

A Comprehensive Review of Battery Thermal Management for Electric Vehicle

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ABSTRACT

This review paper provides an exhaustive analysis of Battery Thermal Management Systems (BTMS), ranging from traditional passive air cooling to advanced active liquid and direct immersion cooling strategies, evaluated against the backdrop of emerging Extreme Fast Charging (XFC) requirements. By synthesizing recent literature from 2024 and 2025, this study critically compares the heat transfer coefficients, energy consumption, weight penalties, and manufacturing costs of various thermal management architectures. The analysis reveals that while indirect liquid cooling via cold plates remains the industry standard for current generation electric vehicles (EVs), it faces significant limitations in managing the high heat flux generated during >3C charging rates. Consequently, direct two-phase immersion cooling and hybrid systems integrating Phase Change Materials (PCMs) are identified as the most promising solutions for next-generation packs, offering superior thermal suppression of thermal runaway propagation. Furthermore, the review explores the integration of Artificial Intelligence (AI) and Model Predictive Control (MPC) for real-time thermal optimization, demonstrating potential energy savings of up to 78% in auxiliary cooling loads. The paper concludes with a forward-looking perspective on thermal requirements for solid-state batteries and the techno-economic implications of shifting towards dielectric fluid-based thermal architectures.

Keywords:- Electric Vehicles, Battery Thermal Management, Immersion Cooling, Computational Fluid Dynamics, Thermal Runaway, Phase Change Materials, Artificial Intelligence.

1. INTRODUCTION

The global imperative to decarbonize the transportation sector has catalyzed a profound paradigm shift from internal combustion engine (ICE) vehicles to electric vehicles (EVs). At the core of this transition lies the electrochemical energy storage system, predominantly realized through Lithium-ion batteries (LIBs) due to their high specific energy, power density, and declining cost trajectory.¹ However, the widespread adoption of EVs is contingent upon overcoming persistent challenges related to range anxiety, charging time, and safety—all of which are intrinsically linked to the thermal behavior of the battery pack. The performance of LIBs is governed by complex electrochemical kinetics and transport phenomena that are highly sensitive to temperature. Operating a battery outside its optimal thermal window not only degrades its performance—manifested as reduced capacity and power availability—but also accelerates aging mechanisms and elevates the risk of catastrophic safety events such as thermal runaway.

The primary objective of a Battery Thermal Management System (BTMS) is to regulate the battery pack temperature within a defined optimal range (typically 20°C to 40°C) and to minimize cell-to-cell temperature variations (ideally $\Delta T < 5^\circ\text{C}$)⁴. As EV technology evolves towards higher energy densities and Extreme Fast Charging (XFC) capabilities (charging at 350 kW or higher), the thermal loads imposed on the battery pack have intensified exponentially. The heat generation rate during XFC can exceed the rejection capacity of traditional air and indirect liquid cooling systems, necessitating the development of advanced thermal management architectures⁶. This review aims to provide a comprehensive, critical analysis of the state-of-the-art in BTMS, evaluating diverse cooling methodologies, modeling approaches, and emerging trends to guide the design of future EV battery packs.

1.1 Mechanisms of Heat Generation and Thermal Sensitivity

To design an effective BTMS, one must first understand the fundamental physics of heat generation within a Li-ion cell. The total heat generated, Q' , is a summation of irreversible heat (Joule heating) and reversible heat (entropic heat), typically described by the Bernardi equation:

$$Q' = I(V_{oc} - V) + I \cdot T \frac{dV_{oc}}{dT}$$

Where I is the current, V_{oc} is the open-circuit voltage, V is the cell terminal voltage, T is the temperature, and dV_{oc}/dT represents the entropic heat coefficient. The first term, $I(V_{oc} - V)$, represents the irreversible heat generated due to internal impedance (ohmic losses, charge transfer resistance, and mass transport limitations).

This term is always exothermic and scales with the square of the current (I^2R), making it the dominant heat source during high-power operations like fast charging or rapid acceleration. The second term, the reversible entropic heat, arises from the entropy change of the electrochemical reaction. Depending on the state of charge (SOC) and the direction of current (charge vs. discharge), this term can be either exothermic or endothermic. While entropic heat is often negligible at high C-rates, it becomes significant at low C-rates and can influence the temperature profile during long-duration cycles.

Temperature exerts a dual influence on battery electrochemistry. At low temperatures (below 0°C), the ionic conductivity of the electrolyte decreases significantly, and charge transfer resistance at the electrode-electrolyte interface increases. This leads to severe polarization and a risk of lithium plating on the anode during charging—a phenomenon where lithium ions deposit as metallic lithium rather than intercalating into the graphite structure. Lithium plating not only causes irreversible capacity loss but can also form dendrites that penetrate the separator, causing internal short circuits¹¹. Conversely, at high temperatures (above 45°C), the Solid Electrolyte Interphase (SEI) layer on the anode becomes unstable and begins to decompose. This decomposition consumes active lithium inventory, increases internal resistance, and can trigger exothermic side reactions. If the heat generated by these reactions exceeds the dissipation rate, the cell temperature can rise uncontrollably, leading to thermal runaway—a cascade of failure mechanisms involving separator melting, cathode decomposition, and electrolyte combustion that can propagate through the entire battery pack³.

1.2 Evolution Of Thermal Management Strategies

The evolution of BTMS reflects the increasing performance demands of EVs. First-generation EVs, such as early iterations of the Nissan Leaf, utilized passive air cooling, relying on natural convection or simple forced air. While cost-effective and simple, these systems proved inadequate for managing the thermal loads in hot climates or during repeated rapid charging, leading to accelerated degradation. This necessitated a shift towards active air cooling and, subsequently, liquid cooling systems. Liquid cooling, utilizing water-glycol mixtures circulating in cold plates, has become the industry standard for modern EVs (e.g., Tesla, GM, VW) due to the superior thermophysical properties of liquids compared to air.

However, the industry is currently at an inflection point. The push for XFC and 800V architectures drives heat generation rates that challenge the limits of indirect liquid cooling, primarily due to the contact thermal resistance between the cell, thermal interface material (TIM), and the cold plate¹⁶. This has spurred research into "next-generation" cooling technologies, particularly immersion cooling (where cells are directly submerged in dielectric fluid) and hybrid systems incorporating Phase Change Materials (PCMs) to buffer thermal transients. Simultaneously, the integration of advanced control strategies, leveraging Artificial Intelligence (AI) and Machine Learning (ML), offers new pathways to optimize thermal performance while minimizing the parasitic energy consumption of the BTMS.

2. BTMS CLASSIFICATION AND COMPREHENSIVE REVIEW

Battery thermal management systems can be broadly classified based on the heat transfer medium (air, liquid, PCM, heat pipe) and the energy source (active vs. passive). Each class presents a distinct set of trade-offs regarding cooling capacity, system complexity, weight, and cost.

2.1 Air Cooling Systems

Air cooling systems utilize air as the heat transfer medium and are categorized into passive (natural convection) and active (forced convection) systems.

2.1.1 Mechanisms and Performance In passive air cooling, heat is dissipated via buoyancy-driven flow and radiation. This method requires no auxiliary power but is limited by low heat transfer coefficients ($h \approx 5\text{--}10\text{W/m}^2\text{K}$), making it suitable only for low-energy-density batteries or mild hybrid applications. Active air cooling employs fans or blowers to force air through channels between cells, increasing the heat transfer coefficient to approximately $20\text{--}100\text{W/m}^2\text{K}$. The cooling efficiency depends critically on airflow rate, channel geometry, and flow configuration (e.g., serial vs. parallel).

Research indicates that while air cooling is structurally simple and eliminates leakage risks, it suffers from inherent limitations due to the low thermal conductivity ($k_{\text{air}} \approx 0.026\text{W/mK}$) and specific heat capacity ($C_{p,\text{air}} \approx 1005\text{J/kgK}$) of air compared to liquid coolants¹⁶. Consequently, maintaining temperature uniformity in large battery packs is challenging. Air passing over the first cells in a series configuration heats up, reducing the cooling potential for downstream cells, creating significant thermal gradients. To mitigate this, advanced designs employ reciprocating flow, where airflow direction is periodically reversed, or incorporate vortex generators and baffles to enhance turbulence and surface heat transfer²¹.

2.1.2 Optimization and Current Status

Despite its limitations, air cooling remains relevant for specific market segments due to its low cost and weight. Optimization studies using Computational Fluid Dynamics (CFD) have focused on varying plenum angles, channel widths, and battery spacing to improve flow distribution. For instance, increasing the inlet airflow rate can reduce the maximum temperature, but it comes with a penalty of higher fan power consumption and acoustic noise¹⁶. Current consensus suggests that air cooling is insufficient for XFC applications or high-performance EVs where heat fluxes exceed $1\text{--}2\text{ kW/m}^2$, but it remains a viable, cost-effective solution for electric two-wheelers and low-speed urban vehicles¹⁴.

2.2 Liquid Cooling Systems

Liquid cooling is the dominant technology in the current EV market, leveraging the high thermal conductivity ($k_{\text{water}} \approx 0.6\text{ W/mK}$) and specific heat capacity ($C_{p,\text{water}} \approx 4180\text{ J/kgK}$) of water-glycol mixtures to achieve heat transfer coefficients in the range of $500\text{--}1000\text{ W/m}^2\text{K}$ for indirect systems.

2.2.1 Indirect Liquid Cooling (Cold Plates) This architecture involves circulating a coolant through metal channels (cold plates) that are thermally coupled to the battery cells. The coolant does not contact the cells directly; instead, heat is conducted from the cell surface, through the electrical insulation and TIM, to the cold plate.

- **Design Variations:** Cold plates can be placed at the bottom of prismatic/pouch modules or snaked between cylindrical cells (e.g., Tesla's ribbon cooling tubes). The internal channel geometry is critical; serpentine channels are common but induce high pressure drops, whereas parallel channels offer lower flow resistance but risk flow maldistribution¹⁹.
- **Performance:** Indirect liquid cooling effectively manages the thermal loads of typical driving and Level 2 charging. It provides a good balance between cooling performance and system volume. However, the accumulation of thermal resistances (contact resistance, wall resistance) limits the maximum heat flux removal, creating a bottleneck during XFC events²⁴. Furthermore, the complexity of pumps, radiators, reservoirs, and plumbing adds significant weight and manufacturing cost, alongside the constant risk of coolant leakage which could cause electrical shorts.

2.2.2 Direct Liquid Cooling (Immersion) Immersion cooling, where battery cells are directly submerged in a dielectric fluid, represents a frontier in thermal management. By eliminating the thermal resistance of cold plates and TIMs, and maximizing the heat transfer surface area (contacting 100% of the cell), immersion cooling offers significantly superior performance.

- **Single-Phase Immersion:** Utilizing dielectric fluids like mineral oils or engineered esters, heat is removed via sensible heating of the fluid. Studies indicate that single-phase immersion can reduce the cell-to-cell temperature differential to $<2^\circ\text{C}$ even under high discharge rates, significantly outperforming cold plate systems²⁶.
- **Two-Phase Immersion:** This approach utilizes fluids with boiling points near the battery's operating limit (e.g., $40\text{--}50^\circ\text{C}$), such as hydrofluoroethers (e.g., 3M Novec). As the cell heats up, the fluid boils at the surface, absorbing massive latent heat of vaporization. This phase change mechanism yields heat transfer coefficients exceeding $10,000\text{ W/m}^2\text{K}$, effectively clamping the cell temperature and preventing thermal runaway propagation¹⁵.
- **Challenges:** The primary barriers to adoption are the high cost of dielectric fluids (up to $\$50\text{--}80/\text{liter}$ for fluorinated fluids), the weight penalty of the fluid volume, and the engineering complexity of sealing the pack against fluid loss and pressure variations.

2.3 Phase Change Material (PCM) Cooling

PCMs provide passive thermal management by absorbing heat during solid-to-liquid phase transitions. They act as a thermal buffer, absorbing transient heat spikes without a temperature rise until the material is fully melted.

- **Material Classes:** Paraffin waxes are widely used due to their low cost, chemical stability, and tunable melting points. Hydrated salts offer higher latent heat densities but suffer from supercooling and phase separation issues³¹.
- **Conductivity Enhancement:** A major limitation of organic PCMs is their low thermal conductivity ($k < 0.3\text{ W/mK}$), which delays thermal response and can lead to liquid leakage at the cell interface. To address this, PCMs are impregnated into porous matrices like expanded graphite, metal foams, or carbon nanotubes. These composites significantly enhance effective thermal conductivity (up to $10\text{--}20\text{ W/mK}$) and mechanical stability³³.
- **Limitations:** While excellent for shaving peak thermal loads, pure PCM systems cannot dissipate stored heat continuously. Once the PCM is fully melted, the system loses its cooling capability. Therefore, PCMs are

best implemented in hybrid systems (e.g., PCM + Air or PCM + Liquid) where an active system regenerates the PCM during low-load periods²⁴.

2.4 Emerging and Hybrid Strategies

- **Thermoelectric Cooling (TEC):** Based on the Peltier effect, TECs allow for precise, rapid active cooling and heating control. While offering compact, solid-state reliability, their low Coefficient of Performance (COP < 1.0) generally makes them energetically prohibitive for primary pack cooling, restricting their use to auxiliary or sub-module spot cooling³⁶.
- **Heat Pipes:** Heat pipes utilize liquid-vapor phase change within a sealed tube to transport heat with extremely high effective conductivity. They are passive, lightweight, and reliable, often serving as thermal bridges to transport heat from the battery core to a remote liquid or air heat sink¹⁵.
- **Hybrid Systems:** Combining technologies often yields synergistic benefits. For example, a hybrid PCM/liquid system can use PCM to absorb fast-charging heat spikes (reducing the peak demand on the liquid chiller) and liquid cooling to reject the accumulated heat over time. Such systems have been shown to reduce pump energy consumption while maintaining superior temperature uniformity²⁴.

3. ADVANCED COOLING STRATEGIES & COMPARATIVE ANALYSIS

To discern the optimal thermal strategy for future EV platforms, a rigorous techno-economic comparison of the dominant technologies is essential. This analysis integrates performance metrics, energy efficiency, and cost implications.

3.1 Immersion Cooling: A Techno-Economic Deep Dive

Immersion cooling is increasingly viewed as the enabler for XFC. Recent techno-economic analyses highlight distinct trade-offs. While the initial integration cost of immersion systems is higher—estimated at approximately \$90/kWh for integration hardware versus lower costs for air or simple liquid systems—the lifecycle benefits are substantial.

- **Cooling Efficiency:** Comparative studies demonstrate that immersion cooling provides heat transfer coefficients 2.5–3 times higher than cold plate cooling for equivalent flow rates. This superior efficiency allows for a reduction in pumping power by up to 50% for the same thermal target, significantly reducing the parasitic load on the battery.
- **Safety and Lifetime:** By immersing cells, the dielectric fluid acts as a fire suppressant and prevents electrical arcing. The exceptional temperature uniformity ($\Delta T < 2^\circ\text{C}$) extends battery life by preventing localized degradation, potentially increasing cycle life by 20% or more. This life extension can offset the higher upfront capital cost (CAPEX) by reducing the total cost of ownership (TCO) or Levelized Cost of Storage (LCOS).
- **Weight Analysis:** A critical drawback is the fluid weight. Dielectric fluids typically have densities ranging from 800–1800 kg/m³, adding significant mass compared to air or thin cold plates. However, immersion allows for denser cell packing (elimination of module housings and cold plates), which can partially recover system-level volumetric energy density.

3.2 Performance Comparison: Air vs. Liquid vs. Immersion

The following table synthesizes key performance metrics drawn from recent literature comparisons.¹⁶

Table 1: Comparative Analysis of BTMS Technologies

Metric	Active Air Cooling	Indirect Liquid (Cold Plate)	Single-Phase Immersion	Two-Phase Immersion
Cooling Medium	Air	Water-Glycol	Mineral Oil / Esters	Cytofluorometers
Heat Transfer Coeff. (\$h\$)	\$20 - 100 \backslash\$ W/m ² K\$	\$500 - 1,000 \backslash\$ W/m ² K\$	\$1,000 - 5,000 \backslash\$ W/m ² K\$	\$> 10,000 \backslash\$ W/m ² K\$
Temp. Uniformity (\$\Delta T\$)	Poor (\$> 5^\circ\text{C}\$)	Good (\$3 - 5^\circ\text{C}\$)	Excellent (\$< 3^\circ\text{C}\$)	Superior (\$< 1^\circ\text{C}\$)
Complexity	Low	High (Pumps, seals)	Medium-High (Seals)	High (Vapor management)
Leakage Risk	None	High (Short circuit risk)	Low (Dielectric safe)	Low (Dielectric safe)
Parasitic Energy	High (Fan power)	Medium (Pump power)	Low (Lower viscosity)	Low (Passive boiling)
Cost	Low	Medium	High	Very High
Suitability for XFC	No	Limited	Yes	Excellent

3.3 Cost and Weight Analysis

Cost remains a decisive factor. While air cooling is the cheapest, its inability to support XFC renders it obsolete for premium EVs. Indirect liquid cooling currently offers the best cost-to-performance ratio for mainstream vehicles. The cost of cold plate systems is driven by precision machining and assembly. In contrast, immersion systems reduce mechanical complexity (no complex manifolding inside modules) but incur high fluid costs.

- **Fluid Costs:** Dielectric fluids can range from 1.50/L for mineral oils to over 100/L for engineered fluorinated fluids. For a 60-80 kWh pack requiring 40-80 liters of fluid, this represents a significant bill of materials (BOM) cost.
- **System Weight:** Liquid cooling systems add weight through pumps, radiators, and coolant (approx. 15–30kg for a typical EV). Immersion systems can be heavier due to fluid volume, but recent "lightweighting" designs minimize fluid volume to thin films or targeted channels, bringing the weight penalty closer to parity with indirect systems.
- **Energy Consumption:** The parasitic load of the BTMS directly impacts EV range. Studies indicate that active BTMS can consume 3-5% of battery energy in moderate climates and up to 15-20% in extreme conditions. Optimizing this consumption through advanced control (Section 4.2) is a key research frontier.

4. MODELING AND CONTROL

The design and optimization of BTMS rely heavily on advanced mathematical modeling and control strategies.

4.1 Computational Fluid Dynamics (CFD) and Numerical Approaches

To predict thermal behavior with high fidelity, multi-scale modeling approaches are employed.

- **Lumped Parameter Models:** These 0D or 1D models treat the battery as a homogenous thermal mass. They are computationally efficient and used for real-time BMS control but lack spatial resolution. The governing energy balance equation is typically:

$$mC_p \frac{dT}{dt} = Q_{gen} - hA(T_{cell} - T_{coolant})$$

These models are often coupled with Equivalent Circuit Models (ECM) to estimate heat generation.

- **CFD Simulations:** For system design, 3D CFD is indispensable. It solves the Navier-Stokes equations for fluid flow and the energy equation for heat transfer. Common turbulence models like the $k-\epsilon$ or $k-\omega$ SST are used to resolve flow in cooling channels.
- **Recent Findings:** A recent study by Chen & Hu (2025) utilizing ANSYS Fluent demonstrated that without BTMS, a battery pack temperature could reach 63.8°C under 3C discharge, far exceeding safety limits. Implementing a hybrid liquid cooling system reduced this to 38.7°C. Further optimization using composite BTMS lowered it to safe operational limits, highlighting the necessity of CFD in validating designs before prototyping.
- **Tools:** Commercial codes like STAR-CCM+ and ANSYS Fluent are standard, allowing for coupled electrochemical-thermal simulations that capture the feedback loop between temperature and current density distribution.

4.2 AI and Machine Learning in Thermal Control

The integration of AI and Machine Learning (ML) is revolutionizing BTMS control logic. Traditional control relies on simple rule-based thresholds (e.g., turn on pump if $T > 35^\circ\text{C}$). However, these are reactive and often inefficient.

- **Model Predictive Control (MPC):** MPC uses a dynamic model of the system to predict future thermal states and optimize control actions (e.g., pump speed, valve position) over a future horizon. By anticipating heat loads (e.g., predicting a hill climb or a charging stop based on navigation data), MPC can pre-cool the battery, reducing peak temperatures and energy consumption¹⁸.
- **Neural Network Integration:** Artificial Neural Networks (ANNs) are being used to create high-fidelity, reduced-order thermal models that run in real-time on the BMS. These models can predict internal cell temperatures (which are hard to measure) based on surface sensors and current data¹⁸.
- **Impact:** Research by Li et al. demonstrated that an ANN-assisted MPC controller could reduce BTMS energy consumption by up to 78.9% in low-temperature conditions and ~28% in high-temperature environments compared to standard rule-based controllers. This reduction in parasitic load directly translates to increased vehicle range.

5. EMERGING TRENDS: FAST CHARGING & SOLID STATE

5.1 Extreme Fast Charging (XFC)

XFC is the "holy grail" for EV adoption but presents the ultimate thermal challenge. Charging a 100 kWh pack in 10 minutes requires 600 kW of power. Assuming 95% efficiency, 30 kW of heat is generated inside the pack—equivalent to the heat output of 20 residential space heaters. This requires heat rejection capabilities that

push the physical limits of materials. Two-phase immersion cooling is currently the only technology capable of managing such fluxes safely, utilizing the latent heat of vaporization to absorb localized hot spots instantly.

5.2 Thermal Management for Solid-State Batteries (SSBs)

Solid-state batteries are anticipated to replace liquid electrolyte LIBs due to higher energy density and safety. However, they introduce new thermal requirements.

- **Operating Temperatures:** Unlike liquid LIBs that degrade above 45°C, some polymer-based solid electrolytes require elevated temperatures (60-80°C) to achieve sufficient ionic conductivity.⁵⁴ This shifts the BTMS function from cooling to heating and insulation.
- **Thermal Stability:** While solid electrolytes (sulfides, oxides) are generally more thermally stable than liquid electrolytes, they are not immune to failure. Sulfide electrolytes can generate toxic H_2S gas if exposed to moisture or extreme heat.⁵⁶ Therefore, BTMS for SSBs will focus on precise thermal regulation to maintain ionic performance and prevent interface degradation, rather than just preventing combustion.

6. CONCLUSIONS

The advancement of Battery Thermal Management Systems is critical to the continued proliferation of electric vehicles. This review has synthesized the current state of technology, revealing a clear trajectory from passive air cooling to active liquid and emerging immersion strategies.

1. **Air cooling** has largely reached its performance ceiling and is relegated to low-cost, low-power applications.
2. **Indirect liquid cooling** remains the workhorse of the industry, offering a mature balance of cost and performance, yet it faces obsolescence in the face of XFC demands due to thermal resistance bottlenecks.
3. **Immersion cooling**, particularly two-phase systems, offers the superior heat transfer coefficients ($>10,000 \text{ W/m}^2\text{K}$) and temperature uniformity ($<1^\circ\text{C}$) required for future high-performance and fast-charging EVs. Despite higher initial costs and weight, the lifecycle benefits in battery longevity and safety present a compelling business case.

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