Contents lists available at ScienceDirect



International Communications in Heat and Mass Transfer



journal homepage: www.elsevier.com/locate/ichmt

Enhanced thermal management of lithium-ion pouch cells via hybrid approach of phase change material-liquid cooling

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ARTICLE INFO	A B S T R A C T		
Keywords: Lithium-ion battery Thermal management Phase change material Liquid cooling	Effective thermal management is crucial for safe, high-performance operation of lithium-ion batteries in electric vehicles (EVs). However, conventional passive or active cooling methods alone struggle to provide sufficient heat dissipation while maintaining uniform battery temperatures. This computational study investigates a hybrid thermal management system combining lateral phase change material (PCM) layers for temperature stabilization with vertical liquid cooling channels. The system was evaluated for a lithium-ion pouch cell module with PCM thicknesses ranging from 1 to 7 mm (melting point 26 °C) and a 0.5 mm liquid coolant channel using Novec-774 at 15–20 °C inlet and 90 lpm flow rate. Key findings reveal the 7 mm PCM achieved superior thermal regulation, constraining mean/maximum cell temperatures to 32.5 °C/39.1 °C compared to 113.8 °C/188.1 °C for the ineffective 1 mm case. Lower coolant inlet temperatures further enhance the performance, with a 5 °C inlet yielding 24.6 °C/29.2 °C mean/max, versus 26.0 °C/29.8 °C at 15 °C inlet. The hybrid passive-active approach combines lateral heat absorption via PCM with vertical forced convection cooling to effectively regulate battery temperatures. The proposed approach achieves superior cooling with up to 73 % reduction in maximum temperature compared to conventional liquid cooling, while maintaining temperature uniformity within 5 °C across the battery module.		

1. Introduction

With the growing popularity of electric vehicles (EVs), the need for efficient thermal regulation of lithium-ion batteries (LIBs) has become increasingly crucial [1,2]. This is especially true nowadays: "range anxiety" and "charge anxiety" are the two primary driving factors [3] that has led to an ever-growing demand for higher charging speeds and higher energy density of batteries. Energy density is improved by packing more LIB "cells" within the same volume resulting in lesser available "unused" space to implement thermal regulation. Higher charging speeds require faster rejection of the heat generated in the cells to keep them in the ideal temperature window [4].

There are several reasons why thermal regulation is crucial for an EV LIB for long life. User safety is of primary concern, LIBs are susceptible to undergo thermal runaway that may result in catastrophic effects and danger to human lives [5]; effective thermal management is paramount to prevent this. Secondly, real-time performance of LIBs (e.g., charge/ discharge rates) is highly dependent on the battery cells being in their ideal temperature window, high-charging rate LIB cells are only as good as the cooling system that can regulate its temperature [6]. Thirdly, cell degradation is highly dependent on the temperature profile it has been subjected to; a poorly managed cell will lose its capacity faster [7]. Lastly, LIBs have multiple cells connected in series with each other that restricts the overall health and performance of the entire battery pack to the weakest cell in the chain; this means uniformity in thermal regulation is critical [8–10]. The optimal range for LIB temperatures during operation is between 20 and 40 °C while temperature gradient from module to module should be below 5 °C [11]. Higher temperatures can accelerate the degradation of electrode materials, reduce the battery's cycle life, and even lead to thermal runaway, posing serious safety risks [12].

Conventional cooling methods, both passive (e.g., phase change materials) and active (e.g., air/liquid cooling), have been widely employed to regulate the temperature of LIBs in EVs [13]. Passive

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https://doi.org/10.1016/j.icheatmasstransfer.2025.108997

Available online 8 May 2025

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International Communications in Heat and Mass Transfer 165 (2025) 108997

cooling systems based on phase change materials (PCMs) have gained popularity due to their ability to stabilize temperatures by absorbing latent heat. However, they suffer from critical limitations such as low thermal conductivity and limited heat dissipation capacity once the PCM is fully melted [14,15]. These constraints become particularly pronounced under high charge/discharge rates or extended operating periods, where the PCM alone is unable to maintain battery temperatures within the safe range. Additionally, the unidirectional heat absorption of PCM layers may lead to thermal gradients and hotspot formation, further reducing the effectiveness of passive cooling.

To overcome these shortcomings, recent research has shifted toward hybrid thermal management systems that combine passive PCM layers with active cooling mechanisms, such as liquid or air cooling. These hybrid configurations aim to harness the thermal buffering capability of PCMs while ensuring continuous heat removal via active convection. For instance, Wei and Agelin-Chaab [16] demonstrated that hybrid cooling combining air convection and water evaporation achieved a 73.5 % reduction in maximum surface temperature, outperforming air- or water-cooling alone. Similarly, Chen et al. [17] compared air, direct liquid, and fin-based cooling systems, noting that air cooling required 2-3 times more energy to achieve the same thermal control. Further studies by Mousavi et al. [18] and Xin et al. [19] confirmed the superior performance of PCM-liquid hybrid systems, particularly in high-stress thermal environments. Mousavi et al. [18] showed that a hybrid design incorporating PCM with liquid filled mini-channel plates can decrease average battery temperature by 10.3 K versus active cooling alone under constant heat loads. Xin et al. [19] tested three BTM systems containing PCM and liquid cooling. They determined that a hybrid BTM combining a 4-mm thick PCM layer with 0.1-m/s water flow can maintain battery temperatures below 49 °C, demonstrating effective thermal control even under a 2C discharge rate and 37 °C ambient temperature. Shengxin E et al. [20] investigated the air-channel arrangement, PCM thicknesses, and inlet air temperature on the hybrid heat extraction potential of lithium-ion battery packs. The study determined that a 4 mm thick PCM with an inlet air temperature of 301.15 K maintained battery temperatures below 313.64 °C and a maximum temperature gradient of 4.98 °C, demonstrating an optimized passive thermal management strategy. Lokhande and Tiwari [21] studied a lithium-ion pouch cell with PCM mini-chambers and blocks using simulations, comparing three PCMs at 1C to 4C discharge rates. The composite PCM mini-chamber system provided the best thermal regulation and heat extraction, maintaining safe cell temperatures up to 4C discharge rates. Mohammed et al. [22] proposed a BTM system incorporating multiple PCMs and mini air channels integrated with thin heat sinks for a lithium-ion battery pack. Key findings showed the optimal PCM arrangement lowered the maximum temperature by 2.6 K and improved the temperature uniformity by 89 % compared to the worst-performing of air-cooling alone case after 3600 s discharge. Leng et al. [23] tested a heat pipe in PCM as hybrid BTM design focusing on surface temperature profiles without analysing underlying heat transfer mechanisms. Results reveal superior performance when the heat transfer coefficient is below 12 W/m²K and phase change material thermal conductivity ranges from 0.1 to 5 W/mK. In a recent numerical study, Moaveni et al. [24] evaluated a hybrid BTM system containing PCM, cooling channels, and enhancements like fins and nanoparticles. They added nanoparticles to the PCM at a 9 % volumetric concentration and 4 extended fins to the cooling channels in the hybrid mode. Their findings revealed peak cell temperature declines by 5.18 K and 10.36 K respectively compared to the hybrid mode without enhancements.

Recent studies have continued to advance the development of hybrid battery thermal management systems for improving both efficiency and practicality. Liu et al. [25] proposed a novel PCM–liquid hybrid system utilizing composite PCMs with enhanced thermal conductivity using honeycomb structure, achieving improved uniformity and lower peak temperatures during fast charging. They showed that the honeycomb fin structure increases the heat exchange power and efficiency due to the higher heat transfer area. Saxena et al. [26] studied a novel heat exchanger combining PCM and an integrated liquid cooling channels for enhanced thermal management under realistic driving cycles. They used zigzag changes within the PCM domain and showed reduction in weight and pumping power by up to 53 % and 84 %, respectively. Yao et al. [27] examined a novel web shaped cooling channel inside the PCM to improve the hybrid PCM-liquid cooling system and showed than they can control the phase change process by 80 % with the novel heat exchanger. Furthermore, a recent review on advanced thermal management using hybrid PCM-metal foam and immersion cooling technologies shows the capability of this hybrid method for further improvements in Li-ion thermal management battery packs [28].

The above literature survey reveals that most prior studies have focused on evaluating single hybrid cooling configurations. The coupled effects of PCM type, PCM thickness, coolant flow rate, and coolant inlet temperature on the overall thermal regulation performance have not been as thoroughly investigated. Furthermore, the underlying heat transfer mechanisms and thermal regulation dynamics enabled by the interactive combination of lateral PCM heat absorption and vertical liquid cooling convection are not yet fully understood. This study provides comprehensive parametric investigation of the hybrid PCM-liquid cooling system and the in-depth analysis of the coupled thermal regulation processes. By systematically varying key parameters such as PCM thickness, cooling channel inlet velocity, and coolant inlet temperature, the study aims to identify the optimal configuration that ensures efficient heat dissipation and minimizes temperature gradients across the battery cells. The in-depth analysis of these coupled thermal regulation mechanisms represents a unique contribution of this work, offering guidance for the future development and optimization of hybrid cooling systems to enhance the performance, longevity, and safety of lithium-ion batteries in electric vehicles and beyond. The rest of this paper is organized as follows: Section 2 provides a detailed description of the thermal management system and the problem statement. Section 3 discusses the mathematical modelling and simulation approach used in this study. Section 4 presents the results and discussion, analysing the effectiveness of the hybrid passive-active system. Finally, Section 5 summarizes the key conclusions with suggesting avenues for future research.

2. System description and problem statement

The thermal management system consists of a battery module containing 208 Li-ion pouch cells configured electrically in 4 groups of 37, 57, 57 and 57 cells in parallel (Fig. 1). The individual cells have dimensions of 400 mm \times 125 mm \times 5 mm and experience internal heat generation during 3C charge/discharge cycles according to the electric vehicle powertrain demands. To regulate cell temperatures, the module integrates hybrid passive and active cooling components tailored to the battery geometry. As depicted in Figs. 1-2, the system features thin 1 mm thermal interface material layers that ensure efficient conductive heat transfer between the cells and the encasing PCM layers. These PCM layers have a varying thickness (t) ranging from 1 to 7 mm. The PCM material used is organic paraffin wax, with three different types selected based on their melting temperatures, as presented in Table 1. These PCMs, namely RT18HC, RT21HC, and RT25HC, were chosen to maintain the cell temperatures within the optimal operating range of 20 to 40 °C (the ageing threshold).

The PCMs with melting points close to the desired battery temperature can effectively absorb heat during charge/discharge cycles, helping to maintain the cells within the safe temperature window. The RT18HC PCM, with a melting range of 17–19 °C, was chosen to provide thermal regulation near the lower end of the optimal battery operating temperature range. The RT21HC PCM, with a melting range of 20–23 °C, was selected to target the middle of the optimal range, providing a balance between heat absorption capacity and temperature regulation. The RT25HC PCM, with a melting range of 22–26 °C, was chosen to



Fig. 1. Geometry of the PCM-HTF battery cooling system.



Fig. 2. Physical domain of the PCM-HTF battery cooling system.

Table 1

Thermophysical properties of the cooling materials [29,30].

Property	RT18HC	RT21HC	RT25HC	Novec774
Specific heat (J/kgK)	2000	2000	2000	1130
Heat of fusion (J/kg)	260,000	190,000	230,000	-
Solidus temperature (°C)	17	20	22	-
Liquidus temperature (°C)	19	23	26	-
Viscosity (Pas)	0.021	0.022	0.023	0.00087
Density (solid) (kg/m ³)	880	880	880	1600
Thermal conductivity(W/mK)	0.2	0.2	0.2	0.06

cover the upper end of the optimal battery operating temperature range, allowing for thermal regulation in applications with higher heat generation or longer charge/discharge cycles. The PCM layers are arranged laterally around the cell module to facilitate transverse heat spreading, thereby reducing hotspots. These layers are contained using 1 mm aluminum plates to prevent material leakage without significantly obstructing diffusion.

Along the vertical direction, straight 2 mm thick cooling channels above and below every cell group convey the engineered coolant (Novec-774) as the cooling HTF. This liquid coolant loop links to supply/ return headers powered by a pump providing the flow rate of 90 lpm across the battery pack. The chosen coolant flow rate was selected based on a balance between thermal effectiveness and practical application in EV cooling systems. It ensures sufficient convective heat transfer under the assumed constant heat generation without introducing excessive pumping requirements or pressure drop. Similar flow rates have been reported in prior battery thermal management studies under high C-rate scenarios [18,19].

Likewise, the fluid loop integrates a cooling subsystem to enable adjustable inlet temperatures from 5 to 15 °C. This hybrid configuration combines stabilization from lateral PCM absorption with vertical cooling convection to holistically manage battery temperatures. Lateral PCM layers minimize spatial thermal gradients across cells that generate mechanical stresses with potential material cracks leading to failure. Meanwhile, vertical cooling fluid circulation prevents cumulative temperature rise over long charge/discharge durations that accelerate ageing through rapid chemical changes. Balancing PCM thickness alongside cooling channel flow intensity and temperature regulates battery temperature uniformly in space and time. Thereby enabling safe, efficient electric vehicle operation meeting drive cycle power needs.

As mentioned, four different thicknesses are studied for the PCM layer. Table 2 presents the mass of PCM using RT25HC as an important issue dealing with thermal management system of a Li-ion battery pack. For the PCM thickness of 1 mm, the total PCM mass in the battery pack is \sim 36 kg while it is \sim 139 kg for the case with the PCM thickness of 7 mm. Although a lower PCM mass reduces the weight of the battery pack, it should be investigated if the integrated PCM unit is capable of thermally regulating the batteries, which is the focus of this study.

It should be noted that Novec-774 was chosen due to its **dielectric nature**, low viscosity, and compatibility with electronic components, making it suitable for EV battery cooling. Similarly, the selected RT-series PCMs (RT18HC, RT21HC, and RT25HC) offer a range of melting points within the optimal battery operating temperature window (20–40 $^{\circ}$ C), ensuring tailored thermal buffering across different heat generation scenarios.

3. Mathematical modelling and simulation

For laminar transient fluid flow inside the PCM, the enthalpyporosity model developed by Brent et al. [31] is utilized to account for the melting process. The Boussinesq approximation is employed to model the density changes in the liquid PCM arising from convective effects. All other thermodynamic properties including density ρ , specific

Table 2	
Summary of the PCM mass	for different studied cases.

Total PCM thickness for one cell	РСМ Туре	PCM mass for one cell (kg)	Total PCM mass (kg)
1 mm	RT25HC	0.17	35.66
3 mm	RT25HC	0.34	69.98
5 mm	RT25HC	0.50	104.30
7 mm	RT25HC	0.67	138.62

heat Cp, thermal conductivity k, and dynamic viscosity μ , are all assumed constant [32] during phase change, and their values are provided in Table 1. The fluid flow is treated as laminar, transient, incompressible and Newtonian, with viscous dissipation neglected. Noslip conditions are applied at wall boundaries. With these assumptions, the governing equations of continuity, momentum, and energy are specified as [33,34]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \, \vec{V} \right) = 0 \tag{1}$$

$$\rho \frac{\partial \overrightarrow{V}}{\partial t} + \rho \left(\overrightarrow{V} \cdot \nabla \right) \overrightarrow{V} = -\nabla P + \mu \left(\nabla^2 \overrightarrow{V} \right) - \rho_{ref} \beta \left(T - T_{ref} \right) \overrightarrow{g} - A_m \frac{\left(1 - \lambda \right)^2}{\lambda^3 + 0.001} \overrightarrow{V}$$
(2)

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \left(\rho C_p \, \vec{V} T \right) = \nabla \cdot (k \nabla T) - \left[\rho \frac{\partial \left(\lambda L_f \right)}{\partial t} + \rho \nabla \cdot \left(\vec{V} \lambda L_f \right) \right] \tag{3}$$

 A_m is much zone constant set to 10⁵, according to the previous works [35–37]. λ (melting ratio of PCM) is defined as [35,38]:

$$\lambda = \frac{\Delta H}{mL_f} = \begin{cases} 0 \text{ if } T < T_{Solidus} \\ 1 \text{ if } T > T_{Liquidus} \\ \frac{T - T_{Solidus}}{T_{Liquidus} - T_{Solidus}} \text{ if } T_{Solidus} < T < T_{Liquidus} \end{cases}$$
(4)

The Reynolds Averaged Navier-Stokes (RANS) is employed to model the turbulent flow by averaging the Navier-Stocks equations and can be expressed as [39]:

$$\rho \overline{u}_k \frac{\partial \overline{u}_i}{\partial x_k} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \overline{u}_i}{\partial x_j} \right) + \frac{\partial R_{ij}}{\partial x_j}$$
(5)

where R_{ii} is the Reynolds stress tensor written as:

$$R_{ij} = -\rho \overline{u'_i u'_j} = \mu_t \left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) - \frac{2}{3} \mu_t \frac{\partial \overline{u}_k}{\partial x_k} \delta_{ij} - \frac{2}{3} \rho k \delta_{ij}$$
(6)

where μ_t is the turbulent viscosity and k is the turbulent kinetic energy. u'_i and u'_j are turbulent fluctuations considering the starting point of the derivation of the RANS equations as follows:

$$u_i = \overline{u}_i + u'_i \tag{7}$$

The shear-stress transport (SST) k- ω model is used in this study to solve the turbulent flow equation developed by Mentor [40]. This model is formed by converting the k- ε model into the k- ω formulation to accurately simulate the near-wall region and the free-stream independence of the k- ε model in the zones which are far away from the walls. In this model, the turbulence kinetic energy, k, and the specific dissipation rate, ω , are obtained from the following transport equations for the steady-state condition [41]:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial k}{\partial x_j} \right) + \widetilde{G}_k - Y_k \tag{8}$$

$$\frac{\partial}{\partial \mathbf{x}_i} (\rho \omega \mathbf{u}_i) = \frac{\partial}{\partial \mathbf{x}_j} \left(\Gamma_{\omega} \frac{\partial \omega}{\partial \mathbf{x}_j} \right) + G_{\omega} - \mathbf{Y}_{\omega} + D_{\omega}$$
(9)

 Γ_k and Γ_ω are the effective diffusivities of k and ω obtained as:

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k} \tag{10}$$

$$\Gamma_{\omega} = \mu + \frac{\mu_t}{\sigma_{\omega}} \tag{11}$$

 \widetilde{G}_k and G_k as representative of turbulence kinetic energy are calculated as:

$$G_k = \min(G_k, 10\rho\beta^*k\omega) \tag{12}$$

$$G_k = -\rho \overline{u'_i u'_j} \frac{\partial u_j}{\partial x_i} \tag{13}$$

and G_{ω} as representative of the production of ω is:

$$G_{\omega} = \frac{\alpha}{\nu_t} G_k \tag{14}$$

The turbulent flow equations are solved along with the continuity and energy equations as follows to determine the velocity and temperature distribution in the domain:

$$\nabla . \left(\rho \, \vec{V} \right) = 0 \tag{15}$$

$$\nabla \cdot \left(\rho C_p \overrightarrow{V} T\right) = \nabla \cdot (k \nabla T) \tag{16}$$

where C_p and k are the specific heat coefficient and thermal conductivity of the fluid, respectively.

The Reynolds number (*Re*) for the Novec-774 coolant under the given flow rate (90 LPM) for t = 3 mm is approximately 24,000, indicating turbulent flow regime. To accurately capture near-wall effects and possible flow separation within narrow cooling channels, the SST $k-\omega$ model was selected. This turbulence model provides improved accuracy in low and moderate *Re* numbers while retaining robustness for high-gradient regions, making it well-suited for this hybrid cooling system.

The following boundary conditions were used at the relevant boundary:

- At the PCM-cell interface: $-k_{PCM}\nabla T_{PCM} = -k_{cell}\nabla T_{cell}$
- At the PCM-liquid interface: $-k_{PCM}\nabla T_{PCM} = h_{PCM-liquid}(T_{PCM} T_{liquid})$
- At the outer boundaries of the PCM layers: Adiabatic condition $(\nabla T = 0)$
- For the cooling channels: Specified inlet flow rate ($\dot{m} = 90 LPM$)

In this study, the governing equations were solved using ANSYS-FLUENT software. The SIMPLE algorithm was employed for the pressure-velocity coupler and the Green-Gauss cell-based model was used for the variables' discretization. Furthermore, the QUICK method was employed to resolve the momentum and energy equations as pressure correction formulae, which, in turn, was managed by applying the PRESTO method. The convergence criteria for the mass, momentum, and energy conservation equations were set as 10^{-6} , 10^{-6} and 10^{-6} , respectively [42].

In this study, a constant volumetric heat generation rate of 72.12 W was applied within the lithium-ion pouch cells to represent internal heat generation during 3C charge/discharge cycles. The cell casing is modelled as aluminum with a thermal conductivity of 202 W/mK, specific heat of 871 J/kgK, and density of 2719 kg/m³, reflecting typical pouch cell construction. This assumption simplifies the thermal analysis by focusing on the cooling system's performance rather than electrochemical modelling of the battery behaviour.

4. Mesh analysis and model validation

To ensure the accuracy and reliability of the numerical results, a comprehensive grid sensitivity analysis is conducted by systematically varying the mesh density. The objective is to identify the optimal cell size that achieves mesh-independent solutions while maintaining computational efficiency. The grid sensitivity study is performed for the case having RT25HC as the PCM type, 90 lpm flow of the cooling HTF, and 7-mm thickness for the PCM layer, which represents the most performing configuration examined in this study. The mesh density is varied from a coarse grid with 561,210 elements to a fine grid with 963,430 elements. The evolution of the liquid fraction is monitored as

the key parameter to assess grid convergence. Fig. 3 presents the results of the mesh sensitivity analysis for simulation of the hybrid PCM-liquid cooling system under consideration. Three different mesh densities are compared in Fig. 3-a: 561,210 elements (coarsest), 780,770 elements (medium), and 963,430 elements (finest). The liquid fraction curves for all three mesh densities follow a similar S-shaped pattern with only minor differences visible. The close agreement between the medium and fine mesh results suggests that mesh independence has been achieved with the 561,210-element mesh. Further refinement to 780,770 or 963,430 elements produces negligible changes in the solution, indicating that the additional computational cost of the finest mesh is likely unnecessary.

Fig. 3-b examines the effect of time step size on the simulation results. Three different time steps are compared: 0.05, 0.10, and 0.20 s. The liquid fraction curves for all time steps are virtually indistinguishable throughout the entire 1800-s simulation. This good agreement across different time steps indicates that the solution is temporally converged even at the largest time step of 0.20 s. The middle time step of 0.10 s was used for efficient yet more accurate predictions of the PCM melting behaviour and overall thermal management performance. Fig. 4 displays the structure of the selected mesh with 561,210 nodes.

For model validation, a well-established PCM phase change case in rectangular enclosures was selected for two key reasons. First, the fundamental phase change mechanisms in the battery thermal management system can be represented by those in simple rectangular PCM enclosures, making this a suitable baseline validation case. Two, the rectangular geometry with one heated wall can be considered a simplified analog of the battery-PCM interface, through which the phase change and natural convection effects can be verified before the model is applied to more complex geometries. A cavity with an aspect ratio of 0.714 was employed for validation, where a constant temperature condition was imposed on the left boundary and adiabatic conditions were maintained on the remaining sides. This configuration was aligned with the setups utilized by Gau and Viskanta [43], Kashani et al. [44] and Brent et al. [31] in their investigations. The solid-liquid interface progression as predicted by the current model was compared with results from these prior studies, as shown in Fig. 5. The maximum local deviation in interface position was found to be 6.7 %, which was observed near the top of the cavity at t = 17 min. This deviation was determined to be well within acceptable ranges for phase change simulations, through which it was demonstrated that the fundamental physics of solid-liquid phase transitions and associated heat transfer processes could be accurately captured by the model. Therefore, the validated model can be considered well-suited for investigating the more complex phase transition scenarios that are encountered in battery thermal management systems.

5. Results and discussion

This study explores a hybrid thermal management approach combining the strengths of passive PCM layers for temperature



Fig. 4. Mesh structure of the PCM-HTF cooling system of the Li-ion battery cell.



Fig. 5. The CFD simulation for the solid-liquid boundary in a domain was validated quantitatively for (a) 2 min, (b) 10 min, and (c) 17 min. Measurement versus (I) Kashani et al. [44] computations, (II) Gau and Viskanta [43] experimental outcomes, (III) Brent et al. [31] computations, and (IV) present simulations.

stabilization alongside active liquid cooling channels to provide sustained heat removal. Lateral PCM layers minimize spatial thermal gradients across cells that generate mechanical stresses with potential material cracks leading to failure. Meanwhile, vertical cooling fluid circulation prevents cumulative temperature rise over long charge/ discharge durations that accelerate ageing through rapid chemical changes. Balancing PCM thickness alongside cooling channel flow intensity and temperature regulates battery temperature uniformly in space and time. Thereby enabling safe, efficient electric vehicle



Fig. 3. Exploring the impact of the mesh sensitivity on the liquid fraction evolution for: (a) the cell density and (b) the time step size.

operation meeting drive cycle power needs.

5.1. Effect of varying the PCM layer thickness

Optimizing the thickness of the PCM layers laterally encasing the battery cells is crucial for achieving effective thermal management in the hybrid PCM-liquid cooling system. This section evaluates four different thicknesses of the PCM (RT25HC): 1 mm, 3 mm, 5 mm, and 7 mm. Increasing the PCM layer thickness provides a greater thermal mass capable of storing more energy via latent heat of fusion. This enhanced thermal inertia helps dampen transient temperature spikes and lateral temperature gradients across the cell array during charge/discharge cycles. However, an excessively thick PCM layer adds unnecessary mass and volume to the overall system, which is highly undesirable for vehicle applications where weight and compact sizing are priorities.

Liquid-fraction contour plots in Fig. 6 visually depict the temporal evolution of the melting process for different PCM thicknesses over the 1800s (0.5 h) simulated charge cycle. For the 1 mm thickness case, the liquid fraction contours indicate that the PCM undergoes rapid, complete melting within the first 600 s, transitioning entirely to the liquid



Fig. 6. liquid-fraction contour distributions in the Li-ion cell-PCM system through the midplane under the conditions of 90 lpm flow of the cooling HTF.

phase. This premature melting severely limits the PCM's ability to provide continued thermal regulation beyond the initial cycle stage. In contrast, the 3 mm PCM thickness exhibits a more gradual melting behaviour, with the liquid fraction progressing steadily. At 1800s, while a significant portion has melted, some solid regions still remain, indicating a degree of sustained thermal buffering capacity. The 5 mm and 7 mm PCM thickness cases display even slower melting progression rates compared to the thinner configurations. For the 5 mm case, the 1800s contours reveal that although a substantial melting front has propagated, a sizable solid PCM region persists around the cell peripheries. The 7 mm PCM thickness exhibits the slowest melting rate, with a considerable solid fraction remaining even after the 1800s simulated duration. This gradual phase transition suggests that the thicker 7 mm PCM configuration retains significant thermal mass and latent heat storage potential to provide extended thermal regulation capabilities.

The data presented in Fig. 7 provide a more quantitative measure of the melting progression within the PCM layers. At the charge time of 1800 s, the liquid fraction values indicate 0.92, 0.81, 0.57, and 0.42 for the PCM layer of 1-, 3-, 5-, and 7-mm thickness. This data shows that even at 1800 s, the 1 mm PCM layer has almost completely melted, with only around 7.5 % of its mass remaining in the solid state. This implies that the 1 mm PCM layer has essentially exhausted its thermal regulation capacity by this time. However, the thicker PCM layers still maintain significant solid fractions, enabling them to continue providing thermal regulation beyond the simulated duration of 1800 s. The 3 mm PCM layer has 19.2 % of its mass remaining solid, while the 5 mm and 7 mm layers have 42.9 % and 57.8 % solid fractions, respectively. Thus, compared to 1-mm layer, thicker PCM layers (3 mm, 5 mm, and 7 mm) undergo a more gradual melting process, enabling sustained thermal regulation over extended charge/discharge cycles.

Fig. 8 shows the temperature contour distributions within the Li-ion cell-PCM system at different durations for the four PCM thicknesses: 1 mm, 3 mm, 5 mm, and 7 mm). At 600 s, the temperature contours reveal that the PCM layer of 1 mm-thickness has already reached its melting point and is unable to provide further thermal regulation. High temperatures are observed near the cell surfaces, indicating insufficient thermal buffering capacity. With the 3 mm PCM thickness, the temperature contours show lower temperatures near the cell surfaces, suggesting that the PCM is still absorbing heat and undergoing the phase change process. The 5 mm and 7 mm PCM thicknesses exhibit even lower temperatures near the cell surfaces, indicating a greater capacity for heat absorption and thermal regulation at this early stage. As time advances to 1200s, the 1 mm PCM thickness exhibits high temperatures throughout, as the PCM has completely melted and can no longer provide thermal regulation. The 3 mm PCM thickness shows higher temperatures near the cell surfaces, indicating that the PCM is approaching its melting limit and will soon be unable to provide further thermal regulation. The 5 mm and 7 mm PCM thicknesses maintain lower temperatures near the cell surfaces, suggesting that they still have significant thermal buffering capacity remaining. As time further advances to 1800s, the 1 mm PCM thickness continues to exhibit high temperatures throughout, with no thermal regulation capability. The 3 mm PCM



Fig. 7. Transient Liquid-fraction profile for different thickness of PCM layer for the coolant flow rate of 90 lpm of the cooling HTF.



Fig. 8. Temperature contour distributions in the Li-ion cell-PCM system through the midplane under the conditions of 90 lpm flow of the cooling HTF PCM tempreture in the midplane.

thickness also shows high temperatures near the cell surfaces, indicating that it has reached its melting limit and is no longer effective for thermal regulation. The 5 mm PCM thickness exhibits higher temperatures near the cell surfaces compared to earlier time steps, but still maintains some thermal regulation capacity. The 7 mm PCM thickness displays the lowest temperatures near the cell surfaces, suggesting that it still has substantial thermal buffering capacity remaining even after 1800s.

Quantitative analysis of the temperature profiles in Fig. 9 highlights the stark differences in thermal regulation potential across the PCM thickness range. The 1 mm PCM is unable to control temperatures effectively, with peak cell temperatures exceeding the critical 100 °C threshold by 1800s. The 3 mm configuration, while offering improvement over the 1 mm case, also fails to provide adequate temperature regulation after 1200s, with peak temperatures surpassing 40 °C. However, the 5 mm PCM thickness demonstrates superior thermal



Fig. 9. Temperature profiles in the Li-ion cell-PCM system through the midplane under the conditions of 90 lpm flow of the cooling HTF PCM tempreture in the midplane.

management capabilities by constraining peak cell temperatures below 25 °C throughout the entire 1800s simulation. The 7 mm PCM case achieves the most impressive performance, maintaining the lowest sustained peak temperature of around 21 °C, even at the end of the 1800s cycle.

The non-monotonic temperature profile for the 1 mm PCM case can be attributed to the complete melting of the PCM layer within the initial stages of the simulated charge/discharge cycle. Once the PCM has fully melted, the temperature of the battery cell begins to rise more rapidly, as the PCM can no longer provide any latent heat absorption to stabilize the temperature. During the initial phase when the PCM is undergoing melting, the temperature remains relatively constant, as the latent heat of fusion is being absorbed. However, after the PCM has completely melted (around 600 s), the battery cell temperature starts to increase more sharply due to the continued heat generation, without the buffering effect of the PCM. This behaviour is in contrast to the thicker PCM cases (3 mm, 5 mm, and 7 mm), where the PCM layer is not fully melted within the simulated time frame, and the PCM continues to absorb heat through the latent heat of fusion, resulting in a more gradual temperature increase.

Fig. 10 presents the 3D temperature contour distributions through the entire battery domain over the time intervals: 600 s, 1200s, and 1800s. Over the whole operating duration of 1800s, the temperature contours reveal distinct patterns across different PCM thicknesses, further reinforcing the observations from the 2D contours. Thinner PCM layers (1 mm and 3 mm) exhibit localized hotspots and lateral temperature non-uniformities, rendering them ineffective for sustained temperature regulation. Meanwhile, the thicker 5 mm and 7 mm configurations promote temperature homogeneity across the cell array for an extended period of 1800 s. This is attributed to the increased thermal mass associated with thicker PCM layers, enabling them to absorb and store a larger amount of heat before reaching their melting limits.

Complementing these visual representations, the average temperature profiles in Fig. 11 quantify the maximum temperature values attained for each PCM thickness case. Once again, the 1 mm PCM thickness reaches an alarmingly high peak temperature of around 115 °C by the end time of 1800s, well above the safe operating range for lithium-ion batteries. The 3 mm PCM thickness also exhibits a peak temperature of around 45 °C, indicating that it has exhausted its thermal regulation capabilities. Meanwhile, the 5 mm and 7 mm PCM layers keep outperforming their thinner counterparts by restricting the maximum cell temperatures below 35 °C, which within the desirable 15–40 °C range for safe lithium-ion battery operation.

Fig. 12 shows the mean and maximum cell temperatures for the four PCM thicknesses considered. For the 1 mm PCM thickness, the data reveals a significantly high mean temperature of 113.77 $^{\circ}$ C and a maximum temperature of 188.12 $^{\circ}$ C. These temperatures are well above the recommended operating range for lithium-ion batteries, which confirms the inability of the 1 mm PCM layer to effectively regulate the cell temperatures. In contrast, the 3 mm PCM thickness exhibits a



Fig. 10. 3D Temperature contour distributions in the Li-ion cell-PCM system through the whole battery domain under the conditions of 90 lpm flow of the cooling HTF PCM temperature in the midplane.



Fig. 11. Temperature profiles in the Li-ion cell-PCM system through the whole battery cell under the conditions of 90 lpm flow of the cooling HTF.

substantially lower mean temperature of 44.77 $^{\circ}$ C and a maximum temperature of 68.43 $^{\circ}$ C. While these temperatures are higher than the optimal range, they represent a significant improvement over the 1 mm case. The 5 mm PCM thickness demonstrates further improvement, with a mean temperature of 33.33 $^{\circ}$ C and a maximum temperature of 43.44 $^{\circ}$ C. These temperatures fall within or near the recommended operating range for lithium-ion batteries, indicating the effectiveness of the 5 mm PCM layer in regulating cell temperatures. Finally, the 7 mm PCM thickness exhibits the best thermal regulation performance, with a mean temperature of 32.52 $^{\circ}$ C and a maximum temperature of 39.07 $^{\circ}$ C. These temperatures are well within the optimal operating range for lithium-ion batteries, ensuring safe and efficient operation.

5.2. Effect of varying the PCM type

The choice of phase change material (PCM) type significantly influences the thermal regulation capabilities of the hybrid PCM-liquid cooling system for lithium-ion batteries. This section explores the behaviour of three PCMs: RT18HC, RT21HC, and RT25HC, with melting temperature ranges of 17-19 °C, 20-23 °C, and 22-26 °C, respectively, for the PCM thickness of 25.5 mm (t = 7 mm). Fig. 13 presents the liquidfraction contours for the three PCMs at t = 1800s. Starting with RT18HC, the liquid-fraction contours indicate a significant portion of the PCM has already melted, suggesting an advanced melting progression. The contours indicate liquid fractions approaching 0.6 in most regions, implying that nearly 60 % of the RT18HC has transitioned to the liquid phase. In contrast, RT21HC exhibits a more moderate melting rate, with liquid fractions ranging from 0.3 to 0.5, indicating a partial phase change state. RT25HC, with the highest melting point range, displays the slowest melting progression, as evident from the liquid fractions predominantly below 0.4, signifying that a substantial portion remains in the solid phase.

Fig. 14 presents temperature distribution contours through the midplane of the cell-PCM system for three different types of PCMs: RT18HC, RT21HC, and RT25HC. For RT18HC with melting temperature range of 17 to 19 °C, the temperature contours reveal relatively low temperatures throughout the PCM region, indicating that the PCM has undergone significant melting stage by t = 1800s. In the case of RT21HC, the temperature contours show higher temperatures within the PCM region compared to RT18HC. This suggests that RT21HC, with its higher melting temperature range of 20 °C to 23 °C, has not melted as extensively as RT18HC by t = 1800s. The higher temperatures indicate that the PCM is still in the process of melting and absorbing heat from the cells. For RT25HC, which has the highest melting temperature range of 22 °C to 26 °C among the three PCMs, the temperature contours reveal even higher temperatures within the PCM region. This observation implies that RT25HC has experienced melting and heat absorption during the simulated time frame, resulting in higher overall temperatures. Quantitatively comparing the temperature distributions, the RT18HC contours show the coolest regions, with temperatures largely below 30 °C within the PCM area. The RT21HC contours exhibit temperatures ranging from 30 °C to 40 °C in the PCM region, while the RT25HC contours reveal the highest temperatures, predominantly above 40 °C within the PCM region. These observations indicate that the choice of PCM type and its corresponding melting temperature range significantly influence the thermal regulation capabilities of the PCM-liquid cooling system.

Quantitative analysis of the average liquid fraction profiles in Fig. 15 reinforces the observed trends. At the end of the simulated time of t = 1800 s, RT18HC exhibits a liquid fraction around 0.53, indicating that it has almost completely melted. In contrast, RT21HC has a liquid fraction of around 0.41, while RT25HC shows the lowest liquid fraction of approximately 0.32, signifying that a substantial portion (68 %) of the PCM remains in the solid state. The analysis of these liquid-fraction profiles highlights the trade-off between initial thermal buffering and sustained thermal regulation capabilities associated with different PCM types. By carefully selecting the appropriate PCM based on the specific thermal management requirements and operating conditions of the lithium-ion battery system, it is possible to optimize the hybrid PCMliquid cooling approach for effective temperature regulation throughout the charge/discharge cycles.

Fig. 16 shows the 3D temperature contour distributions which provide a comprehensive visualization of the thermal regulation performance across the entire battery domain. For the RT18HC case, the temperature contours reveal that a significant portion of the battery domain exhibits relatively low temperatures, primarily below 30 °C, owing to the extensive melting and latent heat absorption by this PCM. In the case of RT21HC, the temperature distribution is more heterogeneous, with regions ranging from approximately 30 °C to 40 °C,



Fig. 12. Mean and Maximum Cell Temperatures in the Li-ion cell-PCM system through the whole battery cell under the conditions of 90 lpm flow of the cooling HTF.



Fig. 13. Liquid-fraction contours in the Li-ion cell-PCM system through the midplane for three different types of PCM: RT18HC, RT21HC and RT25HC at t = 1800 s.



Fig. 14. Temperature distribution contours in the Li-ion cell-PCM system through the midplane for three different types of PCM: RT18HC, RT21HC and RT25HC at t = 1800s.

reflecting the partial melting state and moderate heat absorption capacity. For RT25HC, the temperature contours reveal the highest temperatures within the battery domain. A considerable portion of the domain exhibits temperatures above 40 $^\circ$ C, indicating that RT25HC has



Fig. 15. Transient average PCM liquid-fraction profiles through the whole Liion cell-PCM battery under the conditions of 90 lpm flow of the cooling HTF and PCM layer thickness of 7 mm.



Fig. 16. 3D Temperature contour distributions in the Li-ion cell-PCM system through the whole battery domain under the conditions of 90 lpm flow of the cooling HTF and PCM layer thickness of 7 mm.

undergone the slowest melting and heat absorption during the simulated time frame.

The comparison of mean and maximum cell temperatures in Fig. 17 quantifies the thermal regulation effectiveness of each PCM type. RT18HC achieves the lowest mean and maximum cell temperatures of 25.96 °C and 29.79 °C, respectively, falling well within the recommended operating range of 15–40 °C for lithium-ion batteries. This superior thermal regulation performance can be attributed to the extensive melting and heat absorption by RT18HC during the initial stages of the charge/discharge cycle. However, it is important to note that PCMs with lower melting temperature ranges, such as RT18HC, may reach their melting limit earlier, potentially compromising their ability to provide sustained thermal regulation over extended periods. RT21HC exhibits slightly higher mean and maximum cell temperatures of 31.35 °C and 39.04 °C, respectively. While these temperatures are still within the recommended operating range, they are higher than those achieved by RT18HC, reflecting the partial melting state and moderate heat S. Sen et al.



Fig. 17. Mean and Maximum Cell Temperatures in the Li-ion cell-PCM system through the whole battery cell under the conditions of 90 lpm flow of the cooling HTF and PCM layer thickness of 7 mm.

absorption capacity of RT21HC.

RT25HC, with the highest melting temperature range, demonstrates mean and maximum cell temperatures of 32.52 °C and 39.07 °C, respectively. These temperatures are within or slightly above the recommended operating range, indicating that RT25HC effectively regulates cell temperatures during the simulated time frame. However, it is important to note that PCMs with higher melting temperature ranges, like RT25HC, exhibit a slower melting rate and may not offer as effective initial thermal buffering as PCMs with lower melting temperature ranges. Nonetheless, their ability to maintain their solid phase for a longer duration enables prolonged heat absorption and thermal regulation capabilities, which can be advantageous for applications with extended charge/discharge cycles or higher heat generation rates.

In summary, the selection of an appropriate PCM type should balance the trade-off between initial thermal buffering and sustained thermal regulation capabilities, based on the specific thermal management requirements and operating conditions of the lithium-ion battery system. PCMs with lower melting temperature ranges, such as RT18HC, provide effective initial thermal buffering but may reach their melting limit earlier, potentially compromising their ability to provide sustained thermal regulation over extended periods. Conversely, PCMs with higher melting temperature ranges, like RT25HC, exhibit a slower melting rate and may not offer as effective initial thermal buffering. However, they can maintain their solid phase for a longer duration, enabling prolonged heat absorption and thermal regulation capabilities, which can be advantageous for applications with extended charge/ discharge cycles or higher heat generation rates.

5.3. Effect of varying the HTF temperature

The inlet temperature of the HTF plays a crucial role in determining the thermal regulation behaviour of the hybrid PCM-liquid cooling system for lithium-ion batteries. This section investigates the impact of varying the HTF inlet temperature by considering three cases: T = 5 °C, 10 °C, and 15 °C. The liquid fraction profiles presented in Fig. 18 reveal that a higher HTF inlet temperature accelerates the melting progression of the PCM (RT18HC). At the initial stage of 600 s, the liquid fraction profiles for all three inlet temperatures are nearly identical, indicating a minimal influence of the HTF temperature during the early stages of melting. However, as time progresses, distinct differences become apparent. By 1800 s, the system with a 15 °C inlet temperature exhibits the highest liquid fraction of approximately 0.32, followed by the 10 $^\circ\mathrm{C}$ case at around 0.31, and the 5 $^\circ\text{C}$ case at approximately 0.30. This trend suggests that a higher HTF inlet temperature enhances the heat transfer rate from the PCM, promoting faster melting and a more advanced liquid fraction.



Fig. 18. Liquid-fraction profiles in the Li-ion cell-PCM system for different HTF inlet temperature (5, 10, and 15C) under the conditions of 90 lpm flow of the cooling HTF, PCM thickness of 7 mm, and PCM type of RT18HC.



Fig. 19. Temperature profiles in the Li-ion cell-PCM system for different HTF inlet temperature (5, 10, and 15C) under the conditions of 90 lpm flow of the cooling HTF, PCM thickness of 7 mm, and PCM type of RT18HC.

PCM system for the three different inlet temperatures of HTF: T = 5 °C, 10 °C, and 15 °C. At the initial time of 600 s, the temperature profiles for all three inlet temperatures exhibit similar trends, with peak temperatures around 20 °C, indicating minimal impact from the HTF temperature during the early stages. However, as time progresses to 1200 s and 1800 s, distinct differences emerge. By t = 1800 s, the system with an HTF inlet temperature of 5 °C maintains the lowest peak temperature of around 21.8 °C, indicating effective heat removal and temperature regulation. The 10 °C inlet temperature case exhibits a peak temperature of approximately 22.7 °C, while the 15 °C inlet temperature case reaches the highest peak temperature of around 23.4 °C. This trend demonstrates that a lower HTF inlet temperature enhances the cooling capacity of the system, resulting in more effective temperature regulation within the battery cells.

The sudden jumps that appear in Fig. 19 can be directly correlated to the phase change behaviour of the PCM (RT18HC). The first jump around 650 s coincides with the PCM transitioning from a primarily solid state to a partially melted state, as indicated by the liquid fraction reaching 0.125 (Fig. 18). This phase change triggers a divergence in the temperature profiles, as lower HTF inlet temperatures better extract heat from the partially melted PCM. The second jump around 1285 s occurs as the PCM approaches a more advanced melting state, with the liquid fraction increasing to 0.225 (Fig. 18). This higher degree of melting diminishes the PCM's latent heat absorption capacity, making the temperature regulation more dependent on the HTF inlet conditions.

Fig. 20 presents the mean and maximum cell temperatures within the lithium-ion cell-PCM system for different inlet temperatures of the HTF. As the inlet temperature increases from 5 °C to 10 °C and 15 °C, both the mean and maximum cell temperatures exhibit a corresponding increase. Specifically, the system with a 5 °C inlet temperature achieves the lowest maximum cell temperature of 29.15 °C, followed by the 10 °C case at 29.51 °C, and the 15 °C case at 29.79 °C. A similar trend is observed for the mean cell temperatures, with the 5 °C case exhibiting the lowest value of 24.63 °C, while the 10 °C and 15 °C case show higher mean cell temperatures of 25.30 °C and 25.96 °C, respectively. The observed trends can be attributed to the temperature gradient between the HTF

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Fig. 20. Mean and maximum cell temperatures in the Li-ion cell-PCM system through the whole battery cell for different HTF inlet temperature (5, 10, and 15C) under the conditions of 90 lpm flow of the cooling HTF and PCM thickness of 7 mm.

and the PCM/battery cells. A lower HTF inlet temperature results in a larger temperature gradient, enhancing the heat transfer rate from the cells to the HTF. Consequently, this higher cooling capacity leads to more effective temperature regulation and lower mean and maximum cell temperatures. Conversely, a higher HTF inlet temperature reduces the temperature gradient, diminishing the heat transfer rate and resulting in higher cell temperatures.

It is worthy to note that while a lower HTF inlet temperature provides superior thermal regulation performance, it may also increase the energy consumption and operational costs associated with the cooling system. Additionally, excessively low inlet temperatures may lead to overcooling and potential condensation issues, which could adversely affect the performance and durability of the battery system. Therefore, in the design and operation of hybrid cooling systems for lithium-ion batteries, it is crucial to strike a balance between the HTF inlet temperature, the desired thermal regulation performance, energy efficiency, and operational costs.

6. Conclusion

This computational study systematically investigated a novel hybrid thermal management approach combining passive phase change materials (PCMs) and active liquid cooling for enhanced temperature regulation in lithium-ion battery packs. The key quantitative findings are summarized as follows:

- Optimal PCM selection is crucial, balancing initial thermal buffering capacity and sustained heat absorption over prolonged periods. RT18HC (17–19 °C melting range) achieved superior initial performance, constraining mean/maximum cell temperatures to 25.96 °C/ 29.79 °C. However, it reached 53 % liquid fraction by 1800s, limiting long-duration effectiveness. RT25HC (22–26 °C melting range) exhibited slower melting at 32 % liquid fraction, but higher 32.52 °C/39.07 °C mean/maximum temperatures.
- 2. PCM thickness significantly impacts thermal regulation capabilities. Insufficient 1 mm thickness failed completely with 113.77 °C mean and 188.12 °C maximum cell temperatures. 3 mm showed improvement at 44.77 °C mean but still inadequate 68.43 °C maximum. 5 mm thickness effectively restricted mean/maximum to 33.33 °C/43.44 °C. Optimal 7 mm PCM further reduced mean/ maximum to 32.52 °C/39.07 °C while maintaining 58 % solid fraction after 1800s for prolonged thermal inertia.
- 3. Decreasing coolant inlet temperature from 15 °C to 5 °C for the optimal 7 mm PCM configuration further enhanced performance by increasing the temperature gradient for heat transfer. Mean/

maximum cell temperatures declined from 25.96 °C/29.79 °C to 24.63 °C/29.15 °C at 5 °C inlet.

The hybrid passive-active thermal management approach synergistically couples the lateral temperature stabilization of PCM phase change with sustained vertical heat extraction via liquid cooling channels. Collectively, the optimal 7 mm RT18HC PCM coupled with 5 °C coolant inlet at 90 LPM flow rate constrained battery temperatures below 30 °C with minimal spatial non-uniformities across the pack. This computational study quantifies the coupled influence of key PCM properties (type, thickness) and active cooling parameters (inlet temperature, flow rate) to strategically optimize lithium-ion battery thermal performance within desired operating bounds.

Future research directions should explore the performance of the hybrid PCM-liquid cooling system across a broader range of operating conditions, composite PCMs, and novel flow channel designs. Particularly, investigating the system's thermal management capabilities under various C-rates (from 1C to 5C and beyond) would provide valuable insights for fast-charging applications. The integration of artificial intelligence and machine learning approaches could also help develop predictive models for optimizing the hybrid system's performance across different charging scenarios. Moreover, while this study focused primarily on the thermal performance of the hybrid PCM-liquid cooling system, it is acknowledged that system-level factors such as cooling power consumption, energy density trade-offs, and packaging constraints play a critical role in practical battery thermal management system (BTMS) design. Future work should also aim to incorporate these criteria into a comprehensive multi-objective analysis to evaluate the overall system efficiency and viability for electric vehicle applications.

CRediT authorship contribution statement

Surojit Sen: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. Jasim M. Mahdi: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. Pouyan Talebizadehsardari: Writing – review & editing, Visualization, Software, Resources, Project administration, Methodology, Investigation. Antonino La Rocca: Supervision, Resources, Project administration, Conceptualization. Alasdair Cairns: Resources, Funding acquisition, Conceptualization.

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.

Data availability

The data that has been used is confidential.

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