

A Critical Review of Composite Phase Change Materials in Lithium-Ion Battery Thermal Management

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Abstract

The rapid adoption of lithium-ion batteries in electric vehicles has heightened concerns over thermal safety and performance optimization, particularly the prevention of thermal runaway. Effective battery thermal management systems (BTMS) are therefore essential. This review focuses on composite phase change materials (CPCMs) as advanced solutions for BTMS, examining their thermal characteristics, modification strategies, and performance outcomes. The study evaluates key composite structures such as expanded graphite, metal foams, and nanoparticle-enhanced organic PCMs. Research objectives include assessing improvements in thermal conductivity, efficiency of temperature regulation, and effectiveness in mitigating thermal runaway. Methodologically, the review synthesizes experimental findings from peer-reviewed studies involving thermal property characterization, computational simulations, and performance testing under varied discharge rates. Results show expanded graphite composites deliver thermal conductivity enhancements of 400–1700%, while metal foam composites reduce cell temperature by 4–13 °C. Nanoparticle integration offers moderate improvements of 31–124% depending on concentration. Hybrid systems that couple CPCMs with active cooling provide superior thermal uniformity and safety. The findings confirm that multi-component CPCMs with three-dimensional thermal

networks hold strong potential as next-generation BTMS for electric vehicles.

Keywords: Composite phase change materials, Lithium-ion battery, Thermal management, Expanded graphite, Thermal conductivity, Thermal runaway

1. Introduction

Lithium-ion batteries have emerged as the predominant energy storage technology for electric vehicles due to their superior energy density, extended cycle life, and operational efficiency (Kibria et al., 2024). The global transition toward electric mobility has accelerated the deployment of high-capacity battery systems, which generate substantial heat during charge-discharge cycles. Excessive heat generation poses critical challenges including performance degradation, accelerated aging, and thermal runaway incidents that threaten both vehicle safety and battery longevity (Kumar & Rao, 2024). Battery thermal management systems are essential for maintaining optimal operating temperatures within the recommended range of 25–40 degrees Celsius while ensuring temperature uniformity across battery modules (Paul et al., 2025). Traditional cooling approaches including air cooling and liquid cooling present limitations in terms of energy consumption, system complexity, and thermal response characteristics. Air cooling systems demonstrate insufficient heat dissipation capacity for high-power applications, while liquid cooling requires complex

infrastructure with associated parasitic power losses (Xiao et al., 2024).

Phase change materials have attracted considerable research interest as passive thermal management solutions due to their ability to absorb substantial latent heat during solid-liquid phase transitions at nearly constant temperatures (Kumar & Rao, 2024). However, conventional phase change materials suffer from inherently low thermal conductivity in the range of 0.2-0.3 W/(m·K), which severely limits heat transfer rates and thermal response during critical thermal events (Srivastava et al., 2022). This fundamental limitation has motivated extensive research into composite phase change materials that incorporate high thermal conductivity enhancers to address the performance gap. Composite phase change materials integrate thermal conductivity enhancement additives including expanded graphite, metal foams, carbon nanotubes, and metallic nanoparticles within the phase change material matrix (Ali et al., 2024). These composites exhibit synergistic properties combining high latent heat storage capacity with improved thermal transport characteristics. The development of optimized composite formulations represents a critical research frontier for enabling safe, efficient thermal management in next-generation electric vehicle battery systems. This review provides comprehensive analysis of composite phase change material technologies, their thermal performance characteristics, and implementation strategies for lithium-ion battery thermal management applications.

2. Literature Review

2.1 Phase Change Materials in Battery Thermal Management

Phase change materials function as passive thermal regulators by absorbing heat through latent heat of fusion during melting transitions, thereby maintaining

battery temperatures within acceptable operational ranges (Zhang et al., 2023). Organic phase change materials, particularly paraffin waxes, dominate battery thermal management applications due to their favorable characteristics including appropriate melting temperatures, high latent heat values exceeding 200 J/g, chemical stability, and non-corrosive properties (Wang et al., 2023). Research by Rao et al. (2016) demonstrated that paraffin-based phase change materials could maintain battery surface temperatures below 45 degrees Celsius during 2C discharge rates, representing temperature reductions of approximately 15 degrees Celsius compared to air cooling.

2.2 Thermal Conductivity Enhancement Strategies

The fundamental challenge in phase change material applications stems from thermal conductivity values below 0.3 W/(m·K) for most organic compounds, which impedes rapid heat absorption and distribution (Liu et al., 2021). Multiple enhancement strategies have been investigated to address this limitation. Expanded graphite composites represent the most extensively studied approach, where worm-like porous graphite structures create three-dimensional thermal conduction networks within the phase change material matrix (Sarı & Karaıpekli, 2007). Research by Yu and Tao (2022) reported thermal conductivity values of 7.82 W/(m·K) for paraffin/expanded graphite composites with 20 weight percent expanded graphite content, representing a 47-fold improvement over pure paraffin. Metal foam integration provides alternative enhancement mechanisms through high thermal conductivity metallic skeletons that facilitate heat transfer throughout the composite (Siavashi et al., 2020). Copper and aluminum foams with porosities ranging from 85-95% have demonstrated effective thermal conductivity improvements while maintaining

adequate phase change material loading capacity. Nanoparticle additives including metallic oxides, carbon nanotubes, and graphene nanoplatelets offer enhancement through increased interfacial heat transfer and thermal bridge formation within liquid phase change materials (Zou et al., 2018).

2.3 Hybrid Thermal Management Systems

Recent research trends emphasize hybrid configurations combining passive phase change material cooling with active thermal management strategies (Zhang et al., 2020). Liquid cooling channels integrated with composite phase change materials provide enhanced heat dissipation capacity while reducing parasitic power consumption compared to pure liquid cooling systems (Mousavi et al., 2021). Experimental investigations by Kong et al. (2020) demonstrated that hybrid systems achieved maximum battery temperatures of 41.1 degrees Celsius and temperature differentials of 4 degrees Celsius during 3C discharge conditions. Fin structures incorporated within phase change material modules enhance heat transfer through extended surface area and improved thermal conduction pathways (Xiao et al., 2023).

2.4 Thermal Runaway Prevention

Thermal runaway represents the most severe failure mode in lithium-ion batteries, characterized by self-accelerating exothermic reactions that can propagate through entire battery modules (Feng et al., 2020). Phase change materials demonstrate capability in thermal runaway mitigation by absorbing heat during critical temperature excursions and preventing propagation to adjacent cells (Wilke et al., 2017). Research by Al-Hallaj (2022) showed that inorganic composite phase change materials reduced maximum temperatures during thermal runaway events from 578 degrees Celsius to 179 degrees Celsius in short-

circuited cells and from 230 degrees Celsius to 108 degrees Celsius in adjacent cells. The effectiveness of phase change materials in thermal runaway scenarios depends critically on thermal conductivity, latent heat capacity, and melting temperature alignment with battery operating conditions.

3. Objectives

The present study aims to achieve the following research objectives:

1. To evaluate the thermal performance of composite PCMs with additives such as expanded graphite, metal foams, and nanoparticles for lithium-ion battery thermal management.
2. To analyze how composition parameters influence thermal conductivity, latent heat, and melting temperature using experimental data.
3. To compare composite PCM configurations in regulating battery temperatures and preventing thermal runaway under high discharge rates.
4. To identify key design and optimization strategies that balance thermal performance with weight, cost, and system complexity.

4. Methodology

4.1 Research Design

This comprehensive review employs systematic analysis of peer-reviewed research articles, experimental studies, and computational investigations published in reputable scientific journals during the period 2007-2025. The research design incorporates qualitative synthesis of thermal management concepts with quantitative analysis of experimental performance data reported in the literature. Multiple databases including Web of Science, Scopus, ScienceDirect, and IEEE Xplore

were systematically searched using keywords related to composite phase change materials, lithium-ion batteries, and thermal management systems.

4.2 Sample Selection and Data Collection

A total of 583 relevant publications were initially identified through database searches, from which 60 high-quality research articles were selected based on relevance, experimental rigor, and data quality criteria. Selection criteria prioritized studies reporting quantitative thermal performance data, validated experimental methodologies, and comprehensive characterization of composite phase change materials. Research investigations covering various composite formulations including expanded graphite, metal foams, carbon nanotubes, and metallic nanoparticles were included to ensure comprehensive coverage of enhancement strategies.

4.3 Analytical Tools and Techniques

Data extraction focused on thermal property measurements including thermal conductivity values obtained through transient hot wire methods, differential scanning calorimetry analysis for phase change temperatures and latent heat determination, and battery thermal testing under various discharge rate conditions. Thermal performance metrics including maximum battery temperature, temperature differentials across modules, cooling duration, and thermal runaway propagation characteristics were systematically documented. Comparative analysis techniques were employed to evaluate relative performance improvements across different composite configurations and identify optimal design parameters. Statistical validation was performed where multiple studies reported similar experimental conditions to

assess consistency and reliability of reported performance enhancements.

4.4 Synthesis Approach

The synthesis methodology integrates experimental findings across diverse research investigations to establish comprehensive understanding of composite phase change material performance characteristics. Quantitative data from thermal conductivity measurements, latent heat analysis, and battery thermal testing were compiled and analyzed to identify trends, optimal configurations, and performance limitations. The analysis framework considers multiple factors including composite composition, additive concentration, thermal network morphology, and testing conditions to provide holistic assessment of thermal management effectiveness.

5. Results

5.1 Thermal Conductivity Enhancement of Composite PCMs

Table 1 presents thermal conductivity values for various composite phase change material formulations reported in the literature. Expanded graphite composites demonstrate the most substantial thermal conductivity improvements, with enhancements ranging from 400% to 1700% depending on additive concentration and graphite structure. Metal foam composites achieve thermal conductivity values of 13-44 times higher than pure paraffin for copper and nickel foams at porosities of 85-95%. Nanoparticle-enhanced phase change materials show more modest improvements, with thermal conductivity increases of 31-124% for carbon-based and metallic oxide nanoparticles.

Table 1: Thermal Conductivity of Composite Phase Change Materials

Composite Type	Additive Content	Thermal Conductivity (W/m·K)	Enhancement Factor	Reference
Pure Paraffin	-	0.22-0.23	Baseline	Sari & Karaipekli, 2007
Paraffin/EG	10 wt%	0.82	3.7×	Sari & Karaipekli, 2007
Paraffin/EG	20 wt%	7.82	34×	Yu & Tao, 2022
Paraffin/EG	5 wt%	1.492	4.2×	Li et al., 2021
Paraffin/Copper Foam	90% porosity	3-8	13-35×	Xiao et al., 2013
Paraffin/Metal Foam	85-97% porosity	0.56-2.75	2.5-12×	Zhang et al., 2020
Paraffin/Al ₂ O ₃ NPs	5 wt%	0.40	1.8×	Kumar et al., 2025
Paraffin/CNT/Graphene	3:7 ratio	0.36	1.55×	Zou et al., 2018

The data reveals that expanded graphite composites provide superior thermal conductivity enhancement compared to nanoparticle additives, particularly at higher loading fractions. The formation of three-dimensional interconnected graphite networks enables efficient heat conduction pathways throughout the composite material. Metal foam composites demonstrate excellent thermal performance but involve trade-offs with weight and phase change material loading capacity due to the solid metallic skeleton structure occupying significant volume within the composite.

5.2 Phase Change Characteristics and Latent Heat Capacity

Table 2 summarizes the phase change temperature ranges and latent heat capacities for various composite phase change materials. The addition of thermal enhancement additives generally produces minimal effects on melting temperatures, with deviations typically below 5 degrees Celsius from pure phase change material values. Latent heat capacity experiences moderate reductions proportional to additive content, as the non-phase-change components dilute the effective energy storage capacity per unit mass of composite material.

Table 2: Phase Change Properties of Composite PCMs

Material	Melting Point (°C)	Latent Heat (J/g)	Heat Reduction (%)	Reference
Pure Paraffin	42-44	258	-	Sari & Karaipekli, 2007
Paraffin/EG 10%	41-43	232	10%	Sari & Karaipekli, 2007
Pure PA/SEBS	-	179.2	-	Liu et al., 2023
PA/SEBS/EG 6%	-	167.5	6.5%	Liu et al., 2023
Paraffin/Silica/Graphene	58-59	125	28%	Wang et al., 2023
PA/SBS/TPU/EG	52-55	156	15%	Zhang et al., 2023
Paraffin RT-42	38-43	174	-	Multiple sources

The results indicate that composite formulations with 10-20 weight percent thermal enhancement additives maintain 70-90% of the original latent heat capacity of pure phase change materials. This represents an acceptable trade-off considering the substantial thermal conductivity improvements achieved. Higher additive concentrations beyond 20 weight percent generally provide diminishing returns in thermal conductivity enhancement while increasingly compromising latent heat storage capacity. Optimal composite designs must balance these competing factors to maximize overall thermal management effectiveness.

5.3 Battery Thermal Performance with Composite PCMs

Table 3 presents experimental battery thermal performance data comparing different thermal management approaches. Composite phase change materials demonstrate substantial improvements in maximum battery temperature control compared to natural convection or pure phase change material cooling. Temperature reductions of 6-19 degrees Celsius have been achieved during high discharge rate conditions using optimized composite formulations.

Table 3: Battery Temperature Performance with Different Thermal Management Systems

Cooling System	Discharge Rate	Max Temperature (°C)	Temperature Reduction (°C)	Reference
Natural Convection	3C	51.2-81.6	Baseline	Kumar et al., 2025
Pure Paraffin PCM	3C	47.8	3.4	Kumar et al., 2025
PCM + 5% Al ₂ O ₃	3C	45.6	5.6	Kumar et al., 2025
PCM + 10% Al ₂ O ₃	3C	43.2	8.0	Kumar et al., 2025
PCM + EG Composite	2C	48.9	13.7	Wang et al., 2023
PCM + Copper Foam	2C	37.2	14.0	Wang et al., 2015
Hybrid PCM + Liquid	3C	41.1	~10	Kong et al., 2020

The experimental data demonstrates that composite phase change materials with expanded graphite or metal foam additives provide superior thermal performance compared to nanoparticle-enhanced phase change materials at equivalent discharge rates. The enhanced thermal conductivity of graphite and metal foam composites enables more rapid heat absorption from battery surfaces and improved thermal distribution throughout the phase change material volume. Temperature uniformity also improves significantly, with temperature differentials reducing from 8-12 degrees Celsius for pure phase

change materials to 2-4 degrees Celsius for optimized composite systems.

5.4 Thermal Conductivity Enhancement Methods Comparison

Table 4 provides comparative analysis of different thermal conductivity enhancement strategies employed in composite phase change materials. The data reveals distinct performance characteristics and implementation considerations for each enhancement approach. Expanded graphite composites achieve the highest thermal conductivity improvements while maintaining relatively high phase change material

loading capacity due to the porous structure of expanded graphite particles.

Table 4: Comparison of Thermal Enhancement Methods

Enhancement Method	Thermal Conductivity Increase	Weight Impact	Cost Factor	Leakage Prevention	Reference
Expanded Graphite	400-1700%	Low	Low	Excellent	Yu & Tao, 2022
Metal Foam (Cu)	1300-4400%	High	Medium	Good	Xiao et al., 2013
Metal Foam (Al)	600-1800%	Medium	Medium	Good	Multiple sources
Nanoparticles	30-120%	Very Low	High	Poor	Zou et al., 2018
Carbon Nanotubes	35-55%	Very Low	Very High	Poor	Wang et al., 2015
Hybrid (CNT+Graphene)	120-155%	Low	High	Good	Zou et al., 2018

Metal foam composites demonstrate the highest absolute thermal conductivity values but introduce significant weight penalties that may compromise battery pack energy density in vehicle applications. The high thermal conductivity of metal foams also provides effective heat distribution but reduces the volumetric phase change material content to approximately 85-95% depending on foam porosity. Nanoparticle additives offer minimal weight impact but provide relatively modest thermal conductivity improvements and may introduce stability issues related to particle agglomeration and settling in liquid phase change materials. Expanded graphite represents the most balanced enhancement approach, delivering

substantial thermal conductivity improvements with minimal weight penalty and excellent leakage prevention through capillary absorption within the porous graphite structure.

5.5 Thermal Runaway Prevention Performance

Table 5 summarizes thermal runaway prevention capabilities of different composite phase change material systems. Composite phase change materials demonstrate substantial effectiveness in preventing thermal runaway propagation between battery cells. Maximum temperature reductions during thermal runaway events range from 60-70% depending on composite formulation and thermal event severity.

Table 5: Thermal Runaway Prevention with Composite PCMs

System Configuration	TR Cell Max Temp (°C)	Adjacent Cell Max Temp (°C)	Prevention Effectiveness	Reference
No Thermal Management	578	230	Baseline	Wilke et al., 2017
Paraffin/EG Composite	179	108	69-53% reduction	Wilke et al., 2017
Inorganic PCM	189	109	67-53% reduction	Al-Hallaj, 2022
Hybrid PCM + Liquid	230	<120	60-48% reduction	Kshetrimayum et al., 2019
Hydrated Salt PCM	250	115	57-50% reduction	Zhi et al., 2024

The results demonstrate that composite phase change materials effectively absorb heat during thermal runaway events, significantly reducing peak temperatures and preventing propagation to adjacent battery cells. The thermal runaway mitigation effectiveness depends critically on the thermal conductivity of the composite, which determines the rate of heat extraction from failing cells. Composites with expanded graphite or metal foam enhance thermal conductivity 10-fold or more, enabling rapid heat absorption and distribution that prevents adjacent cells from reaching thermal runaway onset temperatures. The latent heat storage capacity also plays a crucial role, as the phase change material must

possess sufficient energy absorption capacity to handle the extreme heat release rates during thermal runaway events, which can exceed 100 W per cell during rapid failure scenarios.

5.6 Hybrid System Performance Enhancement

Table 6 presents performance data for hybrid thermal management systems combining composite phase change materials with active cooling strategies. Hybrid configurations demonstrate superior thermal performance compared to either passive or active cooling alone, with synergistic benefits including reduced parasitic power consumption and enhanced thermal response characteristics.

Table 6: Hybrid Thermal Management System Performance

System Type	Max Temp at 4C (°C)	Temp Difference (°C)	Power Consumption	Coolant Flow Rate	Reference
Passive PCM Only	45.2	8.3	None	N/A	Mousavi et al., 2021
Active Liquid Only	38.6	4.5	High	3.9 L/min	Multiple sources
Hybrid PCM + Liquid	32.8	2.4	Moderate	0.5 L/min	Mousavi et al., 2021
PCM + Nano-Liquid	35.4	3.2	Moderate	1.2 L/min	Jilte et al., 2021
PCM + Microchannel	34.2	2.8	Low-Moderate	0.8 L/min	Kshetrimayum et al., 2019

The experimental data reveals that hybrid systems reduce maximum battery temperatures by an additional 6-9 degrees Celsius compared to passive phase change material cooling alone during high discharge rates. More significantly, hybrid configurations achieve these temperature reductions with coolant flow rates reduced by 60-80% compared to pure active liquid cooling systems. This reduction in flow rate translates directly to decreased parasitic power consumption by cooling system pumps and reduced system complexity. Temperature uniformity also improves substantially in hybrid systems, with

temperature differentials decreasing to 2-3 degrees Celsius compared to 8-10 degrees Celsius for passive systems alone.

6. Discussion

6.1 Thermal Enhancement Mechanisms

The substantial thermal conductivity improvements achieved through expanded graphite, metal foam, and nanoparticle additives stem from distinct physical mechanisms that merit detailed examination. Expanded graphite composites create continuous three-dimensional thermal conduction networks through interconnected graphite lamellae that span the

phase change material matrix (Sarı & Karaipekli, 2007). The worm-like morphology of expanded graphite provides extremely high aspect ratio structures that form percolating networks even at relatively low mass fractions of 10-20%. These graphite networks enable direct thermal conduction pathways that bypass the low thermal conductivity organic phase change material matrix, resulting in effective thermal conductivity values approaching those of the graphite additive itself in the direction of graphite alignment. Metal foam enhancement operates through similar network formation principles but with fundamentally different structure (Siavashi et al., 2020). Open-cell metal foams provide rigid, interconnected metallic skeletons with porosity typically ranging from 85-97%. The solid metal ligaments possess thermal conductivities exceeding 200 W/(m·K) for aluminum and 400 W/(m·K) for copper, creating highly effective heat conduction channels throughout the composite volume. However, the trade-off involves reduced phase change material loading capacity, as the metal foam structure occupies 3-15% of the composite volume depending on porosity.

Nanoparticle enhancement mechanisms differ substantially from network-forming approaches (Zou et al., 2018). Dispersed nanoparticles increase thermal conductivity through enhanced phonon transport at particle-matrix interfaces and modification of thermal boundary layer characteristics in liquid phase change materials. However, nanoparticle enhancements remain limited by several factors including: particle agglomeration that reduces effective surface area, sedimentation issues in liquid phases, and the fundamental constraint that dispersed particles cannot form continuous conduction pathways comparable to network structures. These limitations explain why

nanoparticle-enhanced phase change materials typically achieve thermal conductivity improvements of only 30-120% compared to 400-1700% for network-forming additives.

6.2 Optimization of Composite Formulations

The selection of optimal composite formulations requires careful balance of multiple competing factors including thermal conductivity enhancement, latent heat retention, weight considerations, leakage prevention, and cost. Expanded graphite emerges as the most versatile enhancement approach based on comprehensive analysis of these factors (Yu & Tao, 2022). At mass fractions of 10-15%, expanded graphite composites achieve thermal conductivity improvements of 400-800% while retaining 75-85% of the original phase change material latent heat capacity. The porous structure of expanded graphite provides excellent capillary absorption of liquid phase change material, effectively preventing leakage during repeated thermal cycles without requiring additional encapsulation.

Metal foam composites offer superior thermal conductivity enhancements but involve significant trade-offs (Xiao et al., 2013). The high weight of copper and nickel foams may compromise battery pack energy density, while aluminum foams offer better weight characteristics but lower thermal conductivity. The optimal metal foam porosity represents a critical design parameter that balances thermal conductivity enhancement against phase change material loading capacity. Research indicates that porosities of 90-93% provide effective compromise, delivering thermal conductivity improvements of 600-1200% while maintaining phase change material volume fractions above 90%. Nanoparticle additives demonstrate limited practical utility as standalone enhancement strategies due to

modest performance improvements and potential stability issues (Zou et al., 2018). However, hybrid approaches combining low concentrations of nanoparticles with expanded graphite or metal foam may offer synergistic benefits. The nanoparticles can enhance thermal conductivity in regions between network structures, potentially improving overall thermal uniformity. Such hybrid formulations require careful optimization to avoid excessive latent heat dilution while maintaining dispersion stability.

6.3 Thermal Management System Design

Effective thermal management system design must address multiple operational scenarios including normal discharge conditions, rapid charging requirements, and extreme thermal abuse situations. Pure passive phase change material systems demonstrate adequate performance during moderate discharge rates up to 2-3C but encounter limitations during high-power demands or rapid charging scenarios (Kumar & Rao, 2024). The finite latent heat capacity of phase change materials becomes fully consumed during extended high-power operation, after which only sensible heat absorption remains available, leading to progressive temperature rise. Hybrid thermal management systems combining composite phase change materials with active cooling address these limitations through complementary thermal response characteristics (Mousavi et al., 2021). The phase change material component provides rapid thermal buffering during transient high-power events, absorbing heat spikes without requiring immediate active cooling response. The active cooling system operates continuously at reduced power levels to extract accumulated heat from the phase change material, maintaining the composite in a partially solidified state ready for subsequent thermal events. This approach reduces peak cooling system power

requirements by 50-70% compared to pure active cooling while ensuring continuous thermal management capability.

The spatial arrangement of composite phase change materials within battery modules represents another critical design consideration (Kong et al., 2020). Sandwich configurations with phase change material layers between battery cells provide effective lateral heat spreading and cell-to-cell thermal isolation. However, heat extraction from the phase change material volume requires careful attention to thermal path design. Integration of aluminum or copper fins, heat pipes, or liquid cooling channels within the phase change material volume enhances heat extraction rates and prevents localized phase change material overheating during extended operation.

6.4 Thermal Runaway Mitigation Strategies

The capability of composite phase change materials to prevent thermal runaway propagation represents one of their most valuable attributes for battery safety (Wilke et al., 2017). During thermal runaway events, failing cells release heat at rates exceeding 100-200 W over time periods of 10-30 seconds, creating intense localized heating that can trigger runaway in adjacent cells. Composite phase change materials with high thermal conductivity rapidly absorb and distribute this heat throughout the phase change material volume, significantly reducing peak temperatures experienced by adjacent cells. The effectiveness of thermal runaway prevention depends critically on three composite properties: thermal conductivity, latent heat capacity, and thermal mass. High thermal conductivity enables rapid heat extraction from failing cells before adjacent cells reach critical temperatures typically around 130-150 degrees Celsius where internal exothermic reactions accelerate (Feng et al., 2020). Adequate latent heat capacity ensures sufficient

energy absorption capability to handle the total heat release during thermal runaway events, which can reach 100-300 kJ for large format cells. Thermal mass of the composite phase change material system provides additional sensible heat absorption after latent heat capacity is exhausted, further buffering temperature rise during extended thermal events.

Research indicates that composite phase change material systems can reduce thermal runaway propagation risks by 70-85% compared to conventional thermal management approaches (Al-Hallaj, 2022). This substantial safety enhancement justifies the added weight and complexity of phase change material integration in high-performance battery systems. However, phase change material selection must consider thermal stability at elevated temperatures, as some organic phase change materials may decompose or combust at temperatures exceeding 200-250 degrees Celsius, potentially exacerbating thermal runaway scenarios rather than mitigating them.

7. Conclusion

This comprehensive review demonstrates that composite phase change materials represent highly effective passive thermal management solutions for lithium-ion battery applications in electric vehicles. Expanded graphite composites emerge as the most promising enhancement approach, achieving thermal conductivity improvements of 400-1700% while maintaining excellent phase change material loading capacity and leakage prevention characteristics. Metal foam composites provide even higher thermal conductivity enhancements but involve weight penalties that may compromise battery pack energy density. Nanoparticle additives offer limited standalone benefits but may provide value in hybrid composite formulations. Experimental evidence

confirms that composite phase change materials effectively maintain battery temperatures within optimal operating ranges during high discharge rate conditions, achieving temperature reductions of 6-19 degrees Celsius compared to natural convection cooling. Thermal uniformity improves substantially with temperature differentials decreasing from 8-12 degrees Celsius for passive systems to 2-4 degrees Celsius for optimized composite configurations. The thermal runaway prevention capabilities of composite phase change materials represent a critical safety advantage, with experimental studies demonstrating 60-70% reductions in peak temperatures during thermal abuse scenarios.

Hybrid thermal management systems combining composite phase change materials with active cooling demonstrate superior performance compared to either approach independently. These systems achieve maximum battery temperatures 6-9 degrees Celsius lower than passive phase change material cooling alone while reducing coolant flow requirements by 60-80% compared to pure liquid cooling systems. This synergistic performance enhancement translates to improved thermal response characteristics with significantly reduced parasitic power consumption, addressing a fundamental limitation of conventional active cooling approaches. Future research directions should focus on several critical areas to advance composite phase change material technology for battery thermal management. Development of form-stable composite structures with enhanced thermal conductivity networks exceeding 10 W/(m·K) while maintaining latent heat capacities above 150 J/g represents an important technical challenge. Investigation of non-flammable phase change materials and composites for improved safety during extreme thermal events requires continued attention.

Optimization of hybrid thermal management system architectures that integrate composite phase change materials with advanced active cooling strategies offers significant potential for next-generation electric vehicle battery systems. Comprehensive lifecycle analysis examining thermal performance degradation, mechanical stability, and cost-effectiveness over extended operational periods will guide practical implementation decisions.

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