A REVIEW ON PCM-BASED HYBRID BTMS FOR LI-ION BATTERY: STRATEGIES FOR THERMAL CONDUCTIVITY ENHANCEMENT AND STRUCTURAL ENHANCEMENT

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ABSTRACT

Effective thermal management is crucial for the safety, performance, and longevity of lithium-ion batteries operating under high power and energy density conditions. Though phase change material (PCM)-based battery thermal management systems (BTMS) offer passive temperature regulation through latent heat absorption, PCM's low thermal conductivity limits heat dissipation under severe operating conditions. Current review widely investigates and systematically summarizes recent advances in PCM-based hybrid BTMS for lithium-ion batteries, with particular emphasis on strategies for thermal conductivity enhancers and structural enhancement strategies. Thermally conductive filler-enhanced PCM composites, metal foam and fin-assisted structures, heat pipe-assisted systems, and hybrid PCM configurations combined with air or liquid cooling are critically overviewed and summarized highlighting design synergies and limitations. Additionally, current challenges related to PCM leakage, electrical insulation, weight penalties, and structural complexities are identified. The review concludes by outlining future perspectives to adopt a more integrated approach that encompasses these considerations.

Keywords- Battery Thermal Management Systems, Lithium- ion Battery, Thermally Conductive Fillers, Hybrid PCM configurations

INTRODUCTION

Lithium-ion batteries (LIBs) have emerged as the leading energy storage solution for our electric future, powering everything from smartphones to promisingly growing EV sector. With high energy density and long lifespan, these batteries are making themselves ideal for the demands of modern transportation. However, the performance and safety of LIBs are inherently linked to their operating temperature, posing significant challenges such as thermal runaway risks due to overheating. Consequently, effective thermal management systems are indispensable for optimizing battery performance and ensuring safety (Nishad et al., 2025). The performance of batteries is closely tied to their operating temperature (typically safe between 200C - 400C), which is influenced by environmental conditions (Hu et al., 2025). Effective battery thermal management

system (BTMS) plays a crucial role in maintaining battery temperatures within limits. BTMS can use various cooling or heating strategies, including air cooling, liquid cooling, phase change material (PCM), heat pipes and thermoelectric coolers. Each approach is chosen based on application requirements such as power density, cost, size constraints, and environmental conditions. Hybrid cooling strategies using PCM for LIBs represent a promising approach to managing thermal loads in high-performance applications such as electric vehicles and energy storage systems. These strategies combine the passive thermal buffering capacity of PCMs which absorb and store heat during phase transitions with active cooling methods like air or liquid circulation, heat pipes, or thermoelectric coolers. However, challenges remain, including the low thermal conductivity of many PCMs, the need for effective encapsulation to prevent leakage and the integration of these materials into compact, lightweight and cost-effective battery modules. Ongoing research focuses on improving PCM formulations, incorporating thermally conductive additives and optimizing hybrid system designs to meet the demanding thermal management needs of next-generation battery technologies.

RESEARCH METHODOLOGY

Fundamentals of PCM-Based BTMS

PCM based BTMS acts as a passive thermal management method. A PCM is a material which absorbs heat during melting and releases it during solidification, maintaining the battery temperature within a safe range. When the battery heats up during charging or discharging, the PCM melts and absorbs the excess heat, preventing temperature rise. Once the battery cools, the PCM solidifies, releasing the stored heat to the surroundings (Jie et al., 2025). This method offers several benefits, including uniform temperature distribution, no power consumption, silent operation, and enhanced battery life and safety. Despite these advantages, conventional PCM-based BTMS suffer from inherent limitations. Most PCMs exhibit low thermal conductivity, which restricts heat dissipation and leads to localized temperature accumulation under high C-rate operation. In addition, large PCM volumes are often required to achieve sufficient thermal buffering, resulting in increased system mass and reduced pack-level energy density. These limitations motivate the development of enhanced and compact PCM-based BTMS. Commonly used PCMs for battery applications include organic PCMs such as paraffin waxes, inorganic PCMs such as salt hydrates, and eutectic mixtures. Table 1. shows the comparison of thermophysical properties between organic PCMs and inorganic PCMs (Zhi et al., 2022)

Table 1. Thermophysical properties of organic PCMs and inorganic PCMs (Zhi et al., 2022)

Thermophysical properties	Organic PCMs		Inorganic PCMs
	Paraffin materials	Non-paraffin materials	
Representative materials	Paraffin	Fatty acids, lipids, alcobols, glycol	Salt hydrates, metals inorganic compounds
Thermal conductivity (W/(m•K))	0.2	0.13–0.15	0.49–1.22
Latent heat capacity (kJ/kg)	60–269	140–230	86–328
Melting point (°C)	20–70	16–200	-33–117
Density (kg/m³)	760	850–1240	1450–2100
Volume change	Large	Small	Small
Thermal stability	Stable	Stable	Instable
Cost	Lower	High, 3 times of paraffin	Lowest
Phase separation and Supercooling	Non-existent	Non-existent	Existent
Corrosion	Non-corrosive	Non-corrosive	Corrosive

Thermal Conductivity Enhancement Strategies

To address the issue of low thermal conductivity of pure PCMs, few researchers have introduced thermal conductivity enhancers (TCEs), carbon-based materials, metals, and nitrides, often incorporated into composite or encapsulated structures. These TCEs allow the composite PCM (CPCM) to effectively absorb heat generated by the battery through latent heat during phase transition, which is critical for maintaining the optimal operating temperature range of 20^0C - 40^0C.

A macro-encapsulated CPCM battery cooling pack by infiltrating paraffin wax into graphite foam and encapsulating it with a 3D-printed polyethylene-boron nitride composite layer to prevent leakage is developed by Nishad et al. (2025). The study showed conductive foams outperformance over simple fillers because of development of continuous 3D heat-transfer networks. The graphite foam composite achieved a high thermal conductivity of 7.85 W/m·°C, about 37.5 times higher than pure paraffin. A boron nitride–based encapsulation layer ensured electrical safety while maintaining good thermal conductivity. Rahmanian et al. (2025) observed that graphene-based thermal conductivity enhancers effectively limited the maximum temperature of battery to 47.82 °C during 5C discharge. Though graphene outperformed copper foam and metal plates due to superior thermal bridging, its large-scale applicability was limited by higher cost and scalability challenges compared to copper foam. Li et al. (2025) proposed a CPCM with 10% expanded graphite (EG), 90% paraffin wax (PW). The inclusion of EG enhanced the material's thermal conductivity to 2.5 W/m·K, which significantly improved the temperature uniformity of the battery pack. By optimizing its combination with liquid cooling pipes, the hybrid BTMS reduced peak battery temperature by 7 K compared to pure PCM cooling. Luo et al. (2024) investigated effect of CPCM enhanced with carbon-based materials

(fibre, graphene, expanded graphite), metals (nano-copper, foams), and nitrides (boron nitride) on temperature distribution during phase transition. The study ensured temperature uniformity by integrating CPCM into liquid cold plates and addressed excessive temperature gradients at the module level. Dilbaz et al. (2024) evaluated PCM, liquid-assisted, and hybrid BTMS for li-ion battery pack. The study exhibited notable heat transfer enhancement in a cooling system integrated with liquid and nanofluids (water/Al2O3) through reduction in peak temperature by 28% and cell temperature differences restriction of 5 °C. Chen et al. (2023) experimentally prepared a microencapsulated PCM slurry (MPCMS) with three base liquids (water, ethanol, and silicone oil). Graphene (GE) as TCE was added in slurry with 0.05 wt%, which enhanced thermal conductivity by 10.3%. The GE-MPCMS-Si coolant showed superior thermal stability and durability over pure silicone oil by promoting both convective heat transfer and latent heat absorption. Rostami et al. (2022) created a heatsink employing nano-PCM, composed of CaCl2·6H2O enhanced with graphene nanoparticles. It was observed that using graphene in PCM, combined with helical microchannels for nanofluid flow, ensured effective heat extraction from the battery to the PCM, particularly when assisted by the high thermal conductivity of the nanoparticles. Liu et al. (2021) prepared a CPCM using paraffin (PW)/expanded graphite (EG)/high-density polyethylene (HDPE) and nano silver (nano-Ag). While the CPCM exhibited high latent heat and low leakage rate, the study concluded that enhancers alone were insufficient for high-rate (3C) discharge heat dissipation and must be coupled with liquid cooling to maintain peak temperature below 450C. Table 2. shows critical overview of TCEs for PCM in BTMS.

Table 2. Critical overview of thermal conductivity enhancers for PCM in BTMS

Enhancer Type	Materials	Thermal Properties	Primary Function	Challenges	Performance	Reference
Pure PCM	Paraffin Wax (PW)	Thermal conductivity (0.2 W/m K); Latent heat (165 kJ/kg for RT-42)	Low energy consumption; isothermal latent heat absorption	Low thermal conductivity; leakage during melt; failure on latent heat depletion.	Without cooling, high discharge rates (3C) can lead to unsafe temperatures (59.60^0C peak,10.82^0C difference).	Luo et al. (2024), Dilbaz et al. (2024), Rahmanian et al. (2025), Nishad et al. (2025)
Carbonaceous Foams & Matrices	Graphite Foam (GF); Expanded Graphite (EG)	GF high thermal conductivity, 7.85 W/m.^{0}C	Efficient 3D conductive networks formation; EG acts as a supporter to reduce PW leakage	leakage during melt, reduced PCM mass fraction and latent heat storage (e.g., GF_PW latent heat 82.9%–83.9% of pure PW).	EG/octadecane in a cold plate reduced BTMS energy consumption. Composite PW/EG/HDPE/nano-Ag showed low leakage.	Liu et al. (2021), Luo et al. (2024), Nishad et al. (2025)
Carbon Nanomaterials	Graphene (GE)	High thermal conductivity	Effective in thermal bridging, controlled maximum temperature	Scalability, complexity and cost barriers	Only GE peak temperature 47.82 ^{0}C at 5C discharge, Integration with, PCM, and heat-pipe 39.23^0C peak	Rahmanian et al. (2025)
Metallic Enhancers	Copper (Cu) Plate; Copper Foam (80%/90% porosity);	High thermal conductivity	Provides strong thermal pathways and structural enhancement.	Increases overall weight and cost	Copper plate control system achieved 52.10^0C peak at 5C; Copper foam (80% porosity) achieved 54.22^0C peak at 5C.	Liu et al. (2021), Rahmanian et al. (2025)

	Nano-Silver (Nano-Ag)				Nano-Ag is used as a thermal enhancer in CPCM melt blending	
Nitrides (Electrical Insulators)	Boron Nitride (BN)	High thermal conductivity; Low electrical conductivity.	Required during simultaneous high heat transfer and electrical insulation	BN concentration >40 wt% can compromise 3D printability	PE/BN coating (40 wt% BN) used for encapsulation measured thermal conductivity of 1.5 W/m.^{0}C	Nishad et al. (2025)
Encapsulation/Polymer Matrices	High-Density Polyethylene (HDPE); PE/BN composite shell	High thermal conductivity	Provides structural stability, preventing PCM leakage	Encapsulation layer adds mass, reducing the effective latent heat density of the final composite	PE/BN macro-encapsulation of GF_PW composite resulted in zero leakage and high thermal conductivity 4.5-4.6 W/m.^{0}C	Liu et al. (2021), Nishad et al. (2025)
Microencapsulated Slurry (MPCMS)	MPCM + Silicone Oil + Graphene	High thermal conductivity	Combines liquid convection efficiency with PCM latent heat absorption	Base liquid requirement to ensure long-term stability	GE-MPCMS-Si reduced peak temperature by 14.49^{0}C and temperature variance by 3.8^{0}C^2	Chen et al. (2023)
Nano-PCMs	CaCl2·6H2O + Graphene nanoparticles	High thermal conductivity	Ensures effective heat extraction from battery	At Re $\geq$ 500, the PCM may remain entirely solid	In hybrid heatsinks with nanofluid flow, increasing flow rate reduces heat stored in PCM effectively	Rostami et al. (2022)

Structural and Hybrid Enhancement Strategies

To mitigate impact of low thermal conductivity and uneven melting of PCMs on heat dissipation from li-ion batteries, structural enhancements, metallic fins or foams, prove their necessity by facilitating faster heat distribution and preventing heat from being trapped in the liquid layer around the battery surface. These enhancements prevent hot spots, control unwanted convection, and keep battery temperature uniform, making PCM effective during high discharge rates and ensure that battery stays within a safe operating temperature, protecting its performance and lifespan. The hybrid enhancement strategies for BTMS involve the integration of PCM with secondary active or passive components, structural enhancements, heat pipes or liquid cooling. Corresponding research is discussed further herewith. Hu et al. (2025) showed structural enhancement in hybrid BTMS by integrating PCM with heat pipes and aerogel insulation to handle extreme temperatures from -400C to 400C. The system utilized an irregular aerogel container to maintain uniform spacing around a 9-cell pack, using clover-shaped copper fins to enhance PCM conductivity. For hybrid functionality, used passive heat storage sodium carbonate decahydrate PCM with a 15 mm thick aerogel insulation layer for low-temperature retention and active water-cooled heat pipes for high-rate discharge (2C or higher). Ismail et al. (2025) examined the impact of system scale and fin orientation on thermal performance of BTMS. On comparison among vertical, horizontal, A-shaped, and V-shaped fins across 10 mm and 100 mm scales, horizontal fins proved superiority for large-scale systems and long-duration loading by suppressing thermal non uniformity. Luo et. al. (2025) investigated an active hybrid system integrating annular thermoelectric coolers (ATEC) with PCM for cylindrical batteries. A coaxial cooling design linking annular fin frame with the inner and outer ATECs ensured

balanced thermal contact and prevented heat accumulation at the pack's core. The proposed hybrid enhancement used active ATEC current management alongside passive PCM latent heat with optimal configuration of 8 annular fins and 12% EG mass fraction to effectively balance cooling performance along with system power consumption. Najafi Khaboshan et al. (2024) evaluated a three-way hybrid passive strategy combining PCM, copper fins, and copper metal foam. The fins acted as a heat distribution network, facilitating heat spread, while metal foam ensured uniform heat distribution between the battery and the environment. This hybrid synergy achieved a 75% reduction in temperature difference compared to pure PCM systems, maintaining optimal operational safety under high rate 3C discharge. Zare et al. (2024) introduced a structural enhancement using a combination of internal and external fins to create PCM silos around cylindrical batteries. This configuration addressed the low thermal conductivity of PCM by providing direct conduction paths through the material while simultaneously extending the external surface area for heat dissipation to the ambient environment. The 4 internal-external fins showed optimal structural balance, providing nearly uniform cooling, a 17.45 K reduction in surface temperature at 5C discharge, and offered superior energy density and heat storage capacity compared to more crowded fin configurations. Alghassab (2024) investigated metallic fin geometries to improve the passive cooling efficiency of paraffin-based BTMS. An optimal configuration was identified focusing on the height and thickness of longitudinal copper fins, 4 fins at 10 mm height, proving superior cooling effects compared to configurations with shorter, more numerous fins (10 fins of 3 mm height). Hybrid material selection showed that copper's 60% higher thermal conductivity provides 2–30C better cooling than aluminum, though it incurs a weight penalty due to higher density. A hybrid fin-enhanced liquid cooling system using expanded graphite (EG) modified CPCM was developed by Liu et al. (2023). A specialized configuration utilizing two-layer PCM separated by cylinders and indirect fin contact significantly improved temperature uniformity. This hybrid strategy also optimized coolant flow, demonstrating that a counter flow scheme significantly reduced maximum temperature differences compared to parallel flow during demanding 5C discharge cycles. Mostafavi & Ankur Jain (2022) worked on a theoretical foundation for the transient effectiveness and efficiency of fins embedded in PCMs. The analysis coupled transient heat diffusion within a rectangular fin with the phase change kinetics of the surrounding PCM. It demonstrated that fin effectiveness was higher for thinner and longer fins. Conversely, fin efficiency was lower for longer fins because it took longer time for heat to diffuse throughout a longer fin, pushing it further from the ideal isothermal condition. Summary of structural and hybrid enhancements strategies for BTMS is discussed in Table 3.

Table 3. Summary of structural and hybrid enhancements strategies for BTMS

Structural Enhancement Strategy	Hybrid Strategy (Passive/Active)	Key Finding	Identified Limitations	References
Irregular aerogel container surrounding battery pack + clover-shaped copper fins	Passive: aerogel insulation/PCM for cold; Active: water-cooled heat pipes for high-rate discharge	Fins improved PCM conductivity, PCM and aerogel increased the insulation period by 600% over PCM alone; handled extreme conditions from -40^{0}C to 40^{0}C	Effect of insulation thickness diminishes beyond 15 mm. High initial PCM temperatures risk exceeding 40°C limits during discharge	Hu et al. (2025)
Coaxial structure: annular fin frame linking inner/outer Annular Thermoelectric Coolers (ATECs)	Passive: PCM latent heat storage; Active: ATEC current control	Optimal setup (8 fins, 12% EG, 0.8 A) keeps peak temperature < 321.01 K and temperature difference < 3.41 K with minimized power consumption	TEC systems have relatively high cost and power consumption, Excessive current or % EG diminishes the role of PCM latent heat	Luo et al. (2025)
Compared vertical, horizontal, A-shaped, and V-shaped fins across 10 mm and 100 mm scale	Passive: Heat transfer rate improvement through fins	At 480s, 9 vertical fins achieved 38.3^{0}C peak with a 2.4^{0}C non uniformity, at 720s, 7 horizontal fins achieved 42.5^{0}C peak with a 2.6^{0}C non uniformity	Fins offer no meaningful improvement compared to PCM alone for small scale system, the cell discharge rate and external conditions were constant in time	Ismail et al. (2025)
Compared and optimized longitudinal copper & aluminium fins	Passive: High-conductivity copper fins with paraffin wax	6 copper fins (0.2 mm thick, 11.67 mm high) gave optimal performance, 4 longitudinal fins of 10 mm height perform better than 10 fins of 3 mm height	Fin count has minimal impact for highly conductive PCMs, Fin material cost and weight limits applicability	Alghassab (2024)
PCM with 4 combinations (with copper/aluminium) of fins and metal foam	Passive Hybrid: Heat transfer enhancement combining PCM, rectangular fins, and metal foam	Copper fins with copper metal foam yielded the lowest battery surface temperature compared to other material combinations in both normal and harsh environmental conditions	High computational cost for simulations, PCM inhomogeneity for multiple thermal cycles	Najafi Khaboshan et al. (2024)
Cylindrical and 4 longitudinal internal-external fins (11 mm long, 1 mm thick, 65 mm high) creating PCM silos around the battery	Passive: Heat transfer enhancement with Internal-external fins	4 internal-external fins are optimal; reduced battery surface temperature by 9,90 K and 17.45 K at 3C and 5C discharge respectively compared to PCM without fins	Applicable to cylindrical batteries only; increased fin quantity reduces PCM volume and total latent heat capacity	Zare et al. (2024)
CPCMs and liquid cooling with fins and counter flow	Passive: EG-modified PCM with fins; Active: counter-flow water cooling channels	EG (12-16%) reduces peak temperature by 7.66°C at 5C; with fins and counter-flow cooling limits peak temperature < 46.2°C temperature difference < 4.2°C at 5C	Fins effect diminishes on high EG content (>12%), system intricacy	Liu et al. (2023)
Analytical model coupling transient diffusion of fin with constant cross-section embedded in PCM	Passive: Heat transfer enhancement combining PCM, rectangular fins	thinner/longer fins maximize effectiveness, but longer fins decrease efficiency	Validates small Stefan numbers only; Neglects convection in liquid phase and assumes temperature-independent properties	Mostafavi & Ankur Jain (2022)

CONCLUSIONS

• Though TCEs significantly improve heat spreading and peak temperature suppression in PCM-based BTMS, yet introduce trade-offs, including reduced latent heat capacity, increased cost and system weight, and risks of PCM leakage.

• While carbon-based TCEs, being highly conductive, may increase electrical short-circuit risks, requiring insulation or specialized encapsulation.

• Structural enhancers, fins and metal foams create high-conductivity pathways into the PCM bulk, enabling faster heat distribution and reducing thermal trapping near the battery surface

while adding weight and structural complexity.

• Recent research increasingly focuses on hybrid and multifunctional BTMS rather than single-material solutions, integrating enhanced PCMs with active cooling methods, for maintaining thermal stability under high-power and extreme operating conditions.

• This review highlights that no single TCE or structural enhancement provides an optimal solution.

• Effective BTMS performance relies on synergistic hybrid architectures that balance thermal conductivity, latent heat storage, safety, weight, and durability to ensure reliable lithium-ion battery operation within the optimal temperature range.

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