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Research Progress on Liquid-Cooled Thermal Management Systems for Lithium-Ion Batteries: From Single-Cooling to Multi-Strategy Coordination

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***Abstract*— *The thermal management system of lithium-ion batteries is a critical factor affecting the safety and driving range of new energy vehicles. With its high heat transfer efficiency and strong adaptability, liquid cooling technology has gradually become the mainstream solution for battery thermal management systems. This paper systematically reviews the development of liquid-cooled thermal management for lithium-ion batteries, tracing the technological evolution from single-cooling techniques to "liquid cooling–phase change material coupling" and "biomimetic flow channel collaborative optimization." Based on an investigation of battery heat generation mechanisms and thermal management objectives, the paper highlights the limitations of traditional liquid cooling plate designs and analyzes the advantages and shortcomings of composite systems combining phase-change materials with liquid cooling. It further discusses the performance improvements achieved through topological optimization and biomimetic flow channel design. Research indicates that multi-strategy coordination and intelligent control represent the inevitable future direction for lithium-ion battery thermal management systems. However, challenges such as large-scale manufacturing, long-term operational stability, and lifecycle cost control remain core issues that must be addressed before industrialization.*

Keywords*— *biomimetic flow channels, liquid cooling, lithium-ion battery, thermal management, topological optimization

I. INTRODUCTION

The global energy transition and the advancement of the "dual carbon" goals have positioned electric vehicles as the core vehicle for low-carbon transportation [1]. As the "heart" of electric vehicles, lithium-ion batteries dominate the power battery market due to their high energy density, long cycle life, and low self-discharge rate [2]. However, lithium-ion batteries are extremely sensitive to operating temperature, with their optimal operating range typically limited to 20–40°C, and temperature differences between cells must be kept within 5°C [3]. During charging and discharging, especially under high-rate conditions, intense electrochemical reactions inside the battery generate a large amount of heat; if this heat cannot be dissipated in a timely manner, it will not only accelerate capacity degradation and shorten cycle life, but may also trigger thermal runaway, leading to catastrophic consequences such as fire or even explosion [4]. Thermal runaway caused by battery overheating has become the primary cause of electric vehicle fires, highlighting the critical importance of an efficient Battery Thermal Management System (BTMS)— it is not only a performance guarantor but also a key factor in ensuring safety.

In the heat generation process of lithium-ion batteries, heat sources can be attributed to Joule heating from ohmic resistance, enthalpy change heat from electrochemical reactions, and irreversible heat caused by polarization effects, among which ohmic heat dominates under high-rate discharge conditions [5]. If this heat cannot be dissipated in a timely manner, it will trigger a positive feedback loop of "temperature rise—reaction acceleration—increased heat generation," which in severe cases can lead to separator shrinkage, internal short circuits, and ultimately thermal runaway [6]. Looking back at the evolution of BTMS, the technological path has undergone a transition from crude to refined, from passive to active, and from single-cooling methods to multi-technology composite coupling. Early air-cooling solutions featured simple structures and low costs, but their low specific heat capacity and low thermal conductivity resulted in inherent limitations in heat dissipation capability [7]. In high-power-density applications, air cooling often requires several times the energy consumption of liquid cooling to achieve the same cooling effect. Phase-change materials (PCMs) utilize the latent heat of solid-liquid phase change to absorb large amounts of heat and offer excellent temperature uniformity; however, their low thermal conductivity makes it difficult to dissipate heat promptly, and they become completely ineffective once the latent heat is exhausted [8]. Although heat pipe technology possesses extremely high thermal conductivity, its high cost, complex manufacturing processes, and sensitivity to gravitational orientation limit its large-scale application in automotive operating conditions [9]. It is against this backdrop that liquid cooling technology has emerged as the mainstream choice for contemporary power battery thermal management, thanks to its thermal conductivity far exceeding that of air, flexible structural adaptability, and exceptional cooling efficiency[10]. From the serpentine water-cooling tubes in Tesla's cylindrical batteries to the integrated liquid-cooling plates at the bottom of battery packs on Volkswagen's MEB platform, liquid-cooling solutions have been thoroughly validated in mass-produced vehicles [11] .

However, the logic of technological evolution is not one of linear replacement. In recent years, the academic community has keenly recognized that single-liquid-cooling solutions still face deep-seated challenges, such as the difficulty of eliminating localized hotspots, excessive pump power consumption, and failure to meet temperature uniformity standards [10][12]. The fundamental solution to these challenges lies in breaking down the barriers between cooling methods and moving toward the synergy of multiple physical mechanisms. A clear trend is the coupling of liquid cooling with PCM, leveraging the complementary characteristics of PCM for peak shaving and valley filling, and liquid cooling for continuous heat removal, to achieve the spatiotemporal redistribution of thermal loads [13][14] the introduction of bionics and topological optimization has revolutionized the traditional design paradigm of straight/serpentine flow channels, shifting channel structure design from "empirical trial-and-error" to "algorithmic optimization" [15][16]. This paper follows this technical logic, aiming to clarify key advancements, diagnose existing bottlenecks, and assess future trends within the evolutionary trajectory from internal optimization of liquid cooling technology to the integration of external strategies, thereby providing a reference framework for the design and development of high-performance battery thermal management systems.

II. FUNDAMENTALS OF LIQUID-COOLED THERMAL MANAGEMENT AND TRADITIONAL DESIGNS

2.1 Battery Heat Generation Mechanisms and Thermal Management Objectives

Understanding how heat is generated is the foundation of thermal management system design. The sources of heat in lithium-ion batteries during charging and discharging can be categorized into three types: first, Joule heating caused by ohmic resistance as electrons and ions move through the electrodes and electrolyte; second, entropy changes inherent to the electrochemical reactions when lithium ions are inserted into and extracted from the electrode materials; and third, irreversible heat resulting from the polarization effect [5]. Under high-rate discharge conditions, ohmic heat often dominates, turning the battery's interior into a rapidly heating miniature boiler. Studies have shown that when a battery discharges at rates exceeding 3C, the internal heat generation rate can far exceed its natural heat dissipation capacity, causing temperatures to rise to dangerous levels within minutes [17]. More critically, the battery's layered structure and uneven current density distribution result in spatially non-uniform heat generation rates, often creating significant temperature differences between the edges and centers of the electrodes, as well as between regions near and far from the tabs [5]. Once this thermal non-uniformity exceeds a threshold, it triggers a vicious cycle of positive feedback: the higher the local temperature, the more intense the electrochemical reaction, the greater the heat generation, which may ultimately lead to separator shrinkage, internal short circuits, and even thermal runaway [6] .

Therefore, the design objective of a thermal management system is by no means simply to "cool down," but rather to simultaneously achieve three seemingly contradictory goals: keeping the battery's maximum temperature within a safe range; minimizing temperature differences between individual cells within the battery pack; and reducing the system's own additional energy consumption as much as possible [9]. Generally, the maximum allowable temperature for lithium-ion batteries is approximately 50–60°C; however, to ensure long-term durability, it is typically desirable for them to operate below 40°C [4]; the maximum temperature difference between cells should be less than 5°C [3]. These three metrics constitute the core framework for evaluating the performance of any thermal management system.

2.2 Typical Structure and Early Limitations of Liquid-Cooled Plates

Liquid cooling technology removes heat through forced convection of a cooling fluid (typically a glycol-water mixture) within a metal cold plate; indirect contact liquid cooling is currently the mainstream solution for automotive applications [18]. The choice of cooling fluid directly affects system performance; in recent years, the introduction of novel cooling media such as nanofluids and liquid metals has opened up new possibilities for further improving system performance [19]. Traditional liquid cooling plate designs mostly revolve around straight, flat channels or serpentine coils. Flat channels are simple to manufacture and have low flow resistance; however, as the fluid flows in a straight line, the boundary layer continuously thickens. Once the thermal boundary layer is fully developed, heat transfer efficiency drops significantly, and the cooling effect in the downstream region of the cooling plate is much weaker than in the upstream region, resulting in a temperature gradient along the flow direction [20]. Serpentine channels disrupt the boundary layer by forcing the fluid to change direction repeatedly, significantly improving the heat transfer coefficient and temperature uniformity. However, this comes at the cost of a sharp increase in flow resistance and a substantial rise in pump power consumption [11][12]. This "heat transfer efficiency-pressure drop" seesaw effect constitutes a fundamental design dilemma for traditional liquid cooling plates. Furthermore, early research revealed a deep-seated physical contradiction: while heat transfer is most intense and temperatures are lowest near the channel walls, in the "fin region" between the two channels and in areas far from the channels, heat must travel through multiple layers of material via solid-state conduction to reach the cooling source. These regions often become thermal dead zones, resulting in a temperature distribution characterized by alternating "hot and cold spots" [21]. This non-uniformity becomes increasingly pronounced with the trend toward high-rate charging and discharging or larger battery sizes, and the limitations of traditional empirical design are becoming increasingly apparent [10][12] .

To address these issues, researchers have explored various improvement strategies. For example, Mohapatra et al. [22] proposed an improved meandering microchannel cold plate design that segments the flow channels to enhance heat transfer capacity while reducing pressure loss. Kumar et al. [23] systematically compared four indirect liquid-cooled BTMS schemes: serpentine channels, wavy channels, jacket-type channels, and microchannels. The results showed that at a high discharge rate of 5C, serpentine and wavy channels exhibited temperature difference exceedance issues, while the microchannel and jacket-type schemes demonstrated the best overall performance. Furthermore, a multi-U-shaped microchannel design, which introduces low-temperature coolant into the high-temperature core of the battery for heat exchange, can reduce the maximum battery temperature and temperature difference by 5.83K and 0.06K, respectively, after optimization, while simultaneously reducing the pressure drop by 89% [24]. These studies clearly demonstrate that the geometric configuration of liquid-cooled plate channels has a decisive impact on the performance of thermal management systems.

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III. COUPLING OF LIQUID COOLING AND PHASE-CHANGE MATERIALS: TOWARD HYBRID COOLING

3.1 Synergistic Mechanisms and Advantages of Hybrid Cooling

Since each standalone cooling method has its limitations, coupling two or more cooling mechanisms naturally emerges as a technical solution. Among these, the hybrid solution combining liquid cooling and PCM has garnered the most attention, as it ingeniously leverages the high latent heat of PCM to compensate for the shortcomings of liquid cooling in handling transient thermal shocks [14][25]. The operating logic of this hybrid system can be summarized as "PCM for peak shaving, liquid cooling for valley filling": under normal temperature or low-load conditions, when the battery generates minimal heat, the PCM remains in a solid state and absorbs heat through its own sensible heat capacity; However, during high-rate scenarios such as rapid acceleration or fast charging, the battery surface temperature rises rapidly, causing the PCM to undergo a solid-liquid phase transition. It absorbs a large amount of heat in a nearly isothermal manner, acting like a "buffering sponge" between the battery and the cold plate to smooth out temperature peaks [13]; the liquid cooling system operates continuously to dissipate the heat absorbed by the PCM and the battery's ongoing heat generation, while simultaneously aiding the solidification of the melted PCM to restore its latent heat capacity [26]. Lebrouhi et al. [25] simulated the thermal behavior of this system using a low-cost lumped-parameter numerical model, verifying the feasibility of the coupled scheme and its thermal management effectiveness.

Numerous experimental and simulation studies have confirmed the effectiveness of this synergy. Ahmad et al.[13] [13] coupled fin-enhanced PCM with air cooling; the results showed that the coupled system significantly reduced the maximum battery temperature and markedly improved temperature uniformity compared to pure air cooling.Regarding liquid-cooled-PCM hybrid systems, Xin et al. [27] tested the hybrid system under extreme conditions of high ambient temperature and rapid discharge, demonstrating that this approach can effectively suppress the battery's maximum temperature within safe limits, exhibiting thermal stability far surpassing that of standalone liquid cooling.Xin et al. [28] performed multi-objective optimization of a CPCM-liquid cooling hybrid system using an NSGA-II-optimized artificial neural network; the optimized system demonstrated significant improvements in both battery temperature and thermal uniformity. Wei et al. [26] combined PCM with liquid cooling for $LiFePO_4$ battery packs, successfully controlling the temperature rise of the battery pack and extending the high-temperature operating time.Jhariya et al.[14] further noted in their review that the combination of nano-enhanced PCM and liquid cooling can increase the effective thermal conductivity by approximately 42% while significantly shortening the phase-change response time; however, the long-term sedimentation and agglomeration issues of nano-fillers still require further resolution.

3.2 The Fatal Flaws of Low PCM Thermal Conductivity and Leakage Risks

No technical solution is flawless. While composite cooling systems demonstrate excellent thermal performance, they also introduce the inherent flaws of PCMs. The two most prominent issues are as follows: First, PCMs have extremely low thermal conductivity; the thermal conductivity of paraffin-based PCMs is typically around 0.2W/(m·K), which is virtually indistinguishable from that of insulation materials [8]. Such a low thermal conductivity means that heat transfer within the PCM relies primarily on slow thermal conduction. Heat from the battery struggles to penetrate deep into the PCM in a timely manner, leaving a large portion of the PCM effectively in a "standby" state, and the latent heat of phase change cannot be fully utilized [14]. Second, the increased fluidity of PCM after melting poses a leakage risk; if liquid PCM seeps out and comes into contact with electrical components, it may cause short circuits or corrosion [8] .

To address these two major challenges, the academic community has explored multiple improvement strategies. A review by Gassoumi et al.[29] summarizes three primary approaches: adding highly thermally conductive fillers, such as expanded graphite, carbon fibers, carbon nanotubes, or metal foams, to PCM to form composite PCM; using microencapsulation technology to encapsulate PCM within micron-scale polymer or inorganic shells; constructing a highly thermally conductive network within the PCM using fin structures. Further experimental validation has also yielded encouraging results: in an experiment on cylindrical lithium-ion batteries, Al_2O_3 nanoparticles were doped into paraffin PCM at different ratios and coupled with liquid cooling; under 3C discharge conditions, the battery temperature was reduced by approximately 10.35°C compared to natural convection conditions [30]. Under higher-rate 5C discharge conditions, a composite system combining multi-fin channels with a multi-layer PCM mixture could control the maximum battery pack temperature to 36.13°C, maintaining a temperature difference within 4.04°C, thereby providing a feasible solution for the safe high-rate operation of power batteries [31] .

Although these improvements effectively enhance PCM performance, they inevitably increase material costs and processing complexity. The fins occupy a portion of the volume that would otherwise be filled with PCM, sacrificing the system's energy storage density; the long-term sedimentation and agglomeration issues of nanofillers remain to be investigated [14]. Furthermore, long-term operational stability under real-world driving conditions has not yet been fully validated. A review by Gassoumi et al. notes that PCM-liquid cooling hybrid systems currently remain at the balancing point of the "high performance–low cost–long lifespan" triangle, and the industrialization process is still in its infancy.

IV. INNOVATIONS IN LIQUID-COOLED PLATE DESIGN:TOPOLOGICAL OPTIMIZATION AND BIONICS-INSPIRED CONVERGENCE

If the liquid cooling–PCM coupling addresses the issue of "spatio-temporal redistribution of heat from the battery to the cold plate," then the internal flow channel design of the liquid cooling plate addresses the "last mile" problem of heat transfer from the cold plate wall to the cooling medium. In recent years, the rise of topological optimization and biomimetic flow channel design has revolutionized the efficiency of this "last mile."

4.1 From Empirical Design to Algorithm-Driven Topological Optimization

Traditional runner designs largely rely on engineering experience and parametric sweeps, adjusting dimensional parameters within a given layout topology, and are unable to break free from the constraints of predefined structural frameworks [32]. Topology optimization, on the other hand, is a more thorough mathematical method: within a given design space and boundary conditions, it uses algorithms to automatically find the optimal material distribution, thereby generating runner configurations that transcend human intuition [15]. A review by Teng et al. [34] notes that the application of topological optimization methods in BTMS represents a paradigm shift in liquid-cooled plate design, moving from "empirical trial and error" to "algorithmic optimization."

Recent studies have fully demonstrated the powerful advantages of topological optimization methods. Yang Zhiying et al.[15] performed topological optimization of liquid cooling plate heat dissipation channels based on the variable density method, resulting in a tree-like branched channel structure. Its heat transfer efficiency significantly outperformed that of traditional serpentine channels, while the increase in pump power was limited, achieving an effective improvement in overall thermal-hydraulic performance.Fu Zhi'ao [33] investigated liquid-cooled plates with porous media fillers. By adjusting the filler structure using topological optimization principles, they reduced the maximum battery temperature while improving temperature uniformity. Niu et al.[35] employed orthogonal experimental design combined with simulation optimization to conduct systematic parameter screening of liquid-cooled battery modules, identifying the optimal combination of flow channel structures and cooling parameters.

At a deeper level, topological optimization methods have been extended from laminar flow assumptions to turbulent flow conditions. An experimental study of cold plates based on turbulent topological optimization demonstrated that the performance evaluation criteria (PEC) of turbulent topologically optimized cold plates were 66% and 56% higher than those of conventional serpentine and rectangular cold plates, respectively [36]. Furthermore, an experimental study on topological optimization that incorporates length-scale control indicates that such control can simplify channel structures and improve manufacturability; the experimentally verified deviations in temperature and pressure drop were within 5% and 8%, respectively [37]. In research on LiFePO4 battery modules, topologically optimized cold plates based on non-uniform heat source boundary conditions can improve overall performance by 36% compared to traditional rectangular channel cold plates [38] .

However, topological optimization methods are not without their shortcomings. Optimization results often produce gray-scale elements and jagged boundaries, which must undergo post-processing to be smoothed before they can be converted into manufacturable CAD models; this "translation" process inevitably introduces performance losses [15]. Furthermore, topological optimization is highly sensitive to boundary conditions; even minor changes in heat source distribution, inlet flow velocity, or constraint function weights can lead to drastically different configurations, posing challenges for handling uncertain operating conditions in practical engineering applications [34] .

4.2 Biomimetic Flow Channels: Learning Efficient Transport from Nature

Topology optimization is about "letting algorithms think," while biomimetic design is about "learning from nature." Through billions of years of evolution, structures in nature—such as leaf vein networks, animal vascular systems, and insect wing veins—have long pushed the efficiency of fluid transport to its limits, achieving maximum surface area coverage and minimal transport resistance within finite volume and energy constraints [39]. As summarized by Liu et al. [10], the core value of biomimetic channel design lies in abstracting thermo-fluid coupling problems into transport network optimization problems, using nature's proven efficient strategies to guide engineering design.

Yan et al. [16], inspired by the fractal structure of plant veins, designed biomimetic vein-like liquid cooling channels; experiments and simulations showed that their heat transfer efficiency was 22.43% higher than that of traditional serpentine channels. Tao Yuanbing [40] applied a gradient vein-like design to battery cooling systems; the resulting optimal parameter combination significantly improved cooling efficiency while maintaining low pump power consumption.Wu Chunlong [39] conducted research on enhanced heat transfer in liquid cooling plates based on various biomimetic structures, finding that biomimetic network configurations can effectively eliminate flow dead zones, allowing the coolant to cover the heat-generating surface more uniformly.Saber et al.[41] also emphasized in their review that biomimetic and fractal structures demonstrate great application potential in prismatic battery liquid cooling plates, with pressure losses far lower than those of traditional structures with the same heat transfer level.Further exploration of biomimetic configurations is also underway: a sapling-inspired flow channel design reduces pressure loss by 1.03% and maximum temperature by 32.44% compared to parallel channels at an inlet velocity of 1.5 m/s [42]; maple-leaf-vein-inspired flow channels maintain a temperature difference within 1.75°C, with a pressure drop of only 14.7% that of serpentine channels; after optimization, the temperature difference was further reduced by 11% and energy consumption by 13% [43] .

The true value of biomimetic flow channel design lies in providing methodological insights: abstracting complex thermo-fluidic coupling problems into optimization problems for transport networks, thereby applying nature's proven efficient strategies to inform engineering design. Whether it is the fractal geometry of leaf veins or the hierarchical branching of blood vessels, they all follow Murray's law—the cubic relationship of branch diameters maximizes transport efficiency [16]. However, the finer the structure, the more difficult it is to manufacture, and the higher the cost. Biomimetic flow channels often feature complex geometric characteristics such as three-dimensional surfaces, variable cross-sections, and interconnected branches, which traditional milling or extrusion processes struggle to handle; metal 3D printing technology is therefore essential for their fabrication [39][40]. Although additive manufacturing has already been applied in the aerospace sector, its costs remain relatively high for the mass production of automotive components. Whether the surface roughness, residual stress, and fatigue performance of 3D-printed parts can meet the long-term durability requirements of automotive cold plates still requires thorough reliability verification [10] .

V. CONCLUSION

Lithium-ion battery liquid cooling thermal management systems have undergone iterative upgrades, evolving from single-liquid cooling and conventional channel designs to multi-fluid coupling, topological channel optimization, and intelligent control.Through this evolutionary path, the following core conclusions can be drawn: single-liquid-cooling solutions are constrained by the trade-off between heat transfer performance and flow resistance, and their performance has approached technical limits; the coupling of liquid cooling with PCM can effectively smooth out temperature peaks and valleys and improve temperature uniformity, but before industrialization, its low thermal conductivity and leakage risks remain significant issues. The convergence of topological optimization and biomimetic flow channels has propelled liquid cooling design from empirical trial-and-error optimization to an algorithm-driven quantitative optimization phase. However, both approaches must still adhere to the fundamental physical principle of "maximizing heat transfer per unit of pump power consumption."At the same time, finer structures are more difficult to manufacture and incur higher costs; this inherent tension constrains the large-scale application of advanced solutions. However, intelligent control strategies—such as a liquid cooling delayed activation strategy based on the PCM liquid phase fraction—have been proven to achieve significant energy savings and temperature uniformity without altering the hardware. This suggests that the synergistic optimization of "hardware + algorithms" will be the core focus of the next phase.

VI. OUTLOOK

Looking ahead from the forefront of current research, lithium-ion battery liquid cooling thermal management systems will undergo profound transformations in the following areas. First, artificial intelligence and digital twin technologies will reshape thermal management strategies. Neural network models trained on real-vehicle operational data can predict battery thermal states in real time, enabling a paradigm shift from "passive response" to "active anticipation," ensuring that the cooling system can always adjust operating conditions in advance to run at optimal performance [17]. Second, advancements in materials science will breathe new life into PCM-liquid cooling hybrid systems. High-thermal-conductivity shaped PCMs, flexible composite PCMs, and eutectic phase-change materials capable of operating across a wide temperature range are expected to overcome thermal conductivity and leakage bottlenecks while maintaining high latent heat [44]. Third, the ongoing cost reduction and precision improvements in additive manufacturing technology will enable complex biomimetic flow channels to transition from the laboratory to the production line, providing manufacturing feasibility for customized cooling plates. Finally, a comprehensive evaluation framework from a full lifecycle perspective—which simultaneously considers thermal performance, energy efficiency, manufacturing costs, maintainability, and recyclability—will gradually replace the competition based solely on performance metrics, becoming the true guide for the implementation of next-generation thermal management systems. It is foreseeable that as battery cell energy density continues to rise and charging rates advance toward 4C and even 6C, liquid-cooled thermal management systems will play an increasingly critical role in balancing "safety" and "performance." This technological evolution from "cooling" to "intelligence" is far from over.

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