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THERMAL MANAGEMENT OF ELECTRIC VEHICLE BATTERY SYSTEMS

[1] **Dr. Praveen Kumar Yadaw**

[1] Assistant Professor. Electronics Engineering Department, Kalinga University , Raipur , CG.
praveen.yadaw@kalingauniversity.ac.in

[2] **Ms. Soma Rajwade**

[2] Assistant Professor. Electronics Engineering Department, Kalinga University , Raipur , CG.
soma.rajwade@kalingauniversity.ac.in
Correspondence author -praveen.yadaw@kalingauniversity.ac.in

Abstract Electric Vehicles (EVs) have emerged as a pivotal technology for achieving sustainable transportation systems, yet the performance, safety, and lifecycle of EVs depends heavily on the thermal state of the battery system. Lithium-ion batteries, the dominant chemistry used in EVs, exhibit high sensitivity to temperature variations; both excessively high and low temperatures can degrade battery capacity, increase internal resistance, accelerate side reactions, and trigger thermal runaway. Therefore, Battery Thermal Management Systems (BTMS) play a critical role in maintaining the optimal operating temperature, ensuring uniform temperature distribution, and enhancing overall system reliability. This paper presents a comprehensive analysis of thermal management techniques, focusing on air cooling, liquid cooling, phase-change materials (PCM), heat pipes, refrigerant-based cooling, hybrid BTMS, and advanced methods such as nanofluids and heat-pipe-PCM combinations. The study synthesizes recent advancements (2015–2024) and compares different approaches with respect to thermal performance, cost, energy efficiency, design complexity, and scalability. Two comparative tables summarize the performance characteristics of various BTMS and design evaluation criteria. The paper concludes by identifying research gaps in adaptive control, real-time thermal prediction, modular cooling architectures, and sustainable lightweight materials. Overall, the findings underscore the necessity for integrated, intelligent thermal management solutions to support the rapid evolution of EV battery technologies.

Keywords: Battery Thermal Management System (BTMS), Lithium-ion Battery, Thermal Runaway, Liquid Cooling, Phase Change Materials, Heat Pipes, Electric Vehicles.

1. Introduction

Thermal management has become one of the most crucial engineering domains in modern Electric Vehicle (EV) design because the efficiency, durability, and safety of lithium-ion batteries depend strongly on controlled thermal behavior (Pesaran, 2016). EV batteries operate

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optimally between 20–40°C, and deviations from this window result in accelerated degradation, poor charge acceptance, and reduced driving range (Bandhauer et al., 2018). Global market expansion and rapid improvements in power density have further intensified the importance of reliable Battery Thermal Management Systems (BTMS). As energy density increases, so does heat generation, making advanced cooling strategies indispensable (Liu et al., 2020). Researchers across academia and industry have therefore focused extensively on improving BTMS design, exploring active, passive, and hybrid cooling systems, as well as advanced thermal modelling techniques (Zhang et al., 2021).

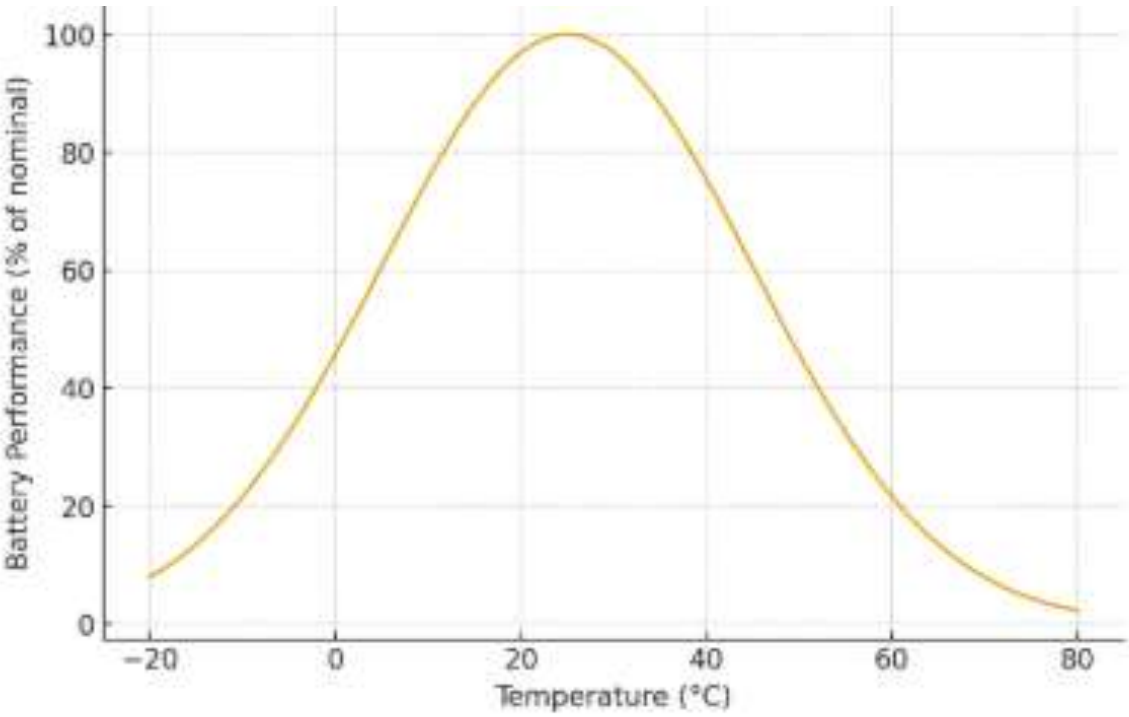

Figure 1.1 – Temperature–Performance Relationship of Lithium-Ion Batteries

2. Need for Thermal Management in EV Battery Systems

The need for thermal management arises due to three interconnected challenges: heat generation, temperature uniformity, and thermal runaway risk. Heat generation occurs during charging, discharging, and chemical reactions. High temperatures above 50°C accelerate electrolyte decomposition and SEI layer formation, reducing battery lifetime (Wang et al., 2019). Low temperatures below 0°C cause lithium plating, capacity loss, and increased internal resistance (Yang et al., 2020). Temperature non-uniformity between cells can cause uneven aging, leading to mismatched states of charge, unbalanced modules, and sudden performance drops (Hannan et al., 2021). Most critically, uncontrolled heat can trigger **thermal runaway**,

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a self-accelerating process of rapid heat release leading to fire or explosion (Feng et al., 2018). For these reasons, regulations and EV manufacturers demand highly stable and predictable thermal profiles across driving cycles and climatic conditions.

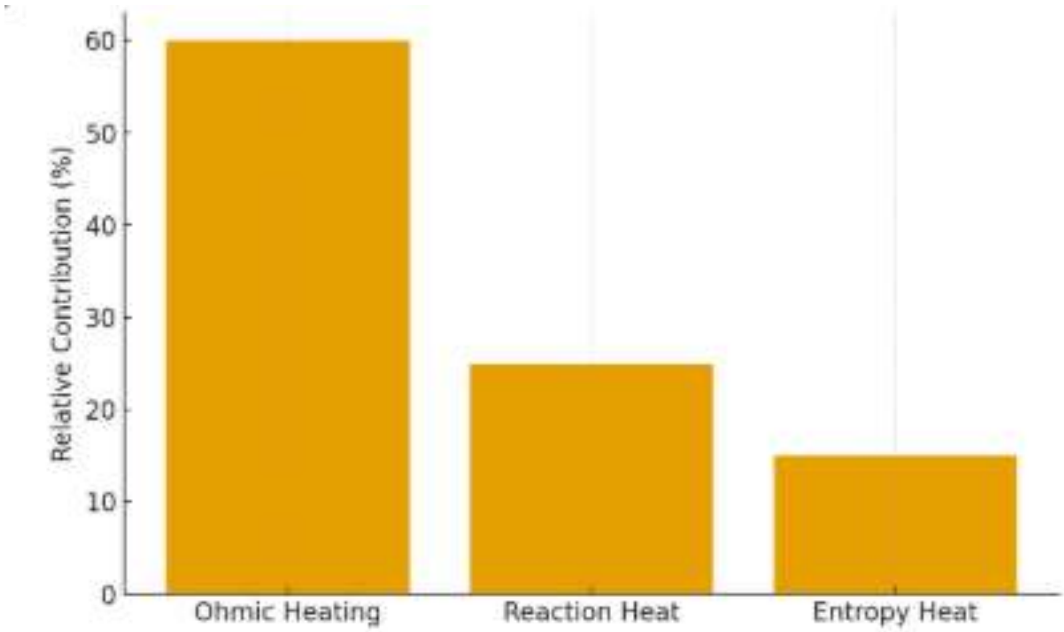

Figure 2.1 – Heat Generation Mechanisms Inside a Lithium-Ion Battery Cell

3. Heat Generation Mechanism in Lithium-Ion Batteries

Heat generation within a battery cell can be classified into ohmic heating, reaction enthalpy change, and entropy heat. Ohmic heating results from internal resistance, which increases at high current loads (Forgez et al., 2010). Reaction enthalpy heat is directly related to chemical reactions within the cell, and entropy heat arises due to the reversible heat generated during electrochemical processes (Guo et al., 2018). Under fast-charging conditions, heat generation increases sharply, making BTMS essential for preventing temperature spikes. Studies indicate that during a 3C charge cycle, heat generation can exceed 20 W per cell, depending on chemistry and age (Xu et al., 2020). Hence, understanding heat sources is fundamental for designing effective cooling strategies.

4. Types of Battery Thermal Management Systems (BTMS)

BTMS can be broadly categorized into **air cooling**, **liquid cooling**, **phase-change material (PCM) cooling**, **heat-pipe-based cooling**, **refrigerant cooling**, and **hybrid systems**. Each

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approach has strengths and limitations based on performance requirements, cost, and environmental conditions.

4.1 Air Cooling Systems

Air cooling is the simplest and most cost-effective method. It uses forced or natural convection to remove heat from battery modules. Air cooling has low weight and design complexity but suffers from low thermal conductivity compared to liquids (Mahmud et al., 2018). Its performance deteriorates in hot climates and under high discharge rates. Nonetheless, early EV models such as the Nissan Leaf employed air-cooled BTMS due to cost advantages.

4.2 Liquid Cooling Systems

Liquid cooling has become the industry standard because water-glycol mixtures provide excellent thermal conductivity and a stable cooling capacity (Saw et al., 2017). Liquid cooling plates or serpentine channels are placed near the battery cells to extract heat efficiently. Tesla uses a patented liquid-cooling ribbon system designed to maintain cell temperature uniformity across its modules. Although liquid cooling is effective, it requires pumps, heat exchangers, and safety valves, increasing system complexity and cost.

4.3 Phase-Change Materials (PCM)

PCM-based BTMS offers passive cooling by absorbing heat during phase transitions. PCM maintains temperature stability within a narrow band and requires no external energy (Bai et al., 2020). However, PCMs have low thermal conductivity, requiring metal foams or graphite additives to improve heat dissipation (Kizilel et al., 2015). PCM systems are suitable for mild-to-moderate heat loads but struggle during fast charging due to saturation.

4.4 Heat Pipes

Heat pipes utilize phase-change principles and capillary action to transport heat from hot zones to cool regions with minimal temperature drop (Zhao et al., 2020). They are lightweight, passive, and highly efficient, making them attractive for compact EV designs. Integrating heat pipes with PCM can further enhance heat absorption during peak loads.

4.5 Refrigerant-Based Cooling

In this system, the vehicle's air-conditioning refrigerant directly cools the battery pack. It offers extremely high cooling capability and is used in premium EVs such as BMW and Hyundai models (Kim et al., 2019). However, the design is highly complex and requires precise integration with the HVAC system.

4.6 Hybrid Cooling Systems

Hybrid BTMS combine multiple methods, such as liquid + PCM or heat pipe + PCM, to achieve both high cooling capacity and passive thermal buffering (Rehman et al., 2022). These

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systems are ideal for high-power EVs where rapid heat spikes occur during fast charging and regenerative braking.

5. Comparative Analysis of BTMS Approaches

A systematic comparison of major BTMS types is shown in **Table 1**, highlighting performance trade-offs.

Table 1. Comparison of Thermal Management Options for EV Battery Packs

BTMS Type	Cooling Efficiency	Cost	Weight	Complexity	Suitability
Air Cooling	Low	Low	Very Low	Low	Low-power EVs
Liquid Cooling	High	Medium	Medium	High	Most EVs
PCM Cooling	Medium	Low	Medium	Low	Moderate loads
Heat Pipes	High	Low	Low	Medium	Compact EVs
Refrigerant Cooling	Very High	High	High	Very High	Premium EVs
Hybrid Systems	Very High	High	Medium	High	High-performance EVs

6. Thermal Modelling and Simulation Techniques

Thermal modelling is critical in predicting battery behaviour and optimizing BTMS design. Common techniques include 1D lumped models, 2D/3D finite-element models (FEM), and computational fluid dynamics (CFD). According to Prasad et al. (2021), multi-physics models integrating electrical, thermal, and aging processes allow engineers to simulate real-world conditions with higher accuracy. CFD simulations help optimize channel geometry, airflow distribution, and coolant properties (Zhu et al., 2022). Artificial intelligence (AI)-based predictive models are gaining traction for real-time thermal estimation (Hossain et al., 2023).

7. BTMS Design Requirements

BTMS design must meet several criteria:

1. **Maintain battery temperature within 20–40°C**
2. **Ensure temperature difference among cells < 5°C**
3. **Operate with minimal energy consumption**

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4. **Prevent thermal runaway propagation**
5. **Fit within packaging constraints**
6. **Provide high reliability and low maintenance**

Table 2 summarises essential design requirements.

Table 2. Key BTMS Design Criteria for Electric Vehicle Batteries

Requirement	Description
Temperature Control	Maintain optimal temperature range for performance and safety
Uniformity	Cell-to-cell temperature variation < 5°C
Energy Efficiency	Lower parasitic load to extend EV driving range
Safety	Prevent thermal runaway and enhance crash-worthiness
Scalability	Applicable to various battery pack sizes
Durability	Long-term, corrosion-resistant, vibration-tolerant design

8. Recent Trends and Innovations in BTMS

Recent research developments focus on enhancing cooling capacity, improving safety, and reducing system energy consumption. Nanofluids containing graphene, Al_2O_3, or CuO nanoparticles have shown significantly higher thermal conductivity, improving liquid cooling efficiency by up to 30% (Srinivasan et al., 2022). Flexible thermal interface materials and 3D-printed cooling plates offer reduced thermal resistance and customizable shapes (Roy et al., 2021). Ultra-fast charging demands more efficient thermal systems, where hybrid BTMS are becoming increasingly practical.

Edge-AI-based BTMS enables real-time thermal prediction and intelligent fan/pump control (Zhang et al., 2023). Additionally, advanced PCM composites with metal foams provide improved thermal buffering for peak heat loads. Fire-proof BTMS using ceramic coatings and non-flammable electrolytes are also under active development to enhance safety (Feng et al., 2021).

9. Challenges in BTMS Development

Despite progress, several challenges persist:

- High manufacturing cost of liquid and hybrid BTMS.
- Increased system weight reducing vehicle range.
- Long-term degradation of PCM and coolant materials.
- Complexity of integrating BTMS with BMS electronics.

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- Ensuring reliability under harsh driving conditions.
- Recycling and disposal of thermal materials.

These challenges necessitate research in lightweight materials, sustainable coolants, modular cooling plates, and predictive maintenance algorithms.

10. Future Research Directions

Future BTMS development is expected to focus on:

1. **AI-integrated BTMS for predictive thermal control**
2. **Solid-state battery cooling strategies**
3. **Lightweight, recyclable thermal interface materials**
4. **Smart PCM with controllable melting points**
5. **Modular cooling systems for battery-swapping EVs**
6. **Advanced fire-retardant coatings**
7. **Integration with vehicle digital twins for real-time diagnostics**

These innovations will improve EV reliability, reduce thermal risks, and support ultra-fast charging infrastructure.

11. Conclusion

Thermal management of EV batteries is a multidimensional engineering challenge involving heat transfer, electrochemistry, materials science, and control systems. This paper reviewed key BTMS technologies, including air, liquid, PCM, heat pipe, refrigerant, and hybrid cooling systems. Liquid and hybrid systems offer superior performance, while PCM and heat pipes provide passive, low-energy solutions. Advances in nanofluids, composite PCMs, AI-based prediction, and fire-resistant materials represent promising directions. To meet future EV performance and safety demands, integrated and intelligent BTMS designs will be essential.

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