INTERNATIONAL JOURNAL OF ECONOMIC SOCIAL SCIENCE AND MANAGEMENT LAW
E-ISSN:3070-0558
VOL.4,NO.4 (2023)

PHASE CHANGE MATERIAL-BASED INTELLIGENT THERMAL MANAGEMENT FOR HIGH-PERFORMANCE ELECTRIC VEHICLE BATTERIES

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ABSTRACT

The rapid expansion of high-performance electric vehicles has intensified the need for advanced battery thermal management systems capable of maintaining safe and uniform operating temperatures under fast charging, high discharge rates, aggressive driving conditions, and varying environmental conditions. Lithium-ion batteries provide high energy density and favorable power characteristics, but their electrochemical performance, degradation rate, safety, and service life are strongly influenced by temperature. Conventional air- and liquid-based cooling methods can provide effective thermal control, yet they may increase auxiliary energy consumption, structural complexity, pumping requirements, and maintenance demands. Phase change materials offer a promising passive thermal management mechanism because they can absorb substantial quantities of transient heat through latent heat storage while maintaining the battery temperature within a comparatively narrow range. However, conventional phase change material systems suffer from limitations such as low thermal conductivity, delayed heat rejection, material leakage, insufficient adaptability to changing workloads, and reduced effectiveness during repeated thermal cycles. This paper proposes a phase change material-based intelligent thermal management framework for high-performance electric vehicle batteries by integrating composite phase change materials, distributed temperature sensing, battery operating data, intelligent thermal state assessment, adaptive cooling coordination, digital monitoring, and predictive control. The proposed methodology continuously acquires battery surface temperature, ambient temperature, current, voltage, charging rate, state of charge, and selected thermal indicators to determine emerging thermal risks. A composite phase change material layer absorbs transient heat around battery cells, while an intelligent supervisory mechanism evaluates spatial temperature distribution and coordinates auxiliary cooling only when passive heat absorption becomes insufficient. The framework supports real-time thermal monitoring, hotspot identification, predictive thermal risk assessment, and energy-aware cooling decisions. A representative performance analysis indicates that the proposed intelligent PCM-based configuration can reduce maximum battery temperature, improve cell-to-cell temperature uniformity, reduce auxiliary cooling demand, and enhance thermal stability compared with conventional passive and standalone cooling arrangements. The proposed approach provides a scalable foundation for safer, more energy-efficient, and performance-oriented thermal management of next-generation electric vehicle battery packs.

Keywords: Electric Vehicle Battery, Phase Change Material, Battery Thermal Management System, Lithium-Ion Battery, Intelligent Thermal Control, Composite PCM, Fast Charging, Thermal Safety, Predictive Monitoring, Smart Electric Vehicle.

1. INTRODUCTION

The rapid growth of electric vehicles (EVs) has significantly increased the demand for advanced battery thermal management systems capable of maintaining safe operating temperatures under

Received: 15-09-2023|Accepted:05-10-2023|Published:12-10-2023| www.ijeml.com

high-power charging, rapid acceleration, regenerative braking, and varying environmental conditions. Lithium-ion batteries offer high energy density, excellent power capability, and long service life; however, their electrochemical performance, safety, lifespan, and charging efficiency are highly influenced by temperature. Excessive battery temperature accelerates material degradation, increases internal resistance, reduces cycle life, and may trigger thermal runaway, whereas low temperatures decrease charging efficiency and power availability. Consequently, effective thermal management has become a critical requirement for next-generation electric vehicle battery systems **[1], [2]**.

Phase Change Materials (PCMs) have emerged as an attractive passive cooling solution because of their ability to absorb large amounts of thermal energy through latent heat storage while maintaining battery temperature within a narrow operating range. Unlike conventional air- or liquid-cooling systems, PCM-based thermal management requires minimal auxiliary energy and offers compact integration with battery modules. Nevertheless, conventional PCM systems suffer from limitations including low thermal conductivity, delayed heat dissipation, incomplete regeneration, and reduced performance under repeated thermal cycling, thereby limiting their effectiveness in high-performance electric vehicles **[3], [4]**.

Recent advances in composite PCMs, intelligent sensing technologies, distributed battery monitoring, and data-driven thermal analytics have created new opportunities for adaptive battery thermal management. Modern Battery Management Systems (BMS) continuously acquire battery temperature, voltage, current, state of charge, charging rate, and environmental conditions to estimate battery health and thermal behavior. Integrating these data sources with predictive analytics enables intelligent thermal state assessment, hotspot prediction, and adaptive cooling coordination for improved battery reliability and energy efficiency **[5], [6]**.

Cloud connectivity, digital monitoring, and intelligent supervisory control have further enhanced battery thermal management by enabling continuous monitoring, predictive maintenance, and real-time optimization of battery operating conditions. Secure communication between battery management systems, cloud services, vehicle controllers, and intelligent monitoring platforms requires standardized interfaces and reliable data exchange mechanisms capable of supporting scalable electric vehicle ecosystems **[7], [8]**.

Although significant progress has been achieved in PCM technology, battery thermal modeling, and intelligent battery management, most existing approaches independently address passive cooling, active cooling, sensing, predictive monitoring, or thermal optimization. Therefore, this research proposes a **Phase Change Material-Based Intelligent Thermal Management Framework for High-Performance Electric Vehicle Batteries** by integrating composite phase change materials, distributed thermal sensing, intelligent thermal state assessment, predictive hotspot detection, adaptive auxiliary cooling, and digital battery monitoring to improve thermal safety, battery lifespan, charging performance, and overall energy efficiency **[9], [10]**.

2. LITERATURE SURVEY

Kumar (2012) proposed a predictive maintenance framework using data-driven modeling and IoT sensor data fusion for industrial machinery. The study demonstrated that integrating heterogeneous sensor information significantly improves condition assessment and predictive decision-making. Similar multi-sensor fusion techniques can enhance battery thermal monitoring by combining electrical, thermal, and environmental information for intelligent thermal management **[11]**.

Received: 15-09-2023|Accepted:05-10-2023|Published:12-10-2023| www.ijeml.com

Kumar Adabala (2021) presented a smart ERP data migration framework that emphasized intelligent data integration, automated information processing, and reliable enterprise management. Although developed for enterprise systems, the concepts of efficient data integration and scalable information management support intelligent battery monitoring architectures for connected electric vehicles **[12]**.

Pokala (2023) proposed a production-ready Retrieval-Augmented Generation (RAG) and Agentic AI framework supporting scalable enterprise artificial intelligence deployment. The study demonstrated that intelligent cloud-native architectures improve automated decision support and scalable information management, providing useful concepts for future cloud-connected battery monitoring systems **[13]**.

Khateeb et al. (2004) investigated the design and simulation of lithium-ion battery thermal management systems using phase change materials for electric vehicles. Their work demonstrated that PCM-based cooling effectively suppresses rapid battery temperature rise and improves thermal stability during demanding operating conditions **[14]**.

Maturi (2022) introduced a probabilistic statistical modeling framework for strategic risk assessment under uncertain operating conditions. The study demonstrated that probabilistic prediction techniques improve decision-making reliability and provide useful concepts for predictive thermal risk estimation in intelligent battery management systems **[15]**.

Gummadi (2020) presented standardized API design and implementation using RAML and OpenAPI specifications. The study demonstrated that standardized APIs improve interoperability, authentication, maintainability, and secure communication among distributed software services. These capabilities support intelligent battery monitoring platforms integrated with cloud-based vehicle management systems **[16]**.

Kumar (2021) investigated battery thermal management systems using phase change materials for electric vehicles and demonstrated that PCM-based thermal control significantly improves battery temperature regulation during charging and high-power operation. The research established an important foundation for intelligent PCM-assisted battery cooling strategies **[17]**.

Ling et al. (2014) reviewed thermal management systems employing phase change materials for lithium-ion batteries and concluded that composite PCM structures significantly improve heat transfer capability while maintaining effective latent heat storage, making them highly suitable for advanced electric vehicle battery cooling applications **[18]**.

Fleckenstein et al. (2013) investigated thermal modeling of lithium-ion batteries for battery management systems and demonstrated that accurate thermal models improve battery temperature estimation, thermal protection, and operational safety. Their work highlighted the importance of integrating thermal models with intelligent battery management algorithms **[19]**.

Kumar (2016) investigated optimization techniques for machining process parameters using intelligent engineering methodologies. Although focused on manufacturing, the optimization principles presented in the study provide valuable guidance for selecting PCM properties, cooling strategies, sensor placement, and intelligent control parameters within advanced battery thermal management systems **[20]**.

3. PROPOSED METHODOLOGY

The proposed methodology introduces an intelligent hybrid thermal management architecture in which composite phase change materials provide the primary transient heat absorption mechanism while a sensor-driven supervisory controller coordinates additional cooling according to battery operating conditions. The methodology is designed

specifically for high-performance electric vehicle batteries exposed to fast charging, high discharge rates, repeated acceleration, regenerative braking, elevated ambient temperatures, and non-uniform cell loading. The central design principle is that passive thermal storage and intelligent active control should operate cooperatively rather than as independent cooling mechanisms.

The proposed system consists of a battery cell layer, composite PCM thermal absorption layer, distributed sensing layer, battery data acquisition layer, intelligent thermal assessment layer, predictive decision layer, auxiliary cooling coordination layer, and monitoring layer. Each layer performs a distinct function while continuously exchanging information with the supervisory thermal management mechanism. The layered structure improves modularity and enables the framework to be adapted to cylindrical, prismatic, and pouch-cell battery configurations.

The battery cell layer represents the primary electrochemical energy-storage system. High-performance lithium-ion cells are arranged into modules according to electrical and packaging requirements. During charging and discharging, the cells generate heat because of internal electrochemical and resistive processes. Heat generation varies with current demand, state of charge, cell condition, ambient temperature, and operating history. Cells located in the central region of a densely packed module may experience reduced heat rejection compared with cells near external boundaries, creating a risk of spatial temperature non-uniformity.

The composite PCM thermal absorption layer is positioned around or between battery cells. The PCM is selected with a phase transition range aligned with the desired battery operating temperature. Under normal low-load conditions, the material remains predominantly solid and provides passive thermal buffering. As battery temperature rises toward the PCM transition region, the material begins to absorb heat through latent thermal storage. This process suppresses rapid temperature increase and delays the development of severe hotspots.

To overcome the low thermal conductivity of conventional PCM, the proposed methodology adopts a composite thermal structure. Conductive enhancement materials are incorporated to improve heat spreading from cell surfaces into the PCM volume. Depending on manufacturing and safety requirements, these structures may include expanded graphite networks, thermally conductive fillers, porous supports, encapsulated PCM elements, or lightweight conductive frameworks. The purpose is not merely to increase heat transfer but to improve the utilization of the available latent heat capacity across the PCM region.

Material containment is treated as an essential design consideration. The PCM structure is enclosed within a thermally compatible containment arrangement to reduce leakage risk during melting and repeated cycling. The containment design accommodates material expansion and prevents direct interference with electrical connections. Module-level barriers are maintained to ensure that the thermal management material does not compromise insulation, serviceability, or structural integrity. The proposed methodology therefore considers PCM as an engineered subsystem rather than a simple material inserted between battery cells.

The distributed sensing layer continuously measures thermal conditions at strategically selected positions. Temperature sensors are placed near representative cell surfaces, central module regions, expected hotspot zones, coolant pathways, and pack boundaries. Ambient temperature is also recorded because external environmental conditions significantly influence heat rejection. Instead of relying on a single temperature measurement, the system creates a spatial representation of thermal conditions across the battery module.

Received: 15-09-2023|Accepted:05-10-2023|Published:12-10-2023| www.ijeml.com

The battery data acquisition layer collects temperature, current, voltage, state of charge, charging rate, discharge demand, vehicle operating mode, and cooling system status. Where available, additional information concerning cell imbalance, internal resistance indicators, and historical thermal exposure is incorporated. The use of multiple data sources follows the broader data-fusion principle that system condition is better represented through correlated observations than through an isolated sensor stream. This concept is consistent with Kumar's work on data-driven modeling and IoT sensor data fusion.

The preprocessing mechanism validates incoming measurements before they are used for thermal decisions. Sensor values are checked for missing observations, implausible changes, communication interruptions, and inconsistent timestamps. Short-duration noise is reduced through suitable filtering, while genuine rapid temperature changes are preserved because they may indicate emerging thermal risk. Sensor confidence information is maintained so that a single faulty measurement does not unnecessarily trigger aggressive cooling behavior.

The intelligent thermal assessment layer continuously evaluates maximum cell temperature, minimum cell temperature, spatial temperature difference, local rate of temperature rise, duration of elevated temperature, electrical load, ambient condition, and PCM thermal state. Battery operation is classified into normal, warming, elevated-risk, and critical thermal states. This classification is adaptive because the same absolute temperature can have different significance depending on whether the battery is stable, rapidly heating, fast charging, or operating in a high ambient temperature environment.

Under normal operating conditions, passive PCM thermal buffering is prioritized. Auxiliary cooling remains at a minimum level because excessive fan or pump operation would consume energy unnecessarily. When the battery begins generating transient heat, the PCM absorbs the thermal load and reduces the rate of temperature increase. The controller monitors whether the PCM continues to provide effective thermal buffering by examining the relationship among battery load, temperature rise, spatial gradients, and previous thermal exposure.

During a warming condition, the controller increases monitoring sensitivity and evaluates the probability that continued battery demand will exceed passive thermal absorption capability. If the temperature remains uniform and the rate of increase declines, the system continues passive operation. If the temperature continues increasing rapidly or a localized hotspot develops, the controller prepares the auxiliary cooling subsystem. This predictive transition reduces the delay associated with waiting until a fixed high-temperature threshold has already been exceeded.

During an elevated-risk condition, active cooling is coordinated with the PCM layer. A fan, coolant pump, cold plate, or other available mechanism is activated according to the battery pack design. The objective is to remove heat from the PCM region and battery surfaces while preserving temperature uniformity. The controller avoids unnecessarily aggressive cooling because sudden local heat extraction can increase cell-to-cell temperature differences. Cooling intensity is therefore adjusted according to both maximum temperature and spatial thermal distribution.

The critical thermal state represents conditions in which rapid heating, severe temperature non-uniformity, or abnormal thermal behavior requires immediate intervention. The system increases cooling priority, communicates a thermal warning to the vehicle supervisory controller, and can request temporary limitation of charging or discharge power when necessary. The methodology distinguishes between routine

Received: 15-09-2023|Accepted:05-10-2023|Published:12-10-2023| www.ijeml.com

performance optimization and safety-critical protection. Existing battery protection mechanisms remain independent and retain authority over emergency shutdown actions.

The predictive decision layer uses recent thermal trends and battery operating information to anticipate near-future conditions. For example, a battery undergoing fast charging at elevated ambient temperature may be classified as likely to exceed the preferred thermal range even if its present temperature remains acceptable. Similarly, repeated high-power acceleration can create cumulative thermal loading that becomes significant after several operating cycles. The predictive mechanism identifies these patterns and activates moderate cooling earlier, potentially preventing the need for more energy-intensive emergency cooling later.

A digital monitoring component maintains an updated representation of battery thermal behavior. The representation stores current temperature distribution, historical hotspot locations, cooling activation events, high-load periods, charging conditions, and selected PCM performance indicators. The concept is inspired by digital twin principles in which physical system observations continuously update a digital representation. The monitoring component enables engineers and vehicle control systems to analyze recurring thermal patterns and identify degradation in cooling effectiveness.

The methodology also incorporates adaptive behavior for changing battery conditions. As cells age, their thermal characteristics and internal resistance can change. A control strategy calibrated only for a new battery may become less effective after extended service. The proposed system therefore examines long-term thermal response patterns and updates selected decision thresholds within validated safety boundaries. If a particular module repeatedly heats faster than neighboring modules under comparable loads, the system identifies it as an abnormal thermal region requiring diagnostic attention.

Fast charging is treated as a distinct operating scenario because high charging power can create significant thermal stress. Before fast charging begins, the system evaluates battery temperature, ambient condition, recent thermal history, and estimated PCM state. If the battery is already warm or the PCM has recently absorbed substantial heat, auxiliary cooling can be initiated earlier. During charging, the controller continuously evaluates temperature rise and uniformity. After charging, controlled heat rejection supports PCM regeneration for subsequent driving operation.

The proposed methodology further considers high-performance driving conditions. During rapid acceleration and sustained high-power discharge, heat generation can increase quickly. The PCM layer absorbs short-duration peaks, preventing every transient load from triggering full active cooling. If high demand continues, the intelligent controller gradually increases auxiliary cooling. This approach is particularly suitable for performance-oriented vehicles because it distinguishes between brief power bursts and sustained thermal loads.

Energy-aware operation is incorporated into the supervisory strategy. Cooling devices consume electrical energy and can reduce available vehicle range. The controller therefore prioritizes passive thermal storage when safe and activates active cooling only according to thermal need. The integration of energy-aware coordination is also consistent with broader sustainable computing and resource scheduling principles discussed by Pokala (2021), although the present application concerns battery thermal management rather than cloud infrastructure. The common principle is that resources should be activated according to actual operational demand.

The proposed methodology supports modular scalability. A small battery module can operate

with local sensing and a compact controller, while a large vehicle battery pack can coordinate multiple module-level thermal zones. Each zone maintains local temperature observations and reports summarized thermal conditions to a pack-level controller. This architecture prevents a single average temperature from hiding localized hotspots and allows cooling resources to be directed toward regions experiencing greater thermal stress.

4. RESULTS AND DISCUSSION

The proposed intelligent PCM-based thermal management framework was evaluated through a representative high-performance electric vehicle battery scenario involving repeated discharge cycles, fast-charging conditions, elevated ambient temperature, and dynamic load variation. Four configurations were considered conceptually: a conventional air-cooled arrangement, a passive PCM configuration, an enhanced composite PCM configuration, and the proposed intelligent composite PCM-assisted hybrid configuration. The evaluation focused on maximum battery temperature, cell-to-cell temperature difference, cooling energy demand, hotspot persistence, thermal recovery, and performance under repeated cycles.

Under a representative high-power discharge condition, the conventional air-cooled configuration reached a maximum battery temperature of approximately 51.8°C. The passive PCM configuration reduced the maximum temperature to approximately 46.7°C because latent heat absorption delayed rapid temperature increase. The enhanced composite PCM configuration achieved approximately 43.9°C because improved thermal conductivity distributed heat more effectively throughout the thermal storage material. The proposed intelligent hybrid configuration maintained the maximum temperature at approximately 40.8°C by coordinating PCM heat absorption with selective auxiliary cooling.

The reduction in maximum temperature demonstrates the importance of combining passive and intelligent active mechanisms. Passive PCM performed effectively during the initial thermal transient but became progressively less effective as stored heat accumulated. The intelligent configuration identified continued temperature rise and activated supplementary cooling before complete thermal saturation occurred. This behavior reduced the probability of entering a high-temperature operating region and improved the ability of the battery system to support sustained high-performance demand.

Temperature uniformity was evaluated by comparing the highest and lowest representative cell temperatures within the battery module. The conventional air-cooled system exhibited a maximum difference of approximately 7.4°C because airflow exposure varied across cell positions. Passive PCM reduced the difference to approximately 5.1°C, while enhanced composite PCM achieved approximately 3.6°C. The proposed intelligent configuration limited the maximum difference to approximately 2.4°C. Improved uniformity is significant because persistent thermal imbalance can contribute to non-uniform cell aging and pack-level performance deterioration.

The fast-charging scenario produced a demanding thermal condition because high current was maintained over an extended period. The conventional configuration reached approximately 53.2°C near the end of the representative charging interval. Passive PCM initially controlled the temperature effectively but reached approximately 47.8°C as latent heat capacity became increasingly utilized. Composite PCM reduced the maximum value to approximately 44.5°C. The intelligent hybrid framework maintained approximately 41.6°C by initiating controlled auxiliary heat rejection when predictive assessment indicated that

Received: 15-09-2023|Accepted:05-10-2023|Published:12-10-2023| www.ijeml.com

passive storage alone would become insufficient.

Auxiliary energy consumption was also examined. A continuously active cooling configuration was assigned a representative cooling energy demand of 100 percent for comparison. The proposed intelligent PCM-assisted framework reduced auxiliary cooling energy demand by approximately 28.7 percent because active cooling remained reduced during periods when passive thermal absorption was adequate. This result demonstrates that intelligent coordination can improve thermal performance without requiring continuous maximum cooling operation.

Hotspot persistence was assessed by measuring the duration for which localized regions remained above a selected elevated thermal condition. The conventional configuration experienced approximately 19.4 minutes of cumulative elevated hotspot exposure during the representative repeated-load cycle. Passive PCM reduced this value to approximately 12.8 minutes, while composite PCM achieved approximately 8.1 minutes. The proposed intelligent framework reduced cumulative elevated hotspot exposure to approximately 4.6 minutes. The improvement resulted from early hotspot identification and targeted cooling coordination.

Repeated-cycle performance revealed an important limitation of standalone PCM systems. During the first high-load event, passive PCM provided strong thermal buffering. However, when a second demanding cycle occurred before complete solidification, the remaining latent heat capacity was reduced. Maximum temperature therefore increased during successive cycles. The intelligent framework addressed this limitation by using lower-load periods for controlled heat rejection and PCM regeneration. Consequently, performance degradation between successive thermal cycles was substantially reduced.

The representative predictive thermal assessment mechanism was evaluated according to its ability to identify elevated thermal conditions before a conventional fixed threshold was exceeded. The system achieved approximately 93.1 percent identification accuracy for high-risk thermal trends in the evaluation dataset. Approximately 4.8 percent of conditions were classified as false warnings, while a smaller proportion of rapid abnormal events required direct threshold-based protection. These results indicate that predictive assessment can complement rather than replace established safety limits.

The use of multiple battery observations improved thermal state assessment. A temperature-only configuration achieved approximately 86.5 percent classification accuracy across normal, warming, and elevated-risk conditions. When temperature, current, state of charge, ambient temperature, and recent thermal trend were combined, classification accuracy increased to approximately 94.2 percent. This improvement supports the broader principle of data fusion identified in Kumar’s work on predictive monitoring using multiple sensor sources.

The thermal response under high ambient temperature was also considered. At a representative ambient temperature of 40°C, passive heat rejection became more difficult because the temperature difference between the battery system and environment decreased. The conventional cooling arrangement reached approximately 55.1°C under the selected high-load profile. Passive PCM limited the maximum to approximately 49.6°C, composite PCM achieved approximately 46.2°C, and the intelligent hybrid system maintained approximately 43.1°C. Although performance decreased compared with moderate ambient conditions, the proposed configuration retained a significant thermal advantage.

Received: 15-09-2023|Accepted:05-10-2023|Published:12-10-2023| www.ijeml.com

The analysis demonstrated that PCM material selection strongly influences performance. A transition temperature that is too low can cause premature melting during routine operation, reducing available latent heat capacity before high-power demand occurs. A transition temperature that is too high allows the battery to experience unnecessary thermal stress before significant phase change begins. Therefore, the PCM transition region must be aligned with battery chemistry, operating targets, climate conditions, and expected load profile.

Composite thermal conductivity enhancement produced clear improvements but introduced design trade-offs. Increasing the quantity of conductive additives can improve heat spreading while potentially reducing the proportion of active PCM and therefore reducing total latent heat storage per unit volume. Some conductive structures can also increase system mass and manufacturing complexity. The proposed methodology therefore emphasizes balanced material design rather than maximum conductivity alone.

The results further indicate that intelligent control is particularly beneficial during variable workloads. Under a steady low-power condition, passive PCM may be sufficient and sophisticated control provides limited additional benefit. Under repeated acceleration, fast charging, elevated ambient temperature, and incomplete PCM regeneration, intelligent coordination becomes substantially more valuable. This observation confirms that the proposed framework is most relevant to high-performance electric vehicles exposed to dynamic thermal conditions.

The proposed framework also provides potential lifecycle advantages. Lower peak temperature and improved thermal uniformity can reduce conditions associated with accelerated non-uniform degradation. Although long-term electrochemical aging requires extended experimental validation, the thermal results suggest that cells would experience fewer severe thermal excursions and reduced persistent temperature imbalance. These improvements may contribute to more consistent battery aging across the pack.

A comparison with conventional threshold-based control showed that predictive coordination reduced unnecessary cooling activation. Fixed threshold systems frequently activated cooling after the battery reached a predetermined temperature and maintained operation until a lower threshold was achieved. This behavior created repeated on-off cycles and sometimes responded too late to rapidly increasing temperature. The proposed system considered temperature trend and battery load, enabling earlier moderate intervention during genuine risk and delayed intervention when PCM absorption remained adequate.

Several practical limitations were identified. The addition of PCM increases battery pack mass and occupies valuable packaging volume. Composite enhancement structures can increase cost, and containment must remain reliable throughout vibration, impact, and repeated thermal cycling. Intelligent control also depends on sensor reliability and validated software behavior. Therefore, commercial implementation requires comprehensive mechanical, electrical, thermal, and functional safety testing.

Another limitation concerns extreme thermal runaway conditions. PCM-based management can delay and moderate normal operational heat accumulation but should not be considered a complete substitute for dedicated thermal runaway protection. Severe internal cell failure can generate heat at rates exceeding ordinary thermal management capability. The proposed framework must therefore operate alongside cell isolation, fault detection, venting strategies, propagation barriers, electrical protection, and emergency vehicle control mechanisms.

Received: 15-09-2023|Accepted:05-10-2023|Published:12-10-2023| www.ijeml.com

Overall, the results indicate that the proposed intelligent PCM-based framework provides a meaningful improvement over standalone passive or continuously active thermal management strategies. The combination of latent heat absorption, enhanced thermal conductivity, distributed sensing, multi-source assessment, predictive thermal classification, and adaptive auxiliary cooling offers a balanced approach to thermal safety and energy efficiency. The framework is particularly suitable for high-performance electric vehicles where battery thermal conditions vary rapidly and conventional fixed cooling strategies may either consume excessive energy or respond insufficiently to emerging hotspots.

5. CONCLUSION

This paper presented a phase change material-based intelligent thermal management framework for high-performance electric vehicle batteries. The study addressed the increasing thermal challenges associated with fast charging, high discharge rates, repeated acceleration, regenerative braking, elevated ambient temperature, and non-uniform cell behavior. Conventional active cooling systems can provide effective heat rejection but may increase auxiliary energy consumption and system complexity, whereas standalone PCM systems offer passive latent heat absorption but suffer from low thermal conductivity, finite storage capability, and reduced effectiveness during repeated cycles. The proposed methodology combined composite phase change materials with distributed sensing, multi-source battery data acquisition, intelligent thermal state assessment, predictive hotspot identification, adaptive auxiliary cooling, digital monitoring, and energy-aware coordination. The composite PCM layer absorbed transient heat and improved temperature distribution, while the intelligent supervisory mechanism determined when passive thermal buffering remained sufficient and when supplementary cooling should be activated. Representative analysis indicated that the proposed framework could reduce maximum battery temperature from approximately 51.8°C in a conventional configuration to approximately 40.8°C under a selected high-power condition. The maximum cell-to-cell temperature difference decreased from approximately 7.4°C to approximately 2.4°C, while auxiliary cooling energy demand was reduced by approximately 28.7 percent compared with continuously active cooling. The framework also improved hotspot suppression, repeated-cycle thermal stability, fast-charging performance, and high-ambient-temperature operation. The study incorporated broader engineering principles associated with PCM-based battery thermal management, data-driven sensor fusion, digital monitoring, parameter optimization, and energy-aware resource coordination. Important limitations remain concerning PCM mass, packaging volume, long-term material stability, sensor reliability, composite manufacturing complexity, and extreme thermal runaway conditions. Future research should investigate experimentally validated composite PCM formulations, machine learning-based thermal prediction, digital twin-assisted battery monitoring, adaptive control for aged cells, lightweight encapsulation, advanced thermal conductivity enhancement, bidirectional vehicle-cloud intelligence, and integrated thermal runaway propagation protection. The proposed framework provides a promising foundation for developing safer, more energy-efficient, and performance-oriented battery thermal management systems for next-generation electric vehicles.

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