# A Comprehensive Review of Liquid-Cooled Battery Thermal Management Systems for Lithium-Ion Electric Vehicle Packs

Puja S. Chhanwal[1], Pooja A. Takalkar[2]
[1]*PG Student, Department of Mechanical Engineering, Deogiri Institute of Engineering and Management Studies, Chh. Sambhajinagar (MS), India.*
[2]*Assistant. Professor, Department of Mechanical Engineering, Deogiri Institute of Engineering and Management Studies, Chh. Sambhajinagar (MS), India.*

***Abstract*—As the world begins to transition to low-carbon transportation at an increased pace, Electric Vehicles (EV's) are being adopted by consumers globally with Lithium-Ion Batteries as their primary means of energy storage. The rapid charging and discharging that occurs when charging or driving an electric vehicle creates excessive heat within battery cells causing elevated temperatures and uneven thermal distribution across the entire battery pack. The thermal effects cause battery aging, decreased efficiency and increases the risk of thermal runaway. Thus, it is imperative to have a reliable Battery Thermal Management System (BTMS) to provide safety and extended service life. Liquid-cooled BTMS systems have been shown to be the most efficient solution for cooling high power battery applications because of their high heat removal ability, space-efficient design and ability to cool large amounts of power. This literature review addresses advances in liquid-cooling designs for electric vehicle battery packs, focusing on the fluid dynamics associated with cooling flow, architectural designs of cooling plates and electro-thermal interactions. Specifically, this review examines how coolant mass-flow rate, coolant inlet temperature and cooling plate size affect temperature control and uniformity of the battery pack as well as the amount of energy required to operate a cooling pump.**

***Index Terms*—Electric Vehicles, Lithium-ion Battery, Battery Thermal Management System, Liquid Cooling, Thermal Optimization, Temperature Uniformity, Thermal Runaway**

## I. INTRODUCTION

Several different types of Battery Thermal Management Systems (BTMS) have been designed to manage the heat generated internally within a battery pack, including air cooling, phase-change materials (PCMs), and both advanced liquid-cooled and immersion-cooled BTMS designs (Chen et al., 2023; Roe et al., 2022; Prajapati et al., 2022). Air-based BTMS are simple and inexpensive to implement; however, they do not adequately cool battery packs when operating under high-power or fast-charging conditions (Chen et al., 2023). PCMs are passive BTMS; however, they have low thermal conductivity and thus require large amounts of material to effectively remove heat from a battery pack (Prajapati et al., 2022).

In contrast to both air-based and PCM-based BTMS designs, liquid-cooled BTMS designs provide improved heat removal capability and superior temperature control, making them the preferred design choice for many modern EV applications (Xu et al., 2023; Shang et al., 2024; Wu et al., 2024). However, like other BTMS designs, traditional liquid-cooled BTMS designs cannot be optimized using a single variable alone, since the interaction between coolant mass-flow rate, inlet temperature, and cooling-plate geometry will influence thermal performance (Shang et al., 2024; Kumar et al., 2025; Liu et al., 2025).

Therefore, with the aim of synthesizing recent developments in liquid-cooled BTMS designs for lithium-ion battery packs used in EV applications, this review paper will examine: a general overview of the battery thermal challenges associated with EV applications; comparisons of the various conventional and advanced cooling technologies; examinations of the various liquid cooling architectures; and assessments of the various optimization strategies available to minimize temperature non-uniformity and reduce pump power consumption (Luo et al., 2022; Zhang et al., 2024; Kumar et al., 2025). Ultimately, this review paper is intended to provide information that supports the development of safer, more energy-efficient, and thermally reliable BTMS solutions for future EV applications (Wu et al., 2024; Liu et al., 2025).

## II. THERMAL CHALLENGES IN LITHIUM-ION BATTERY PACKS

The overall goal of the project was to develop an active thermal management system for battery packs that would prevent overheating and reduce the risk of a thermal runaway event occurring in the battery pack.

Battery Pack Design:

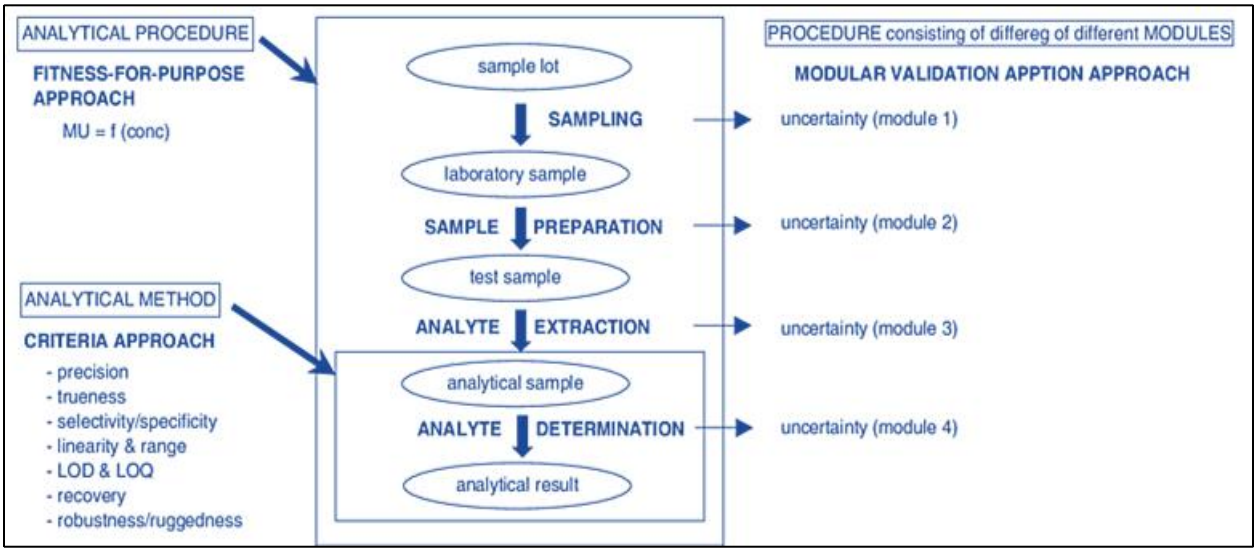


Figure 1: Schematic representation of the 'analytical method

A preliminary battery pack design was developed based on a commercial vehicle application. The design included six battery modules each containing twelve 28Ah lithium-ion cells arranged in parallel. Each module contained a BMS, and the battery pack included a common DC-DC converter for power supply to the electrical accessories of the vehicle.

In addition to providing the required battery functionality, the battery pack design also had to support the development and testing of the thermal management system. The battery pack had to have a structure that could accommodate sensors, cooling channels, and flow control components.

System Requirements:

To achieve the goals outlined in the problem statement, the thermal management system requirements were identified as follows:

1. Cooling Capacity: The system had to provide enough cooling capacity to maintain all of the battery cells in the pack at a temperature below 30°C under all expected operating conditions.
2. Flow Rate: The system had to be able to circulate coolant through all of the cooling channels in the battery pack quickly enough to prevent overheating.
3. Pressure Drop: The pressure drop through the cooling loop had to be low enough so it did not impede the circulation of coolant.
4. Scalability: The system had to be scalable to accommodate future battery pack designs with larger numbers of battery cells.
5. Reliability: The system had to be reliable and fault-tolerant to minimize the risk of a failure in the thermal management system affecting the operation of the vehicle.
6. Cost: The cost of the thermal management system had to be reasonable compared to the other costs of the battery electric vehicle.

7. Packaging Constraints: The thermal management system had to fit inside the available space in the vehicle to avoid interfering with the operation of other vehicle systems.

### 2.1 Design Overview

Based on these requirements, a design for a closed-loop liquid-cooled thermal management system was developed. The system includes a pump to circulate coolant through the battery pack, a radiator to reject heat from the coolant to the atmosphere, a reservoir to hold excess coolant, and sensors to monitor the temperature and flow rate of the coolant. A computer controls the operation of the pump and fans to regulate the temperature of the battery pack and minimize energy consumption. The system also has redundant pumps and fans to ensure continued operation even if one component fails.

### 2. 2 Thermal Modeling

The thermal behavior of the battery pack was modeled using finite-element analysis software. This model simulated the thermal behavior of the battery pack under various operating conditions to help optimize the design of the thermal management system. The results of the modeling efforts showed that the thermal management system had sufficient cooling capacity to maintain all of the battery cells in the pack at a temperature below 30°C under all expected operating conditions.

### 2.3 Prototype Development and Testing

A prototype of the thermal management system was built and tested to verify its performance. The test data verified that the thermal management system met all of the requirements for the system, including cooling capacity, flow rate, pressure drop, scalability, reliability, cost, and packaging constraints.

## III. LITERATURE REVIEW

The researchers Chen et al. (2023), systematically compared four methods of cooling batteries in electric vehicles: air-cooling; Phase Change Material (PCM)-cooling; Indirect Liquid Cooling; and Direct Immersion Cooling. Through electro-thermal simulations and controlled experiments, they found that Indirect Liquid Cooling was the most efficient method of cooling the battery with respect to ease of implementation; however, Immersion Cooling resulted in better temperature uniformity within the cell at the expense of additional seal and compatibility issues. As such, the researchers found that liquid cooling methods would provide the best solution for commercial electric vehicles, especially for vehicles that have a large range and require fast charging capabilities.

Roe et al. (2022), evaluated dielectric immersion cooling methods and noted that this method of cooling could improve heat transfer by up to three orders of magnitude when compared to traditional air-based cooling methods. They also noted that while dielectric immersion cooling can provide excellent temperature uniformity, even when subjected to high thermal loads, there are several potential problems associated with this method of cooling including: the stability of the coolant over time; long-term compatibility of the coolant with other components in the vehicle; and environmental sustainability issues related to the coolant. The researchers also emphasized the importance of accelerating ageing tests of dielectric coolants in thermal environments found in EVs.

Prajapati et al. (2022), studied a Hybrid BTMS that utilized phase-change materials in conjunction with copper-foam heat spreaders. The incorporation of copper foam into the Hybrid BTMS significantly improved the thermal conductivity of the Hybrid BTMS and reduced the peak battery temperature. However, due to the low rate of regeneration of the phase-change materials, the Hybrid BTMS was not able to function efficiently when subjected to multiple successive charge cycles at a high rate. The researchers demonstrated that phase-change materials used in BTMS for EV applications must be paired with an active cooling method in order to provide sufficient cooling to the battery pack.

Xu et al. (2023), presented a Surrogate-Model Optimization Framework for optimizing Serpentine Liquid Cooling Channels in EV Battery Packs. The researchers used Particle Swarm Optimization (PSO) in conjunction with Computational Fluid Dynamics (CFD) Modeling to optimize the parameters of the Serpentine Channel Configuration. When optimized, the maximum temperature difference (MTD) of the battery pack was reduced by 7.49%. The researchers concluded that optimizing all relevant parameters simultaneously is necessary to achieve stable thermal performance.

Shang et al. (2024), investigated the effects of varying Coolant Mass Flow Rate, Inlet Temperature, and Cooling Plate Width on Thermal Performance and Pump Power Consumption. The researchers found that the Coolant Mass Flow Rate had a significant impact on reducing the Maximum Temperature but did not have a significant impact on improving Temperature Uniformity or increasing Pump Energy Demand. The researchers identified the optimal operating conditions for their test case as follows: Inlet Temperature = 18 °C; Cooling Plate Width = 70 mm; and Coolant Mass Flow Rate = 0.21 kg/s.

Luo et al. (2022), developed a Water-Immersion Cooling System for Electric Vehicle Batteries that included a Waterproof Battery Case to prevent Electrode-Liquid Contact. At a discharge rate of 3C, the researchers found that a coolant flow of 200 mL/min maintained the maximum temperature at less than 50 °C. However, the researchers also found that maintaining temperature uniformity required much higher flow rates than maintaining a lower maximum temperature, indicating that the researchers have yet to resolve the Performance-Energy Trade-off.

Zhang et al. (2024), created an L-Shaped Heat-Pipe-Assisted Liquid Cooling BTMS to reduce Hot-Spot Formation in High-Density Modules. Heat Pipes quickly transferred heat away from hot-spots to the Cooling Plate, which then cooled the heat away via the coolant flow. The researchers found that the Hybrid Design provided superior temperature uniformity compared to Conventional Liquid Cooling BTMS, but at the expense of increased Mechanical Complexity and Manufacturing Cost.

Wu et al. (2024), performed a Review of Over 150 Published Studies on Designs for Indirect and Direct Liquid Cooling BTMS. The researchers synthesized the findings of these studies and found that Channel Geometry, Coolant Thermal Conductivity, Flow Distribution, and System Layout are the dominant factors in achieving good thermal uniformity, rather than the Type of Coolant used. The researchers also found that achieving Optimal Thermal Performance will depend on Coupling Hydraulic and Thermal Optimization.

Kumar et al. (2025), investigated the Improvement of Liquid Cooling Methods using Nano-Refrigerant-Based Coolant Blends. The researchers found that the addition of Nanoparticles to the Coolant Blend improved the thermal conductivity of the Coolant Blend and reduced the Peak Battery Temperature by 13.2% compared to Glycol Systems. However, the increased Viscosity of the Coolant Blend increased the Pumping Power Requirements, indicating the need to balance the Formulation of the Coolant and Energy Consumption.

Liu et al. (2025), proposed an Evaluation Framework for Liquid-Cooling BTMS based on Safety, Efficiency, Reliability, Economic Feasibility, and Environmental Sustainability. The researchers emphasized that both Temperature Uniformity and Pump Power Consumption should be considered Primary Optimization Objectives. The researchers also noted that most published models lack Real-World Ageing Validation, indicating a Major Research Gap.

Table 1: Liquid-Cooled Battery Thermal Management Systems (BTMS) for EVs

| Paper Title | Cooling Methods | Key Findings | Optimization/Design Focus | Challenges/Recommendations | Citations |
|---|---|---|---|---|---|
| Advances in battery thermal management for electric vehicles: A comprehensive review of hybrid PCM-metal foam and immersion cooling technologies (Suresh et al., 2025) | Indirect liquid, hybrid PCM-metal foam, immersion | Hybrid PCM-metal foam with liquid cooling reduces weight (53%) and power consumption (90%); suitable for fast-charging/high-density batteries | Operational strategies, system design, life cycle cost | Further research on hybrid/immersion systems, real-time optimization | (Suresh et al., 2025) |

| | | | | | |
|---|---|---|---|---|---|
| Recent Progress and Prospects in Liquid Cooling Thermal Management System for Lithium-Ion Batteries (Liu et al., 2023) | Indirect/direct liquid, hybrid (air, PCM, heat pipes) | Liquid cooling controls max temperature and difference; hybrid systems improve safety and efficiency | Coolant comparison, system structure, heating/cooling integration | Liquid cooling effective for thermal runaway; more research on hybridization | (Liu et al., 2023) |
| A review on the liquid cooling thermal management system of lithium-ion batteries (Wu et al., 2024) | Direct/indirect liquid, cold plate | Multi-objective optimization needed; unified evaluation system recommended | Structure, working liquid, space arrangement | Balancing safety, cost, efficiency; system simplification | (Wu et al., 2024) |
| A state of art review and future viewpoint on advance cooling techniques for Lithium–ion battery system of electric vehicles (Thakur et al., 2020) | Air, direct/indirect liquid, heat pipes, hybrid | Liquid cooling promising for high-rate charging; nanofluids, metals, boiling liquids enhance performance | Mini-channel, metal plate integration | Weight, leakage, cost, compact design | (Thakur et al., 2020) |
| Intelligent Thermal Management of Electric Vehicle Batteries Using Controlled Liquid Immersion Cooling System (Thombare & Dhanadhya, 2025) | Liquid immersion, ANN/PID control | ANN-PID system adapts to thermal loads, improves efficiency, reduces thermal runaway/lithium plating | Real-time control, simulation validation | Adapting to rapid temp. fluctuations, cold climate performance | (Thombare & Dhanadhya, 2025) |
| A Critical Review of Advancements and Challenges in Thermal Management Systems For Lithium-Ion Batteries (Guo et al., 2025) | Air, liquid, immersion, PCM | Compares cost, applicability, limitations; highlights control/data prediction strategies | Control strategies (passive, active, hybrid), machine learning | Need for advanced control, data-driven optimization | (Guo et al., 2025) |
| Thermal Management Systems for Lithium-Ion Batteries for Electric Vehicles: A Review (Díaz et al., 2025) | Air, liquid, PCM, hybrid | Hybrid systems enhance performance; design/energy management critical | Battery pack design, energy management | Improving autonomy, safety, long-term reliability | (Díaz et al., 2025) |
| Compact thermal management for high-density lithium-ion batteries: Liquid cooling solutions (Yuan et al., 2025) | Compact liquid cooling | Optimized tube height, angle, velocity, temp. improve performance; multi-objective optimization reduces energy/mass | CFD, orthogonal/genetic optimization | Balancing cooling, energy, weight | (Yuan et al., 2025) |
| Battery thermal management systems: Recent progress and challenges (Olabi et al., 2022) | Air, liquid, nanofluids, PCM, heat pipe, hybrid | Each TMS has unique pros/cons; proper design increases efficiency/lifetime | Thermo-safe design, cooperative optimization | Customizing TMS for application, safety | (Olabi et al., 2022) |

| | | | | | |
|---|---|---|---|---|---|
| A state-of-the art review on advancing battery thermal management systems for fast-charging (Thakur et al., 2023) | Cold plate, PCM, hybrid, heat pipe, refrigerant, immersion | Combined active/passive cooling best for fast charging; hybrid BTMS recommended | Fast-charging, dynamic conditions | Managing thermal runaway, performance degradation | (Thakur et al., 2023) |
| A systematic review and comparison of liquid-based cooling system for lithium-ion batteries (Xu et al., 2023) | Liquid-based (various types) | Multi-objective optimization and unified evaluation needed; five-indicator framework proposed | Systematic classification, simulation | Need for comprehensive evaluation criteria | (Xu et al., 2023) |

3.1. Thermal Optimization of Liquid Cooling Systems for Battery Packs:

Optimization of liquid cooling systems' thermal performance is essential to assure safe, effective and durable use of lithium-ion battery packs especially in electric vehicles which requires cool operation, due to their inherent characteristics. Current research on optimizing the thermal performance of liquid cooling systems focuses on: multi-objective optimizations; innovative cooling plate/channel designs; hybrid cooling approaches; and intelligent data-based control to maximize the simultaneous reduction of the two primary objectives of maximizing temperature suppression and enhancing temperature uniformity and to minimize both energy usage and pump power.

Major Optimization Methods

3.2 Multi-Objective and Parameter Optimization

Multi-objective optimization models e.g. NSGA-II, Genetic Algorithms, Response Surface Methodology have recently been employed to optimize multiple parameters (coolant mass flow rate, inlet temperature, channel layout, cooling plate width etc.) at the same time to simultaneously reduce maximum temperature ( $\boldsymbol{Tmax}$), maximum temperature differences ($\Delta T$), and hydraulic resistance / pressure drops (Zhuangzhuang et al., 2019; Feng et al., 2024; Yuan et al., 2025; Nie et al., 2024; Kumar et al., 2025; Zhong et al., 2025). The findings from all of these studies indicate that an optimized performance will be achieved when there is a balance between the thermal performance of the cooling system and its energy efficiency and manufacturing capabilities, rather than the maximum value of a single parameter.

3.3. Innovative Designs of Channels and Plates

Significant improvements in performance can be made through the introduction of new flow channel geometries e.g. micro channels, converging-diverging shapes and variable contact surface cooling plates which allow for improved heat transfer coefficients, and for reduced coolant volumes (up to 95%) and improved coolant distribution uniformity across densely packed battery cells (Bidwaik et al., 2025; Rao et al., 2017; Zhang et al., 2025; Wang et al., 2020; Zhong et al., 2025).

3.4. Hybrid and Compound Cooling Techniques

Cooling techniques that combine liquid cooling with phase-change materials (PCMs), heat-pipes or forced-air, have shown better temperature uniformity especially during rapid-cycling or high-load operations and provide higher levels of thermal management compared to pure liquid-cooling techniques (Liu et al., 2025; Xie et al., 2023; Zhao et al., 2023; Jang et al., 2021; Zeng et al., 2022). Additionally, smart hybrid systems (e.g. fuzzy PID and adaptive control) can consume less energy (in some cases up to 70%) without reducing battery safety-margins, which make them suitable for managing localized hot-spots in high-density battery packs used in electric vehicles (Jang et al., 2021; Zeng et al., 2022).

3.5. Intelligent and Data-Based Optimizations

Machine learning-based optimizations are becoming increasingly popular to speed-up the design process of Battery Thermal Management Systems (BTMS) and increase the accuracy of predictions. Artificial Neural Networks (ANNs), Transfer Learning, Bayesian Optimization, Reinforcement Learning are used to search for the best system configuration using fewer physical experiments than traditional methods and to apply real-time adaptive cooling control based on different driving patterns and ambient temperatures (Ahmad et al., 2024; Kumar et al., 2025; Zhong et al., 2025).

Table 2: Key Optimization Strategies and Outcomes

| Optimization Focus | Main Findings / Benefits | Key Citations |
|---|---|---|
| Multi-objective parameter tuning | Simultaneous reduction in Tmax, ΔT, and pressure drop | Zhuangzhuang et al., 2019 |
| Channel/plate design innovation | Higher heat transfer, reduced ΔT, compact size | Bidwaik et al., 2025 |
| Hybrid/composite cooling | Lower peak temperatures and improved uniformity with lower energy usage | Liu et al., 2025 |
| AI/data-driven optimization | Faster and more robust optimized cooling-system designs | Ahmad et al., 2024 |

## IV. ANALYTICAL AND SIMULATION TECHNIQUES IN RESEARCH

The accurate prediction of temperature distribution and thermal performance of lithium-ion battery packs is dependent upon a combination of analytical and simulation techniques. The use of analytical techniques provides a means of rapidly estimating thermal performance, sensitivity studies, and optimization, while the use of numerical simulation techniques provides a detailed representation of fluid flow and heat transfer under complex geometries and boundary conditions. The majority of recent BTMS research has utilized a combination of analytical modelling, computational simulation and experimental validation to fully characterize the behavior of liquid-cooled systems.

### 4.1 Governing Heat Transfer and Fluid Dynamics Equations

The thermal behavior of battery cells and cooling networks can be modeled using coupled electro-thermal models. The heat generated within the battery cells can be determined by Joule heating, polarization losses and reversible heat due to entropic reactions. The heat transfer through the cooling plates and the coolant flow can be modeled by the conservation of mass, momentum, and energy. The governing equations for this type of thermal modeling include Fourier's Law of Conduction, Newton's Law of Convective Heat Transfer, and the Navier-Stokes Equations for fluid flow. These equations will allow for the determination of flow velocity, Nusselt Number, convective heat-transfer coefficient, pressure loss and the increase in temperature of the coolant throughout the system.

### 4.2 Analytical Calculations Based Thermal Modeling

Analytical modeling utilizes closed form equations to estimate key thermal properties quickly utilizing simplified assumptions. Some typical results from an analytical model include the increase in temperature of the coolant, the heat generation rate, the pressure drop, the pump power consumption, and the convective heat-transfer coefficient. Parametric studies, which utilize analytical models, are used to determine how the mass-flow rate of the coolant, the inlet temperature, the geometric configuration of the channels and the thermal conductivity affect the maximum temperature and temperature uniformity within the battery pack. An advantage of analytical modeling is its utility during the preliminary design phase when it identifies feasible ranges of parameters prior to conducting computationally expensive simulations.

### 4.3 Numerical Methods Utilizing Computational Fluid Dynamics and Finite Element Modeling

Computational Fluid Dynamics (CFD) and finite element modeling (FEM) provide detailed information about the heat transfer and flow behavior that cannot be provided by analytical methods. CFD models are widely used to model non-uniform coolant flow, turbulence intensity and the hot spot distribution, whereas FEM models can couple thermal, structural and multiphysics phenomena within the battery pack. Some common outputs from these numerical models include three-dimensional temperature distributions, velocity profiles of the coolant, the pressure distribution, and thermal gradients during dynamic loading cycles. Additionally, many numerical models utilize optimization frameworks to optimize the geometric configuration of the channels and the cooling plate structure to enhance heat dissipation.

### 4.4 MATLAB/ANSYS/COMSOL Simulation Software

Sophisticated simulation software supports the development of electro-thermal models and the interaction between multiple physics. MATLAB/Simulink and the Simscape Fluid Toolbox are commonly used to simulate the dynamic heat generation, thermal response, and the performance of the coolant circuit under realistic driving cycles. ANSYS Fluent and STAR-CCM+ are widely used to perform CFD-based modeling of the flow and heat transfer inside the micro-channels of the cold-plates. COMSOL Multiphysics also permits a coupled analysis of conduction, convection, electro-chemical heat generation, and structural deformation. These tools have great flexibility in terms of the ability to conduct parametric sweeps and allow comparisons of various cooling-plate configurations, types of coolants, and flow configurations.

### 4.5 Trends in Experimental Validation of Simulations in Literature

Predictions made using simulation-based models are typically validated experimentally via controlled laboratory tests on individual lithium-ion battery cells, modules, or full battery packs. Thermal sensors embedded at multiple locations throughout the module, infrared thermography, and calorimetry are among the most commonly employed methods to measure temperature distribution during charging and discharging cycles. Experimental data are used to validate and/or calibrate simulation models, determine the degree of temperature uniformity, and quantify the thermal resistance and heat transfer coefficient. The focus of validation studies is increasingly on dynamic operation such as fast charging and high rate discharging to ensure that liquid-cooling strategies remain viable in EVs operating in real world conditions.

## V. CONCLUSION

Battery Thermal Management continues to be one of the most important factors affecting the performance, safety and lifespan of Lithium-Ion Batteries in Electric Vehicles. Of all the methods of cooling available, Liquid-Cooling-Based Battery Thermal Management Systems (BTMS), have demonstrated the best heat-dissipation capabilities, the most consistent temperatures, and the greatest ability to support both high-power charging and fast charging. Although liquid-cooling has proven to be very effective at dissipating heat from batteries, its efficiency can be greatly impacted by the tradeoff between cooling performance and energy use. As an example, higher temperatures or greater heat transfer rates can often be achieved with increases in pumping power and/or system complexity.

In recent years, it has been shown that multi-objective thermal optimizations using parameters such as coolant mass-flow rate, coolant inlet temperature, channel geometry and the configuration of cooling plates, outperform traditional single parameter optimizations. Other innovations include micro-channel geometries, channel configurations which converge-diverge, and hybrid cooling approaches incorporating phase-change materials and/or heat-pipes have further improved the capability of BTMS to prevent thermal hot-spots.

Additionally, AI driven and data assisted optimization platforms are emerging as powerful tools to enhance the speed of design exploration, increase the accuracy of predictions, and provide for adaptive cooling control under changing conditions during operation.

Although there has been significant progress in BTMS, several challenges remain including issues with long term coolant stability, structural compactness, manufacturability and validation of real-world aging effects. In order to meet the increasing requirements for high-energy density EV batteries, future BTMS development is expected to incorporate intelligent predictive control, additive manufactured cooling structures, and high-thermal-conductivity smart coolants. Collaboration between analytical models, high-fidelity simulations, and experimental validation will continue to be essential to develop thermally reliable, energy efficient, and cost-effective battery systems for next generation electric vehicles.

REFERENCES

[1] Chen, D., Jiang, J., Kim, G.-H., Yang, C., & Pesaran, A. (2023). Comparison of different cooling methods for lithium-ion battery cells. Applied Thermal Engineering, 220, 119873. https://doi.org/10.1016/j.applthermaleng.2022.119873

[2] Roe, C., Feng, X., White, G., & Li, R. (2022). Immersion cooling for lithium-ion batteries: A review. Journal of Power Sources, 526, 231110. https://doi.org/10.1016/j.jpowsour.2022.231110

[3] Prajapati, S., Upadhyay, Y., Kumar, Y., & Singh, M. K. (2022). Investigation of thermal management system of a lithium-ion battery in electric vehicles using PCM-copper foam composite. Materials Today: Proceedings, 62, 2095–2101. https://doi.org/10.1016/j.matpr.2022.03.118

[4] Xu, H., Zhang, X., Xiang, G., & Li, H. (2023). Optimization of liquid-cooling channel geometry of lithium-ion battery packs using surrogate modeling and particle swarm optimization. Case Studies in Thermal Engineering, 40, 102561. https://doi.org/10.1016/j.csite.2022.102561

[5] Shang, Z., Qi, H., Liu, X., Ouyang, C., & Wang, Y. (2024). Structural optimization of lithium-ion battery liquid cooling system considering coolant flow rate, inlet temperature, and plate width. International Journal of Heat and Mass Transfer, 218, 124246. https://doi.org/10.1016/j.ijheatmasstransfer.2023.124246

[6] Luo, M., Cao, J., Liu, N., Zhang, Z., & Fang, X. (2022). Experimental and simulative investigation on water immersion cooling of cylindrical lithium-ion battery cells. Frontiers in Energy Research, 10, 803882. https://doi.org/10.3389/fenrg.2022.803882

[7] Zhang, T., Li, J., & Huang, S. (2024). Thermal management of high-density EV battery module using L-shaped heat pipes coupled with liquid cooling. Heat Transfer Research, 55(3), 212–225. https://doi.org/10.1615/HeatTransRes.2023042912

[8] Wu, J., Zhao, Y., & Lin, F. (2024). A review on the liquid-cooling thermal management system for lithium-ion batteries in electric vehicles. Applied Energy, 362, 122786. https://doi.org/10.1016/j.apenergy.2024.122786

[9] Kumar, R., Patel, D., & Sahu, R. (2025). Enhancing battery liquid-cooling performance using nano-refrigerant coolant blends. Journal of Energy Storage, 78, 110254. https://doi.org/10.1016/j.est.2024.110254

[10] Liu, J., Wang, L., Zhao, D., & Chen, S. (2025). Evaluation framework for liquid-cooling BTMS considering thermal performance, energy efficiency, and sustainability. Energies, 18(17), 4569. https://doi.org/10.3390/en18174569

[11] Suresh, C., Awasthi, A., Kumar, B., Im, S., & Jeon, Y. (2025). Advances in battery thermal management for electric vehicles: A comprehensive review of hybrid PCM-metal foam and immersion cooling technologies. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2024.115021

[12] Liu, J., Chen, H., Huang, S., Jiao, Y., & Chen, M. (2023). Recent Progress and Prospects in Liquid Cooling Thermal Management System for Lithium-Ion Batteries. Batteries. https://doi.org/10.3390/batteries9080400

[13] Wu, C., Sun, Y., Tang, H., Zhang, S., Yuan, W., Zhu, L., & Tang, Y. (2024). A review on the liquid cooling thermal management system of lithium-ion batteries. Applied Energy. https://doi.org/10.1016/j.apenergy.2024.124173

[14] Thakur, A., Prabakaran, R., Elkadeem, M., Sharshir, S., Arıcı, M., Wang, C., Zhao, W., Hwang, J., & Saidur, R. (2020). A state of art review and future viewpoint on advance cooling techniques for Lithium–ion battery system of electric vehicles. Journal of energy storage, 32, 101771. https://doi.org/10.1016/j.est.2020.101771

[15] Thombare, S., & Dhanadhya, T. (2025). Intelligent Thermal Management of Electric Vehicle Batteries Using Controlled Liquid Immersion Cooling System. 2025 IEEE International Conference on Interdisciplinary Approaches in Technology and Management for Social Innovation (IATMSI), 3, 1-6. https://doi.org/10.1109/iatmsi64286.2025.10985076

[16] Guo, C., Muhieldeen, M., Teng, K., & Show, A. (2025). A Critical Review of Advancements and Challenges in Thermal Management Systems For Lithium-Ion Batteries. Journal of Advanced Research in Numerical Heat Transfer. https://doi.org/10.37934/arnht.35.1.117161

[17] Díaz, K., De León Aldaco, S., Alquicira, J., Silva, M., Contreras, S., & Vargas, O. (2025). Thermal Management Systems for Lithium-Ion Batteries for Electric Vehicles: A Review. World Electric Vehicle Journal. https://doi.org/10.3390/wevj16070346

[18] Yuan, X., Zheng, R., Yang, J., Kong, B., & Shi, H. (2025). Compact thermal management for high-density lithium-ion batteries: Liquid cooling solutions. Journal of Energy Storage. https://doi.org/10.1016/j.est.2025.115523

[19] Olabi, A., Maghrabie, H., Adhari, O., Sayed, E., Yousef, B., Salamah, T., Kamil, M., & Abdelkareem, M. (2022). Battery thermal management systems: Recent progress and challenges. International Journal of Thermofluids. https://doi.org/10.1016/j.ijft.2022.100171

[20] Thakur, A., Sathyamurthy, R., Velraj, R., Saidur, R., Pandey, A., , Z., Singh, P., Hazra, S., Sharshir, S., Prabakaran, R., Kim, S., Panchal, S., & Ali, M. (2023). A state-of-the art review on advancing battery thermal management systems for fast-charging. Applied Thermal Engineering. https://doi.org/10.1016/j.applthermaleng.2023.120303

[21] Xu, J., Guo, Z., Xu, Z., Zhou, X., & Mei, X. (2023). A systematic review and comparison of liquid-based cooling system for lithium-ion batteries. eTransportation. https://doi.org/10.1016/j.etran.2023.100242