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Optimization of Liquid Cooling Channels in BTMS for Cylindrical Lithium-ion Battery Modules: A Review

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Abstract

Efficient thermal management is critical for the performance, safety, and lifespan of lithium-ion batteries in electric vehicles. Cylindrical cells, widely used in EV battery packs, pose significant thermal challenges due to their dense arrangement and high power density. Liquid cooling has emerged as one of the most effective strategies for maintaining uniform temperature distribution in cylindrical-cell modules. This review focuses on the optimization of liquid cooling channels in Battery Thermal Management Systems (BTMS) for cylindrical lithium-ion battery modules. Key studies on channel geometries, flow configurations, coolant types, and hybrid techniques are analyzed. Results indicate that serpentine, spiral, and lattice-shaped channels, when combined with nanofluids or PCM integration, significantly enhance thermal uniformity and reduce maximum cell temperatures. Challenges such as pumping power, manufacturing complexity, and coolant stability are also discussed, along with future research directions emphasizing multi-objective optimization and AI-assisted design.

Keywords: *BTMS, Cylindrical Lithium-Ion Battery, Liquid Cooling, Cooling Channel Optimization, Thermal Management, Nanofluids, PCM.*

I. INTRODUCTION

The global electrification of transportation has driven rapid growth in lithium-ion battery applications due to their high energy density, long cycle life, and stable performance [1]. These characteristics make lithium-ion batteries the most dominant energy storage technology for electric vehicles (EVs), hybrid vehicles, and even large-scale energy storage systems. Their ability to deliver consistent power output while maintaining reliability under various operating conditions has further established them as the preferred choice for modern mobility solutions.

Among various cell formats available in the market—such as prismatic, pouch, and cylindrical—the cylindrical type, particularly formats like 18650 and 21700, has gained significant attention and adoption in many electric vehicles [2]. This popularity is largely attributed to their mechanical robustness, which ensures durability under mechanical stresses, their mature and well-established manufacturing processes, and the flexibility they provide for modular assembly in battery packs. The standardization of cylindrical cells also allows ease of scalability, making them suitable for both small and large energy storage systems. Moreover, their ability to achieve high packing efficiency with a uniform structure makes them particularly suitable for automotive applications.

However, the dense arrangement of cylindrical cells in battery modules creates new engineering challenges. When packed tightly together, these cells experience non-uniform heat generation during charging and discharging cycles, which leads to uneven temperature distribution within the battery pack [3]. Such thermal imbalances can accelerate capacity degradation, shorten overall battery lifespan, and, in severe cases, trigger safety issues such as thermal runaway. Thermal runaway, caused by excessive heat and exothermic reactions, poses a significant risk to both the performance and safety of electric vehicles. Therefore, effective thermal management becomes not only a performance requirement but also a critical safety necessity.

Battery Thermal Management Systems (BTMS) are thus indispensable for maintaining cell temperatures within safe operating limits. A well-designed BTMS ensures that all cells operate within an optimal temperature window, preventing hotspots, reducing thermal gradients, and improving the overall efficiency and durability of the pack [4]. Different cooling strategies have been studied and implemented, including passive and active approaches. Passive techniques, such as phase change materials (PCM), absorb latent heat to limit temperature rise, whereas active methods like air cooling and liquid cooling involve continuous heat removal during operation. Among these, liquid cooling has proven to be the most effective solution due to its superior heat transfer properties, especially under conditions of high current demand and rapid charging, where large amounts of heat are generated [5].

The design and optimization of liquid cooling channels play a decisive role in determining the effectiveness of BTMS. Factors such as the maximum cell temperature, the uniformity of temperature distribution across the pack, the magnitude of the temperature gradient, the resulting pressure drop, and the pumping power requirement are all directly influenced by the configuration of these cooling channels. Hence, channel geometry, flow arrangement, and coolant selection become central aspects of BTMS research. This review specifically focuses on recent advancements in the optimization of cooling channels for cylindrical lithium-ion battery modules, drawing attention to both numerical approaches such as Computational Fluid Dynamics (CFD) simulations and experimental validations. In addition, emerging techniques that integrate advanced materials and innovative channel designs are also highlighted, with the aim of providing comprehensive insights into the state-of-the-art progress in this critical area of battery technology.

II. LITERATURE REVIEW

After much research, liquid cooling has been found to be the most efficient technique for high-energy density modules in the thermal management of cylindrical lithium-ion battery packs.Other techniques include air cooling techniques for BTMS and the use of PCM in batteries for passive cooling. However, the need for liquid cooling is growing along with the number of high energy density batteries.

Zhang et al. [6] focused on U-shaped liquid cooling channels for cylindrical packs. Their analysis revealed that a channel width of 2 mm and an inlet temperature of 298 K provided the best balance between thermal uniformity and pumping power. The maximum temperature difference among cells decreased to 3.2 °C, and the pressure drop across the system remained within acceptable limits, highlighting the practical feasibility of U-shaped designs for automotive applications.

Chen et al. [7] proposed a spiral-shaped cooling channel placed between cylindrical cells. This design improved coolant distribution and reduced temperature gradients by 42% compared to conventional parallel channels. The study also noted that the spiral configuration allowed better contact with multiple cells simultaneously, making it highly effective for dense battery modules, particularly under high discharge rates.

Guo et al. [8] conducted a comparative study between serpentine and parallel micro-channel designs using CFD analysis. Their findings indicated that serpentine channels offered superior thermal uniformity but incurred a 25% higher pumping power requirement. The optimized serpentine channel reduced the peak cell temperature to 310 K under a 5C discharge rate, demonstrating that a careful trade-off between thermal performance and pumping efficiency is necessary in BTMS design.

Li et al. [9] experimentally investigated a cold plate with embedded pin-fin structures. Their results showed that pin-fin arrays enhanced local turbulence, thereby improving convective heat transfer and lowering the maximum cell temperature by 6.7 °C relative to smooth channels. The temperature difference among cells was reduced from 4.5 °C to 2.9 °C, highlighting the importance of micro-structural modifications in cooling plates.

Xu et al. [10] developed a dual-layer cooling plate for a 4s6p cylindrical module. CFD analysis indicated that the maximum temperature drop achieved was 12.3 °C at a coolant velocity of 0.3 m/s. The dual-layer design also reduced the inter-cell temperature difference to less than 2 °C, demonstrating that multi-layered cooling approaches can significantly enhance uniformity, especially in high-capacity modules.

Yang et al. [11] investigated the use of nanofluid coolants, including water-Al_2O_3 suspensions, for cylindrical modules. Their study reported an 18% improvement in the heat transfer coefficient and a corresponding reduction in average cell temperature compared to pure water. The enhanced thermal conductivity of nanofluids enables better heat extraction, making them a promising option for high-power EV applications.

Wang et al. [12] explored the impact of coolant inlet direction and positioning on serpentine channel performance. Bottom-inlet configurations were found to enhance flow distribution across all cells, reducing temperature non-uniformity by 35% compared to side-inlet channels. This study underscored the significance of inlet design in minimizing hotspots within cylindrical modules.

Kang et al. [13] introduced cross-drilled cooling channels embedded in module baseplates. Their results showed that cross-drilled patterns effectively mitigated hotspots, achieving a 21% improvement in the thermal uniformity index. The study highlighted the role of innovative channel layouts in enhancing local heat transfer without excessively increasing system complexity.

Liu et al. [14] applied a genetic algorithm to optimize lattice-shaped cooling channels. Their multi-objective optimization considered both minimal pressure drop and maximal heat removal, resulting in a 9.1 °C reduction in average cell temperature while keeping pumping power within acceptable limits. This approach demonstrated the value of computational optimization in designing high-performance BTMS for cylindrical cells.

Sun et al. [15] analyzed liquid cooling plates for Tesla-type cylindrical modules. Their work revealed that non-uniform inlet flow could significantly affect temperature gradients, and adaptive flow distribution strategies were necessary to maintain uniform cooling, especially during fast charging. The study highlighted that flow control and distribution are as critical as channel geometry for thermal management.

Huang et al. [16] investigated PCM-enhanced liquid cooling systems. By integrating PCM into liquid channels, the system provided superior thermal buffering, reducing both maximum temperature and peak temperature gradient during fast-charging cycles. This hybrid approach offers an effective solution for managing transient thermal spikes in high-capacity cylindrical modules.

Overall, the reviewed studies demonstrate that channel geometry, flow configuration, coolant type, and hybrid techniques all play crucial roles in achieving optimal thermal management for cylindrical lithium-ion battery packs. Serpentine, spiral, pin-fin, cross-drilled, and lattice-shaped channels consistently improve temperature uniformity and reduce peak temperatures. Nanofluids and PCM integration further enhance cooling performance, although trade-offs with pumping power, manufacturing complexity, and cost remain important considerations for practical implementations.

III. OBJECTIVE

- Boost temperature optimization, which involves raising or lowering the battery pack's temperature as needed.
- Lowering the tube's pressure loss in order to lower the pump power needed for coolant flow
- Expand the cooling tube's surface area in contact with the battery cells.
- Minimal variation in temperature between the cell and the entire module.

IV. PROPOSED METHODOLOGY

Based on the critical gaps identified in the reviewed literature, a comprehensive methodology is proposed for future research in the field of Battery Thermal Management Systems (BTMS) for electric vehicles. The proposed approach involves the following steps:

- *Model Development:*

ANSYS Fluent will be used to create a 3D CFD model of a cylindrical lithium-ion battery module (96s46p configuration). Based on the electrochemical properties of the Tesla Model 3/Model Y battery pack, the model will incorporate heat generation.

- *Cooling Channel Optimization:*

Between cells, new channel geometries will be added, including multi-pass and triangular/kite-shaped microchannels. The impact of channel size, shape, and direction on coolant distribution and thermal uniformity will be examined using parametric studies.

- *Hybrid Cooling Approach:*

Liquid cooling and PCM/nanofluid-based cooling will be tested in tandem to assess their synergistic effects on uniformity and maximum temperature decrease. PCM melting points and varying nanofluid concentrations will be taken into account.

- *Boundary Conditions:*

Realistic discharge conditions with a range of C-rates (1C–5C), coolant inlet velocities (0.1–0.5 m/s), and ambient temperatures (25–45 °C) will be used for the simulations.

- *Optimization Framework:*

In order to decrease peak temperature and temperature difference (ΔT) while lowering pumping power, surrogate modeling and AI-based multi-objective optimization approaches (such as Gaussian Process Regression and NSGA-II) will be used.

- *Techno-Economic Analysis:*

To make sure the suggested solution is realistically feasible for extensive EV applications, the cost implications will be weighed against the thermal performance increases.

V. CONCLUSION OF LITERATURE REVIEW

From the reviewed studies, it is evident that:

- *Channel Geometry –*

Serpentine, spiral, and lattice-shaped channels significantly improve thermal uniformity, though often at the cost of increased pumping power.

- *Pin-Fin and Cross-Drilled Enhancements –*

These designs enhance local turbulence and heat transfer efficiency.

- *Coolant Type –*

Nanofluids and PCM integration offer additional temperature reduction but present challenges such as cost and long-term stability.

- *Flow Configuration and Inlet Arrangement –*

Proper inlet design plays a key role in minimizing hotspots and improving temperature distribution.

➢ *Performance Outcomes* –

Optimized liquid cooling designs achieve 6–12 °C reduction in maximum cell temperature and 20–40% improvement in thermal uniformity.

➢ *System Importance* –

Efficient liquid cooling channel optimization is vital for safe, durable, and high-performance cylindrical lithium-ion battery modules.

➢ *Future Scope* –

Research should focus on multi-objective optimization, hybrid cooling strategies, AI-assisted design, and experimental validation under real EV operating conditions to further enhance BTMS performance.

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