

Article

Multi-Parameter Analysis of PCM-Based Thermal Management Performance and Thermophysical Characteristics of Lithium-Ion Battery Packs

Yong Ding ¹ , Wenjie Hou ², Fan Yang ² and Zhoujian An ^{1,2,*}

¹ School of Aerospace Engineering, Guizhou Institute of Technology, Guiyang 550025, China; yding@git.edu.cn

² School of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou 730050, China

* Correspondence: anzhoujian@lut.edu.cn

Abstract

A three-dimensional structural model of a cylindrical lithium-ion battery pack incorporating composite phase change material (PCM) is developed in this study, and numerical simulations are conducted using CFD software to investigate the heat dissipation characteristics of the battery pack. The results show that the composite PCM effectively suppresses the temperature rise within the battery pack, maintaining both the temperature and the temperature difference in the battery pack within acceptable ranges. Parameter analysis reveals that increasing the radial thermal conductivity of the battery reduces the heating rate and improves the temperature uniformity of the overall system. Within the investigated parameter range, increasing the thermal conductivity of the composite PCM beyond approximately 1 W/(m·K) results in a region of diminishing improvement in thermal performance. Beyond this range, further increases in thermal conductivity result in only marginal reductions in the maximum temperature, indicating that excessive enhancement of thermal conductivity provides limited thermal benefits and should be balanced with latent heat capacity. An increase in the latent heat of the composite PCM lowers both the maximum temperature and the maximum temperature difference at the end of discharge, thereby enhancing system temperature uniformity. Conversely, enlarging the external air convection heat transfer coefficient yields a limited cooling effect while deteriorating the temperature uniformity within the system. Therefore, on the principle of fully utilizing latent heat and minimizing energy consumption, the external convection heat transfer coefficient should be set as low as possible. This study provides theoretical guidance for the parametric design of PCM-based thermal management systems.

Keywords: phase change material; numerical simulation; battery thermal management



Academic Editor: Vasilis K. Oikonomou

Received: 16 June 2026

Revised: 29 July 2026

Accepted: 3 August 2026

Published: 4 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Currently, energy scarcity and environmental pollution have emerged as two major challenges affecting global economic development. The transportation sector is a significant energy consumer and a major contributor to pollution due to vehicle emissions [1]. In hydrogen fuel cell vehicles and integrated hydrogen energy systems, lithium-ion power batteries typically function as auxiliary units for power response and energy recovery, operating in coordination with fuel cells. Their thermal management performance directly affects vehicle safety and energy efficiency. Lei et al. [2] investigated the anisotropic thermal conductivity of batteries and the influence of swelling on directionality, underscoring the

importance of anisotropic heat conduction within cells for thermal management design. Lei et al. [3] proposed a liquid-immersed thermal management scheme and analyzed the thermal runaway behavior of battery modules, revealing that overheating under overcharge conditions can produce higher peak temperatures than those observed in nail penetration tests. This research on the thermal safety of large-capacity battery modules under extreme operating conditions is particularly critical for high-power demand scenarios in hydrogen-electric hybrid systems. Qi et al. [4] proposed a novel design that combines a liquid cooling plate (LCP) with non-uniform spiral fins (NUSF), offering a cost-effective and engineering-scalable solution to enhance the thermal management performance of lithium-ion battery modules in electric vehicles and energy storage systems. Therefore, advances in battery thermal management technology also serve as an essential foundation for advancing hydrogen-fueled transportation.

Proton exchange membrane fuel cells (PEMFCs), as highly efficient clean energy conversion devices, have demonstrated broad application prospects in transportation and stationary power generation [5]. The structural design of bipolar plate flow channels is a key factor that governs the mass transfer efficiency and power density of PEMFCs [6]. In recent years, researchers have sought to enhance reactant mass transfer and improve cell output performance through the optimization of flow channel geometries. Qi et al. [7] proposed a novel channel design strategy based on a semi-parallel and semi-interdigitated mixed flow field, which combines the structural merits of parallel and interdigitated flow fields to effectively improve reactant distribution uniformity and cell power density. Additionally, embedding non-uniform bluff bodies in the flow channels has been proven to significantly enhance convective mass transfer. Qi et al. [6] systematically investigated the effects of bluff body geometry, size, and arrangement on the net output power of PEMFCs, revealing the underlying mechanism by which non-uniform configurations achieve spatially differentiated mass transfer enhancement and multi-physics field homogenization along the channel. Beyond flow field optimization, air cooling technology also represents an important research direction for PEMFC systems. Meanwhile, photovoltaic-PEMFC hybrid energy systems, as integrated energy solutions that combine solar power generation with hydrogen utilization, have also attracted considerable attention in the fields of renewable energy storage and distributed power supply [8–11].

However, lithium-ion batteries, known for their long cycle life, high energy density, low self-discharge rate, and absence of memory effects, are currently considered an ideal power source for new energy systems and are widely used in electric vehicles [12]. As the power source, the operational performance of lithium-ion batteries directly affects the reliability and safety of vehicles [13]. However, lithium-ion batteries are sensitive to temperature [14]. Typically, the optimal operating temperature range for lithium-ion batteries is between 25 °C and 50 °C [15], and the maximum temperature difference among cells within a module should not exceed 5 °C [16]. Prolonged exposure to unsuitable temperatures or excessive temperature differences can lead to various performance issues and potential safety risks [17]. During normal operation, lithium-ion batteries generate a substantial amount of heat. If this heat is not dissipated in a timely manner and accumulates within the battery, it leads to a continuous rise in temperature [18–20]. Particularly in high-temperature environments, where the initial battery temperature is already elevated, the heat generated during charge and discharge cycles can quickly cause the battery pack to overheat [21,22]. This not only results in significant degradation of battery performance but also substantially increases the risk of thermal runaway within the pack [23,24]. Therefore, it is essential to implement external thermal management strategies to effectively dissipate heat from the batteries.

In current research, the battery thermal management system (BTMS) is recognized as a critical technology for ensuring battery performance and safety. Based on the heat transfer medium, BTMS can be categorized into four types: air cooling, liquid cooling, heat pipe cooling, and PCM-based thermal management systems [25–27]. In terms of energy consumption, thermal management systems can be classified as active or passive cooling. Compared to active cooling methods, passive cooling approaches offer several advantages [28–30]. PCM-based battery thermal management represents a novel passive thermal management approach. Compared with conventional methods, it offers advantages such as a simple structure, high heat dissipation efficiency, excellent temperature uniformity, and no additional energy consumption, demonstrating significant potential for practical applications [31–33]. During reversible phase transition processes, PCM can absorb or release substantial latent heat while maintaining an almost constant temperature [34]. This characteristic not only effectively controls battery temperature rise but also greatly improves temperature uniformity within the battery pack [35].

In recent years, numerous scholars have conducted research on PCM-based battery thermal management systems [36–38]. Wang et al. [39] numerically analyzed the performance of a PCM-based BTMS, demonstrating that phase change materials exhibit favorable heat storage and temperature-uniforming capabilities. Lin et al. [40] systematically analyzed key parameters, including liquidus temperature, discharge rate, thermal conductivity, filling thickness, and latent heat, to elucidate the melting evolution process of PCM in battery thermal management systems. Zhang et al. [41] systematically analyzed, through numerical simulation, the influence of the thermophysical properties of 50 PCMs on BTMS performance. Jilte et al. [42] investigated an optimized system incorporating a double-layer PCM structure through numerical simulation.

Despite the great potential of PCMs in battery thermal management, their intrinsic drawbacks—low thermal conductivity, poor heat transfer capability, and high flammability—can significantly impair battery performance [43]. In contrast, composite phase change materials (CPCM) offer distinct advantages, including high thermal conductivity, non-flammability, and excellent stability [44,45]. Zhou et al. [46] systematically explained the influence mechanism of PCM coverage on cooling performance. Their research confirmed that adopting a full-side composite PCM structure is an effective and feasible approach for battery module thermal management. Aliya et al. [47] developed a novel flexible CPCM using polyethylene glycol as the phase change core. The material was effectively encapsulated and supported by a rigid matrix of styrene-ethylene-propylene-styrene block copolymer and a flexible network of polyolefin elastomer, thereby improving its form stability. Zhang et al. [48] integrated a CPCM into a module and systematically evaluated its thermal performance under controlled forced convection. The results showed that, compared with pure paraffin, the CPCM consistently improved temperature uniformity within the module and reduced the average temperature. Qi et al. [49] found that a hybrid liquid cooling and phase change system incorporating CPCM significantly reduced both the peak surface temperature and its uniformity in the module. Zhang et al. [50] performed a comprehensive thermal analysis of a 16-cell lithium-ion battery pack using CFD. They observed that the introduction of PCM extended the thermal regulation duration to approximately 12.5 min, effectively buffering thermal shocks during peak load conditions. Qiu et al. [51] prepared and applied a flame-retardant flexible CPCM for temperature control and thermal runaway prevention in battery packs.

This study proposes a thermal management system for cylindrical lithium-ion battery packs based on a CPCM. Numerical simulations are conducted using computational fluid dynamics (CFD) software on a 26650 cylindrical LiFePO₄ battery pack model integrated with CPCM. The aim is to investigate the heat dissipation characteristics and systematically

analyze the effects of key parameters on thermal management performance, including the discharge rate, radial thermal conductivity, thermophysical properties of the PCM, and external environmental conditions. The findings provide valuable references for the design of PCM-based battery cooling systems.

2. Numerical Model

2.1. Battery Thermal Generation Model

Due to the complex internal structure of lithium-ion batteries and the fact that the thermophysical properties of the constituent materials may vary with temperature and state of charge, it is challenging to establish a thermal model that precisely replicates the heat generation process. To simplify the analysis, the following assumptions are adopted for the battery thermal model [52]:

- (1) The battery is homogeneous and generates heat uniformly.
- (2) The thermophysical properties of the battery are constant, independent of temperature and state of charge.
- (3) The thermal conductivity of the battery is anisotropic, with distinct values in the axial and radial directions.
- (4) Radiative heat transfer and internal convection within the battery are neglected.

Prior to conducting numerical analysis on the battery pack, the heat generation rate of the battery must be calculated. In this study, the Bernardi equation from battery heat generation models is employed to determine the heat generation of the battery [24,25,36]. This formula accurately simulates the heat generation rate of the battery under real-world operating conditions and shows the closest agreement with experimental results. It is expressed as follows:

$$q = \frac{Q}{V} = \frac{1}{V} \left(I^2 R + IT \frac{dU_{OCV}}{dT} \right) \quad (1)$$

In this equation, q represents the volumetric heat generation rate of the lithium-ion battery (W/m^3), and V is the volume of the lithium-ion battery (m^3). I denotes the operating current (A), and T is the initial temperature of the battery (K), taken as 298.15 K. The term dU_{OCV}/dT is the entropy heat coefficient (V/K), which is assumed to be constant at 0.4 mV/K. R represents the internal resistance of the battery (Ω), assumed to be constant at 28 m Ω .

This study uses a 26650 cylindrical LiFePO₄ lithium-ion battery with a capacity of 3 Ah. The specification parameters of the battery are derived from the literature and are presented in Table 1. By applying Equation (1) and incorporating the battery parameters listed in Table 1, the heat generation rate of the battery under discharge multiplicities ranging from 1 C to 5 C is calculated. The results are summarized in Table 2.

Table 1. Specification parameters of lithium-ion battery.

Parameters	Value
Capacity (Ah)	3
Battery Diameter (mm)	26
Battery Height (mm)	65
Battery Weight (g)	85
Nominal Voltage (V)	3.2
Discharge Cut-off Voltage (V)	2.0
Internal Resistance (m Ω)	28
Radial Thermal Conductivity [W/(m·K)]	0.98
Axial Thermal Conductivity [W/(m·K)]	26.96
Density (kg/m ³)	2463
Specific Heat Capacity [J/(kg·K)]	1375

Table 2. Battery heat generation rates at different discharge rate.

Discharge Rate (C)	1	2	3	4	5
Heat generation rate (W/m ³)	17,669.46	49,943.21	96,821.26	158,303.61	234,390.25

2.2. Physical Model

The CPCM was prepared using stearic acid (SAT), acrylonitrile-butadiene-styrene copolymer (AC), and expanded graphite (EG) at a mass ratio of 100:18:12. The thermophysical properties of the CPCM are presented in Table 3. The resulting material is a form-stable composite PCM, meaning it does not leak and remains in a solid state both before and after phase change. Thermal conductivity was measured using a TC3100 thermal conductivity analyzer (XIATECH, Xi'an, China) based on the transient hot-wire method, while the phase change temperature and latent heat were determined via differential scanning calorimetry (DSC). Given that the discharge rate of battery packs in new energy vehicles typically does not exceed 3 C during daily operation, the required amount of PCM in this study was estimated based on the heat generation rate of the battery at a 3 C discharge. This approach ensures adequate thermal management for various operating conditions while avoiding unnecessary weight increase. According to Equation (12) and the estimated heat generation of a single cell at a 3 C discharge, the calculated thickness of the composite PCM layer surrounding the battery is 2 mm.

Table 3. Physical properties of prepared composite PCM.

Parameter	Density/(kg/m ³)	Specific Heat Capacity/[J/(kg·K)]	Latent Heat of Phase Change/(kJ/kg)	Phase Change Temperature/(°C)	Phase Change Temperature Range/(°C)	Thermal Conductivity/[W/(m·K)]	Viscosity/[kg/(m·s)]
Value	400	2931	151.64	40.72	2	1.411	10 ¹⁰

The PCM-based thermal management structure for lithium-ion batteries is primarily composed of a battery module and a PCM module. The battery module consists of 25 identical 26650 lithium-ion cells arranged in a 5-series and 5-parallel configuration. The PCM module is designed as a conventional enclosure-type structure with dimensions of 150 mm × 150 mm × 65 mm. This structure features cavities for 25 individual 26650 lithium-ion cells, with a spacing of 4 mm between adjacent cells. The distance between the cells and the enclosure walls is set to half of the inter-cell spacing. The system model is illustrated in Figure 1.

2.3. PCM Model

This study adopts the solidification and melting model based on the enthalpy method in Fluent to solve the heat transfer problem during phase change [20]. Due to the complexity of the phase change heat transfer problems in practice, in order to facilitate the simulation, the following assumptions are proposed [10,20,52]:

- (1) The PCM is in perfect contact with the battery, with no thermal contact resistance.
- (2) Since the PCM applied in this study is a form-stable CPCM, only the heat conduction within the PCM is considered, and the convective heat transfer after the PCM phase change is ignored. The viscosity of the liquid phase PCM is set to 10¹⁰ kg/(m·s).
- (3) The thermal conductivity of the PCM is isotropic.
- (4) The PCM is homogeneous, and its density, specific heat capacity, and thermal conductivity do not vary with temperature.
- (5) Radiation during the heat transfer process is ignored.

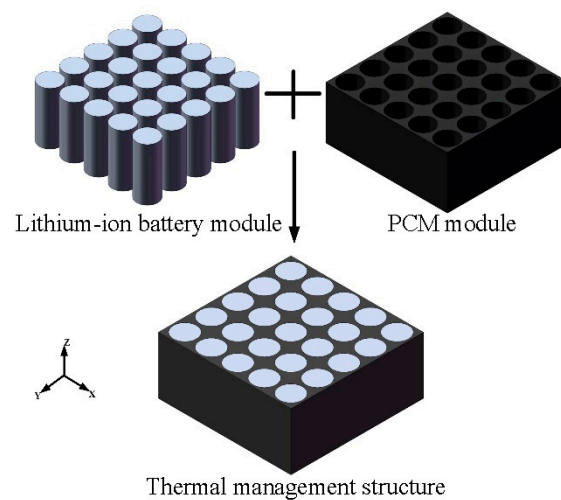


Figure 1. System model.

Based on the above assumptions, the continuity equation, momentum equation, and energy conservation equation of the PCM during the phase change heat transfer process are as follows.

Continuity equation:

$$\nabla \cdot (\rho_{\text{PCM}} u) = 0 \quad (2)$$

Momentum equation:

$$\rho_{\text{PCM}} \frac{\partial u_i}{\partial t} + \rho_{\text{PCM}} \mu_{\text{PCM}} \nabla u u_i = \mu_{\text{PCM}} \nabla^2 u_i - \frac{\partial p}{\partial x_i} + \rho_{\text{PCM}} g_i + S_i \quad (3)$$

Energy equation:

$$\rho_{\text{PCM}} \frac{\partial H}{\partial t} + \rho_{\text{PCM}} \nabla u H = k_{\text{PCM}} \nabla^2 T_{\text{PCM}} \quad (4)$$

In the above equation, ρ_{PCM} represents the density of PCM (kg/m^3); u is the velocity vector of PCM (m/s); T_{PCM} is the current temperature of PCM (K); k_{PCM} is the thermal conductivity of PCM ($\text{W}/(\text{m} \cdot \text{K})$); S is the momentum source term (N); μ is the dynamic viscosity of PCM ($\text{kg}/(\text{m} \cdot \text{s})$); p is the pressure (Pa); g is the local gravitational acceleration (m/s^2); H is the total enthalpy of PCM (J/kg). The total enthalpy is calculated as follows:

$$H = h + \Delta H \quad (5)$$

$$h = \int_{T_0}^T C_{\text{PCM}} dT \quad (6)$$

$$\Delta H = \beta \gamma \quad (7)$$

$$\beta = \begin{cases} 0 & T_{\text{PCM}} < T_s \\ \frac{T_{\text{PCM}} - T_s}{T_l - T_s} & T_s \leq T_{\text{PCM}} \leq T_l \\ 1 & T_{\text{PCM}} \geq T_l \end{cases} \quad (8)$$

Here, h represents the sensible enthalpy value of PCM (J/kg); ΔH represents the latent enthalpy value occupied by PCM (J/kg); γ represents the latent heat of phase change in PCM (J/kg); β represents the liquid phase ratio of PCM; T_s represents the melting point temperature of PCM (K); T_l represents the temperature at which PCM completely melts (K).

Assuming no heat exchange between the PCM-battery module and the external environment, the heat generated by the lithium-ion battery is completely absorbed by the

battery itself and the PCM. Theoretical calculations can be utilized in combination with the relevant thermophysical properties of the lithium-ion battery; the total heat generation of the lithium-ion battery Q is:

$$Q = Q_{\text{PCM}} + Q_{\text{cell}} \quad (9)$$

$$Q_{\text{PCM}} = m_{\text{PCM}}C_{\text{PCM}}(T_1 - T_0) + m_{\text{PCM}}H_{\text{PCM}} \quad (10)$$

$$Q_{\text{cell}} = m_{\text{cell}}C_{\text{cell}}(T_1 - T_0) \quad (11)$$

Here, m_{PCM} represents the mass of PCM (kg); C_{PCM} denotes the specific heat capacity of PCM (J/(kg·K)); m_{cell} indicates the mass of the battery (kg); C_{cell} represents the specific heat capacity of the battery (J/(kg·K)); H is the latent heat of phase transition of PCM (kJ/kg); T_1 is the phase transition temperature of PCM (K); T_0 is the initial temperature of PCM (K).

Based on this, the required mass of PCM can be estimated:

$$m_{\text{PCM}} = \frac{Q - Q_{\text{cell}}}{C_{\text{PCM}}(T_1 - T_0) + H_{\text{PCM}}} \quad (12)$$

$$V = \frac{m_{\text{PCM}}}{\rho_{\text{PCM}}} \quad (13)$$

$$V_{\text{PCM}} = V_{\text{box}} - N\pi r_{\text{cell}}^2 H \quad (14)$$

where $N = 25$, and the diameter and height of each cylindrical battery cell are 26 mm and 65 mm, respectively. In the numerical model, the spacing between adjacent battery cells was set to 4 mm, corresponding to an equivalent single-side PCM thickness of 2 mm around each battery cell. The distance between the peripheral battery cells and the outer wall of the container was also set to 2 mm.

In summary, the required PCM mass was first determined through an energy balance analysis under the 3C discharge condition to meet the specified thermal regulation target. Then, by considering the PCM density and the available packing space within the 5×5 cylindrical battery arrangement, the inter-cell spacing was optimized to 4 mm, resulting in an equivalent single-side PCM thickness of 2 mm. This optimized thickness provides adequate heat storage capacity while maintaining a favorable compromise between thermal management capability, module volume, mass, and structural compactness.

2.4. Initial Conditions and Boundary Conditions

Before the formal simulation, the initial state is defined as

$$t = 0; T(x, y, z) = T_{\text{amb}} \quad (15)$$

where T_{amb} is the ambient temperature. In this study, the ambient temperature was set to a constant value of 298.15 K (25 °C), and the initial temperatures of both the PCM and the batteries were assumed to be equal to the ambient temperature.

The boundary conditions for lithium-ion batteries and PCM are:

$$\lambda_c \frac{dT_c}{dn} = \lambda_{\text{pcm}} \frac{dT_{\text{pcm}}}{dn} \quad (16)$$

The boundary conditions of PCM with the external environment are:

$$\lambda_{\text{pcm}} \frac{dT_{\text{pcm}}}{dn} = h(T_{\text{pcm}} - T_{\text{amb}}) \quad (17)$$

where λ_c , λ_{pcm} , and h represent the thermal conductivity of the battery, the thermal conductivity of the PCM, and the convective heat transfer coefficient, respectively; T_c is the battery temperature. In this study, the thermal boundary conditions for all six surfaces (top, bottom, and four sides) of the battery thermal management system model are set to natural convection with identical convective heat transfer coefficients. Unless otherwise stated, the coefficient is initially set to $5 \text{ W}/(\text{m}^2 \cdot \text{K})$.

2.5. Meshing

The geometric model was developed using SolidWorks (SolidWorks2021) software and subsequently imported into ICEM CFD for meshing. Numerical simulations of the battery pack were conducted using the CFD software ANSYS Fluent 2022 R2. To ensure solution accuracy, the convergence criteria for the residuals of the momentum, continuity, and energy equations were set to 10^{-6} , 10^{-6} , and 10^{-9} , respectively. A time step of 1 s was employed, with a maximum of 20 iterations per time step. Second-order upwind schemes were applied for the spatial discretization of the momentum and energy equations.

In this study, the maximum temperature of the battery during a 3 C discharge was simulated. As shown in Figure 2, when the mesh count of a single lithium-ion battery cell increased from 32,000 to 140,712, the corresponding change in the maximum temperature was less than $0.005 \text{ }^\circ\text{C}$. To improve computational efficiency, a meshing scheme with 32,000 cells was adopted for a single lithium-ion battery cell.

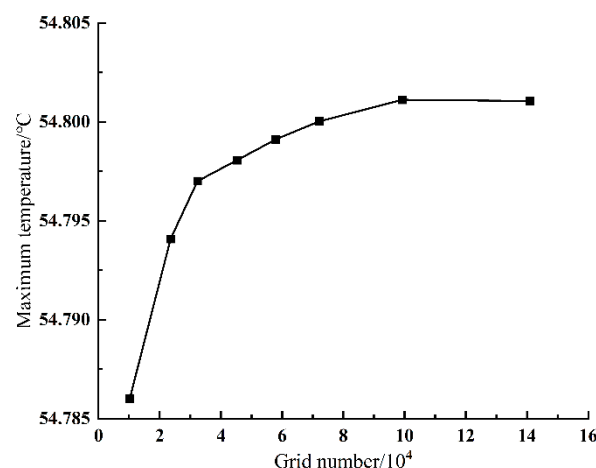


Figure 2. Grid independence verification for a single cell.

To validate the model, this study compares its predictions with data from the literature. Under an ambient temperature of $25 \text{ }^\circ\text{C}$ and a convective heat transfer coefficient of $5 \text{ W}/(\text{m}^2 \cdot \text{K})$, the maximum surface temperature of the battery during discharge at different rates was simulated and compared with the data reported by Zhang [53]. As shown in Figure 3, the temporal evolution of the maximum surface temperature at discharge rates of 1 C, 3 C, and 5 C is in excellent agreement with the literature data, thereby demonstrating the accuracy of the proposed model.

Furthermore, quantitative validation was performed using the root mean square error (RMSE) to evaluate the deviation between the simulated and experimental temperatures. The RMSE values for the 1C, 2C, and 3C discharge conditions were $1.52 \text{ }^\circ\text{C}$, $0.64 \text{ }^\circ\text{C}$, and $4.71 \text{ }^\circ\text{C}$, respectively. The relatively low RMSE values indicate good agreement between the numerical predictions and experimental measurements. Although a relatively larger deviation was observed under the 3C discharge condition, it can be attributed to the increased heat generation rate, non-uniform internal heat generation, and measurement uncertainties under high-rate discharge conditions. Overall, the proposed model provides

reliable predictions of the temperature evolution of lithium-ion battery cells under different discharge rates.

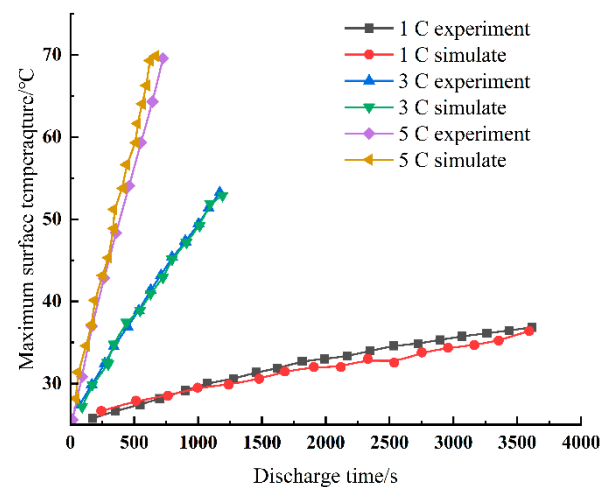


Figure 3. Single cell model validation.

Moreover, in this study, the ambient temperature and the initial temperatures of both the lithium-ion battery and the CPCMC are set to 298.15 K (25 °C), together with a discharge rate of 3 C, as the initial conditions for simulating the liquid fraction of the CPCMC. The results indicate that, as shown in Figure 4, a meshing scheme with a total grid count of 1,273,800 for the thermal management system of the lithium-ion battery pack achieves the best computational efficiency while maintaining calculation accuracy.

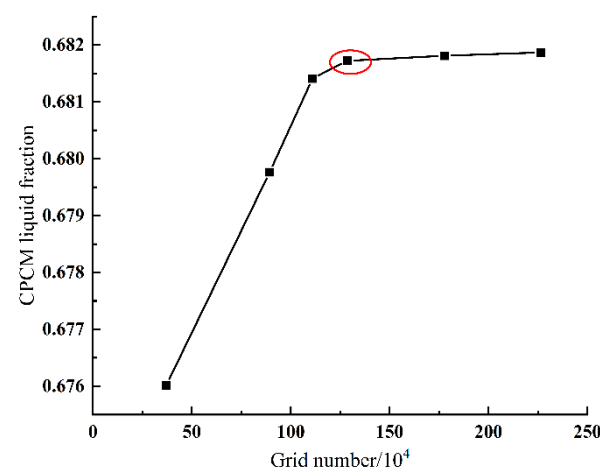


Figure 4. Validation of system-level grid independence.

3. Results and Discussion

3.1. Temperature Variation Characteristics of a Single Battery Cell in the Absence of Composite PCM

Figure 5 shows the temperature change curves of the maximum temperature of a single cell without encapsulated composite PCM when it is only cooled by natural convection of air during discharge at 1C–5C rates. From the figure, it can be seen that the maximum temperatures of the single cell without PCM at 1C–5C are 42.57 °C, 57.84 °C, 72.15 °C, 86.14 °C, and 99.97 °C, respectively. Only at the 1 C discharge rate does the maximum temperature of the single cell not exceed 50 °C, which is within the optimal working temperature range of lithium-ion batteries (25–50 °C). At discharge rates of 3 C and above, the battery temperatures all exceed 60 °C. At the 5 C discharge rate (abuse condition), the

maximum temperature of the single cell reaches as high as 99.97 °C, which will greatly impair the performance of lithium-ion batteries and may even cause thermal runaway. Therefore, it is necessary to adopt appropriate thermal management measures to enhance heat dissipation and ensure that the battery operates within a suitable temperature range.

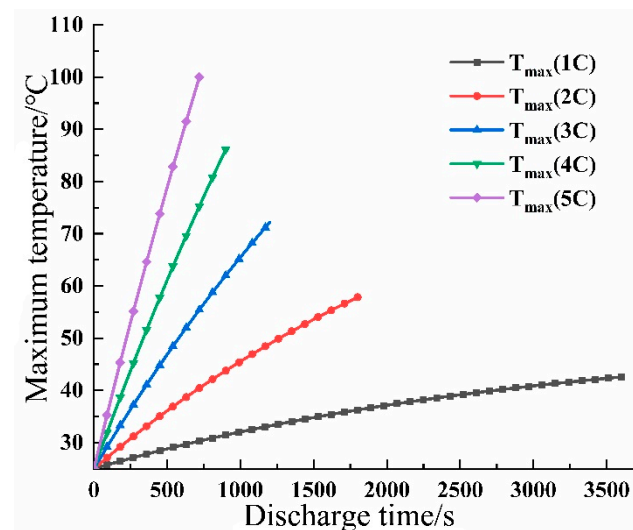


Figure 5. Maximum temperature variation curves of single cell without wrapped composite PCM.

3.2. Thermal Management Characteristics of Lithium-Ion Battery Packs Based on Composite PCM

3.2.1. Temperature Variation Within the Battery Pack Under Different Discharge Rates

In this section, the influence of wrapping SAT-AC/EG composite PCM on the temperature variation within the battery pack under different discharge rates (1 C–5 C) is investigated through numerical simulations. Figure 6 presents the maximum temperature profiles of the battery pack with composite PCM at various discharge rates. As shown, compared to the bare cells, the temperature rise rate of the battery pack with composite PCM is significantly reduced across all discharge rates. At the end of the discharge, the maximum temperatures are 38.38 °C, 43.37 °C, 46.40 °C, 50.84 °C, and 56.57 °C for 1 C, 2 C, 3 C, 4 C, and 5 C, respectively. As mentioned earlier, the amount of composite PCM used in this study was determined based on the heat generation rate at a 3 C discharge. The simulation results show that at the end of the 3 C discharge, the maximum temperature inside the battery pack (46.40 °C) remains within the optimal operating temperature range (25–50 °C), indicating that the design meets the thermal management requirements. Although the maximum temperatures under the 4C and 5C discharge conditions exceeded the recommended operating temperature range, they did not exceed 60 °C. This suggests that the proposed thermal management strategy can effectively mitigate excessive temperature rise to some extent under high-rate discharge conditions. Additionally, it can be observed from the curves that only under the 1 C discharge rate does the maximum temperature curve lack an inflection point where the slope decreases. This is because, at 1 C, the maximum temperature inside the battery pack never reaches the phase change temperature of the composite PCM (40.72 °C). Consequently, the composite PCM absorbs heat solely as sensible heat throughout the process. The appearance of inflection points in the other curves is attributed to the phase change process of the composite PCM.

Figure 7 illustrates the maximum temperature difference curves among cells within the battery pack incorporating composite PCM under various discharge rates. As can be observed, the maximum temperature difference remains below 5 °C across all discharge rates, satisfying the thermal management requirements. Although the 3 C discharge generates more heat compared to the 1 C discharge, the peak value of the maximum

temperature difference does not occur at the end of the discharge and is significantly lower. This is because, during the 3 C discharge process, the composite PCM reaches its phase change temperature and begins to melt, absorbing a substantial amount of latent heat during the nearly isothermal phase transition. This not only effectively mitigates the temperature rise in the cells but also greatly enhances the temperature uniformity within the pack. In summary, the composite PCM effectively slows down the temperature increase within the battery pack through three mechanisms: heat conduction, sensible heat storage, and latent heat storage, thereby keeping the internal temperature and temperature difference within reasonable limits. Since the amount of composite PCM used was estimated based on the 3 C discharge condition, and to simplify the subsequent workload, the 3 C discharge rate is selected as the representative case for further investigation in this study.

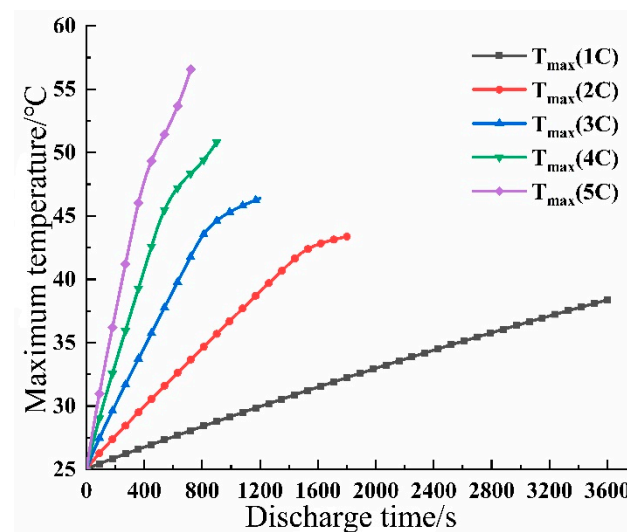


Figure 6. Variation curves of maximum temperature inside the battery pack embedded in composite PCM matrix at different discharge rate.

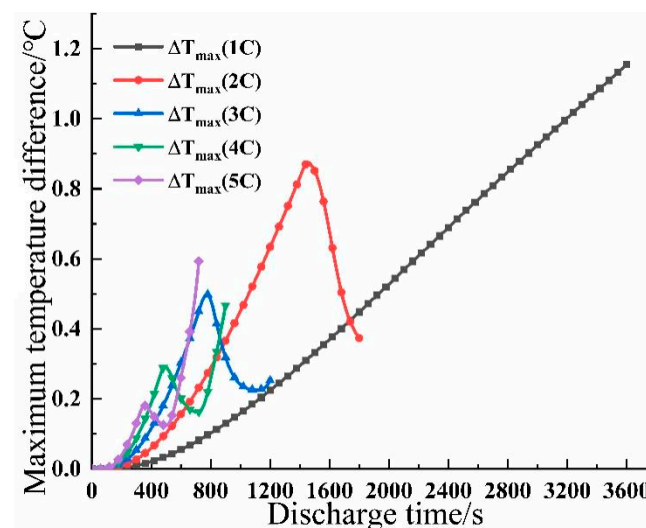


Figure 7. Variation curves of maximum temperature difference between cells of wrapped composite PCM at different discharge rate.

3.2.2. Influence of the Radial Thermal Conductivity of the Battery on Temperature Variation Within the Battery Pack

The radial thermal conductivity of the selected battery is 0.98 W/(m·K). To further investigate the influence of battery parameters on thermal management performance, this

section employs the controlled variable method, setting the radial thermal conductivity (consistent with circumferential thermal conductivity) to 0.3, 0.5, 1.5, 2, and 3 W/(m·K), respectively, to explore its impact on thermal management effectiveness.

Figure 8 shows the variation curves of the maximum temperature within the battery pack under the 3 C discharge for different radial thermal conductivity values. The results indicate that as the radial thermal conductivity increases, the temperature rise rate of the maximum temperature decreases. This is because higher radial thermal conductivity enhances the battery's internal heat diffusion capacity, enabling faster heat transfer to the composite PCM and subsequently to the external environment.

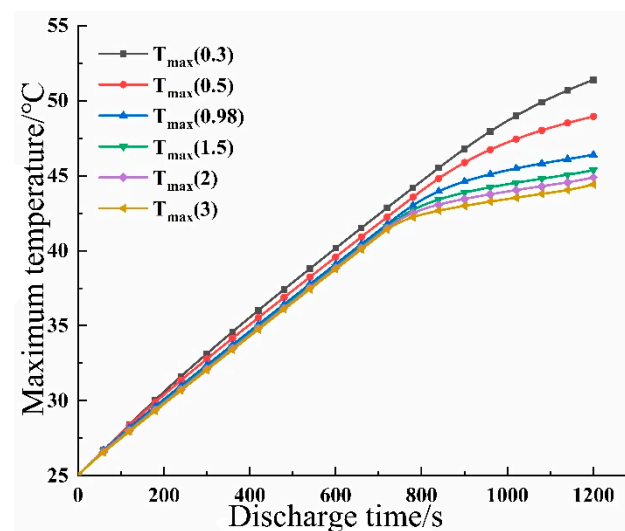


Figure 8. Variation curves of the maximum temperature inside the battery pack embedded in a composite PCM matrix under different cell radial thermal conductivity.

At the end of the 3 C discharge, the maximum temperatures within the battery pack for radial thermal conductivity of 0.3, 0.5, 0.98, 1.5, 2, and 3 W/(m·K) are 51.40 °C, 48.95 °C, 46.40 °C, 45.38 °C, 44.90 °C, and 44.42 °C, respectively. When the radial thermal conductivity increases from 0.3 W/(m·K) to 3 W/(m·K), the maximum temperature decreases by 6.98 °C. Notably, 6.02 °C of this reduction (86% of the total) occurs when the thermal conductivity increases from 0.3 W/(m·K) to 1.5 W/(m·K). Beyond 1.5 W/(m·K), further increases in thermal conductivity result in progressively smaller temperature reductions.

Figure 9 presents the temperature contour of the thermal management system from a top view at the end of the 3 C discharge. A lower radial thermal conductivity of the battery leads to greater radial thermal resistance within the cell. This impedes heat transfer from the battery to the composite PCM, causing heat to accumulate inside the battery and resulting in an increase in the maximum battery temperature. Consequently, the temperature gradient within the entire system—including both the battery module and the composite PCM module—becomes more pronounced, deteriorating the overall temperature uniformity. Therefore, in the design of lithium-ion batteries, efforts should be made to address the issue of low radial thermal conductivity through improvements in manufacturing processes and material properties.

3.2.3. Influence of PCM Thermal Conductivity on Temperature Variation Within the Battery Pack

The thermal conductivity of PCM is a crucial external factor affecting thermal management performance. The composite PCM prepared in this study exhibits a thermal conductivity of 1.411 W/(m·K). To further elucidate the influence of PCM thermal conductivity on temperature variation within the lithium-ion battery pack, a control variable

approach was adopted. The thermal conductivity of the PCM was set to 0.3, 0.5, 1, 2, and 3 W/(m·K) while keeping other parameters unchanged. Figure 10 presents the maximum temperature profiles of the battery pack during the 3 C discharge under different PCM thermal conductivity. As shown, when the thermal conductivity increases from 0.3 to 3 W/(m·K), the maximum temperatures at the end of the discharge are 47.64 °C, 47.10 °C, 46.58 °C, 46.40 °C, 46.26 °C, and 46.13 °C, respectively. With increasing PCM thermal conductivity, the maximum temperature within the battery pack decreases. However, once the thermal conductivity exceeds about 1 W/(m·K), further increases have a diminishing effect on reducing the maximum temperature. Therefore, for a specific thermal management system, it is not necessary to pursue an excessively high thermal conductivity for the PCM. Currently, the thermal conductivity of PCM is commonly enhanced by incorporating highly conductive additives such as expanded graphite (EG) or metal nanoparticles. However, this improvement often comes at the cost of a significant reduction in latent heat, which may increase the required amount of composite PCM to meet the thermal management objectives, thereby adding weight and complexity to the system. Consequently, for a given thermal management application, the thermal conductivity of the PCM should not be considered in isolation; rather, a comprehensive analysis incorporating the corresponding latent heat is essential for optimal material selection.

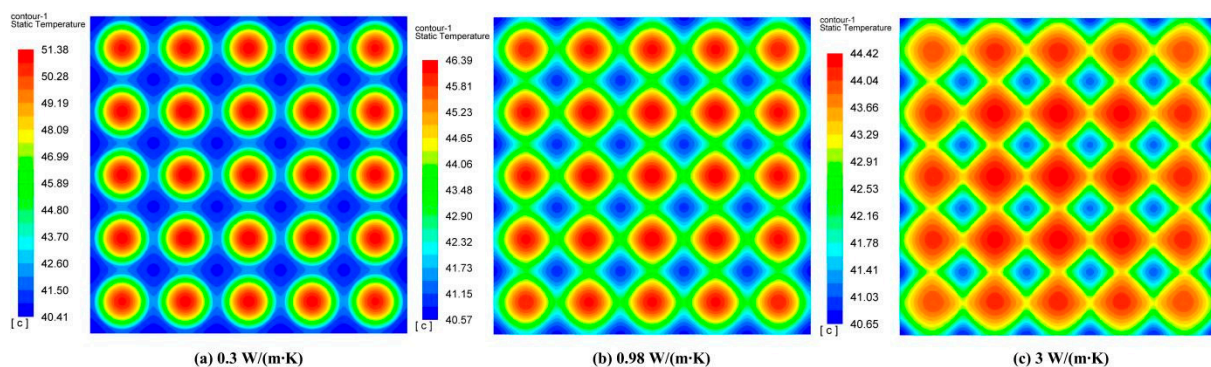


Figure 9. Temperature contours at the end of the 3C discharge: (a) 0.3 W/(m·K), (b) 0.98 W/(m·K), (c) 3 W/(m·K).

Figure 11 shows the variation curves of the maximum temperature difference among cells under different PCM thermal conductivity during the 3 C discharge. As the thermal conductivity of the PCM increases, the maximum temperature difference among cells rises more rapidly in the early stage of the discharge, with a slightly higher peak value. This is because higher thermal conductivity of the PCM leads to greater thermal diffusivity within the PCM module, making the influence of external convective heat transfer on the temperature gradient among cells more pronounced. Once the PCM in the central region of the system—where heat dissipation conditions are relatively poor—begins to melt earlier than that in the peripheral region, the maximum temperature difference among cells starts to decrease. Moreover, with higher PCM thermal conductivity, the decline in the maximum temperature difference becomes more significant, resulting in a smaller maximum temperature difference among cells at the end of the discharge.

3.2.4. Influence of PCM Latent Heat on Temperature Variation Within the Battery Pack

In the initial configuration, the latent heat of the composite PCM was 151.64 kJ/kg. To investigate the influence of PCM latent heat on thermal management performance, the latent heat value was varied to 100, 125, 175, and 200 kJ/kg while keeping other parameters unchanged. Figure 12 presents the maximum temperature variation curves within the battery pack during the 3 C discharge for different PCM latent heat values. As shown, when

the latent heat is set to 100, 125, 151.64, 175, and 200 kJ/kg, the corresponding maximum temperatures at the end of the discharge are 47.07 °C, 46.67 °C, 46.40 °C, 46.26 °C, and 46.15 °C, respectively. With increasing latent heat, the maximum temperature within the battery pack decreases. This is because a higher latent heat results in a lower liquid fraction after absorbing the same amount of heat, thereby slowing down the melting rate and leading to a smaller temperature rise.

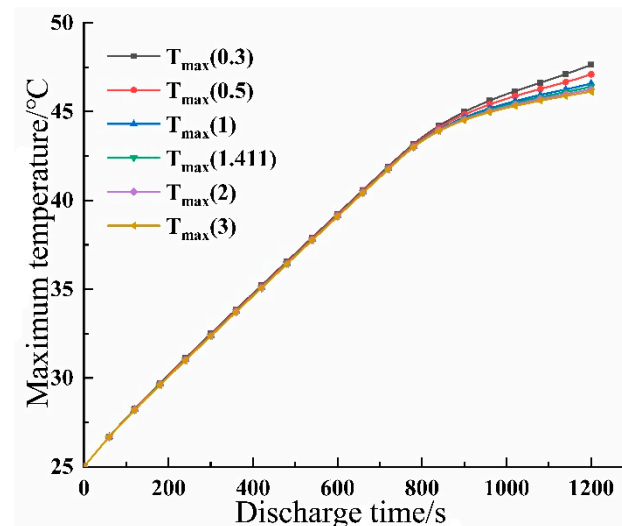


Figure 10. Variation curves of the maximum temperature inside the battery pack with different PCM thermal conductivity.

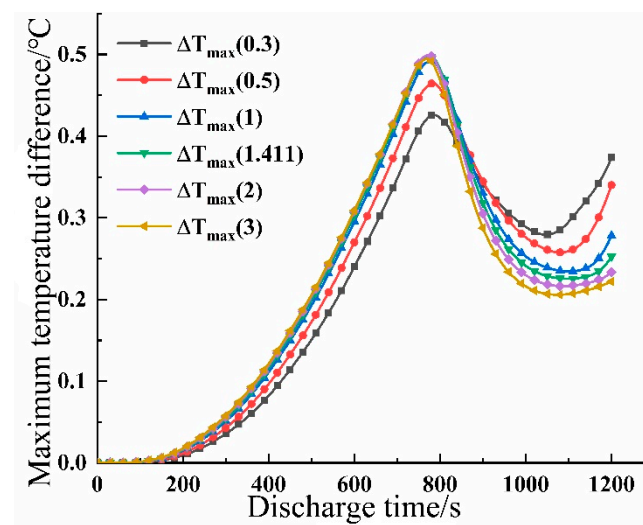


Figure 11. Variation curves of maximum temperature difference between cells with different PCM thermal conductivity.

Figure 13 illustrates the variation curves of the maximum temperature difference among cells during the 3 C discharge for different PCM latent heat values. As can be observed, in the early stage, the temperature within the battery pack has not yet reached the phase change temperature of the PCM, and heat storage occurs only as sensible heat. Therefore, varying the latent heat does not affect the maximum temperature difference among cells during this period. Once the PCM in the central region reaches the melting temperature earlier than that in the peripheral region, the maximum temperature difference curve begins to decline. A higher latent heat leads to a more pronounced decrease in the maximum temperature difference, resulting in a smaller temperature difference among

cells at the end of the discharge and improved temperature uniformity within the system. Specifically, when the latent heat of the PCM is 100, 125, 151.64, 175, and 200 kJ/kg, the corresponding maximum temperature differences among cells at the end of the discharge are 0.47 °C, 0.34 °C, 0.25 °C, 0.22 °C, and 0.19 °C, respectively.

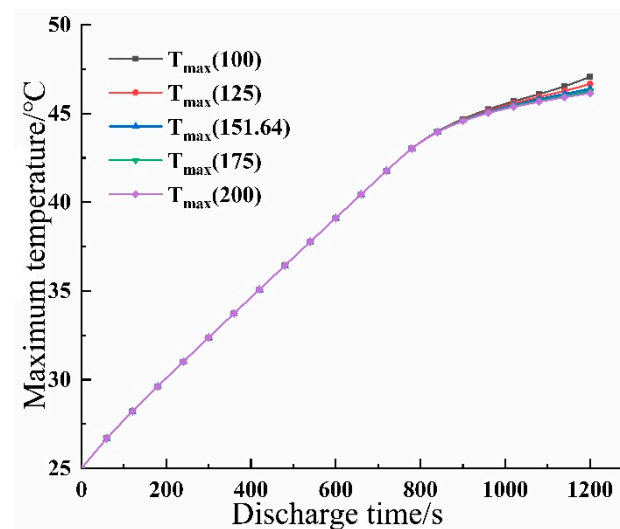


Figure 12. Maximum temperature variation curves within the battery pack based on PCM with different latent heat values.

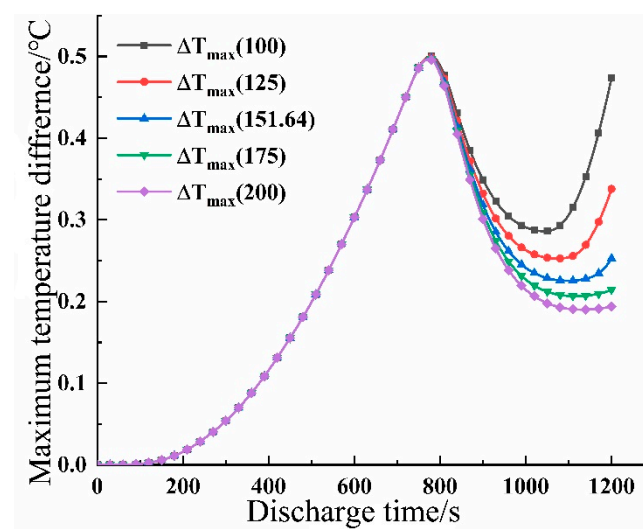


Figure 13. Variation curves of maximum temperature difference between cells based on PCM with different latent heat values.

3.2.5. The Influence of the Convective Heat Transfer Coefficient of External Air on the Temperature Variation Characteristics Within the Battery Pack

This section continues to apply the control variable method to study the influence of the external convective heat transfer coefficient on system thermal management performance. The external convective heat transfer coefficients are set to 5, 10, 20, 30, and 40 W/(m²·K). The variation in the maximum temperature within the battery pack over time is shown in Figure 14. From the figure, when the external convective heat transfer coefficient is 5, 10, 20, 30, and 40 W/(m²·K), the peak maximum temperatures are 46.40 °C, 46.14 °C, 45.66 °C, 45.20 °C, and 44.76 °C, respectively. It can be seen that as the external convective heat transfer coefficient increases, the maximum temperature gradually decreases. This is because increasing the external convective heat transfer coefficient accelerates heat

dissipation at the system boundary. However, since the maximum temperature occurs in the middle of the system where heat dissipation conditions are the worst, increasing the external convective heat transfer coefficient does not have a significant effect on reducing the system's peak temperature.

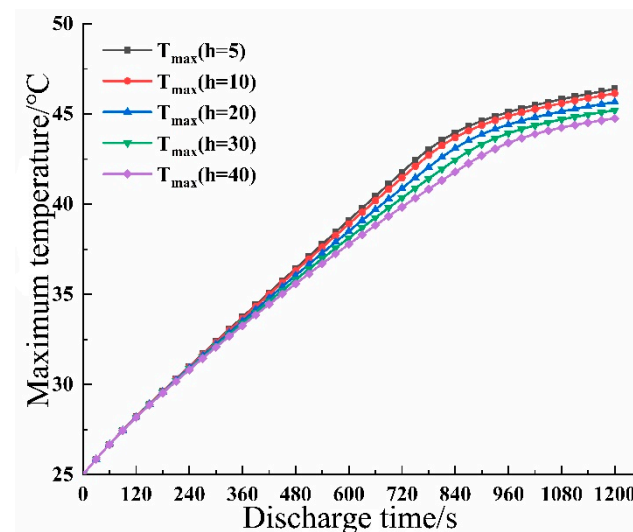


Figure 14. Variation curves of maximum temperature inside the battery pack with different external convective heat transfer coefficients.

The temporal evolution of the maximum temperature difference among cells is illustrated in Figure 15. As can be observed, when the external convective heat transfer coefficient is set to 5, 10, 20, 30, and 40 $\text{W}/(\text{m}^2\cdot\text{K})$, the corresponding peak values of the maximum temperature difference among cells are 0.50 °C, 0.92 °C, 1.61 °C, 2.16 °C, and 2.62 °C, respectively. It is evident that a larger external convective heat transfer coefficient leads to poorer temperature uniformity within the system. This is because increasing the convective heat transfer coefficient accelerates heat dissipation from the peripheral cells, which inherently benefit from better heat dissipation conditions compared to the centrally located cells. In contrast, cells in the central region are less affected by changes in the external convective heat transfer coefficient, resulting in an enlarged temperature gradient within the system. Furthermore, as the external convective heat transfer coefficient increases, it becomes more difficult for the internal temperature to reach the phase change temperature of the composite PCM. Consequently, the inflection point where the maximum temperature difference curve begins to decline appears later, and the subsequent decline is less pronounced. In some cases, a secondary rise no longer occurs before the end of discharge due to the relatively low liquid fraction of the composite PCM at the end of discharge. This significantly reduces the efficiency of latent heat utilization within the system. The external convective heat transfer coefficient should be optimized based on a comprehensive evaluation of the maximum battery pack temperature, temperature uniformity, CPCM latent heat utilization efficiency, and auxiliary energy consumption. Therefore, an excessively low or high convective heat transfer coefficient is not necessarily desirable, and an appropriate value should be selected to achieve a balance between thermal regulation performance and energy consumption.

Under natural convection conditions, a relatively low heat transfer coefficient can help maintain a more uniform temperature distribution within the battery module and promote a larger phase change region of the CPCM. However, it may also weaken the heat dissipation capability of the system to the surrounding environment.

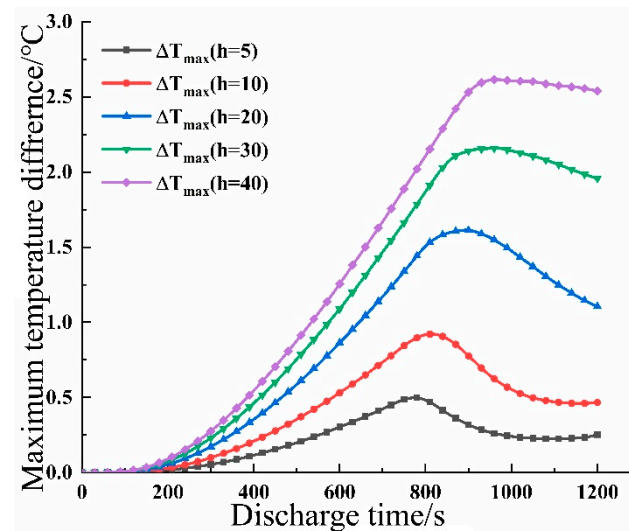


Figure 15. Variation curves of maximum temperature difference between cells with different external convective heat transfer coefficients.

In contrast, increasing the heat transfer coefficient through forced convection, such as air cooling, can effectively reduce the maximum temperature of the battery pack, but this may simultaneously increase fan power consumption and reduce the spatial uniformity of CPCMs latent heat utilization. Since the present study does not incorporate models for fan power consumption, flow resistance, or auxiliary system energy requirements, the optimal operating condition in terms of overall energy efficiency cannot be quantitatively determined at this stage.

Future studies will incorporate fan power consumption, pressure drop, and system coefficient of performance (COP) into a multi-objective optimization framework to achieve a balanced design considering maximum temperature, maximum temperature difference, latent heat utilization efficiency, and auxiliary energy consumption.

4. Conclusions

This paper presents a composite PCM-based battery thermal management system designed for a cylindrical lithium-ion battery pack. Using the controlled variable method, the individual effects of key parameters—including discharge rate, battery radial thermal conductivity, PCM thermal conductivity, latent heat, and external air convective heat transfer coefficient—on the thermal management performance were systematically analyzed. The conclusions are as follows:

- (1) The composite PCM can effectively mitigate the temperature rise within the battery pack through three mechanisms: heat conduction, sensible heat storage, and latent heat storage, thereby maintaining the internal temperature and temperature difference within reasonable ranges for discharge rates up to 3 C.
- (2) Under the CPCMs properties and boundary conditions adopted in this study, the single-factor variation results indicate that the maximum temperature of the battery pack decreases as the radial thermal conductivity increases, with the change being particularly pronounced in the low thermal conductivity region of 0.3–1.5 W/(m·K). Judging solely from the single-factor trend, cylindrical batteries with a radial thermal conductivity in the range of 1–1.5 W/(m·K) exhibit better compatibility with the CPCMs prepared in this work. This conclusion provides directional guidance for battery selection rather than representing a globally optimal value.
- (3) During the single-factor analysis, as the PCM latent heat increases, the maximum temperature within the battery pack at the end of discharge decreases, accompanied

by a reduction in the maximum inter-cell temperature difference and improved system temperature uniformity.

- (4) Increasing the external convective heat transfer coefficient results in a slight decrease in the maximum temperature within the pack, but its effect on reducing the system's peak temperature is not significant. Moreover, a higher external convective heat transfer coefficient worsens the temperature uniformity within the system. Based on the principles of maximizing latent heat utilization and reducing energy consumption, the convective heat transfer level should be synergistically optimized to seek the parameter combination that minimizes energy consumption while meeting the constraints on maximum temperature and temperature difference.

In our future work, the following investigations will be carried out:

- (1) A transient model incorporating charge–discharge cycles will be developed to examine the thermal response and solidification rate of the PCM during repeated melting–solidification processes, thereby revealing the temperature accumulation effect under long-term cycling. This will overcome the limitations of the single-discharge analysis and enable a more realistic evaluation of the system's sustained thermal management capability.
- (2) To address the bottleneck posed by the limited latent heat capacity of a single PCM, coupling strategies that combine PCMs with active cooling methods such as heat pipes, liquid cooling, and air cooling will be explored. The PCM will be employed to handle transient high-rate temperature spikes, while active cooling ensures continuous heat extraction and timely PCM re-solidification, thereby extending the applicable operating conditions of the battery system.
- (3) To better reflect real-world application environments, realistic thermal boundary conditions—such as elevated ambient temperatures and mechanical vibration—will be introduced to refine the numerical model. An experimental platform will be established to conduct systematic tests under various ambient temperatures and operating conditions, with the goal of validating and promoting the engineering application of the thermal management system.

Author Contributions: Y.D.: Investigation, Methodology, Writing—original draft, Funding acquisition; W.H.: Investigation, Writing—review and editing; F.Y.: Data curation, Formal analysis; Z.A.: Funding acquisition, Conceptualization, Supervision, Resources. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Guizhou Provincial Major Scientific and Technological Program (XKBF (2025) 031); the Guizhou Science and Technology Innovation Leading Talent Workstation (KXJZ (2025) 024); the Guizhou Provincial Basic Research Program (Natural Science) (MS [2025] 189; ZD [2026] 076); the Wuwei City Major Science and Technology Special Projects (WW25A03ZDQ002); and the Scientific Start-up Project of GuiZhou Institute of Technology (2023GCC019, XJGC20190948).

Data Availability Statement: Data will be made available by the authors upon request due to privacy or ethical restrictions.

Conflicts of Interest: The authors declare that they have no financial and personal relationships with other people or organizations that can inappropriately influence their work; there is no professional or other personal interest of any nature or kind in any product, service and company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

References

- Yu, K.; Liu, Y.; Yang, Y. Review on form-stable inorganic hydrated salt phase change materials: Preparation, characterization and effect on the thermophysical properties. *Appl. Energy* **2021**, *292*, 116845. [\[CrossRef\]](#)
- Lei, S.; Lan, H.; Tao, B.; Zhang, Z.; Wang, H. Anisotropic thermal conductivity quantification in prismatic lithium-ion batteries. *J. Energy Storage* **2026**, *162*, 122112. [\[CrossRef\]](#)
- Lei, S.; Lan, H.; Tao, B.; Zhang, C.; Zhang, X.; Wang, L. Experiments on liquid-immersed thermal runaway management for large energy-stored lithium-ion battery modules. *Therm. Sci. Eng. Prog.* **2025**, *68*, 104347. [\[CrossRef\]](#)
- Qi, W.; Liu, Y.; Wang, X.; Ge, S.; Yu, J.; He, Z.; Tuo, J.; Wang, H.; Zhou, S.; Jin, C.; et al. Performance enhancement of battery thermal management based on liquid cooling plate channels embedded with non-uniform spiral fin structures. *Appl. Therm. Eng.* **2026**, *300*, 131501. [\[CrossRef\]](#)
- Kim, C.; Na, Y. Enhancing power density of PEMFC with narrow distribution zone using parallel serpentine hybrid flow field. *Renew. Energy* **2025**, *241*, 122315. [\[CrossRef\]](#)
- Qi, W.; Yu, L.; Zhao, S.; Guo, Y.; Ge, S.; Zhang, Y.; Cheng, J.; He, Z. Mechanism of PEMFC output performance improvement via non-uniform bluff body structures in bipolar plate flow channels: Flow field regulation and mass transfer enhancement. *Renew. Energy* **2026**, *271*, 126020. [\[CrossRef\]](#)
- Qi, W.; Zhu, M.; Zhao, S.; Gui, F.; Yu, L.; Guo, Y.; Zhou, Z.; Ge, S.; He, Z.; Zhang, Y.; et al. Performance enhancement of proton exchange membrane fuel cells based on semi-parallel and semi-interdigitated mixed flow field. *Int. J. Hydrogen Energy* **2026**, *231*, 154871. [\[CrossRef\]](#)
- Kireeti, S.K.; Teja, P.N.S.; Ramesh, K.N.; Prasad, B.S. A comprehensive review of battery thermal management systems: Cooling technologies, modelling approaches, and future perspectives for energy storage applications. *J. Energy Storage* **2026**, *176*, 123396. [\[CrossRef\]](#)
- Tian, W.; Yang, J.; Zhang, C.; Hong, L.; Zhu, Y.; Mao, Z.; Li, B. Recent advances in thermal management technology of lithium-ion batteries for land-sea-air-space high-end equipment: A comprehensive review. *J. Energy Storage* **2026**, *175*, 123321. [\[CrossRef\]](#)
- Jiang, Z.; Zou, B.; Cong, L.; Xie, C.; Li, C.; Qiao, G.; Zhao, Y.; Nie, B.; Zhang, T.; Ge, Z.; et al. Recent progress and outlook of thermal energy storage technologies. *Energy Storage Sci. Technol.* **2022**, *11*, 2746–2771.
- Zhang, H.; Zhao, C.; Zhang, Z.; Liu, J.; Panchal, S.; Xiaobin, X.; Zhou, F. Review on the thermal management and thermal suppression of high-energy-density lithium-ion batteries based on energy-efficient liquid cooling techniques. *Appl. Therm. Eng.* **2026**, *302*, 131709. [\[CrossRef\]](#)
- Ismail, M.; Panter, J.R.; Landini, S. Numerical investigation of fin geometries on the effectiveness of passive, phase-change material-based thermal management systems for lithium-ion batteries. *Appl. Therm. Eng.* **2025**, *262*, 125216. [\[CrossRef\]](#)
- Amba Prasad Rao, G.; Shravan Kumar, S.R. A review of integrated battery thermal management systems for lithium-ion batteries of electric vehicles. *e-Prime Adv. Electr. Eng. Electron. Energy* **2024**, *8*, 100526–100548. [\[CrossRef\]](#)
- Talebizadehsardari, P.; Hosseinzadeh, K.; Mohammed, H.I.; Maarof, H.A.; Rashid, F.L.; Togun, H.; Biswas, N.; Al Miaari, A.; Ali, H.M.; La Rocca, A.; et al. Phase change materials in thermal management of Li-ion batteries: A state-of-the-art review. *J. Energy Storage* **2026**, *145*, 119782. [\[CrossRef\]](#)
- Ali, A.O.; Abdelrehim, O.; Saafan, M.M.; Elmarghany, M.R.; Hamed, A.M. Comprehensive review of battery management systems for electric vehicles: Thermal management, charging strategies, and emerging technologies. *J. Power Sources* **2025**, *658*, 238269–2387288. [\[CrossRef\]](#)
- Mohammed, A.H.; Esmaeeli, R.; Aliniagerdroudbari, H.; Alhadri, M.; Hashemi, S.R.; Nadkarni, G.; Farhad, S. Dual-purpose cooling plate for thermal management of prismatic lithium-ion batteries during normal operation and thermal runaway. *Appl. Therm. Eng.* **2019**, *160*, 114106. [\[CrossRef\]](#)
- Paneerselvam, P.; Narendranathan, S.K.; Suyamburajan, V.; Murugaiyan, T.; Singh Shekhawat, K.; Rengasamy, G. A review on recent progress in battery thermal management system in electric vehicle application. *Mater. Today Proc.* **2024**. [\[CrossRef\]](#)
- Yang, Y.; Ma, Y.; Lian, P.; Zhang, L.; Chen, Y.; Sheng, X. Advanced engineering of binary eutectic hydrate composite phase change materials with enhanced thermophysical performance for high-efficiency building thermal energy storage. *Sol. Energy Mater. Sol. Cells.* **2025**, *288*, 113631. [\[CrossRef\]](#)
- Es-satte, M.; Afaynou, I.; Faraji, H.; Choukairy, K.; Regragui, I.; Amghar, K.; Boucetta, M.; Saadeddine, S.; Bourich, M. Phase change materials, bionic structures and artificial intelligence for lithium-ion battery thermal management: A comprehensive review. *Int. Commun. Heat Mass Transf.* **2026**, *173*, 110870. [\[CrossRef\]](#)
- Huang, R.; Li, Z.; Hong, W.; Wu, Q.; Yu, X. Experimental and numerical study of PCM thermophysical parameters on lithium-ion battery thermal management. *Energy Rep.* **2020**, *6*, 8–19. [\[CrossRef\]](#)
- Shi, J.; Xu, Y.; Liu, G.; Nie, X.; Lan, Q.; Liu, X. Application of cascaded phase change materials in battery thermal management: Temperature control performance and cycle charge/discharge analysis. *Appl. Therm. Eng.* **2025**, *280*, 128201. [\[CrossRef\]](#)
- Huang, Y.; Zhao, Y.; Xu, W.; Bai, W.; Shen, X.; Wang, J.; Lu, Y.; Wang, Z. Study on the influence of high-rate charge/discharge cycle numbers and spacing on thermal runaway propagation in lithium-ion batteries. *J. Energy Storage* **2025**, *115*, 116005.

23. Ianniciello, L.; Biwolé, P.H.; Achard, P. Electric vehicles batteries thermal management systems employing phase change materials. *J. Power Sources* **2018**, *378*, 383–403. [\[CrossRef\]](#)
24. Lu, M.; Zhang, X.; Ji, J.; Xu, X.; Zhang, Y. Research progress on power battery cooling technology for electric vehicles. *J. Energy Storage* **2020**, *27*, 101155. [\[CrossRef\]](#)
25. Pilali, E.; Soltani, M.; Hatefi, M.; Shafiei, S.; Salimi, M.; Amidpour, M. Passive thermal management systems with phase change material-based methods for lithium-ion batteries: A state-of-the-art review. *J. Power Sources* **2025**, *632*, 236345.
26. Jiang, K.; Liao, G.; E, J.; Zhang, F.; Chen, J.; Leng, E. Thermal management technology of power lithium-ion batteries based on the phase transition of materials: A review. *J. Energy Storage* **2020**, *32*, 101816.
27. Guo, J.; Jiang, F. A novel electric vehicle thermal management system based on cooling and heating of batteries by refrigerant. *Energy Convers. Manag.* **2021**, *237*, 114145. [\[CrossRef\]](#)
28. Maddipatla, S.; Kong, L.; Osterman, M.; Kim, J.; Pecht, M. The Impact of C-Rate, Float Charging and Temperature on Pouch Lithium-Ion Battery Swelling. *Batteries* **2025**, *11*, 419. [\[CrossRef\]](#)
29. Droese, D.; Luc, P.-M.; Otto, M.; Schlösser, A.; Evans, D.; Kowal, J. Evaluation of Commercial Sodium-Ion Batteries by State-of-the-Art Lithium-Ion Battery Configurations. *Batteries* **2025**, *11*, 420. [\[CrossRef\]](#)
30. Schabenberger, T.; Durdal, A.; Kücher, S.; Jossen, A. SOC-Dependent Compression of Lithium-Ion Battery Electrodes. *Batteries* **2025**, *11*, 430. [\[CrossRef\]](#)
31. An, Z.; Huang, Z.; Mombeki Pea, H.J.; Du, X.; Zhang, D.; Fu, J.; Ding, Y. PCM-based thermal management and fire suppression of lithium-ion batteries: A comprehensive review of current technologies and future directions. *Renew. Sustain. Energy Rev.* **2026**, *226*, 116369–116418. [\[CrossRef\]](#)
32. Akkuş, F.; Işık, M.Z. A review of thermal management systems of lithium-ion batteries used in electric vehicles. *J. Traffic Transp. Eng. Engl. Ed.* **2025**, *12*, 1763–1783. [\[CrossRef\]](#)
33. Iskandarani, H.; El Ghossein, N.; Kanaan, H.Y.; Sari, A. Review of Fast Charging Strategies in Lithium-Ion Battery Electric Vehicles. In Proceedings of the 2025 7th International Conference on Renewable Energy for Developing Countries (REDEC), Beirut, Lebanon, 24–26 September 2025.
34. Liu, J.; Zhang, H.; Jin, X.; Zhao, K.; Wang, Z.; Cui, Y. Influence of Low-Temperature Cycling History on Slight Overcharging Cycling of Lithium-Ion Batteries. *Batteries* **2025**, *11*, 427. [\[CrossRef\]](#)
35. Bressan, M.; Campagnoli, E.; Giarretto, V. Experimental Evidence on the Effect of Temperature on the Performance of a Lithium-Ion Battery. *Batteries* **2025**, *11*, 439. [\[CrossRef\]](#)
36. Pal, R.K.; Paw, J.K.S.; Ganesan, P.; Tong, C.W. Modeling and simulation of phase change material-based passive and hybrid thermal management systems for lithium-ion batteries: A comprehensive review. *J. Energy Storage* **2025**, *116*, 116011. [\[CrossRef\]](#)
37. Wang, Q.; Yan, H.; Yang, Y.; Zhao, X.; Huang, H.; Huang, Z.; Zhu, Z.; Liu, S.; Yi, B.; Huang, G.; et al. Review of Fault Detection Approaches for Large-Scale Lithium-Ion Battery Systems: A Spatio-Temporal Perspective. *Batteries* **2025**, *11*, 414. [\[CrossRef\]](#)
38. Tang, W.; Liu, X.; Li, X.; Shen, J.; Liao, Z.; Gong, M. State of Health Estimation for Energy Storage Batteries Based on Multi-Condition Feature Extraction. *Batteries* **2026**, *12*, 34. [\[CrossRef\]](#)
39. Wang, Y.; Wang, Z.; Min, H.; Li, H.; Li, Q. Performance investigation of a passive battery thermal management system applied with phase change material. *J. Energy Storage* **2021**, *35*, 102279. [\[CrossRef\]](#)
40. Lin, S.; Zhou, L. Research on the performance failure of phase change materials thermal management for lithium battery. *Appl. Therm. Eng.* **2024**, *244*, 122743. [\[CrossRef\]](#)
41. Zhang, B.; Zeng, Z.; Yuan, N.; Shi, H. Numerical investigation of lithium-ion battery thermal management system performance influenced by physical properties of PCM. *J. Energy Storage* **2025**, *117*, 116141. [\[CrossRef\]](#)
42. Jilte, R.; Afzal, A.; Panchal, S. A novel battery thermal management system using nano-enhanced phase change materials. *Energy* **2021**, *219*, 119564. [\[CrossRef\]](#)
43. Rajabi, R.; Sun, S.; Wu, B.; Khan, J.; Huang, K. Towards Sustainable Energy Storage: Evaluating the Performance of Three Polymer Electrolytes for Zinc-Ion Batteries. *Batteries* **2026**, *12*, 93. [\[CrossRef\]](#)
44. Lyu, Y.; Siddique, A.R.M.; Majid, S.H.; Biglarbegian, M.; Gadsden, S.A.; Mahmud, S. Electric vehicle battery thermal management system with thermoelectric cooling. *Energy Rep.* **2019**, *5*, 822–827. [\[CrossRef\]](#)
45. Mali, V.; Saxena, R.; Kumar, K.; Kalam, A.; Tripathi, B. Review on battery thermal management systems for energy-efficient electric vehicles. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111611. [\[CrossRef\]](#)
46. Zhou, D.; Luo, Y.; Bi, C.; Li, X.; Deng, J.; Yang, W.; Li, C. Experimental and simulative investigation on battery thermal management system with structural optimization of composite phase change material. *J. Energy Storage* **2023**, *60*, 106613. [\[CrossRef\]](#)
47. Aliya, A.; Gong, Y.; Chen, Y.; Wei, R.; Chen, M. Advanced polyethylene glycol based flexible composite phase change materials enabling stable and efficient lithium-ion battery thermal safety management. *Appl. Therm. Eng.* **2026**, *290*, 130112. [\[CrossRef\]](#)
48. Zhang, X.; Zhang, H.; Almansour, A.; Singh, M.; Kiser, J.D.; Zhu, H.; Halbig, M.C.; Zheng, Y. A Comprehensive Analysis of Thermal Heat Dissipation for Lithium-Ion Battery Packs. *Energies* **2025**, *18*, 2234. [\[CrossRef\]](#)

49. Qi, Z.; Yang, B.; Lei, J. Numerical study on the thermal management performance of square lithium-ion batteries with symmetric double-spiral liquid cooling coupled with composite phase change material. *J. Energy Storage* **2026**, *153*, 120835. [[CrossRef](#)]
50. Zhang, X.; Halbig, M.C.; Singh, M.; Almansour, A.; Zheng, Y. Thermal management of composite phase change material capsule-based lithium-ion battery packs under forced convection. *Appl. Therm. Eng.* **2026**, *297*, 130909. [[CrossRef](#)]
51. Qiu, H.; Zhang, Z.; Ling, Z.; Fang, X. Developing a flame-retardant flexible composite phase change material to realize both temperature control and thermal runaway prevention for lithium-ion battery pack. *Appl. Therm. Eng.* **2024**, *248*, 123301. [[CrossRef](#)]
52. Lai, Y.X. Numerical Study and Lightweight Design of Liquid-Cooled Thermal Management Module for Cylindrical Power Batteries. Master's Thesis, South China University of Technology, Guangzhou, China, 2019. [[CrossRef](#)]
53. Zhang, J. *Numerical Simulation Research on Heat Dissipation of Energy Storage Lithium Battery Pack Based on Air Cooling and PCM*; Nanchang University: Nanchang, China, 2023; pp. 26–28. [[CrossRef](#)]

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