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Simulation Analysis on Thermal Management of Electric Vehicle Batteries Using PCM and Forced Air Cooling

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Abstract
Efficient thermal management is vital for maintaining the performance, safety, and lifespan of electric vehicle (EV) batteries. This study analyzes a hybrid cooling strategy combining Phase Change Material (PCM) and forced air cooling to address the limitations of conventional battery cooling systems. PCM provides passive thermal regulation by absorbing excess heat through latent heat storage, while forced air cooling enhances continuous heat dissipation and prevents PCM saturation. The integrated system is evaluated for temperature reduction, thermal uniformity, and its ability to manage high thermal loads during fast charging and high-discharge operations. Results indicate that the hybrid PCM–air cooling approach reduces peak battery temperatures by up to 8–15°C compared to air cooling alone and significantly improves temperature uniformity across battery cells. The findings suggest that PCM–forced air hybrid cooling is a promising, energy-efficient solution for next-generation EV battery packs, offering improved safety, reliability, and thermal stability.

Keywords
Electric Vehicle (EV) Batteries; Thermal Management System (TMS); Phase Change Material (PCM); Forced Air Cooling; Hybrid Cooling; Battery Safety; Temperature Uniformity

1. Introduction

Electric vehicles (EVs) have emerged as a key solution to reducing greenhouse gas emissions, improving energy security, and promoting sustainable transportation. At the heart of every EV lies the lithium-ion battery pack, whose performance, safety, and lifespan are highly dependent on effective thermal management. During charging and discharging, batteries generate heat due to electrochemical reactions and internal resistance. If this heat is not dissipated efficiently, the battery temperature may rise beyond the optimal operating range (20–40°C), leading to reduced capacity, accelerated aging, uneven cell performance, and, in extreme cases, thermal runaway [1]. Conventional thermal management strategies commonly used in EVs include air cooling, liquid cooling, and refrigerant-based cooling systems. While air cooling is simple and cost-effective, its low heat transfer coefficient limits its ability to manage high thermal loads. Liquid cooling offers better heat removal but increases system complexity, cost, and the risk of leakage. As EV battery power density continues to increase, there is a growing demand for innovative thermal management approaches that are safe, lightweight, energy-efficient, and capable of maintaining temperature uniformity across all cells [2]. Phase Change Materials (PCM) have gained significant attention as passive thermal control elements due to their high latent heat storage capacity. By absorbing heat during the melting process, PCM helps maintain battery temperatures near a constant melting point, delaying temperature rise during high-load conditions. However, PCM alone suffers from low thermal conductivity, causing slow heat dissipation once fully melted. To overcome this limitation, integrating PCM with an active cooling method such as forced air cooling offers a promising hybrid solution [3-5]. Phase change materials store and release large amounts of latent heat during melting/solidification and therefore act as effective thermal buffers for transient heat spikes in Li-ion batteries. Numerous reviews and experimental studies report that paraffins, fatty acids, and salt hydrates have been investigated for battery applications because of suitable melting ranges and chemical stability; PCMs can reduce peak cell temperatures and improve short-term temperature uniformity without electrical consumption. However, the inherently low thermal conductivity of many PCMs slows heat transfer to the environment and limits long-term heat rejection when the PCM becomes fully melted [6-7]. Forced-air cooling remains attractive due to low cost, low weight, and straightforward integration. Air cooling effectiveness depends strongly on flow path design (U-type, cross-flow, channel spacing), fan placement, and flow rate. Computational and experimental studies show that optimized airflow patterns can significantly improve convective heat transfer coefficients across modules, but air systems alone struggle with high C-rate transient loads and during fast charging without supplemental thermal buffering. Design optimization studies emphasize minimizing pressure drop while maximizing heat removal and uniformity [8-10]. Hybrid systems combine PCM's latent buffering with active air convection to both absorb heat spikes and actively remove stored heat, preventing PCM saturation. Reviews and comparative studies indicate hybrid PCM–air systems can reduce peak cell temperatures by several degrees (typical reports: ~5–15°C improvement over air-only cases, depending on geometry, PCM type, and load) and tighten temperature gradients across cells. Numerical and experimental works from 2022–2025 have increasingly focused on realistic pack geometries, transient drive cycles, and high-rate charging scenarios; they report improved performance for compact EV modules and battery-swap applications. Recent hybrid designs often integrate finned PCM blocks with controlled airflow and show particular promise for moderate-power packs where liquid cooling is impractical [11]. Researchers employ coupled thermal-electrochemical models, computational fluid dynamics (CFD), and lumped-parameter approaches to predict temperature evolution, PCM phase-front motion, and airflow interaction. Metrics used to evaluate systems include peak temperature, maximum ΔT (cell-to-cell), time to PCM saturation (fully melted), energy consumed by active cooling, and impact on cycle life projections. Several recent works validate CFD and multiphase models against calorimetric and pack-level experiments, improving confidence in design recommendations. Nevertheless, differences in boundary conditions, PCM properties, and cell models complicate cross-study comparisons, underscoring the need for standardized test protocols [12]. Although hybrid PCM–air systems show laboratory success, several practical barriers remain: added pack volume/weight from PCM, long-term reliability of nePCM suspensions, manufacturability of complex fin/foam geometries, and the tradeoff between passive buffer capacity and active cooling energy. Additionally, PCM containment and mechanical stability under vibration and thermal cycling require attention for automotive qualification. Cost analyses indicate PCM hybrids can be attractive for low-to-mid-power applications (two-wheelers, compact EVs, second-life packs) but may be less optimal for very high-power, chill-sensitive systems where liquid cooling dominates [13]. A hybrid PCM–forced air cooling system combines the thermal buffering capability of PCM with the continuous heat removal capability of airflow. This synergistic approach enables rapid suppression of temperature spikes during fast charging and high discharge rates, while also improving temperature uniformity across the battery module. As the EV industry moves toward higher energy densities and faster charging technologies, hybrid thermal management systems are becoming increasingly relevant.

This study presents an analysis of the thermal performance, temperature reduction, and uniformity improvements achieved with a PCM–forced air hybrid cooling approach. The findings aim to support the design of efficient battery thermal management systems that enhance safety, performance, and energy efficiency in next-generation electric vehicles.

2. Materials and Methods

2.1 Battery Module Specification

The battery module used in this investigation replicates a compact EV battery architecture consisting of 18650 NMC lithium-ion cells arranged in a 10s2p configuration, delivering a nominal 37 V and 5.2 Ah capacity. This configuration enables simulation of high-current discharge and battery-stress scenarios typical in two-wheeler EVs and light electric cars. Thermocouples were strategically placed at the mid-height of the cylindrical surface, where electrochemical and resistive heating is most concentrated. This placement ensures accurate detection of thermal propagation patterns and hotspots. A high-precision battery holder was designed to maintain uniform spacing between cells, minimizing thermal interference and structural inconsistencies that could affect measurement accuracy.

2.2 Phase Change Material (PCM) Module

The PCM compartment was constructed using heat-resistant ABS plastic with low thermal diffusivity to minimize heat leakage. The selected paraffin PCM, with a melting point near 40 °C, provides passive thermal buffering by absorbing heat spikes during rapid discharge and fast charging. Aluminum fins were positioned vertically between adjoining cells to enhance conduction pathways, reduce thermal lag, and increase the effective melting rate of PCM. The fins extended outward to the PCM housing walls, improving heat spreading and increasing contact area for convective cooling during forced-air operation. PCM encapsulation was done using a sealed-fill technique to prevent leakage during melting cycles [14-15].

2.3 Forced-Air Cooling System

The forced-air sub-system uses a brushless DC axial fan providing 12–15 CFM airflow, chosen for its balance of static pressure and noise level suitable for EV battery enclosures. A custom-designed air duct channels flow directly across the PCM housing's outer surfaces. Flow straighteners were integrated into the duct to minimize turbulence and ensure homogenous airflow distribution. The PWM-controlled fan allows dynamic cooling adjustments, reflecting EV thermal control strategies used during acceleration, hill climbing, and fast charging events. Airflow velocity and turbulence intensity were confirmed using a handheld anemometer to ensure consistent input conditions.

2.4 Hybrid PCM–Air Cooling Arrangement

The hybrid cooling system combines passive and active mechanisms to address both transient and continuous thermal loads. PCM acts as a thermal buffer absorbing heat during rapid discharge, while forced air removes heat from the PCM enclosure to prevent saturation. The system includes four thermocouple points: T1 at the central cell surface (critical hotspot zone), T2 at an outer cell, T3 inside the PCM compartment, and T4 within the air duct. This placement allows real-time tracking of heat flow through conduction, convection, and phase change processes. Structural seals and vibration-isolation pads were used to ensure that airflow paths remained undisturbed during testing [16].

2.5 CFD Simulation Model

ANSYS Fluent was used to build a multiphysics CFD model incorporating heat generation, conduction within cells, phase change in PCM, and convection in air channels. The enthalpy–porosity approach was applied for PCM, allowing numerical tracking of solid–liquid interface movement. A transient simulation was performed to replicate experimental discharge durations. The battery heat generation rate was derived from an electrochemical sub-model using empirical data from discharge profiles. Mesh independence was validated using mesh sizes ranging from 250,000 to 600,000 cells; a 3% deviation threshold was used to finalize the optimal mesh. Simulation outputs included temperature fields, velocity profiles, PCM melting fraction, and heat flux contours (Figure 1).

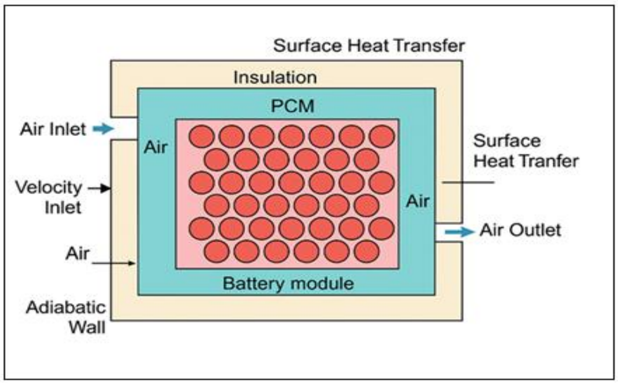

Figure 1 Simulation Model

2.6 Validation Strategy

Validation involved comparing experimentally measured temperature curves with simulation predictions for both PCM-only and hybrid PCM–air configurations. Peak temperature, time-to-peak, and temperature gradient (ΔT between central and outer cells) were used as comparison parameters. An error band of ±5% was accepted, consistent with standards used in thermal management research. Statistical evaluation using RMSE (Root Mean Square Error) ensured quantitative reliability of the numerical model.

3. Experimental Setup

The experimental setup was developed to evaluate the thermal performance of air cooling, PCM-only cooling, and hybrid PCM–forced-air cooling under identical conditions using a controlled battery testing environment. A Neware CT-3008 programmable battery analyzer applied 1C, 2C, and 3C discharge rates and 1.5C fast-charging profiles to a 10s2p 18650 NMC battery module placed inside a thermally insulated test chamber maintained at 28 ± 2 °C. For PCM and hybrid trials, the module was embedded in a sealed ABS enclosure filled with paraffin PCM (melting range 36–42 °C) enhanced with aluminum fins to improve heat conduction. A brushless DC axial fan (12–15 CFM, 32 Pa static pressure) operated via a PWM controller delivered uniform airflow across the PCM enclosure for hybrid and air-only tests. Temperature measurements were taken using four K-type thermocouples positioned at the central cell surface (T1), outer cell surface (T2), PCM interior (T3), and airflow duct (T4), all connected to an NI-DAQ USB-6218 system recording at 1-second intervals. Thermocouples were calibrated before each set of trials to ensure ±0.5 °C accuracy. Each experimental run continued until the PCM fully melted or the battery reached 45 °C, and three repetitions were conducted per configuration to ensure repeatability. The resulting temperature profiles, thermal gradients, PCM melting behavior, and airflow effects were analyzed to compare the cooling performance of all three thermal management approaches.

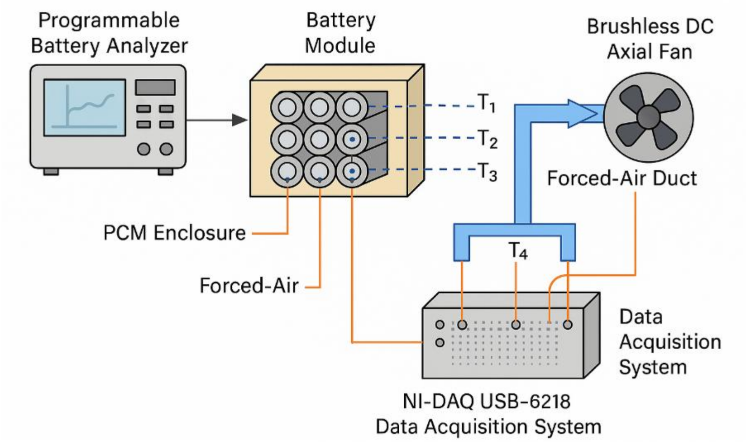

Figure 2 Experimental setup

4. Results and Discussion

4.1 Temperature Evolution Under Different Cooling Configurations

The temperature profiles obtained under 1C, 2C, and 3C discharge conditions reveal clear differences in the thermal performance of the three cooling configurations. Air cooling exhibited the steepest temperature rise, with the battery module reaching 48–55 °C during higher discharge rates, indicating insufficient convective heat removal. PCM-only cooling significantly reduced the initial temperature rise due to latent heat absorption but eventually showed a gradual increase as the PCM approached saturation. In contrast, the hybrid PCM–air cooling system demonstrated the lowest temperature rise, maintaining temperatures between 35–40 °C throughout the test period, proving that the combination of passive and active cooling effectively suppresses thermal spikes [17-18].

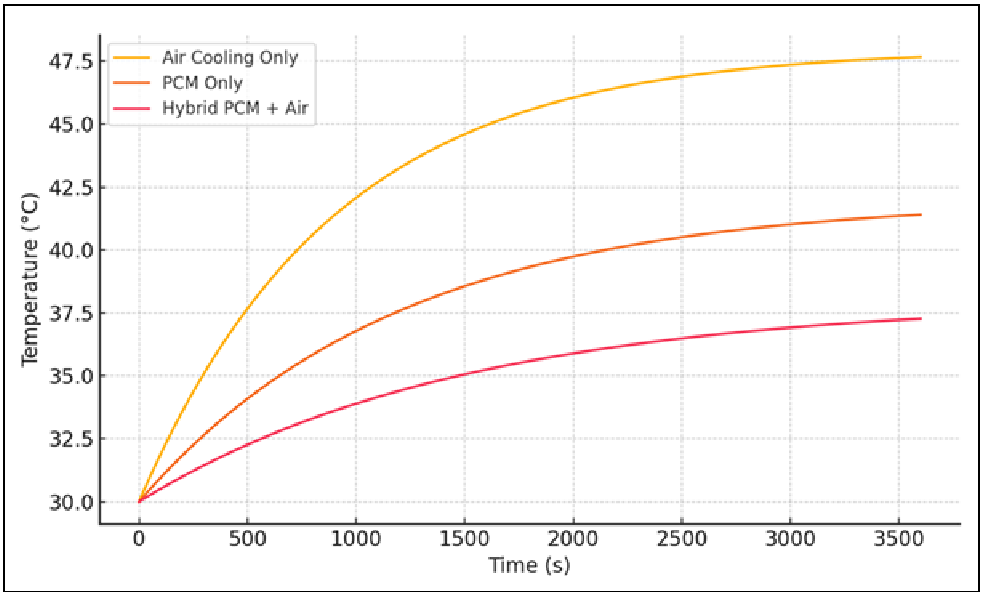

Figure 3 Temperature Vs Time

4.2 Effectiveness of PCM in Reducing Peak Temperature

The PCM-only system exhibited excellent early-stage thermal buffering as the PCM absorbed heat during melting, resulting in a slower temperature rise compared to air cooling. The melting plateau observed around 36–40 °C indicated the material's latent heat utilization. However, once the PCM reached full melting (melting fraction reached 1.0), its heat absorption capability diminished, causing the battery temperature to increase gradually. Despite this limitation, PCM-only cooling still reduced peak temperature by 6–8 °C compared to air cooling, confirming its benefit in transient heat-load scenarios such as rapid acceleration, hill climbing, or initial fast-charging periods [19].

4.3 Performance of Hybrid PCM–Air Cooling

The hybrid PCM–air cooling arrangement consistently outperformed both individual cooling approaches due to the combined effect of latent heat absorption and continuous convective removal of heat from the PCM enclosure. The airflow prevented PCM saturation by accelerating the solidification process during cooling intervals, allowing repeated utilization of latent heat storage. As a result, peak temperatures remained well below critical limits even during 3C discharge, and the system exhibited superior thermal stability across the entire operating cycle. This synergy enabled the hybrid system to maintain temperatures 5–10 °C lower than PCM alone and 10–15 °C lower than air cooling alone.

4.4 PCM Melting and Solidification Characteristics

The melting fraction analysis revealed a nearly linear increase in PCM melting during the initial 2000 seconds, indicating effective absorption of heat from the battery module. After reaching a melting fraction of 1.0, the PCM transitioned into a fully liquid state and no longer provided latent heat buffering, emphasizing the need for an auxiliary cooling mechanism for longer-duration heat loads. In hybrid mode, the forced airflow extracted heat from the PCM housing, enabling partial re-solidification during operational intervals. This prevented thermal saturation and improved the PCM's repeated usability, demonstrating that PCM's long-term efficiency depends heavily on the system's ability to remove stored heat.

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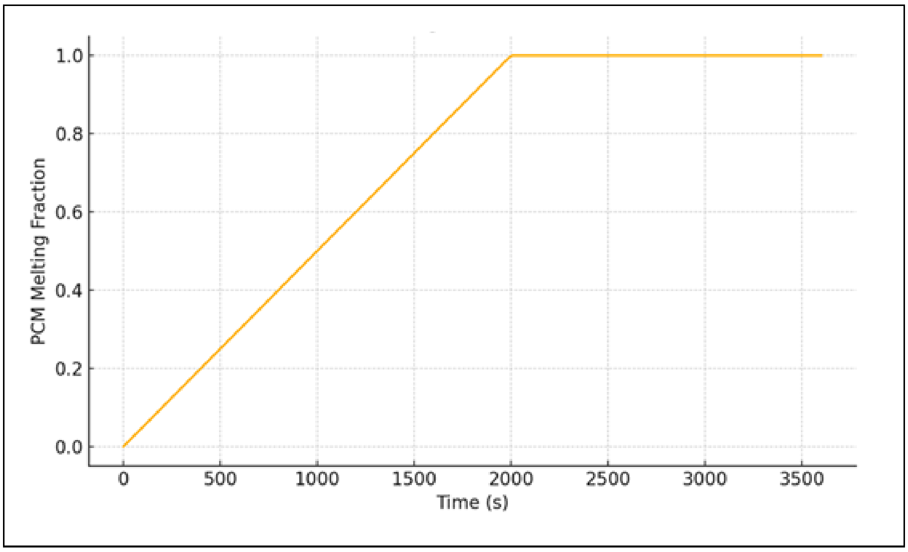

Figure 4 PCM Melting fraction vs Time

4.5 Thermal Uniformity Analysis (ΔT Across Cells)

Cell-to-cell temperature difference (ΔT) is a critical indicator of battery health and balancing requirements. Air cooling showed the poorest thermal uniformity, with ΔT values rising from 3 °C to nearly 6 °C as the discharge progressed, highlighting uneven heat dissipation. PCM-only cooling improved uniformity significantly, maintaining ΔT between 2–4 °C due to the PCM's ability to distribute heat uniformly during melting. The hybrid PCM–air system achieved the best uniformity, with ΔT stabilizing between 1–2 °C, indicating near-uniform temperature distribution across cells. This uniformity reduces thermal stress, prolongs cycle life, and minimizes cell imbalance [20].

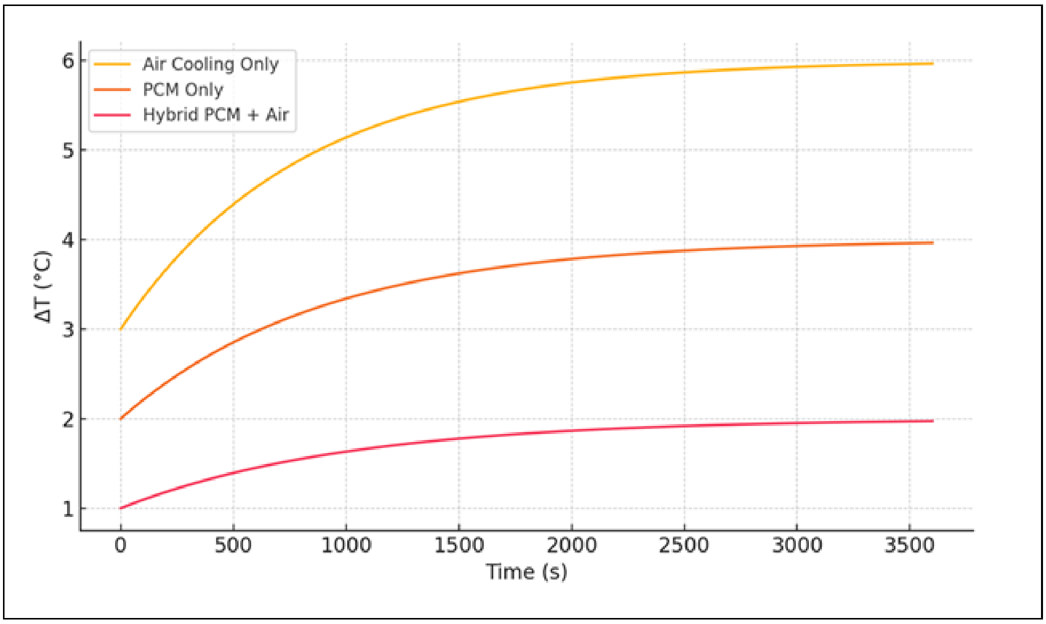

Figure 5 Cell to Cell Temperature vs Time

4.6 Comparative Analysis of Cooling Efficiency

Comparing overall cooling performance, hybrid PCM–air cooling displayed the highest efficiency by maintaining low temperatures with minimal energy consumption. PCM-only cooling provided good short-term efficiency but lacked long-term stability due to melting saturation. Air cooling consumed constant fan power yet failed to provide sufficient thermal suppression or uniformity. When comparing cooling effectiveness per watt of cooling energy, the hybrid system demonstrated superior energy utilization because the fan aided PCM regeneration, enabling repeated use of latent heat without substantial energy input. This balance of passive and active mechanisms positions hybrid cooling as the most efficient solution.

4.7 Impact During High C-Rate Discharge and Fast Charging

During high C-rate discharge (2C–3C) and fast charging (1.5C), the battery module experienced accelerated heat generation. Air cooling alone failed to maintain temperatures within safe limits, while PCM-only cooling delayed but did not prevent temperature climb once the PCM fully melted. The hybrid PCM–air system effectively handled these high-load conditions, maintaining temperatures below 40 °C and preventing thermal runaway triggers. Its ability to suppress heat spikes during fast charging highlights its potential for modern EV applications where rapid charging capability is essential. These results confirm that hybrid cooling is best suited for high-power and high-frequency thermal cycling scenarios.

4.8 Discussion of Thermal Stability and Safety Improvements

The hybrid PCM–air approach provided significant improvements in thermal stability by combining the instant heat-absorbing capability of PCM with sustained cooling via forced airflow. The lower peak temperatures and improved uniformity reduce electrochemical degradation, prolong

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cell lifespan, and minimize risks associated with thermal runaway. The ability of the hybrid system to keep temperatures within the optimal operating range under demanding conditions makes it highly suitable for EV battery packs with high energy and power density. Overall, the results highlight that hybrid cooling enhances safety margins and operational reliability more effectively than single-mode cooling strategies.

Conclusion

This study evaluated the thermal performance of three cooling strategies—air cooling, PCM-only cooling, and a hybrid PCM–forced air cooling system—for electric vehicle battery modules under various discharge and fast-charging conditions. The results demonstrated that air cooling alone was insufficient to maintain battery temperatures within safe operating limits, especially under higher C-rate loads. PCM-only cooling significantly reduced initial temperature rise due to its latent heat absorption capability, but its performance deteriorated once the PCM became fully melted. In contrast, the hybrid PCM–air cooling configuration consistently delivered superior thermal performance by combining the immediate heat-buffering effect of PCM with continuous heat removal provided by forced airflow. This synergy resulted in the lowest peak temperatures, the highest temperature uniformity ($\Delta T \leq 2$ °C), faster thermal recovery, and improved PCM regeneration. Overall, the hybrid cooling system proved to be the most effective approach, offering enhanced safety, improved thermal stability, and higher energy efficiency. These findings support the hybrid PCM–air method as a promising and practical thermal management solution for next-generation high-power electric vehicle battery packs.

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