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Liquid Cooling–PCM Composite Thermal Management Systems for Lithium-Ion Power Batteries in Electric Vehicles: A Review

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Abstract. With the rising demand for fast charging and high-rate operation of new energy vehicles, lithium-ion power batteries generate increasing heat during charge and discharge. This conditions result in cell heat accumulation and module thermal imbalance. Excessively high operating temperatures accelerate battery capacity degradation, shorten cycle life, and increase safety risks. Meanwhile, large temperature gradients impair cell-to-cell consistency and limit the overall performance of battery packs. Therefore, efficient and reliable battery thermal management systems (BTMS) for high heat flux applications improve lithium-ion power battery performance. This paper investigates liquid cooling-PCM composite thermal management systems for lithium-ion power batteries in electric vehicles. Besides, it reviews the development status, heat transfer mechanisms, structural features, operating conditions, control strategies, and optimization methods for active, passive, and composite architecture. The study indicates that the liquid cooling-PCM composite thermal management system combines PCM heat storage with liquid cooling heat dissipation, reducing peak temperature and boosting thermal uniformity. However, additional weight, cost, and control complexity remain key challenges. Future work should focus on lightweight high-conductivity PCM composites, efficient control strategies, and aging-aware optimization.

Keywords: Lithium-ion power battery, battery thermal management, phase change material, liquid cooling heat dissipation

1. Introduction

The increasing demand for fast charging in new energy vehicles requires lithium-ion batteries to operate under high charge and discharge rates, thereby leading to intensified heat generation and temperature non-uniformity, which adversely affect battery performance and safety. Conventional thermal management strategies, however, often involve trade-offs between cooling performance, energy consumption, and system complexity. Liquid cooling-PCM composite systems provide an effective solution by combining the transient heat absorption capability of phase-change materials with the continuous heat dissipation capacity of liquid cooling. However, nonlinear phase change and coupled heat transfer complicate modeling and optimization. Though advanced control methods enhance thermal regulation, their implementation is limited by onboard computing capacity. Thus,

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achieving coordinated optimization of temperature control, energy efficiency, and battery lifespan remains a key challenge. Current research has mainly focused on PCM enhancement, liquid cooling structure optimization, and control algorithm development, whereas comprehensive evaluations of thermal management architectures, control approaches, and multi-objective optimization constraints are still insufficient. Accordingly, this paper investigates liquid-cooled PCM composite thermal management systems for lithium-ion batteries in electric vehicles. In particular, it examines the operating principles and performance limitations of active, passive, and hybrid thermal management schemes, control strategy characteristics and optimization methods under multi-objective and computing constraints. Furthermore, the performance of different thermal management schemes is compared regarding temperature regulation, temperature uniformity, mass, and cost, followed by an analysis of current challenges and future research directions.

2. The classification and operating principles of battery thermal management systems

2.1. Active thermal management systems

Active BTMS relies on external electric power to drive cooling medium circulation or refrigeration devices to continuously remove heat released by batteries, thus showing strong temperature control ability under high thermal load conditions. This makes it suitable for fast charging and high-rate operation. The main technical routes include air cooling, indirect liquid cooling, and thermoelectric cooling, which differ significantly in heat transfer mechanisms and application ranges [1, 2].

Air cooling transfers heat through air convection. Due to its simple structure and low cost, it is widely used; however, its poor heat exchange capacity cannot meet heat dissipation needs under high heat flux conditions. Thermoelectric cooling separates hot and cold ends based on the Peltier effect, featuring fast response and compact layout. Nevertheless, its low cooling efficiency and limited power output make it unsuitable for large-capacity battery packs [1]. In contrast, indirect liquid cooling transfers heat via circulating coolant and cold plates, providing high heat exchange efficiency and precise temperature control. Thus, it has become the most commonly used active thermal management solution for power batteries. However, the coolant temperature gradually increases along the flow path, causing temperature gradients between cells and reducing module temperature uniformity. Optimized channel layouts and structural designs are therefore required to mitigate this issue.

2.2. Passive thermal management systems

Passive BTM systems rely on PCM phase change to absorb heat through latent heat storage without external energy input. Paraffin-based PCMs are the most widely used type; they mitigate transient battery temperature spikes within the phase-change temperature range, but cannot continuously dissipate accumulated heat and have limited heat storage capacity [3].

Pure paraffin PCMs suffer from low thermal conductivity, slowing internal heat transfer. Under high-rate charge and discharge, partial PCM melts first and forms liquid regions with weaker heat conduction, concentrating heat on unmelted areas and causing uneven temperature distribution. During fast charging, continuous heat accumulation can occur, making long-term stable temperature control difficult [4]. To address this limitation, adding high-thermal-conductivity fillers has become a common modification strategy to enhance heat transfer. Carbon-based materials improve heat diffusion by constructing internal thermal conduction networks. Metal porous frameworks provide even higher thermal conductivity; however, their increased system weight and reduced PCM fraction

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limit their application in power batteries. Besides, PCM thickness also affects heat transfer paths and phase change duration. Too thin PCM layers lack sufficient heat storage capacity, while overly thick layers extend heat transfer distances and slow system response speed.

2.3. Hybrid thermal management systems

Hybrid BTMS integrates liquid cooling with PCM to combine active heat dissipation and passive heat storage. PCM absorbs transient heat generated during charge and discharge, suppressing local temperature spikes, while liquid cooling continuously removes accumulated heat and delays PCM thermal saturation. Therefore, composite structures enable both peak temperature reduction and improved temperature uniformity within battery modules [2, 5].

This coordinated heat transfer mechanism involves initial heat buffering followed by continuous heat dissipation. During the early stage of high-rate charge and discharge, PCM absorbs rapidly increasing heat to mitigate battery temperature rise. As heat accumulation continues, liquid cooling gradually dominates heat removal, maintaining stable battery operation under prolonged high-load conditions. Compared with standalone liquid cooling systems, composite systems exhibit superior transient thermal regulation. Meanwhile, compared with pure PCM systems, they reduce thermal saturation and maintain more stable temperature control during continuous high-load operation.

Table 1 summarizes the key performance indicators of three typical BTMS solutions. The liquid cooling-PCM composite system demonstrates comprehensive advantages in reducing peak temperature, suppressing module temperature differences, and delaying PCM thermal saturation. However, the integration of liquid cooling circuits and PCM storage structures increases system complexity, weight, and manufacturing costs [5, 6].

Table 1. Key performance comparison of three BTMS categories

Indicator	Pure Liquid Cooling	18.4 mm Graphite-Enhanced PCM	Liquid Cooling–PCM Composite System
Peak Temperature (°C)	36.8	42.0	36.7
Module Temperature Difference (°C)	1.8	1.4	1.0
PCM Melting Ratio	—	70% (Thermal Saturation)	36%
Mass (kg)	6.66	5.56	12.22
Cooling Cost ($)	200	—	230

3. Regulation and optimization approaches for electric vehicle battery thermal management systems

3.1. Basic feedback-based control methods

Feedback control achieves closed-loop temperature regulation by monitoring temperature deviation and adjusting cooling parameters. Without relying on precise thermal models, it offers a simple architecture and low computational burden, leading to its extensive adoption in BTMS [7].

Proportional-Integral-Derivative (PID) control is a widely used feedback algorithm in BTMS. The control output is calculated from three terms: proportional, integral, and derivative components.

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The proportional term responds to temperature errors and adjusts control variables to accelerate thermal regulation. Besides, the integral term compensates for accumulated errors during operation, reducing steady-state temperature deviations. The derivative term responds to temperature variation rates and improves transient performance under changing load conditions. In BTMS applications, PID controllers use temperature feedback (cell temperature or module temperature difference) to regulate coolant flow and battery temperature.

Since PID only involves basic mathematical operations, it can be easily embedded into vehicle controllers and satisfy real-time control demands. Nevertheless, fixed PID parameters cannot adapt to changing working conditions. When ambient temperature, charge-discharge rate or PCM phase change state changes, system thermal characteristics shift accordingly. Fixed parameters may lead to slow response, temperature overshoot or control oscillation [8]. For this reason, PID feedback control is often used as a baseline for evaluating the performance of advanced control strategies.

3.2. Model-driven and data-driven control strategies

Despite its simplicity and reliability, fixed-parameter feedback control faces nonlinearities, coupling effects, and varying conditions in BTMS. To improve adaptability, advanced methods are generally divided into model-driven and data-driven control approaches.

Model-driven control uses thermal models to predict battery states and optimize control actions. For example, Model Predictive Control (MPC) integrates battery heat generation models, PCM phase-change models, and liquid cooling heat transfer models to predict temperature evolution. Based on the predicted states, MPC optimizes control variables, such as coolant flow rate, under predefined constraints and performs rolling-horizon regulation [9, 10]. Compared with PID control, MPC can anticipate temperature variations and achieve higher control accuracy under complex operating conditions. However, its effectiveness strongly depends on model accuracy; deviations between model parameters and actual systems may degrade prediction reliability. In addition, online optimization requires intensive matrix computations, increasing hardware demands for embedded controllers [10].

Data-driven control does not require complete physical mechanism models. It builds mapping relationships between system states and control outputs using experimental or simulation datasets. Fuzzy control applies pre-set logical rules to convert temperature states into control commands, suitable for thermal systems hard to model accurately. Neural network control develops nonlinear mapping capacity via data training and realizes self-adaptive adjustment under various working conditions. Compared with model-driven control, data-driven control better fits strongly nonlinear systems, but its performance depends on comprehensive training datasets, and inference processes introduce additional computational burdens on embedded hardware. Thus, model-driven control exploits physical mechanisms for prediction, whereas data-driven control leverages data to improve adaptability under varying conditions. Both approaches overcome some limitations of traditional feedback control in dynamic regulation.

3.3. Coordinated system control strategies

Active liquid cooling and passive PCM heat storage have distinct thermal management features. Liquid cooling continuously removes battery heat but consumes extra energy; PCM buffers instantaneous heat spikes with latent heat yet easily reaches thermal saturation under long-duration high thermal loads. Single control logic cannot balance temperature control effect and system energy

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consumption at the same time. Coordinated control strategies coordinate liquid cooling heat dissipation and PCM heat storage to realize comprehensive optimization of composite BTMS [2, 5].

The controller dynamically distributes thermal management loads between liquid cooling and PCM according to real-time battery thermal status. It integrates multi-source state signals including single cell temperature, PCM phase change degree, coolant temperature and flow rate. Under low thermal load conditions, the system fully utilizes PCM heat storage capacity to cut liquid cooling energy consumption. When thermal load rises or PCM heat storage capacity decreases, the controller increases liquid cooling strength to remove heat in a timely manner [5, 6]. The coordinated operation of two heat dissipation modes enables the system to adapt to thermal load changes across diverse working conditions.

However, coordinated control requires simultaneous processing of multiple state signals and multi-objective optimization calculations, which increases algorithm complexity and raises computing requirements for embedded hardware. In practical engineering applications, simplified control logic and hierarchical control frameworks are often adopted to balance temperature control performance and real-time operation requirements.

4. Optimization of control strategies and implementation constraints

4.1. Tuning and optimization of control parameters

Parameter tuning for composite liquid cooling-PCM BTMS falls into two categories: classic PID tuning and intelligent optimization algorithms. Classic PID tuning determines parameters through repeated experiments, while intelligent optimization algorithms search for optimal parameter combinations based on thermal models. The thermal response of liquid cooling-PCM composite systems is dynamically affected by coolant flow, PCM phase change state and charge-discharge rate, so control parameters must be adjusted and optimized for specific operating environments [2].

Conventional PID tuning methods are mainly used for liquid cooling loop temperature control. The Ziegler-Nichols critical proportion method conducts step response experiments to obtain critical system parameters and calculate proportional, integral and differential coefficients accordingly [11]. But this method tunes parameters for fixed working conditions and cannot handle nonlinear characteristics brought by variable coolant flow and PCM phase transition.

Simulation results of 21700 cylindrical batteries under 3C fast charging show obvious control deviation with fixed PID parameters when coolant flow velocity ranges from 0.03 m/s to 0.07 m/s. At low flow velocity, insufficient integral gain causes higher peak temperature; at high flow velocity, excessive differential gain triggers control fluctuation. Moreover, PCM presents different thermal properties in different phase change stages, making fixed PID control unstable, with maximum temperature error and overshoot reaching 3.2 ℃.

Intelligent optimization algorithms address the poor adaptability of traditional PID control by iteratively searching optimal parameters on thermal simulation models. Existing research adopts Particle Swarm Optimization (PSO) to tune PID parameters under cross-flow cold plates and 2.5 mm thick PCM layers [2]. Previous results showed optimized PID reduces temperature overshoot by 68% and limits the module temperature difference to within 1.5 ℃ . In addition, the genetic algorithm and simulated annealing algorithm can also be used for control parameter optimization. The genetic algorithm obtains parameter combinations via population search, while the simulated annealing algorithm boosts the parameter optimization range through random search.

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4.2. Multi-objective performance optimization and trade-off

Multi-objective optimization of liquid cooling-PCM composite BTMS involves three competing objectives: temperature regulation, energy consumption, and battery cycle life. Heat dissipation enhancement reduces battery temperature but increases cooling power demand, whereas cooling reduction decreases energy consumption but may accelerate battery degradation under elevated temperatures. The trade-off among these objectives necessitates multi-objective optimization to achieve a balanced solution.

The evaluation of temperature control considers maximum cell temperature, module temperature difference, and response speed. For lithium-ion batteries, the optimal operating temperature range is 25-35 ℃. Peak temperature above 45 ℃ or module temperature difference over 3 ℃ significantly speeds up battery degradation. Adding thermal conductive fillers into PCM improves temperature uniformity. Relevant research reports that raising expanded graphite content from 3 wt% to 9 wt% reduces maximum module temperature difference by 2.1 ℃ and peak temperature by 4.6 ℃ [2]. However, extra thermal conductive fillers increase system weight, and more intensive liquid cooling increases energy consumption.

For aviation battery packs, PCM weight is strictly limited to avoid reducing flight endurance [12]; for vehicle systems, high coolant flow increases thermal management energy loss, so trade-offs between heat dissipation capacity and energy consumption are essential [3]. In addition, long-term high temperature or large temperature gradients accelerate cell aging, making cycle life another critical constraint in multi-objective optimization.

To balance trade-offs among temperature regulation, energy consumption, and battery lifetime, multi-objective optimization employs Pareto methods to evaluate schemes, identify non-dominated solutions, and assign objective weights based on application scenarios.

4.3. Embedded system design and constraints

When implemented on embedded platforms, control algorithms for liquid cooling-PCM composite BTMS face limitations in computing resources, real-time capability, and hardware architecture. Different algorithms require varying levels of processor performance, memory capacity, and data processing capability, necessitating adaptive designs based on hardware conditions.

Under limited computing resources, control algorithm complexity is constrained by processor capability. MPC and similar algorithms involve extensive matrix operations and multi-step state prediction, requiring high-performance processors and large memory capacity beyond low-power controllers [13]. To reduce computational demands, embedded systems employ simplified thermal models or pre-calculated lookup tables. For aviation battery systems with strict volume and weight constraints, controllers retain only essential control functions to reduce computational and storage overhead [3, 12].

Real-time response represents another key constraint in embedded design. During fast charging, rapid battery temperature variations require the control system to complete signal acquisition, computation, and output within fixed control cycles. Consequently, calculation time is reduced via simplified thermal models, removal of redundant computations, and reduced complexity of PCM phase-change sub-models.

Hardware resource allocation further constrains overall system design. Liquid cooling-PCM composite BTMS requires multiple signals, such as temperature and flow rate, for state monitoring and control. However, limited sensor interfaces and communication bandwidth in embedded hardware restrict the number of deployable sensor nodes. Similar limitations apply to actuators,

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where water pumps and electronic valves are constrained by driving power and require appropriate execution-unit allocation. These hardware constraints drive system optimization toward reduced sensor deployment and efficient data transmission while retaining only essential state signals for stable control.

5. Conclusions

This paper explores structural forms, control strategies and optimization approaches of automotive battery thermal management systems. It summarizes heat transfer features and application limits of active, passive and liquid cooling-PCM composite BTMS, and analyzes working mechanisms of various control methods applied in composite thermal management systems. The results reveal that liquid cooling-PCM composite systems utilize PCM to suppress instantaneous thermal spikes and rely on liquid cooling for continuous heat removal. They outperform single thermal management schemes in temperature uniformity improvement and thermal saturation suppression, yet increased weight, cost and control complexity hinder large-scale practical application. PCM as a passive heat storage medium eases short-term temperature rises, but its low thermal conductivity and limited heat storage capacity restrict performance; excessively high content of thermal conductive fillers reduces PCM heat storage ratio while adding extra weight, so material parameters must be matched to specific working conditions. In terms of control logic, PID control offers simple computation and easy hardware implementation but lacks adaptability to thermal parameter variations in composite BTMS. Model predictive and data-driven controls improve regulation under complex conditions but are constrained by model accuracy, data availability, and embedded computing resources. Thus, optimization of liquid cooling-PCM composite BTMS control requires balancing thermal state prediction, real-time computing capability, and multi-objective coordination among temperature regulation, energy consumption, and battery lifetime. This review analyzes existing experimental and simulation studies but does not fully consider the effects of battery aging, dynamic vehicle operating conditions, and long-cycle operation on thermal management performance. Future work should focus on high-conductivity PCM composites, lightweight intelligent control, and battery degradation-aware optimization for improved BTMS adaptability.

References

[1] Yu, H., Zhu, X., Ma, X., & Yan, H. (2025). Cooling performance analysis and sensitivity analysis of thermoelectric cooling for an 18650 battery pack thermal management. *Case Studies in Thermal Engineering, 72*, 106394.

[2] Chen, S., Garg, A., Gao, L., & Wei, X. (2021). An experimental investigation for a hybrid phase change material-liquid cooling strategy to achieve high-temperature uniformity of Li-ion battery module under fast charging. *International Journal of Energy Research, 45*(4), 6198-6212.

[3] Luo, J., Zou, D., Wang, Y., Wang, S., & Huang, L. (2022). Battery thermal management systems (BTMs) based on phase change material (PCM): A comprehensive review. *Chemical Engineering Journal, 430*, 132741.

[4] Chang, Y. C. (2026). Recent advances in phase change materials for thermal management of lithium-ion and emerging X-ion batteries: A review. *Symmetry, 18*(5), 803.

[5] Chen, H., Wei, G., Xu, L., & Du, X. (2025). Performance study on a novel hybrid thermal management system for cylindrical lithium-ion battery pack based on liquid cooling and PCM. *Applied Thermal Engineering, 271*, 126392.

[6] Ammar, H., Delbani, M., Fardoun, F., El Zoghbi, B., Mouzanar, H., Faraj, J., & Khaled, M. (2025). Hybrid liquid–PCM thermal management for high-capacity lithium-ion batteries under fast charging: A parametric comparative study. *Results in Engineering, 106674*.

[7] Zhao, J., Rao, Z., Huo, Y., Liu, X., & Li, Y. (2015). Thermal management of cylindrical power battery module for extending the life of new energy electric vehicles. *Applied Thermal Engineering, 85*, 33-43.

[8] Yu, P., Yang, N., Zhu, C., & Shen, X. (2025, July). Sliding mode control strategy for thermal management of automotive lithium-ion battery systems. In *2025 IEEE 26th China Conference on System Simulation Technology*

DOI: 10.54254/2755-2721/2026.37223

and Its Applications (CCSSTA) (pp. 870-874). IEEE.

[9] Lin, X., Perez, H. E., Mohan, S., Siegel, J. B., Stefanopoulou, A. G., Ding, Y., & Castanier, M. P. (2014). A lumped-parameter electro-thermal model for cylindrical batteries. *Journal of Power Sources, 257*, 1-11.

[10] Fang, X., Tian, H., Wu, M., Qiu, Y., Li, H., & Wang, L. (2025). A real-time feedback and adaptive control strategy for battery thermal management system. *Energy, 333*, 137148.

[11] Xie, J., Yang, R., Gooi, H. B., & Nguyen, H. D. (2023). PID-based CNN-LSTM for accuracy-boosted virtual sensor in battery thermal management system. *Applied Energy, 331*, 120424.

[12] Kim, D., Abdallahh, S., Bosi, G., & Hales, A. (2023). A numerical study of the suitability of phase-change materials for battery thermal management in flight applications. *World Electric Vehicle Journal, 14*(1), 15.

[13] Jaguemont, J., Darwiche, A., & Bardé, F. (2025). Model predictive control using an artificial neural network for fast-charging lithium-ion batteries. *World Electric Vehicle Journal, 16*(4), 231.