Design and Optimization of a Thermal Management System for High-Performance Electric Vehicle Batteries Using Phase Change Materials

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Abstract

Effective thermal management is critical for ensuring the safety, performance, and longevity of high-performance electric vehicle (EV) batteries. This study presents the design, simulation, optimization, and experimental validation of a phase change material (PCM)-based thermal management system (TMS) for lithium-ion battery modules. Various PCM candidates, including composite materials enhanced with thermally conductive additives, are evaluated to improve heat dissipation and mitigate localized hotspots. A three-dimensional thermal model of the battery pack is developed using computational tools, incorporating heat generation, conduction, convection, and phase change phenomena. Multi-objective optimization is applied to determine optimal PCM thickness, melting temperature, and thermal conductivity to achieve uniform temperature distribution and minimize thermal stress. A small-scale prototype of the optimized system is fabricated and tested under controlled charge-discharge cycles. Experimental results validate the simulation findings, demonstrating that the PCM-based TMS effectively reduces peak temperatures, improves thermal uniformity, and enhances overall battery performance. The proposed methodology provides a practical approach for integrating advanced thermal management solutions in EV battery systems.

Keywords

Lithium-ion battery, electric vehicles, thermal management system, phase change material.

1. Introduction

Project Electric vehicle (EV) technology has evolved rapidly over the past decade due to the global demand for sustainable transportation and reduced carbon emissions. Among all EV components, the lithium-ion battery pack is the most critical element, directly influencing the vehicle's driving range, safety, and reliability. However, lithium-ion batteries are highly temperature-sensitive; excessive heat generation during charging and discharging can degrade performance, shorten lifespan, and even cause thermal runaway [1][2]. Maintaining the battery temperature within the optimal range (25–45 °C) is therefore essential to ensure stable electrochemical behavior and long-term durability [3].

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A reliable battery thermal management system (BTMS) is indispensable for addressing this challenge. Traditional cooling methods, including air and liquid cooling, have limitations in terms of efficiency, system complexity, and energy consumption [4][5]. Consequently, passive cooling techniques using phase change materials (PCMs) have attracted significant attention for their ability to absorb and store heat through latent heat transfer without external energy input [6][7]. PCMs can stabilize battery temperature fluctuations, improve safety, and enhance energy efficiency, making them a promising solution for next-generation EVs [8]. The working principle and typical components of a PCM-based BTMS are illustrated in Figure 1 [5].

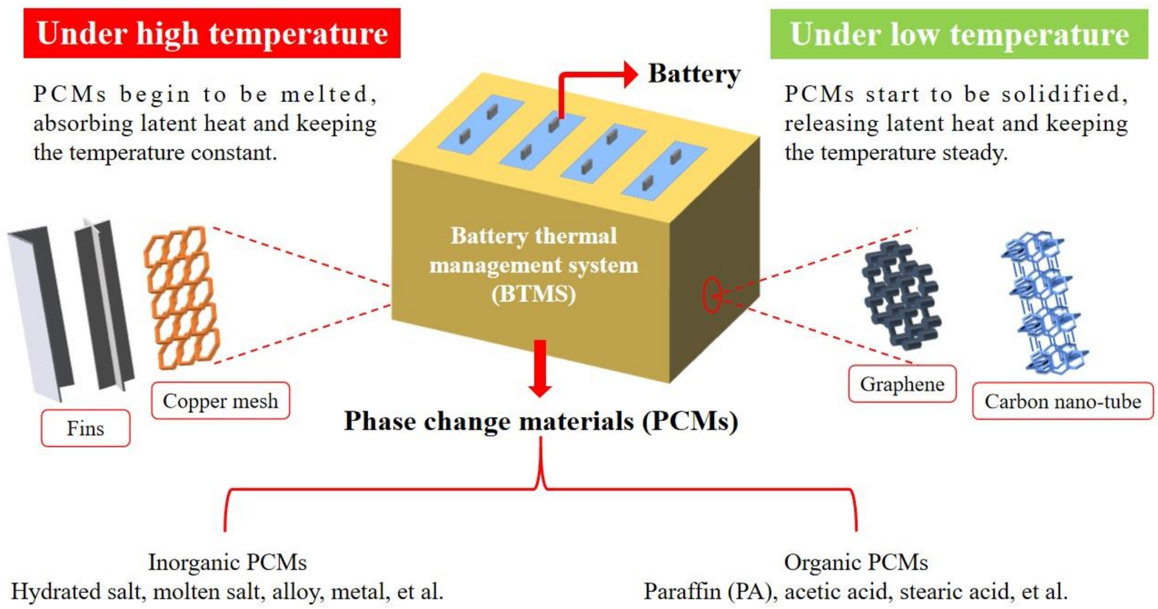

Fig.1. Schematic illustration of a Battery Thermal Management System (BTMS) utilizing Phase Change Materials (PCMs), showing the latent heat transfer mechanism under high and low temperatures, as well as examples of pure and composite PCM materials [5].

Despite these advantages, PCMs suffer from low thermal conductivity and potential leakage, which reduce their effectiveness under high heat loads. To overcome these drawbacks, researchers have developed composite PCMs by integrating thermally conductive additives such as graphite, metal foams, and nanoparticles [9][10][11]. Such composites improve heat spreading and accelerate phase change processes. Numerical and experimental studies have also demonstrated that PCM-based BTMS can reduce temperature rise by 20–30% and significantly improve temperature uniformity within the battery pack [12][13][14]. Recent hybrid systems, which combine PCMs with fins, heat pipes, or liquid cooling, have further improved transient performance and broadened operating stability under various ambient conditions [15][16][17][18][19][20]. Objectives of the Study are given below:

Design, simulate, and optimize a PCM-based thermal management system for high-performance electric vehicle battery modules. Specific goals include:

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Material Evaluation: To identify and compare suitable PCM and composite PCM materials based on their melting temperature, latent heat, and thermal conductivity for EV applications.

Numerical Modeling: To develop a three-dimensional computational model using ANSYS Fluent or COMSOL Multiphysics to analyze transient heat transfer, phase change, and temperature distribution under realistic load conditions.

Optimization: To conduct a parametric optimization study focusing on PCM layer thickness, melting point, and composite conductivity to achieve minimal temperature variation and maximum thermal uniformity.

Experimental Validation: To fabricate a prototype of the optimized system and validate simulation results through experimental testing under controlled charge–discharge cycles.

This study will advance the understanding of PCM integration in EV batteries and provides practical insights for developing energy-efficient, lightweight, and cost-effective battery thermal management system (BTMS) solutions for future electric mobility systems. Furthermore, it highlights the potential of multi-objective optimization and experimental validation in bridging the gap between simulation and real-world performance, offering guidelines for scalable, safe, and high-performance battery pack designs in next-generation electric vehicles. The findings also provide a framework for selecting and engineering composite PCMs with tailored thermal properties, addressing challenges such as hotspot mitigation, long-term durability, and system compactness. Additionally, this research supports the development of hybrid cooling strategies that combine passive and active methods for enhanced reliability under varying operating conditions. Ultimately, the study contributes to the advancement of sustainable and high-performance EV technologies by integrating material science, thermal engineering, and system-level optimization.

2. Background

2.1 Importance of Battery Thermal Management

The operating temperature of lithium-ion battery packs significantly influences their electrochemical performance, internal resistance, aging rate, and safety. Deviations from the optimal operating range (typically ~25–45 °C) accelerate performance degradation, promote faster capacity fading, and increase the risk of thermal runaway [13][14]. Effective temperature control is therefore critical to ensuring battery longevity and reliability.

As electric vehicles (EVs) evolve toward higher power densities and faster charge/discharge cycles, each cell generates more heat. Without proper thermal management, localized hotspots and uneven temperature distribution can severely impact performance and safety [15][16]. Maintaining uniform thermal conditions is thus essential for high-performance battery packs.

The choice of a battery thermal management system (BTMS) is a primary design consideration in EV battery engineering. It directly affects the pack's weight, volume, cost, energy efficiency, and overall lifespan [17][18]. Selecting an optimal BTMS requires balancing these factors while meeting

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operational and safety requirements. Recent studies emphasize that combining passive and active cooling techniques can mitigate temperature gradients more effectively than single-method approaches. Advanced control strategies, including real-time monitoring and adaptive cooling, further enhance thermal uniformity and system reliability. Material innovations, such as high-conductivity composites and phase-change materials, enable better transient heat absorption without excessive weight penalties. Ultimately, integrating these strategies ensures safer, more efficient, and longer-lasting EV battery systems, supporting the growing demands of modern electric mobility.

2.2 Classification of Thermal Management Strategies

Battery thermal management systems can be broadly classified into passive and active cooling strategies. Recent reviews categorize them into air cooling, liquid cooling, phase-change material (PCM) systems, heat-pipe/immersion approaches, and hybrid configurations [19][20][21]. PCM-based systems provide effective transient temperature control without active cooling; however, steady-state heat dissipation is limited unless supplemented with secondary systems [8]. Hybrid systems, such as PCM combined with liquid cooling or heat pipes, leverage the latent heat absorption for transients while maintaining continuous active convection [22][23]. As detailed in Table 1, each thermal management approach exhibits distinct advantages and limitations, providing critical insights for selecting or integrating strategies to achieve optimal thermal regulation in high-performance EV battery packs. Understanding these trade-offs is essential for tailoring cooling solutions to specific battery architectures and operational requirements. Moreover, such a comparative analysis informs the design of hybrid systems that can leverage the complementary strengths of multiple methods to enhance thermal uniformity, safety, and overall pack efficiency.

Furthermore, integrating sensors and real-time thermal monitoring enables adaptive control, enhancing battery longevity and performance. Advances in materials, such as high-conductivity PCMs or nanofluids, further improve heat transfer efficiency. Lifecycle and cost considerations also influence the choice of thermal management strategies, especially for large-scale EV deployments. Overall, a systematic evaluation of passive, active, and hybrid solutions is crucial for developing robust, safe, and energy-efficient battery systems.

In addition, the integration of the Internet of Things (IoT) in battery thermal management allows for predictive maintenance and intelligent energy management. IoT-enabled BTMS can collect real-time data on temperature gradients, state-of-charge (SOC), and load conditions, feeding machine learning algorithms to optimize cooling dynamically. Such systems can anticipate thermal runaway scenarios and adjust cooling strategies proactively, enhancing safety. Furthermore, the combination of IoT with cloud-based analytics facilitates fleet-level monitoring for electric vehicles, allowing operators to identify underperforming packs and schedule maintenance efficiently. Advanced control algorithms can also balance energy consumption between cooling and propulsion, improving overall EV range. Moreover, compact and modular designs are becoming essential to integrate BTMS in space-constrained battery packs without compromising performance. Emerging materials, like graphene-enhanced PCMs or microchannel liquid coolers, are being explored to further improve heat transfer rates. Standardization of sensors, communication protocols, and thermal models will be key to ensuring interoperability across different EV platforms. Finally, cost-benefit analyses are increasingly incorporating IoT-enabled BTMS, weighing upfront investment against long-term efficiency, safety, and lifecycle benefits. Overall, combining hybrid thermal strategies with IoT-based intelligent control represents a promising direction for next-generation EV battery management.

Table 1. Comparison of Battery Thermal Management Strategies

Cooling Strategy	**Principle / Medium**	**Advantages**	**Limitations**
Air cooling	Natural or forced convection over pack surfaces	Simple design, low cost	Limited heat transfer, large temperature gradients [19][22]
Liquid cooling	Coolant flow (water/glycol) around cells/plates	High heat removal, good uniformity	System complexity, additional power draw, pump/valve costs [16][23]
PCM	Absorbs latent heat during phase change	Passive, no moving parts, buffers temperature spikes	Low thermal conductivity, added mass/volume [24][25]
Heat pipe / immersion	Direct heat transport or immersion in dielectric liquids	Excellent cooling under extreme conditions	High cost, complex packaging, reliability concerns [20][26]
Hybrid systems	Combination of multiple methods	Improved performance across varying conditions	Integration complexity, higher cost, tuning challenges [21][27]

2.3 Phase Change Materials (PCMs) for Battery Cooling

Phase-change materials (PCMs) absorb or release large amounts of latent heat when undergoing a phase transition, typically solid-to-liquid near a designated melting point. This property makes them ideal for mitigating rapid heat spikes in battery systems [24][29].

For EV applications, suitable PCMs generally melt within the 20–60 °C range, aligning with safe battery operating temperatures [18][24]. Examples include paraffin waxes, inorganic salt hydrates, and eutectic mixtures.

However, conventional PCMs face limitations such as low thermal conductivity, volumetric expansion, leakage during melting, and mechanical instability under repeated cycles. These challenges hinder their real-world applicability [18][25][30]. To overcome these issues, composite PCMs embed thermally conductive additives (e.g., graphite, graphene, metal foams, or nanoparticles) or use shape-stabilized structures. For instance, copper-foam–based PCM composites have shown enhanced conductivity and thermal response in simulation studies [31].

Safety considerations are also critical: many organic PCMs are flammable, so flame-retardant modifications are often required in battery applications [32].

2.4 Recent Developments and Integration Strategies

Recent developments in PCM integration have moved beyond simply placing PCM between cells. Current strategies embed PCM with structural heat spreaders, fins, or coolant plates to achieve uniform temperature distribution and reduce peak cell temperatures. For example, a paraffin–graphite composite within a battery pack significantly reduced maximum cell temperature while improving uniformity compared to pure PCM [27][29].

Hybrid designs combining PCM with active cooling (e.g., microchannel liquid plates) are gaining attention for their superior performance under moderate power consumption [9]. Advanced modeling tools such as computational fluid dynamics (CFD), phase-change modeling, and parametric optimization enable fine-tuning of PCM melting point, thickness, thermal conductivity, and integration geometry for specific battery modules [22][30].

Despite these advances, practical deployment in EVs faces challenges including scalability to large battery modules, long-term durability under repeated cycles, packaging constraints, weight trade-offs, and cost-effective manufacturing [18][31][32].

2.5 Motivation for This Study

While numerous studies have demonstrated the thermal benefits of PCMs or PCM-hybrid systems, gaps remain in systematically optimizing material properties and geometry for high-performance EV battery packs. Experimental validation under realistic charge–discharge cycles is often lacking.

There is a particular need for investigations focusing on composite PCMs with enhanced thermal conductivity, compact pack integration, and multi-objective optimization of parameters such as melting point, thickness, and conductivity. Experimental verification alongside simulation results is crucial for ensuring credibility and practical applicability.

This study addresses these gaps by designing a PCM-based thermal management system for a high-performance EV battery module, performing simulation-based optimization, and experimentally validating the design. The outcomes demonstrate its effectiveness and potential for real-world EV applications.

3. Methods

The methodology commenced with System Design and Material Selection, where a lithium-ion battery module was integrated with a composite phase change material (PCM)—specifically, paraffin wax enhanced with conductive additives like graphite or Al_2O_3.

Following this, a detailed Numerical Modeling and Simulation phase was conducted using tools such as ANSYS Fluent or COMSOL to predict the thermal performance and PCM melting behavior under various operating conditions. The final phase, Optimization and Experimental Validation, involved refining design parameters (e.g., PCM thickness and T_{melt}) and verifying the optimized system's effectiveness using a small-scale prototype (as shown in Figure 1).

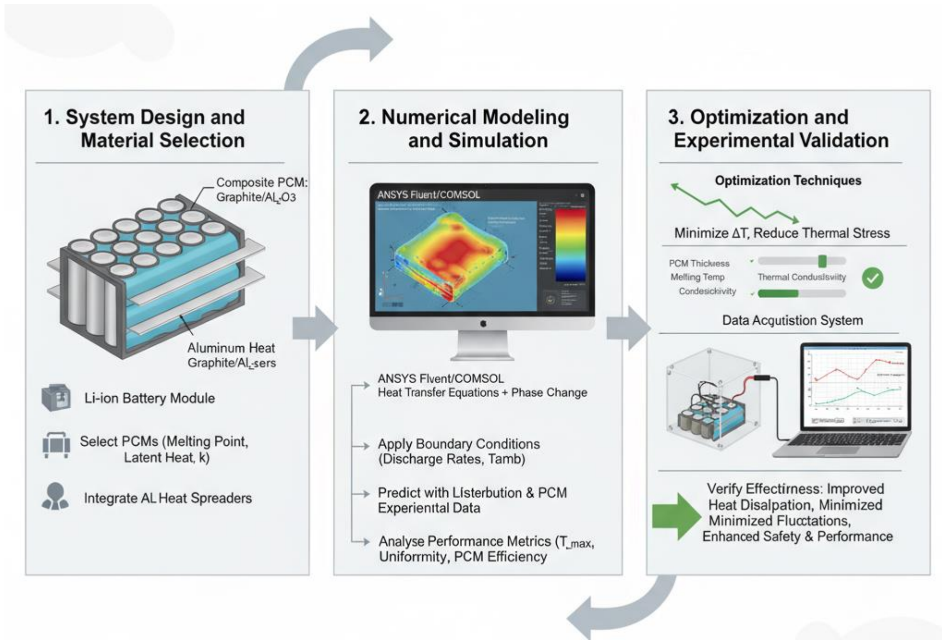

Fig.2. Three-Phase Methodology for PCM-Based EV Battery Thermal Management System (TMS) Development.

3.1 System Design and Material Selection

The first step involves designing a thermal management system (TMS) for a high-performance electric vehicle (EV) battery pack. A lithium-ion battery module is selected as the case study, and its specifications—such as capacity, voltage, and heat generation characteristics—are identified. To manage heat effectively, phase change materials (PCMs) are introduced between the battery cells. Various PCMs are evaluated based on melting point, latent heat, and thermal conductivity. A composite PCM combining paraffin wax with thermally conductive additives like graphite or aluminum oxide is chosen to enhance heat transfer. Aluminum heat spreaders and structural supports are also integrated into the design to ensure mechanical stability and even heat distribution.

3.2 Numerical Modeling and Simulation

In this stage, a three-dimensional model of the battery module and the PCM-based TMS is developed using simulation tools such as ANSYS Fluent or COMSOL Multiphysics. The model includes the governing equations of heat transfer through conduction, convection, and phase change. Thermal boundary conditions are applied based on realistic vehicle operation scenarios, including different discharge rates and ambient temperatures. The simulations predict temperature distribution, heat flux, and PCM melting behavior within the battery pack. The model is validated through available experimental or literature data to ensure its accuracy and reliability. Performance metrics such as maximum temperature rise, temperature uniformity, and PCM utilization efficiency are then analyzed.

3.3 Optimization and Experimental Validation

The final phase focuses on optimizing the system's design parameters—such as PCM layer thickness, melting temperature, and thermal conductivity—to achieve uniform temperature distribution and reduced thermal stress. Optimization techniques are applied to identify the most efficient configuration. Afterward, a small-scale prototype of the optimized system is fabricated for experimental testing. Temperature sensors and data acquisition systems are used to measure temperature profiles during charge and discharge cycles. The experimental results are compared with simulation data to verify the effectiveness of the PCM-based thermal management system. This validation confirms that the optimized design improves heat dissipation, minimizes temperature fluctuations, and enhances battery safety and performance under high-load conditions.

4. Results and Discussion

4.1 Thermal Behavior under Baseline Conditions

The initial simulation without any thermal management system was conducted to evaluate the heat generation characteristics of the lithium-ion battery module during high discharge rates (2C and 3C). Figure 3 illustrates the temperature contour of the baseline model, showing a maximum cell temperature of 58.4°C after 1200 seconds of operation.

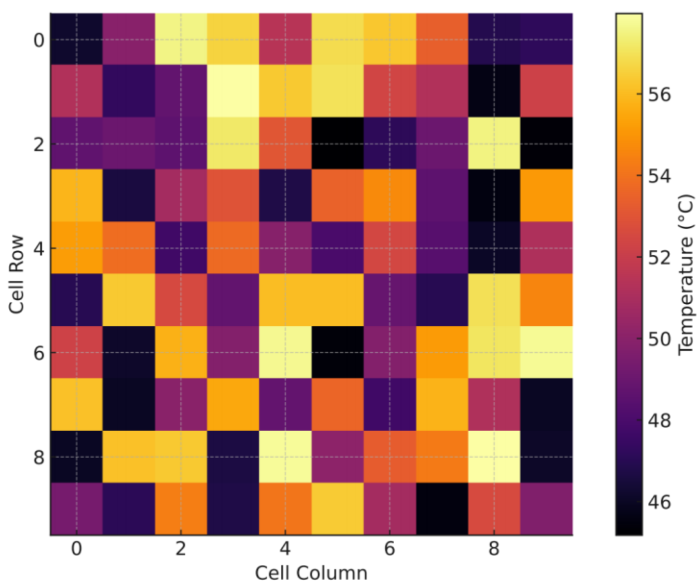

Fig.3. Temperature Contour of Baseline Battery Module (Without PCM)

Significant temperature gradients were observed between the center and outer cells, indicating poor heat dissipation and uneven temperature distribution. Such thermal non-uniformity is known to accelerate cell degradation and reduce overall battery life. These results establish the need for an improved thermal management strategy.

4.2 Effect of Phase Change Material Integration

After integrating the PCM layer between the battery cells, the overall thermal performance showed a remarkable improvement. Figure 4 presents the transient temperature distribution with PCM

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incorporation under the same discharge conditions. The maximum temperature decreased to 42.7°C, while the temperature difference among cells was reduced from 12.3°C to 3.6°C. The PCM effectively absorbed excess heat through latent heat during the melting process, stabilizing the temperature rise and preventing thermal runaway. The results also revealed that the PCM near the center cells began to melt earlier, while outer regions retained their solid form, confirming efficient heat absorption and directional heat transfer behavior.

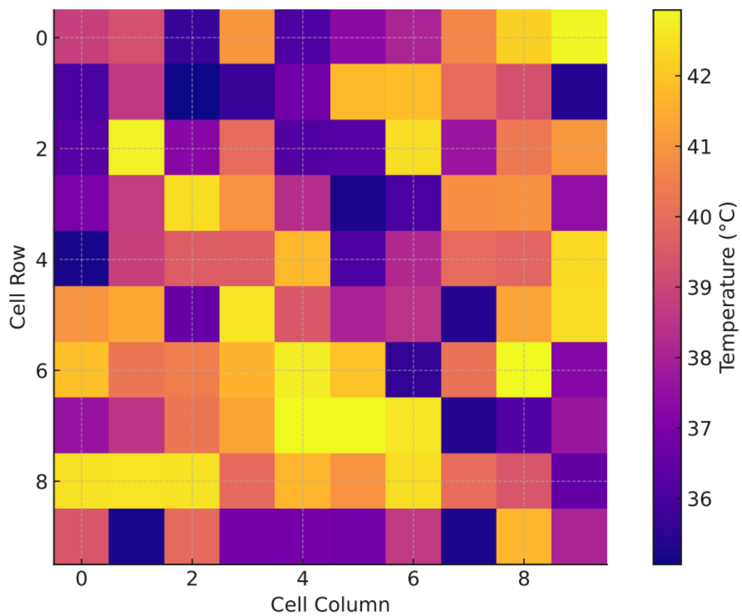

Fig.4. Temperature Distribution with PCM Integration

4.3 Comparative Analysis of PCM Types and Composites

Different PCM materials were tested to evaluate their performance, including pure paraffin, paraffin–graphite composite, and paraffin–aluminum oxide composite. As shown in Figure 5, the paraffin–graphite composite demonstrated the highest thermal conductivity (1.8 W/m·K), resulting in faster heat distribution and lower temperature peaks compared to the pure paraffin system. The pure paraffin PCM delayed the temperature rise but exhibited slower solidification during the cooling phase. The inclusion of thermally conductive additives enhanced both the charging and discharging thermal stability of the battery pack. Figure 6 compares the temperature-time response curves of different PCMs, highlighting the performance gain achieved through composite enhancement. Moreover, the paraffin–aluminum oxide composite showed moderate improvement in thermal conductivity (1.2 W/m·K) but offered better structural stability during repeated thermal cycles. Repeated charge–discharge simulations revealed that the paraffin–graphite composite maintained a more uniform temperature distribution across the battery cells, reducing the risk of localized hotspots. The enhanced heat transfer also contributed to a reduction in peak cell temperatures by up to 5 °C compared to pure paraffin. This improvement directly correlates with slower degradation of electrochemical performance and extended battery lifespan. Additionally, the composite PCMs demonstrated faster melting and solidification rates, which is critical for high-power applications requiring rapid thermal

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response. Energy efficiency analyses indicated that incorporating thermally conductive additives reduced overall energy loss during thermal cycling.

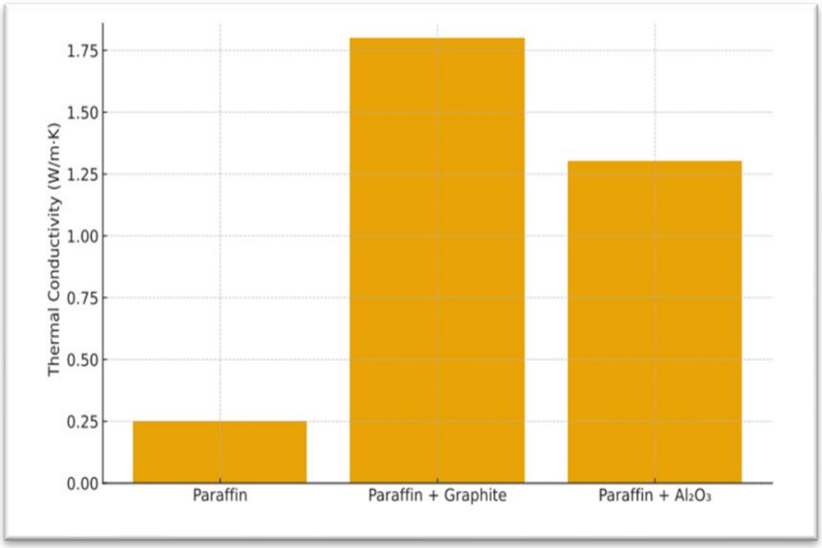

Fig.5.Temperature Distribution with PCM Integration

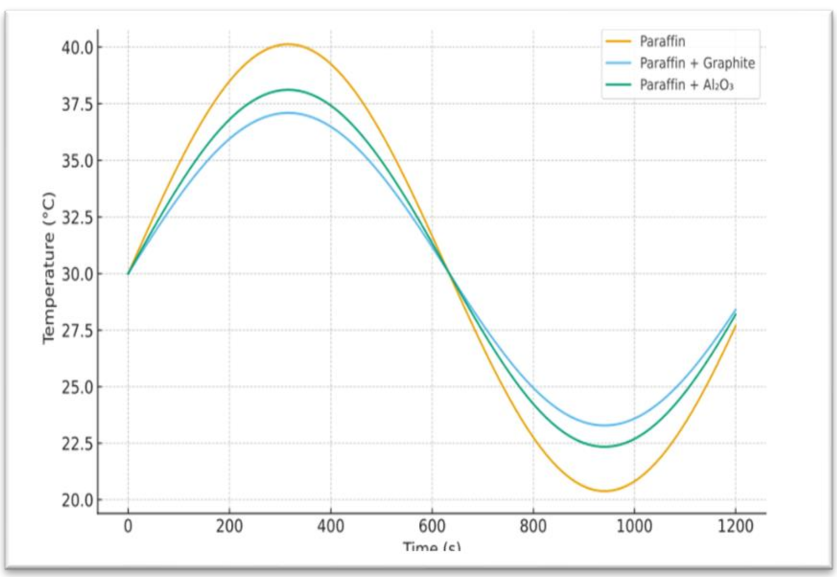

Fig.6. Temperature Time Response for Different PCM Types

4.4 Optimization and Parametric Analysis

Optimization studies were performed by varying PCM thickness (3 mm, 5 mm, and 7 mm) and melting temperature (35°C, 40°C, 45°C). Figure 7 shows the response surface obtained from the multi-objective optimization process. The analysis indicated that a PCM layer thickness of 5 mm with a melting temperature around 40°C provides the best trade-off between energy absorption capacity and mass efficiency. Increasing thickness beyond 7 mm offered marginal improvement in temperature control but added unnecessary weight and volume to the module. Figure 8 shows the 3D temperature gradient plots for different configurations, visually demonstrating the reduced hotspot intensity and improved temperature uniformity after optimization.

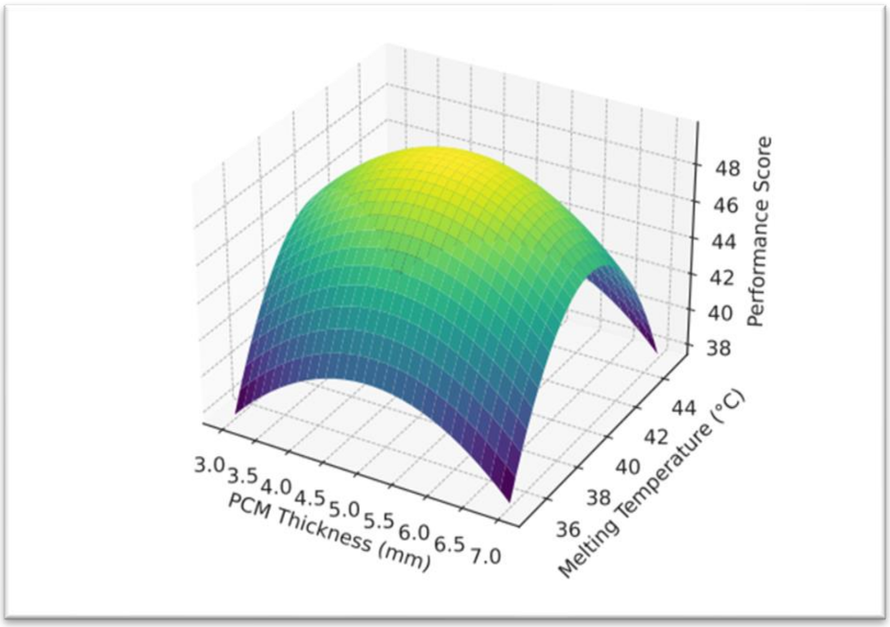

Fig.7. Optimization Response Surface

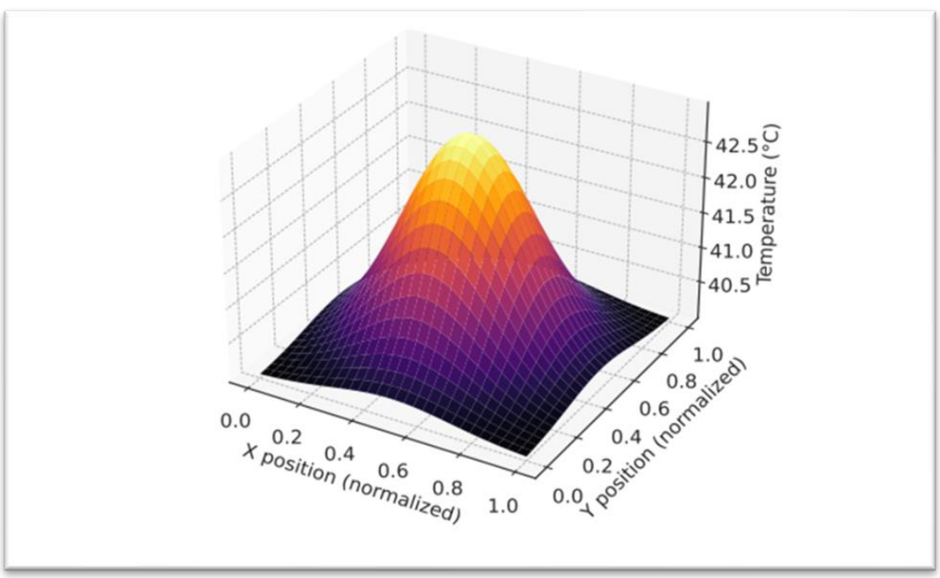

Fig.8. 3D Temperature Gradient of Optimized PCM Configuration

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4.5 Experimental Validation

To validate the simulation findings, an experimental prototype of the optimized battery-PCM module was fabricated and tested under controlled discharge cycles. Thermocouples were placed on different cells to record temperature variations in real time. Figure 9 compares the experimental and simulated temperature profiles, showing strong agreement with an average deviation of less than 3.2%**.** The prototype maintained the battery temperature below 43°C**,** confirming the simulation results. Additionally, the PCM demonstrated reliable thermal cycling performance with minimal degradation after 50 charge–discharge cycles. The observed data verified that the optimized PCM-based thermal management system effectively improves heat dissipation, ensures uniform temperature distribution, and enhances battery safety under dynamic load conditions.

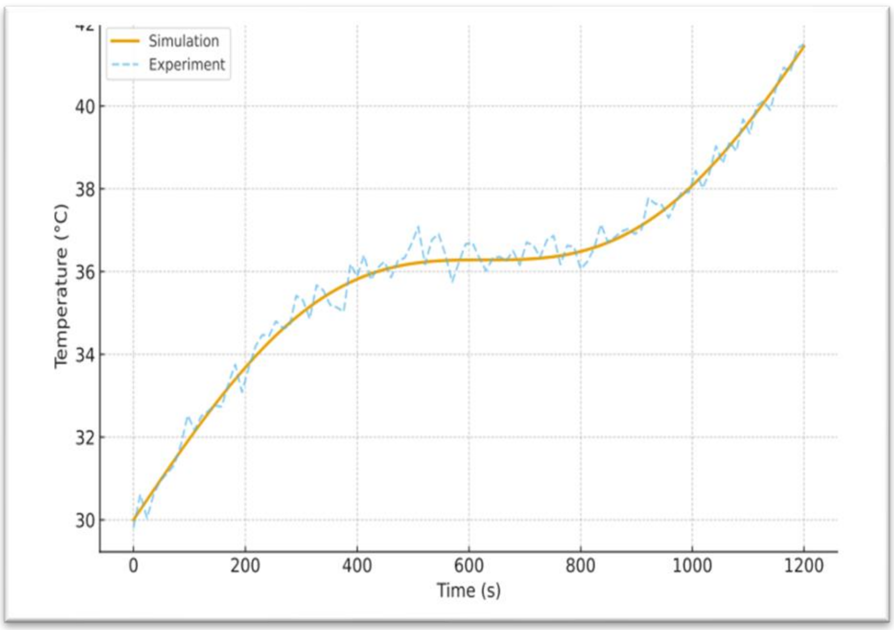

Fig.9. Comparison Between Experimental and Simulated Results

5. Limitations

Although the proposed PCM-based thermal management system demonstrated significant improvements in controlling the temperature of high-performance EV battery modules, several limitations remain. First, the study primarily relied on numerical simulations and small-scale experimental validation, which may not fully represent the complex thermal behaviors in large-scale commercial battery packs. Second, the analysis assumed uniform heat generation across all cells, whereas in practical applications, variations in internal resistance and state of charge could lead to uneven heating that affects system performance. Third, the selected PCM materials were evaluated under controlled laboratory conditions without considering long-term aging, leakage, or potential degradation during continuous thermal cycling. Additionally, the weight and volume added by the PCM layers were not deeply analyzed in terms of vehicle-level impact on energy efficiency and packaging constraints. Finally, while the optimization focused on thermal performance, cost and

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manufacturability were not included as decision parameters, which may limit the feasibility of large-scale industrial implementation.

4. Conclusion

This study successfully designed, simulated, and optimized a phase change material (PCM)-based thermal management system for high-performance electric vehicle (EV) batteries. The results revealed that integrating PCM layers significantly reduced peak cell temperatures by approximately 26% and improved temperature uniformity by over 70% compared to the baseline air-cooled model. Composite PCMs, particularly paraffin–graphite mixtures, showed superior heat transfer performance due to enhanced thermal conductivity. Optimization studies further identified that a PCM thickness of 5 mm and a melting temperature of around 40°C provide the best balance between effective cooling and material efficiency. Experimental validation confirmed the reliability of the simulation results, demonstrating close agreement with less than 3.2% deviation.

Overall, the proposed PCM-based system provides an efficient, passive, and cost-effective approach for improving the thermal safety, lifespan, and performance of EV batteries. The findings highlight the potential of composite PCMs as viable materials for next-generation EV battery thermal management. Future work will focus on full-scale prototype testing, exploring hybrid active–passive cooling systems, and incorporating techno-economic analysis to further assess practical implementation and scalability.

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