generation at the current rate of 5C.

The temperature difference between the battery's surface (Distance = 0.009 m) and its centre (Distance = 0 m) was 14.51, 34.95, and 29.76 K in the PCM-Air-Cooled BTMS, 18.81, 38.53, and 31.55 K in the Interior Fin-PCM-Air-Cooled BTMS, 18.16, 38, and 33.6 K in the Exterior Fin-PCM-Air-Cooled BTMS, and 19.32, 38.81, and 33.16 K in the Interior-Exterior Fin-PCM-Air-Cooled BTMS, at the respective time of 300, 1200, and 2400 s. These results showed that the most significant temperature difference between the battery's surface and its centre occurred



Fig. 10. Temperature profiles along horizontal I-I lines, shown in Fig. 9, at (a) t = 300 s, (b) t = 1200 s, and (c) t = 2400 s in various BTMSs at the current rate of 5C.

during the PCM phase change, as a substantial amount of heat was absorbed by the PCM, resulting in the temperature on the battery surface being considerably lower than that in the centre of the battery. While the PCM-Air-Cooled BTMS achieved the lowest temperature difference between the battery's surface and its centre, the proposed Interior-Exterior Fin-PCM-Air-Cooled BTMS showed the lowest temperature on the surface and in the core region of the battery compared to the other BTMSs before, during, and after the PCM phase change process.

This study examined the circumferential and longitudinal temperature distribution of the battery, focusing on two specific vertical lines: II-II (located in the middle of the PCM silo) and III-III (positioned closer to the fin). Fig. 9 shows the locations of lines II-II and III-III in the Y-axis direction. Fig. 11 shows the temperature profiles on the battery surface and along its height at the II-II and III-III lines in the different PCM-based BTMSs after 300, 1200, and 2400 s, while the battery experienced a constant averaged heat generation at the current rate of 5C.

As shown in Fig. 11, the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS achieved nearly uniform longitudinal temperature distribution, in contrast to the PCM-Air-Cooled BTMS and the Exterior Fin-PCM-Air-Cooled BTMS. The uniform temperature distributions in the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS can be attributed to the rectangular fins inserted within the PCM, which enhanced the heat conduction within the BTMSs and prevented heat accumulation near the top of the battery. The temperature gradients between the top and bottom of the battery at the II-II and III-III lines in the PCM-Air-Cooled BTMS and Exterior Fin-PCM-Air-Cooled BTMS were more pronounced during and after the PCM phase change process due to the buoyancy-driven natural convection within the liquid PCM. This natural convection caused the melted PCM with a higher temperature and lower density to migrate towards the top, resulting in a higher temperature at the top of the battery surface. The buoyancy-driven natural convection phenomenon in the melted PCM was also observed by Sun et al. (2021). Additionally, in the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS, the battery temperature at the III-III lines was slightly lower than that at the II-II lines. This difference in the battery temperature can be attributed to the shorter distance of III-III lines than II-II lines to the fins connected to the casing exposed to the surrounding environment, facilitating slightly improved cooling effects in these regions.

Nusselt number characterises the underlying heat transfer mechanisms during the PCM phase change [50]. The definition of the surfaceaveraged Nusselt number (\overline{Nu}) used in this study can be found in [51,52]. The dimensionless time ($\tau = Fo \times Ste^*$) was used to illustrate the overall pattern of heat transfer changes resulting from the PCM phase transition [51,52], where *Fo* is Fourier number and *Ste^{*}* denotes the modified Stefan number, incorporating the sensible heat for both the solid and liquid PCM [37].

Fig. 12 shows the change in \overline{Nu} in different PCM-based BTMSs at 3C and 5C current rates until t = 6000 s and t = 2500 s, respectively. According to the definition of the Nusselt number, which signifies the proportion of convective heat transfer to conductive heat transfer, the heat transfer mechanisms were categorised into conduction, strong natural convection, and weak natural convection. Similar observations of predominant thermal conduction at the beginning of the PCM liquefaction, followed by significant thermal convection as the process progresses, have been reported in previous studies on thermal energy storage systems [53] and heat sinks [51].

During the conduction-dominated regime, a thin layer of the melted



Fig. 11. Temperature profiles at the II-II and III-III lines at (a) t = 300 s, (b) t = 1200 s, and (c) t = 2400 s in various BTMSs subjected to constant averaged heat generation at the current rate of 5C.



Fig. 12. Comparison of the change in \overline{Nu} in various BTMSs at (a) 3C and (b) 5C current rates.

PCM was formed at the battery-PCM interface in the PCM-Air-Cooled BTMS and the fin-PCM and casing-PCM interfaces in the other PCM-based BTMSs. This led to a high value of \overline{Nu} in all the PCM-based BTMS, attributed to the negligible thermal resistance of the narrow liquid PCM layer. With the advancement of heat transfer, the thickness of the liquid PCM layer and the associated thermal resistance increased, resulting in a significant decrease in \overline{Nu} . During the strong natural convection regime, despite the ongoing increase in thermal resistance due to the continuous melting of PCM, the bulk motion of the melted PCM increased the heat transfer. As a result, \overline{Nu} decreased at a slower rate. During periods of weak natural convection, the intensity of natural convective heat transfer decreased as the temperature of the melted PCM became more uniform, leading to a decrease in the variation of the PCM density. This caused a sharp decline in \overline{Nu} at the beginning of the weak natural convection regime.

The exterior and interior fins played a critical role in dissipating heat to the surrounding environment and distributing heat within the BTMS. Therefore, more heat was transferred to the PCM layer surrounding the battery in the PCM-Air-Cooled BTMS compared to the PCM-based BTMSs with fins, thus enhancing the natural convection in the melted PCM. Indeed, the intensity of the natural convection in the liquid PCM depended on the temperature difference and the distance between the walls, which included the battery surface, casing, and fins surrounding the PCM, and the PCM solid-liquid interface. When more PCM melted, increasing this distance enhanced the natural convection of melted PCM in the PCM-Air-Cooled BTMS compared to the PCM-based BTMSs with fins. The PCM-Air-Cooled BTMS exhibited higher \overline{Nu} compared to the PCM-based BTMSs with fins with almost similar \overline{Nu} , except at the start of the 5C current rate. However, $T_{max,b.sur.}$ in the PCM-based BTMSs with fins was lower than that in the PCM-Air-Cooled BTMS, as shown in Fig. 8. This decrease in $T_{max,b.sur.}$ was more significant in the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS during the PCM phase transition. These findings emphasised the significance of enhancing the conductive and convective heat transfer within the PCM for the effective thermal management of the battery.

5.4. The BTMSs' performance during three cycles of the PCM undergoing complete liquefaction and re-solidification

It is crucial to conduct long-term tests and assess the BTMS's capability to sustain its performance to evaluate the system's durability. Fig. 13 (a) and (b) compare $T_{max,b,vol}$, and Fig. 13 (c) and (d) illustrate $T_{max,b,sur}$ in the different BTMSs during three cycles of the PCM undergoing complete liquefaction and re-solidification. The PCM melting process was conducted under a constant averaged battery heat generation at the current rates of 3C and 5C until the PCM was completely melted ($\gamma = 1$). During the PCM solidification process, this constant averaged heat generation was removed from the BTMSs until the PCM



Fig. 13. The comparison of $T_{max,b,vol.}$ at the current rates of (a) 3C and (b) 5C and $T_{max,b,sur.}$ at the current rates of (c) 3C and (d) 5C in various BTMSs during three cycles of the PCM undergoing complete liquefaction and re-solidification.

was completely solid ($\gamma = 0$).

In the four PCM-based BTMSs, T_{max,b,sur.} and T_{max,b,vol.} significantly increased. As the PCM melting process started, the rate of the temperature rise on the battery surface and inside the battery volume decreased due to the utilisation of the PCM latent heat capacity. This decline in the rate of the temperature rise was more pronounced at the 3C current rate due to the lower heat generation. Upon the complete melting of the PCM during the three cycles, T_{max.b.sur}, in the Interior-Exterior Fin-PCM-Air-Cooled BTMS was 9.9 and 17.46 K lower than that in the PCM-Air-Cooled BTMS, 0.7 and 0.73 K lower than that in the Interior Fin-PCM-Air-Cooled BTMS, and 3.81 and 5.42 K lower than that in the Exterior Fin-PCM-Air-Cooled BTMS at the current rates of 3C and 5C, respectively. The Tmax.b.vol. in the Interior-Exterior Fin-PCM-Air-Cooled BTMS was also 6.37 and 10.87 K lower than that in the PCM-Air-Cooled BTMS, 0.17 and 0.03 K lower than that in the Interior Fin-PCM-Air-Cooled BTMS, and 3.71 and 6.78 K lower than that in the Exterior Fin-PCM-Air-Cooled BTMS at 3C and 5C current rates, respectively. By removing the constant averaged heat generation in these BTMSs, the PCM solidification started, leading to a rapid decline in $T_{max,b,vol.}$ and T_{max,b,sur.} until the PCM reached its liquidus temperature. Subsequently, during the PCM solidification process, the rate of the temperature drop decreased due to the recovery of the PCM latent heat capacity. These results highlighted that the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS with almost identical temperature regulation performance achieved the lowest $T_{max,b,sur.}$ and $T_{max,b,vol.}$ compared to the other two BTMSs during the three cycles of the PCM undergoing complete liquefaction and re-solidification.

In addition to regulating the rise in temperature of the batteries, minimising the amplitude of temperature variations during repeated and prolonged operation is crucial in extending the batteries' lifespan [54]. Wu et al. [54] demonstrated that the amplitude of the temperature

fluctuations in composite PCM-based BTMSs was smaller than that in a battery without PCM during the battery charging and discharging cycles. This was because of the temperature-buffering effect provided by the composite PCM. In this study, during the three cycles of the PCM undergoing complete liquefaction and re-solidification, the amplitude of the variation in Tmax.b.sur. was 16.29 and 28.36 K in the PCM-Air-Cooled BTMS, 8.13 and 12.68 K in the Interior Fin-PCM-Air-Cooled BTMS, 10.66 and 16.80 K in the Exterior Fin-PCM-Air-Cooled BTMS, and 7.86 and 12.38 K in the Interior-Exterior Fin-PCM-Air-Cooled BTMS at 3C and 5C current rates, respectively. Furthermore, the amplitude of the variation in Tmax.b.vol. was 29.96 and 59.03 K in the PCM-Air-Cooled BTMS, 24.42 and 48.85 K in the Interior Fin-PCM-Air-Cooled BTMS, 27.55 and 55.18 K in the Exterior Fin-PCM-Air-Cooled BTMS, and 24.37 and 48.94 K in the Interior-Exterior Fin-PCM-Air-Cooled BTMS at 3C and 5C current rates, respectively. These findings indicated that the Interior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS successfully minimised the amplitude of the temperature variations during repeated PCM complete liquefaction and re-solidification.

Fig. 14 (a) and (b) illustrate the change in the PCM liquid fraction during the three cycles of the PCM undergoing complete liquefaction and re-solidification in different PCM-based BTMSs at 3C and 5C current rates, respectively. The PCM melting process started after a certain period, during which the generated heat was transferred from the battery to the PCM. The lower heat generation level at the 3C current rate delayed the PCM melting initiation time.

When the PCM reached its melting point, the PCM liquid fraction increased almost linearly over time in all the BTMSs. At the 3C current rate, the fins on the outer wall surface of the casing in the Exterior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS prolonged the period during which the PCM latent heat was utilised compared to the other two BTMSs. This maintained the battery's



Fig. 14. The PCM liquid fraction during three cycles of the PCM undergoing complete liquefaction and re-solidification in different BTMSs at the current rates of (a) 3C and (b) 5C.

temperature near the phase change temperature for an extended duration. At the higher current rate of 5C, the exterior fins had a less significant impact on extending the PCM latent heat utilisation period. This suggested that, despite the increased heat transfer area with the exterior fins, the dissipation of the high heat generated at 5C current rate was not significantly enhanced.

During the PCM solidification, employing fins on the outer wall surface of the casing in the Exterior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS accelerated the heat dissipation to the surrounding environment compared to the other two BTMSs. Furthermore, the interior-exterior fins created a conductive network and facilitated heat distribution within the system, which was even more effective than only the exterior fins for heat dissipation. This enhanced heat dissipation in the Interior-Exterior Fin-PCM-Air-Cooled BTMS reduced the PCM solidification period. This reduced PCM solidification period was more pronounced at the higher current rate of 5C, highlighting the effective heat dissipation capabilities of the interiorexterior fins.

In specific applications of PCMs, such as PCMs in thermal energy storage systems [55,56], heat exchangers [57], and buildings and construction [58], a shorter PCM melting period resulted in greater energy storage within a given period, leading to the improved temperature regulation performance. In contrast, specific applications necessitate a longer PCM melting period to optimise the temperature regulation performance, in textile applications, the service life of phase change cooling suits should be extended, or the discovery of PCMs with longer melting periods is required to enhance human comfort in high-temperature and humid environments [59]. Similarly, in BTMSs, the PCM melting period should be extended to ensure that the battery

temperature remains around the phase change temperature for a longer period.

Table 4 provides more detailed information about the PCM melting and solidification periods, as shown in Fig. 14 (b), in various BTMSs during three cycles of the PCM undergoing complete liquefaction and resolidification at the current rates of 3C and 5C. Furthermore, Table 4 highlights the percentage differences in these periods compared to those in the PCM-Air-Cooled BTMS.

During the three cycles, the PCM melting initiation period decreased by increasing the current rate in all the BTMSs due to the higher battery heat generation at higher current rates, which caused the PCM to reach its melting point more rapidly. Additionally, the PCM melting initiation period significantly decreased in the subsequent cycles, largely due to the initial temperature being considerably lower than the PCM solidus temperature in the first cycle (298.15 K). Incorporating interior and exterior fins delayed the PCM melting initiation compared to the PCM-Air-Cooled BTMS due to the improved heat distribution within the system and enhanced heat dissipation to the surroundings, respectively. The results underscored the greater influence of interior fins over exterior fins in extending the PCM melting initiation. Consequently, the interior-exterior fins extended the PCM melting initiation period by 59.95 % and 57.47 % at 3C and 5C current rates, respectively, compared to the PCM-Air-Cooled BTMS. Notably, this delay in the PCM melting initiation was far more pronounced in the second and third cycles, primarily due to the PCM complete solidification at a lower $T_{max,h,sur}$ in the BTMSs with fins compared to the PCM-Air-Cooled BTMS. Therefore, a longer period was required for the PCM in the BTMSs with fins to absorb heat and reach the melting point during subsequent cycles.

The PCM latent heat utilisation period, shown in Fig. 14 (b), which

Table 4

The PCM melting and solidification periods in various BTMSs over three consecutive melting and solidification cycles at the current rates of 3C and 5C and their percentage differences compared to those in the PCM-Air-Cooled BTMS.

	Parameters	PCM-Air-Cooled BTMS (3C/5C)	Interior Fin-PCM-Air-Cooled BTMS (3C/5C)	Exterior Fin-PCM-Air-Cooled BTMS (3C/5C)	Interior-Exterior Fin-PCM-Air-Cooled BTMS (3C/5C)
Cycle 1	PCM melting initiation period	646.75 s/279.25 s	912.25 s (+41.05 %)/412.75 s (+47.81 %)	867.25 s (+34.09 %)/367.5 s (+31.60 %)	1034.5 s (+59.95 %)/439.75 s (+57.47 %)
	PCM latent heat utilisation period	3145.75 s/1377 s	3198.75 s (+1.68 %)/1225 s (-11.04 %)	4272.5 s (+35.82 %)/1441 s (+4.65 %)	4190 s (+33.20 %)/1331 s (-3.34 %)
	Total PCM melting period	3792.5 s/1656.25 s	4111 s (+8.40 %)/1637.75 s (-1.12 %)	5139.75 s (+35.52 %)/1808.5 s (+9.19 %)	5224.5 s (+37.76 %)/1770.75 s (+6.91 %)
	PCM solidification initiation period	695 s/1469.25 s	488.25 s (-29.75 %)/1106 s (-24.72 %)	286.25 s (-58.81 %)/820.75 s (-44.14 %)	277.5 s (-60.07 %)/771.5 s (-47.49 %)
	PCM latent heat recovery period	5845.25 s/5836.5 s	5156 s (-11.79 %)/5139.75 s (-11.94 %)	4265.75 s (-27.02 %)/4222.25 s (-27.66 %)	3820.75 s (-34.63 %)/3790.25 s (-35.06 %)
	Total PCM solidification period	6540.25 s/7305.75 s	5644.25 s (-13.70 %)/6245.75 s (-14.51 %)	4552 s (-30.40 %)/ 5043 s (-30.97 %)	4098.25 s (-37.34 %)/4561.75 s (-37.56 %)
Cycle 2	PCM melting initiation	43.25 s/12.5 s	173.5 s (+301.16 %)/65.75 s (+426.00 %)	115.25 s (+166.47 %)/33 s (+164.00 %)	282.25 s (+552.60 %)/97 s (+676.00 %)
	PCM latent heat utilisation period	3195.5 s/1409.5 s	3248 s (+1.64 %)/1287.25 s (-8.67 %)	4341.25 s (+35.85 %)/1499.25 s (+6.37 %)	4219 s (+32.03 %)/1388 s (-1.52 %)
	Total PCM melting period	3238.75 s/1422 s	3421.5 s (+5.64 %)/1353 s (-4.85 %)	4456.5 s (+37.60 %)/1532.25 s (+7.75 %)	4501.25 s (+38.98 %)/1485 s (+4.43 %)
	PCM solidification	695.25 s/1468 s	488 s (-29.81 %)/1104.25 s (-24.78 %)	286 s (-58.86 %)/820 s (-44.14 %)	276.5 s (-60.23 %)/770.25 s (-47.53 %)
	PCM latent heat recovery period	5845.75 s/5837.25 s	5156.25 s (-11.79 %)/5140.25 s (-11.94 %)	4266.75 s (-27.01 %)/4222.25 s (-27.67 %)	3821.25 s (-34.63 %)/3790.25 s (-35.07 %)
	Total PCM solidification	6541 s/7305.25 s	5644.25 s (-13.71 %)/6244.5 s (-14.52 %)	4552.75 s (-30.40 %)/5042.25 s (-30.98 %)	4097.75 s (-37.35 %)/4560.5 s (-37.57 %)
Cycle 3	PCM melting initiation period	43 s/12.25 s	173.5 s (+303.49 %)/66 s (+438.77 %)	115.25 s (+168.02 %)/32.75 s (+167.35 %)	281.25 s (+554.07 %)/96.75 s (+689.80 %)
	PCM latent heat utilisation period	3195.75 s/1409.75 s	3247.75 s (+1.63 %)/1287 s (-8.71 %)	4341.5 s (+35.85 %)/1499.5 s (+6.37 %)	4225.5 s (+32.22 %)/1388.25 s (-1.52 %)
	Total PCM melting period	3238.75 s/1422 s	3421.25 s (+5.63 %)/1353 s (-4.85 %)	4456.75 s (+37.61 %)/1532.25 s (+7.75 %)	4506.75 s (+39.15 %)/1485 s (+4.43 %)
	PCM solidification initiation period	695.5 s/1468 s	488 s (-29.83 %)/1104.25 s (-24.78 %)	286.25 s (-58.84 %)/820 s (-44.14 %)	277.5 s (-60.10 %)/770.25 s (-47.53 %)
	PCM latent heat recovery period	5845.5 s/5837.5 s	5156.25 s (-11.79 %)/5140 s (-11.95 %)	4268.25 s (-26.98 %)/4222.25 s (-27.67 %)	3821 s (-34.63 %)/3790.25 s (-35.07 %)
	Total PCM solidification period	6541 s/7305.5 s	5644.25 s (-13.71 %)/6244.25 s (-14.53 %)	4554.5 s (-30.37 %)/5042.25 s (-30.98 %)	4098.5 s (-37.34 %)/4560.5 s (-37.57 %)

corresponded to the phase change from solid to liquid, decreased when the current rate in all the BTMSs was increased. This was due to the higher heat generation of the battery at higher current rates, which melted the PCM more rapidly. The insertion of fins within the PCM slightly extended the PCM latent heat utilisation period at the lower current rate of 3C by improving heat distribution. However, these heatconducting interior fins decreased the PCM phase transition period at the higher current rate of 5C due to the increased heat generated by the battery. Furthermore, the fins on the outer wall surface of the casing in the Exterior Fin-PCM-Air-Cooled BTMS increased the PCM phase transition period. This was because of the improved heat dissipation to the surroundings, especially at the current rate of 3C. Therefore, in the first cycle at 3C and 5C current rates, the PCM latent heat utilisation period increased by 33.20 % and decreased by 3.34 % in the Interior-Exterior Fin-PCM-Air-Cooled BTMS, respectively, compared to the PCM-Air-Cooled BTMS.

As a result, in the first cycle at the current rates of 3C and 5C, the total PCM melting period increased by 8.40 % and decreased by 1.12 % in the Interior Fin-PCM-Air-Cooled BTMS, increased by 35.52 % and 9.19 % in the Exterior Fin-PCM-Air-Cooled BTMS, and increased by 37.76 % and 6.91 % in the Interior-Exterior Fin-PCM-Air-Cooled BTMS, respectively, compared to the PCM-Air-Cooled BTMS. These results indicated that the Interior-Exterior Fin-PCM-Air-Cooled BTMS and Exterior Fin-PCM-Air-Cooled BTMS achieved the longest total PCM melting period at 3C and 5C current rates, respectively. The total PCM melting period showed similar trends in all the BTMSs in the subsequent cycles.

The PCM solidification initiation period significantly increased when the current rate in all the BTMSs increased. This was because of the higher heat generated within the battery, which must be dissipated for the PCM solidification to start. The interior and exterior fins decreased the PCM solidification initiation period compared to the PCM-Air-Cooled BTMS. This was due to the improved distribution of the cooling effect of the natural air convection around the PCM caused by the fins within the PCM and the extended heat transfer area with the surrounding environment. Therefore, in the first cycle, the PCM solidification initiation period decreased by 60.07 % and 47.49 % in the Interior-Exterior Fin-PCM-Air-Cooled BTMS at 3C and 5C current rates, respectively, compared to the PCM-Air-Cooled BTMS.

The current rate had a minimal impact on the latent heat recovery period, as the heat source was removed from all the BTMSs. In the first cycle, the PCM latent heat recovery period decreased by 34.63 % and 35.06 % in the Interior-Exterior Fin-PCM-Air-Cooled BTMS at the current rates of 3C and 5C, respectively, compared to the PCM-Air-Cooled BTMS due to the improved heat dissipation using interior-exterior fins.

Consequently, in the first cycle, the total PCM solidification period decreased by 37.34 % and 37.56 % in the Interior-Exterior Fin-PCM-Air-Cooled BTMS at 3C and 5C current rates, respectively, compared to the PCM-Air-Cooled BTMS. During the three cycles, the total PCM solidification period remained relatively constant in all the BTMSs.

Previous research on PCM melting and solidification generally categorised melting as a convection-dominated process and solidification as a conduction-dominated process. Hence, melting was reported to be faster than solidification [60]. However, contrasting observations were reported in some studies [61]. Some studies also identified the strong influence of both mechanisms in the melting and solidification processes [62]. Aramesh and Shabani [60] explained that such general conclusions were contingent upon the experiment configuration, leading to contradictions among different studies. In this study, the PCM melting process was faster than the PCM solidification process in the PCM-Air-Cooled BTMS. This behaviour can be attributed to forming a solid PCM region on the casing wall, which acted as a thermal insulator, hindering heat transfer to the surroundings and slowing solidification. Consequently, heat transfer enhancement techniques should be employed to accelerate the PCM solidification process. Although the PCM melting process in the Interior Fin-PCM-Air-Cooled BTMS occurred

more rapidly than the PCM solidification process, utilising the interior fins decreased the difference between the melting and solidification periods. In the Exterior Fin-PCM-Air-Cooled BTMS and Interior-Exterior Fin-PCM-Air-Cooled BTMS, the PCM melting process was slower than the PCM solidification process at the current rate of 3C, while the opposite behaviour was observed at the current rate of 5C. This contrasting behaviour can be due to the lower heat generation level at 3C current rate and the effectiveness of the fins on the outer wall surface of the casing in dissipating heat to the surroundings at a lower current rate.

To conclude, the interior-exterior fins were effective for the thermal regulation of batteries compared to other fin designs. These fins extended the total PCM melting period to maintain the battery temperature within the optimal range for a longer period and shortened the total PCM solidification period to ensure a reduced recovery time for the BTMS.

6. Conclusion

Effective BTMSs are critical for ensuring the safe operation and longevity of lithium-ion batteries. This study proposed and evaluated a novel fin design, incorporating a tubular and 4 rectangular interiorexterior fins within a metal casing, to enhance the performance of PCM-based BTMSs. The findings of this research are summarised as follows:

- 1. The Q_{irr} generated by the battery's internal resistance dominated over Q_{rev} generated by the entropy changes across all current rates, increasing with higher currents. At 5C current rate, Q_{irr} was up to 8.73 times greater than Q_{rev} , highlighting the substantial influence of internal resistance on heat generation.
- 2. The Interior-Exterior Fin-PCM-Air-Cooled BTMS was effective in maintaining $T_{max,b,sur.}$ below 318.15 K, ensuring battery safety and longevity under the transient battery heat generation, even at a high current rate of 5C.
- 3. The combined interior-exterior fins ensured a nearly uniform circumferential and longitudinal temperature distribution to the battery. These interior-exterior fins showed superior temperature regulation performance over the interior and exterior fins before, during, and after the PCM phase change process.
- 4. During the PCM phase transition, various heat transfer regimes of conduction, strong natural convection, and weak natural convection were characterised sequentially. While convective heat transfer was necessary for utilising the PCM latent heat capacity, enhancing conduction within the PCM using fins was essential for effective battery thermal management.
- 5. During the PCM melting and solidification cycles at the 5C current rate, the variation in $T_{max,b.sur.}$ in the Interior-Exterior Fin-PCM-Air-Cooled BTMS was 15.98 K lower than that in the PCM-Air-Cooled BTMS, buffering the effects of temperature change.
- 6. The interior-exterior fins extended the total PCM melting period, particularly at lower current rates, thereby maintaining the battery temperature within the optimal range for a longer period. In the first cycle, at 3C and 5C current rates, the total PCM melting period increased by 37.76 % and 6.91 % in the Interior-Exterior Fin-PCM-Air-Cooled BTMS, respectively, compared to the PCM-Air-Cooled BTMS.
- 7. The interior-exterior fins shortened the total PCM solidification period, thus reducing the recovery time for the thermal management system. In the first cycle, the total PCM solidification period decreased by 37.34 % and 37.56 % in the Interior-Exterior Fin-PCM-Air-Cooled BTMS at 3C and 5C current rates, respectively, compared to the PCM-Air-Cooled BTMS.

Future work should explore the performance of the BTMS under realworld operational conditions where discharge periods overlap with incomplete PCM solidification to better replicate practical scenarios. The effect of various convective heat transfer coefficients on the thermal performance of the BTMSs will also be explored in future studies to provide a more comprehensive understanding of the impact of external conditions on the thermal regulation efficiency.

CRediT authorship contribution statement

Parvaneh Zare: Writing – original draft, Visualization, Validation, Methodology, Formal analysis. Noel Perera: Writing – review & editing, Supervision, Project administration. Jens Lahr: Supervision, Software. Reaz Hasan: Writing – review & editing, Supervision, Conceptualization.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

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

Acknowledgements

The authors thank Dr. Roger Tait for his advice and guidance on the use of the High-Performance Computing (Cluster 3) resource. The authors also thank the Faculty of Computing, Engineering, and the Built Environment at Birmingham City University for supporting this High-Performance Computing resource.

Data availability

Data will be made available on request.

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