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REVIEW ARTICLE

Thermal Safety, Cooling Technologies, and Predictive Control for Electro-Thermal Management and Intelligent Battery Management Systems in Electric Vehicles

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Abstract

The rapid growth of electric vehicles (EVs) has increased the demand for high-performance lithium-ion battery systems that provide high energy density, long service life, fast charging capability, and reliable operational safety. Among the major challenges affecting EV batteries, thermal management plays a critical role in determining battery performance, efficiency, durability, and safety. Excessive temperatures, non-uniform thermal distribution, and thermal runaway events can accelerate battery degradation and reduce system reliability. Consequently, effective battery thermal management systems (BTMS) and intelligent battery management systems (BMS) have become essential components of modern electric mobility. This paper reviews the thermal behavior and safety challenges of lithium-ion batteries used in electric vehicles, focusing on major battery chemistries including Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate (LFP), Nickel Cobalt Aluminum (NCA), and emerging solid-state batteries. Heat generation mechanisms, thermal runaway propagation, and battery safety concerns are examined, while commonly used cooling technologies such as air cooling, liquid cooling, phase change materials, heat pipes, and hybrid thermal management systems are compared. In addition, the thermal challenges associated with fast charging and their impact on battery aging and safety are discussed. Finally, current research gaps and future directions involving predictive control, data-driven diagnostics, and next-generation thermal management solutions are identified.

Keywords: Electric Vehicles (EVs), Lithium-Ion batteries, Battery Thermal Management System (BTMS), Thermal runaway, Battery Management System (BMS), Fast charging, Thermal safety.

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1. Introduction

The transportation sector is undergoing a significant transformation driven by the increasing adoption of electric vehicles as a sustainable alternative to conventional internal combustion engine vehicles. Growing concerns regarding greenhouse gas emissions, fossil fuel depletion, and environmental pollution have accelerated global efforts

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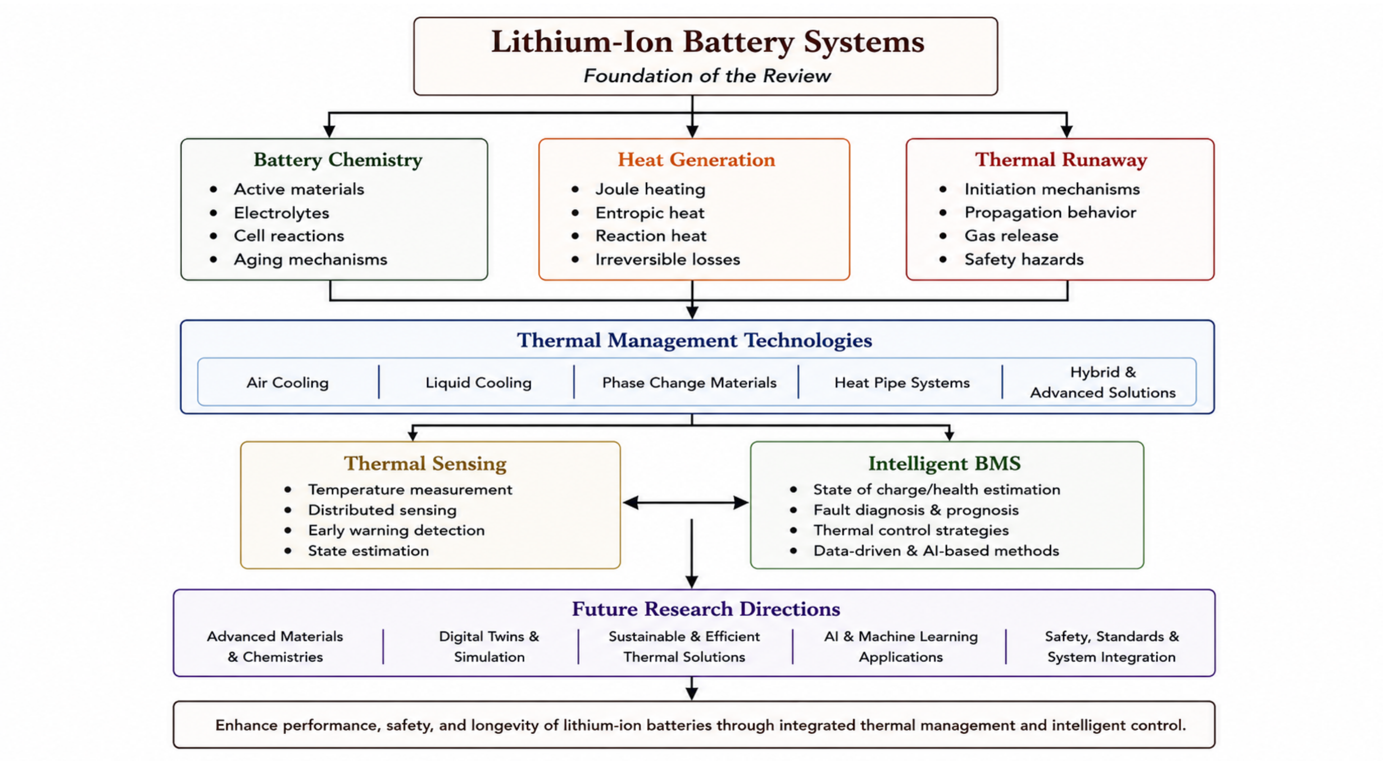
Graphical Abstract: Overall framework.



Acronyms and mathematical notations.

Acronym	Description
ML	Machine Learning
BMS	Battery Management System
SOH	State of Health
PCM	Phase Change Material
LFP	Lithium Iron Phosphate
NMC	Nickel Manganese Cobalt
NCA	Nickel Cobalt Aluminum
Q	Heat generation rate (W)
I	Battery current (A)
V	Battery voltage (V)
R	Internal resistance (Ω)
T	Temperature (K)
SOC	State of charge (%)
SOH	State of health (%)
RUL	Remaining Useful Life (%)
C	Battery capacity (Ah)
k	Thermal conductivity (W/mK)
c_p	Specific heat capacity (J/kgK)
T	Cell temperature
$\frac{\partial U}{\partial T}$	Entropy coefficient

toward transportation electrification [1], [2]. As a result, lithium-ion batteries have emerged as the dominant energy storage technology for modern EVs due to their high energy density, long cycle life, low self-discharge rate, and favorable power characteristics [3], [4].

Despite these advantages, lithium-ion batteries are highly sensitive to operating temperature [5], [6]. Battery performance, charging efficiency, aging characteristics, and safety are strongly influenced by thermal conditions experienced during operation. Elevated temperatures can accelerate side reactions within the cell, resulting in capacity degradation and reduced battery lifespan. Conversely, low temperatures can increase internal resistance and significantly reduce available power and energy output [7], [8]. Therefore, maintaining battery cells within an optimal temperature range is essential for ensuring reliable and safe operation. Thermal management has become one of the most critical challenges in electric vehicle battery systems. During charging and discharging processes, electrochemical reactions and internal resistive losses generate heat within battery cells. If this heat is not effectively dissipated, temperature accumulation may occur, leading to performance degradation, uneven temperature distribution, and potential safety hazards [9], [10]. The situation becomes more critical during high-power driving conditions and fast-charging operations, where heat generation rates increase substantially. One of the most severe safety concerns associated with lithium-ion batteries is thermal runaway. Thermal runaway is a self-accelerating process in which excessive heat generation triggers a sequence of exothermic reactions inside the battery cell. These reactions can result in rapid temperature escalation, gas release, fire, or even explosion under extreme conditions [11], [12]. Several reported EV battery incidents have highlighted the importance of advanced thermal monitoring and protection mechanisms for preventing catastrophic failures.

To address these challenges, BTMS have been integrated into modern EV battery packs. The BTMS technologies are designed to regulate battery temperature, improve thermal uniformity, and enhance overall battery safety and durability [13], [14]. Various cooling approaches, including air cooling, liquid cooling, phase change material cooling, heat pipe cooling, and hybrid cooling systems, have been investigated and implemented in commercial electric vehicles. Each technology offers unique advantages and limitations depending on system requirements, cost considerations, and thermal performance objectives [15], [16].

In parallel with advancements in thermal management hardware, BMS have evolved into intelligent monitoring and control platforms [17]. Modern BMS architectures continuously estimate critical battery parameters such as SOC, SOH, temperature distribution, and fault conditions [18]. Recent developments in AI and ML have further enhanced battery monitoring capabilities by enabling predictive diagnostics, thermal anomaly detection, and adaptive control strategies [19]. These technologies offer new opportunities for improving battery reliability and extending operational lifetime [20].

Furthermore, the growing demand for ultra-fast charging presents additional thermal challenges for EV batteries [20]. Although fast charging significantly reduces charging time and improves user convenience, it can increase heat generation and accelerate battery degradation if not properly managed [21]. Consequently, the integration of advanced thermal control strategies and intelligent battery management techniques has become increasingly important for future electric mobility applications.

This review paper presents a comprehensive analysis of thermal behavior, thermal safety challenges, and intelligent thermal management strategies in lithium-ion batteries for electric vehicles. The review examines battery chemistry characteristics, heat generation mechanisms, thermal runaway phenomena, thermal management technologies, sensing and diagnostic architectures, AI-assisted battery management systems, and thermal issues associated with fast charging. Finally, current research gaps and future development directions are discussed to support the advancement of safer, more efficient, and more reliable electric vehicle battery systems. In addition to thermal regulation, modern electric vehicle battery systems are increasingly expected to support intelligent monitoring and predictive capabilities [22]. Advances in sensing technologies, embedded controllers, and communication networks have transformed conventional battery packs into highly monitored systems capable of generating large volumes of operational data. These developments have enabled real-time monitoring and predictive analytics to improve battery reliability, safety, and performance [23].

Another important trend is the integration of battery thermal management systems with vehicle energy management architectures. Modern BTMS platforms interact with charging systems, power electronics, and vehicle control units, allowing thermal control strategies to adapt according to operating conditions, charging demands, and battery health status. This integration enhances energy efficiency and operational safety [18], [21]. Furthermore, the increasing adoption of connected electric vehicles has highlighted the importance of predictive battery diagnostics and health-aware control strategies. Advanced battery management systems can estimate future thermal conditions, identify potential faults, and support preventive maintenance actions [36], [37]. These capabilities contribute to improved battery utilization, longer service life, and enhanced system reliability [24], [42].

Therefore, a comprehensive understanding of battery thermal behavior and intelligent management techniques is essential for developing safer, more efficient, and reliable electric vehicle battery systems.

2. Battery chemistry and thermal sensitivity

Battery chemistry plays a fundamental role in determining the thermal behavior, energy density, safety characteristics, cycle life, and overall performance of electric vehicle batteries. Different lithium-ion battery chemistries exhibit distinct electrochemical properties that influence heat generation, thermal stability, charging capability, and degradation mechanisms [40], [49]. Consequently, understanding the thermal sensitivity of various battery chemistries is essential for designing effective battery thermal management systems and intelligent battery management strategies [2], [9].

The selection of battery chemistry involves balancing multiple performance objectives including energy density, power capability, operational safety, cost, and thermal robustness. Among the commercially dominant technologies, Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate (LFP), and Nickel Cobalt Aluminum (NCA) batteries are widely deployed in modern electric vehicles. In addition, emerging solid-state battery technologies are attracting significant attention due to their potential to improve safety and energy density while reducing thermal risks [26] ,[27]. Temperature strongly affects electrochemical reaction rates inside lithium-ion cells. Elevated operating temperatures accelerate side reactions, electrolyte decomposition, and electrode degradation, whereas extremely low temperatures increase internal resistance and reduce available capacity [30]. Therefore, each battery chemistry possesses an optimal operating temperature range within which performance and safety can be maintained effectively.

2.1. NMC batteries

Nickel Manganese Cobalt batteries have become one of the most widely adopted battery chemistries in electric vehicle applications due to their favorable balance between energy density, power capability, and cycle life [45]. The cathode material consists primarily of nickel, manganese, and cobalt compounds, with varying compositions used to optimize performance characteristics. The major advantage of the NMC batteries is their high energy density, which enables extended driving range and compact battery pack designs. Modern NMC variants such as NMC622 and NMC811 contain increased nickel content to further improve energy storage capability. However, increasing nickel concentration generally reduces thermal stability and increases susceptibility to thermal runaway under adverse operating conditions [9]. The NMC batteries typically operate efficiently within a temperature range of approximately 20 °C to 40 °C. When temperatures exceed this range, accelerated degradation and electrolyte decomposition may occur, leading to capacity fade and reduced battery lifespan [3]. Consequently, advanced thermal management systems are often required to maintain thermal uniformity within NMC battery packs.

2.2. LFP batteries

Lithium Iron Phosphate batteries are recognized for their excellent thermal stability, enhanced safety characteristics, and long cycle life [26]. The strong phosphate bonding structure within the cathode material provides improved resistance to thermal decomposition compared with nickel-rich battery chemistries.

One of the primary advantages of LFP batteries is their reduced risk of thermal runaway. The chemistry exhibits higher thermal tolerance and lower heat generation under high-load operating conditions. These characteristics make LFP batteries particularly suitable for applications where safety and durability are prioritized over maximum energy density [31].

Although LFP batteries generally possess lower energy density than NMC and NCA batteries, ongoing material and manufacturing improvements continue to narrow this performance gap. In recent years, several electric vehicle manufacturers have increasingly adopted LFP batteries due to their favorable cost, safety, and lifecycle characteristics [45].

2.3. NCA batteries

Nickel Cobalt Aluminum batteries offer some of the highest energy densities among commercially available lithium-ion battery technologies. These batteries are commonly utilized in long-range electric vehicles where maximizing energy storage capacity is a primary objective [45].

The high nickel content within NCA cathodes contributes significantly to enhanced energy density. However, this benefit is accompanied by increased thermal sensitivity and greater challenges associated with thermal management. Elevated temperatures may accelerate degradation processes and increase safety risks if thermal conditions are not properly controlled [27].

Effective cooling strategies and sophisticated battery management systems are therefore essential for maintaining safe operation of NCA battery packs. Continuous temperature monitoring and predictive thermal control methods can significantly reduce the likelihood of thermal instability during aggressive driving and fast-charging conditions [21].

2.4. Solid-state batteries

Solid-state batteries represent one of the most promising next-generation battery technologies for electric vehicles. Unlike conventional lithium-ion batteries that utilize liquid electrolytes, solid-state batteries employ solid electrolytes that can substantially improve safety and thermal stability [43]. The elimination of flammable liquid electrolytes reduces the probability of thermal runaway and fire-related incidents. Furthermore, solid-state batteries have the potential to achieve significantly higher energy densities while maintaining improved safety margins. These advantages have motivated extensive research and industrial investment in solid-state battery development [44]. Despite their

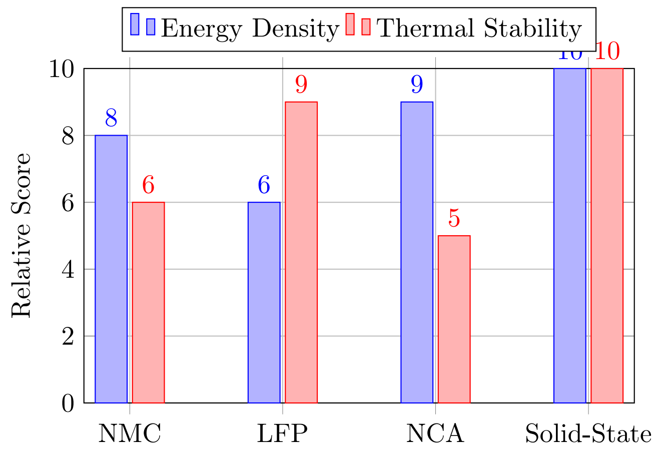


Figure 1: Qualitative comparison of major EV battery chemistries based on energy density and thermal stability.

promising characteristics, several technical challenges remain before large-scale commercialization can be achieved. Manufacturing complexity, interfacial resistance, material stability, and production cost continue to limit widespread adoption. Nevertheless, solid-state batteries are widely regarded as a key enabling technology for future electric vehicle platforms and next-generation battery management systems.

Figure. 1 shows the relative energy density and thermal stability characteristics of major battery chemistries used in electric vehicles. Further, Table1 shows a comparison of major battery chemistries used in electric vehicles. While NCA and NMC batteries provide superior energy density, LFP batteries demonstrate improved thermal robustness. Solid-state batteries have the potential to simultaneously achieve high energy density and enhanced thermal safety, although large-scale commercialization remains under development [44], [45].

Table 1: Comparison of major battery chemistries used in electric vehicles.

Chemistry	Energy density	Thermal stability	Safety	EV Adoption
NMC	High	Moderate	Moderate	Very High
LFP	Moderate	High	High	High
NCA	Very high	Moderate	Moderate	High
Solid-state	Very high	Very high	Very high	Emerging

3. Mechanisms of battery heat generation

Heat generation within lithium-ion batteries is a fundamental factor influencing battery performance, safety, aging characteristics, and overall reliability in electric vehicle applications. During charging and discharging processes, electrochemical reactions occurring inside the battery cell produce heat through multiple mechanisms. Excessive heat accumulation can increase cell temperature, accelerate material degradation, reduce energy efficiency, and potentially initiate thermal runaway events. Therefore, understanding battery heat generation mechanisms is essential for designing effective BTMS and intelligent BMS [2], [3], [9].

Battery heat generation primarily originates from irreversible losses and reversible electrochemical processes. Irreversible heat is produced due to internal resistance within the battery cell, while reversible heat is associated with entropy changes occurring during electrochemical reactions. The combined contribution of these mechanisms determines the total heat generation rate within a battery under different operating conditions [14], [15].

The most widely adopted battery heat generation model for describing the total heat generation rate given by (1).

$$Q = I(V - U) - IT\frac{\partial U}{\partial T} \quad (1)$$

where Q represents the heat generation rate, I denotes battery current, V is the terminal voltage, U is the open-circuit voltage, T represents cell temperature, and $\frac{\partial U}{\partial T}$ is the entropy coefficient. The first term corresponds to irreversible heat generation, while the second term represents reversible heat generation caused by entropy variation during electrochemical reactions [14].

3.1. Ohmic heat generation

Ohmic heat generation is the dominant source of heat under most operating conditions. It results from electrical resistance encountered by current flow through electrodes, electrolyte materials, separators, current collectors, and external electrical connections. According to Joule's law, the generated heat can be expressed by (2).

$$Q_{ohmic} = I^2 R \quad (2)$$

High current operation, rapid acceleration, regenerative braking, and fast-charging conditions significantly increase ohmic heat generation because heat production grows proportionally to the square of current [18], [21]. Battery aging further increases internal resistance, resulting in higher heat generation and reduced efficiency. Consequently, accurate estimation of internal resistance is an important function of modern battery management systems [30].

3.2. Reaction heat generation

Electrochemical reactions occurring at the electrode-electrolyte interfaces also contribute to heat generation. During lithium-ion intercalation and deintercalation processes, polarization effects cause voltage losses that manifest as thermal energy. This reaction heat becomes particularly significant under high-rate charging and discharging conditions [15], [16].

Reaction heat generation depends on current density, state of charge, electrode material properties, and operating temperature. Non-uniform reaction rates may lead to localized temperature gradients within the battery cell, creating thermal hotspots that accelerate degradation mechanisms [20].

3.3. Entropic heat generation

Entropic heat generation arises from reversible thermodynamic processes associated with entropy changes during battery operation. Unlike irreversible heat generation, entropic heat may either increase or decrease battery temperature depending on the operating state and battery chemistry [14], [17].

At specific states of charge, entropy changes can produce cooling effects, while at other operating conditions they contribute additional heat generation. Although entropic heat is generally smaller than ohmic heat, it becomes increasingly important during low-current operation and detailed thermal modeling studies [17].

3.4. Heat generation during fast charging

Fast charging introduces substantial thermal challenges because high charging currents significantly increase heat generation rates. Elevated temperatures produced during fast charging can accelerate lithium plating, electrolyte decomposition, and electrode degradation processes. These effects reduce battery lifespan and increase safety risks if not properly controlled [21], [38].

Advanced battery management systems continuously monitor cell temperature, charging current, and state of charge to prevent excessive temperature rise during fast-charging operations. Intelligent thermal control strategies can dynamically adjust charging rates based on real-time thermal conditions to maintain safe operation [24], [42].

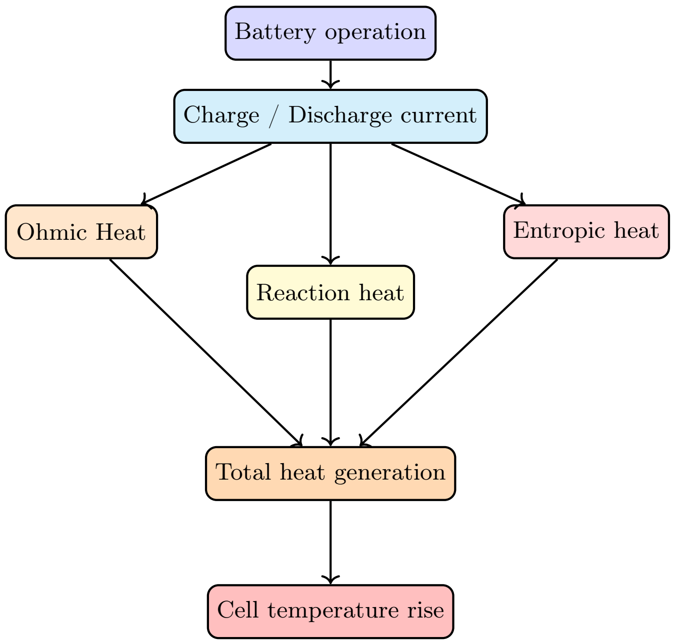


Figure 2: Primary heat generation mechanisms in lithium-ion batteries.

3.5. Impact of heat generation on battery safety

Uncontrolled heat generation can lead to severe safety consequences. As battery temperature increases, reaction rates accelerate, producing additional heat and potentially creating a positive feedback loop. If heat dissipation becomes insufficient, thermal runaway may occur, resulting in rapid temperature escalation, gas generation, cell venting, and possible fire hazards [8], [27]. For this reason, thermal monitoring, heat prediction, and fault diagnosis capabilities have become critical components of modern electric vehicle battery management systems. Accurate thermal modeling enables early detection of abnormal operating conditions and improves overall system safety [23], [32].

Figure 2 illustrates the primary mechanisms responsible for heat generation in lithium-ion batteries. The figure highlights the interactions between electrical losses, electrochemical reactions, entropy effects, and thermal accumulation within the battery system.

4. Thermal runaway and safety risks

Thermal runaway is one of the most critical safety concerns associated with lithium-ion batteries used in electric vehicles. It is a self-accelerating process in which excessive heat generation triggers exothermic chemical reactions inside the battery cell, resulting in rapid temperature escalation and potentially catastrophic failure. Because thermal runaway can lead to fire, explosion, toxic gas release, and complete battery pack destruction, understanding its initiation and propagation mechanisms is essential for developing safe and reliable battery systems [8], [27], [32]. Figure 3 shows the process of thermal runaway initiation, internal degradation processes, governing thermal conditions, and failure progression in lithium-ion batteries.

Under normal operating conditions, heat generated inside a battery cell is effectively dissipated through thermal management systems and surrounding structures. However, when heat generation exceeds heat dissipation capability, cell temperature begins to rise uncontrollably. Elevated temperatures accelerate chemical reaction rates, producing additional heat and creating a positive feedback loop that can ultimately trigger thermal runaway [9], [20].

4.1. Causes of thermal runaway

Thermal runaway may originate from several electrical, thermal, and mechanical fault conditions. Overcharging is one of the most common causes because excessive charging voltage promotes undesirable side reactions, electrolyte decomposition, and lithium plating on the anode surface. These processes generate heat and increase the probability of internal short circuits [21], [38].

External short circuits can also produce extremely high currents, resulting in substantial ohmic heating and rapid temperature rise. Similarly, internal short circuits caused by separator damage, manufacturing defects, dendrite growth, or mechanical deformation can generate localized hotspots that initiate thermal instability [8], [18].

Mechanical damage, including vehicle collisions, crushing, vibration, and penetration damage, may compromise cell integrity and create internal conductive pathways. Such failures frequently trigger localized heating and can rapidly escalate into thermal runaway events if appropriate protection mechanisms are absent [32].

4.2. Stages of thermal runaway

Thermal runaway generally progresses through multiple stages. Initially, abnormal operating conditions cause a gradual increase in battery temperature. As temperature rises beyond critical thresholds, decomposition reactions begin within the solid electrolyte interphase (SEI) layer. These reactions release heat and accelerate temperature growth [20].

At higher temperatures, electrolyte decomposition and electrode degradation reactions become increasingly dominant. Flammable gases are generated, internal pressure rises, and separator materials may begin to melt. Once internal short circuits develop, heat generation increases dramatically and the battery enters an uncontrollable thermal runaway phase [8], [27].

The final stage involves rapid temperature escalation, venting of combustible gases, potential ignition, and propagation of failure to neighboring cells. In battery packs containing hundreds or thousands of cells, thermal propagation can significantly increase the severity of the incident [32], [33].

4.3. Thermal propagation in battery packs

Thermal propagation refers to the transfer of heat from a failed cell to adjacent cells within a battery module or battery pack. When a single cell undergoes thermal runaway, the released thermal energy may raise the temperature of neighboring cells beyond their stability limits, resulting in a cascading failure process [27], [33].

Battery pack architecture, cell spacing, thermal insulation materials, cooling system effectiveness, and module design significantly influence thermal propagation behavior. Modern electric vehicle battery packs incorporate thermal barriers, venting structures, and cooling channels to minimize the risk of propagation between adjacent cells [29], [34].

4.4. Early warning indicators

Early detection of abnormal thermal behavior is essential for preventing catastrophic failures. Several indicators may provide advance warning before thermal runaway occurs, including abnormal temperature rise, rapid voltage fluctuations, excessive internal resistance growth, unusual gas generation, and unexpected state-of-charge deviations [23], [24].

Advanced battery management systems continuously monitor these parameters and employ fault diagnosis algorithms to identify abnormal operating conditions. Machine learning and artificial intelligence techniques have recently demonstrated promising capabilities for predicting thermal runaway events before they reach critical stages [42], [43].

4.5. Safety mitigation strategies

Multiple safety strategies are employed to reduce the likelihood and consequences of thermal runaway. Effective thermal management systems maintain battery temperatures within safe operating limits and minimize temperature gradients across battery modules. Accurate state estimation and fault diagnosis algorithms further improve operational safety by detecting abnormal conditions at an early stage [3], [24].

Additional protection measures include current limiting, voltage balancing, thermal barriers, flame-resistant materials, pressure relief vents, and emergency shutdown mechanisms. These technologies collectively improve battery safety and reduce the probability of severe thermal incidents in electric vehicle applications [29] ,[34]. As electric

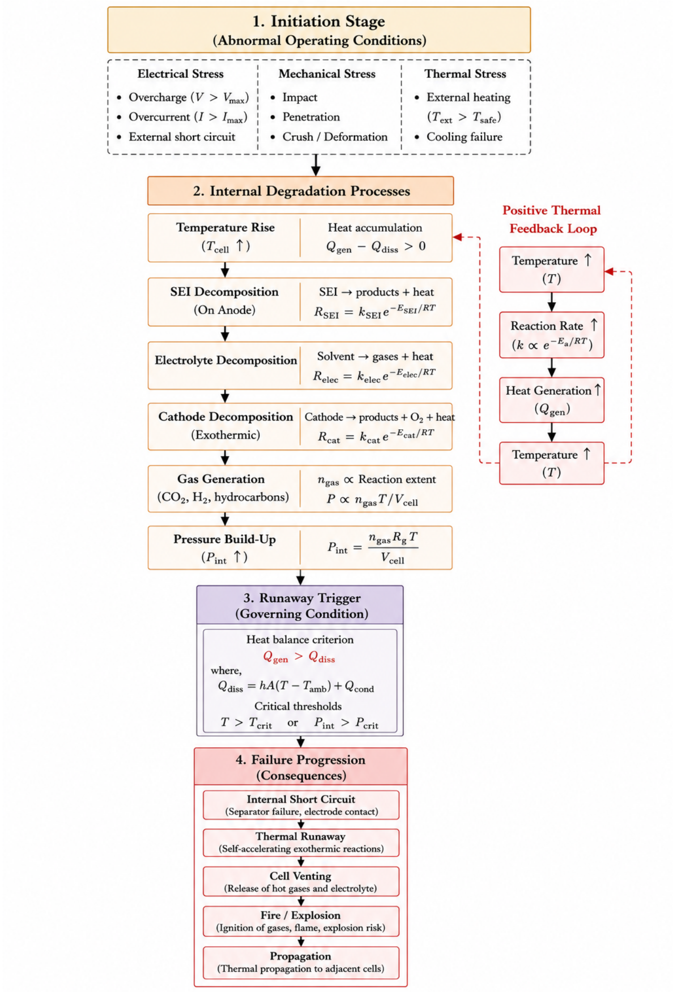


Figure 3: Thermal runaway in lithium-ion batteries.

vehicles continue to adopt higher-energy-density battery chemistries and ultra-fast charging technologies, thermal runaway prevention will remain a major research priority. Future battery systems are expected to integrate advanced sensing technologies, digital twins, and AI-assisted safety diagnostics to achieve higher levels of operational reliability and safety [42], [44].

5. Battery thermal management systems and cooling technologies

The BTMS play a critical role in maintaining lithium-ion batteries within their recommended operating temperature range. An effective BTMS improves battery safety, enhances energy efficiency, extends cycle life, and minimizes temperature non-uniformity across battery packs. As electric vehicles continue to adopt higher-capacity battery systems and fast-charging technologies, advanced thermal management solutions have become increasingly important for ensuring reliable operation under diverse environmental and driving conditions [3], [9], [18]. The primary objective of a BTMS is to maintain battery temperature within a safe operating range, typically between 20°C and 40°C. Excessive temperatures accelerate battery degradation and increase the likelihood of thermal runaway, whereas low temperatures reduce power capability, charging efficiency, and available energy capacity. Consequently, thermal management systems must provide both cooling and heating functions depending on operating requirements [20], [30].

5.1. Air cooling systems

Air cooling is one of the simplest and most economical thermal management approaches used in electric vehicles. In this method, ambient or conditioned air is circulated around battery cells to remove excess heat generated during operation. Air-cooling systems offer advantages such as low cost, simple construction, lightweight design, and minimal maintenance requirements [18]. However, the relatively low thermal conductivity and heat capacity of air limit cooling effectiveness under high-power operating conditions. Temperature non-uniformity may also develop across battery modules, particularly during rapid charging and discharging cycles. For these reasons, air cooling is generally more suitable for small or medium-sized battery systems with moderate thermal loads [19].

5.2. Liquid cooling systems

Liquid cooling has become the most widely adopted thermal management technology in modern electric vehicles. In liquid-cooled systems, a coolant circulates through channels or cooling plates positioned near battery cells, providing significantly higher heat transfer capability than air cooling [18], [29]. The superior thermal properties of liquid coolants enable effective temperature regulation under demanding operating conditions such as fast charging, high-speed driving, and elevated ambient temperatures. Liquid cooling also improves temperature uniformity within battery packs, thereby reducing degradation differences among cells and enhancing overall battery lifespan [20], [29]. Despite these advantages, liquid cooling systems are more complex and expensive than air-cooling systems. Additional components such as pumps, heat exchangers, coolant channels, and control units increase system weight and manufacturing cost [18].

5.3. Phase change material cooling

Phase Change Materials (PCMs) have attracted considerable attention because of their ability to absorb large amounts of thermal energy during phase transitions. When battery temperature increases, PCM materials absorb excess heat while undergoing a solid-to-liquid transition, thereby limiting temperature rise within the battery pack [34]. PCM-based cooling systems offer passive thermal regulation without requiring pumps or fans. However, their thermal storage capacity is finite, and accumulated heat must eventually be dissipated through auxiliary cooling mechanisms. Consequently, hybrid cooling systems combining PCM materials with liquid cooling technologies have emerged as promising solutions for future electric vehicle applications [34], [35].

5.4. Heat pipe cooling systems

Heat pipes utilize evaporation and condensation processes to transfer heat efficiently from high-temperature regions to cooler areas. Because heat pipes provide excellent thermal conductivity and require minimal external power, they have become attractive candidates for advanced battery cooling systems [35]. Heat-pipe-assisted thermal management can improve temperature uniformity and reduce peak cell temperatures under high-power operation. Recent studies have demonstrated that combining heat pipes with liquid cooling systems can significantly enhance thermal performance while reducing overall energy consumption [35].

5.5. Comparison of cooling technologies

Each cooling technology offers distinct advantages and limitations. Air cooling provides simplicity and low cost but offers limited cooling performance. Liquid cooling achieves superior thermal control and is currently the preferred solution for most commercial electric vehicles. PCM and heat-pipe technologies provide additional opportunities for improving thermal uniformity and reducing peak temperatures, particularly when integrated into hybrid thermal management architectures [18], [29], [35]. The selection of an appropriate thermal management technology depends on battery capacity, vehicle application, cost constraints, safety requirements, and expected operating conditions. Future electric vehicles are expected to employ intelligent hybrid cooling systems capable of dynamically adapting thermal control strategies according to real-time battery operating conditions [42], [43]. Table 2 compares the major characteristics of commonly used battery cooling technologies. Figure 4 illustrates a qualitative comparison of cooling effectiveness among these approaches.

Table 2: Comparison of battery cooling technologies.

Cooling method	Performance	Cost	Complexity
Air	Low	Low	Low
Liquid	High	Medium	Medium
PCM	Medium	Medium	Low
Heat pipe	High	Medium	Medium
Hybrid	Very High	High	High

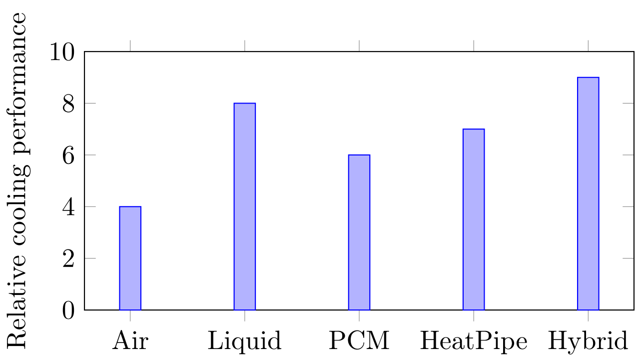


Figure 4: Comparison of battery cooling technologies.

6. AI and smart battery management systems

Modern electric vehicles increasingly rely on intelligent BMS to ensure safe, reliable, and efficient battery operation. Traditional BMS architectures primarily depend on physics-based models and rule-based control strategies for battery monitoring and protection. Although these methods provide acceptable performance under normal operating conditions, they often struggle to handle complex battery behaviors arising from nonlinear electrochemical processes, aging effects, and varying environmental conditions. Recent advances in AI and ML have therefore created new opportunities for enhancing battery management capabilities through data-driven prediction, diagnosis, and control techniques [42], [43]. A smart BMS continuously monitors battery voltage, current, temperature, and other operating parameters while estimating critical battery states such as SOC, and RUL. Accurate estimation of these parameters is essential for improving energy utilization, preventing battery damage, and ensuring operational safety throughout the battery lifetime [23], [24].

6.1. State of charge estimation

State of Charge represents the amount of available energy remaining within a battery relative to its maximum capacity. Accurate SOC estimation is important because it directly influences vehicle range prediction, charging control, and energy management decisions [22]. Conventional SOC estimation methods include Coulomb counting, open-circuit voltage techniques, and Kalman filtering approaches. However, battery nonlinearities, temperature variations, and aging effects can reduce estimation accuracy under practical operating conditions. Machine learning algorithms have demonstrated improved SOC prediction capability by learning complex relationships between battery operating variables and charge status from experimental datasets [42]. Further, deep learning models have been widely investigated for SOC estimation applications. These approaches can achieve high prediction accuracy while adapting to changing battery conditions over time [43].

6.2. SOH estimation

State of health indicates the current condition of a battery relative to its original performance specifications. Battery aging causes gradual reductions in capacity and power capability, making SOH estimation an important component of predictive battery management [30]. Traditional SOH assessment techniques typically require detailed electrochemical measurements and extensive computational resources. In contrast, machine learning methods can estimate battery health using operational data collected during normal vehicle usage. These techniques enable continuous monitoring without interrupting vehicle operation, thereby improving maintenance planning and battery utilization efficiency [43].

6.3. Fault diagnosis and safety monitoring

Battery faults such as overcharging, over-discharging, internal short circuits, sensor failures, and thermal abnormalities can significantly compromise battery safety and reliability. Early detection of such faults is therefore essential for preventing severe battery damage and potential safety incidents [23], [32]. The AI techniques can identify abnormal operating patterns through continuous analysis of battery data. Machine learning algorithms are capable of detecting subtle deviations from normal operating behavior that may not be apparent using conventional threshold-based monitoring methods. As a result, AI-assisted fault diagnosis systems can provide earlier warnings and more accurate fault classification [42], [43].

6.4. Predictive maintenance

Predictive maintenance utilizes historical and real-time battery data to forecast future degradation trends and maintenance requirements. Instead of replacing batteries according to fixed schedules, predictive maintenance enables maintenance decisions to be based on actual battery condition [24]. This approach reduces maintenance costs, minimizes unexpected failures, and improves overall battery utilization. Machine learning models can analyze large volumes of operational data to estimate future performance degradation and predict remaining useful life with reasonable accuracy [43].

6.5. AI-assisted thermal management

Artificial intelligence is increasingly being applied to battery thermal management systems for real-time temperature prediction and adaptive cooling control. Figure 5 shows an illustration for AI-assisted smart battery management system. The AI algorithms can process information from multiple sensors and predict future thermal behavior based on current operating conditions [42]. These intelligent control strategies are expected to become increasingly important as electric vehicles adopt higher-capacity battery packs and ultra-fast charging technologies [24] ,[42]. The integration of AI with battery management systems represents a significant step toward autonomous battery operation. By combining advanced sensing technologies, data analytics, and predictive algorithms, future smart BMS platforms will provide enhanced safety, improved performance, and extended battery lifespan[42], [43], [44].

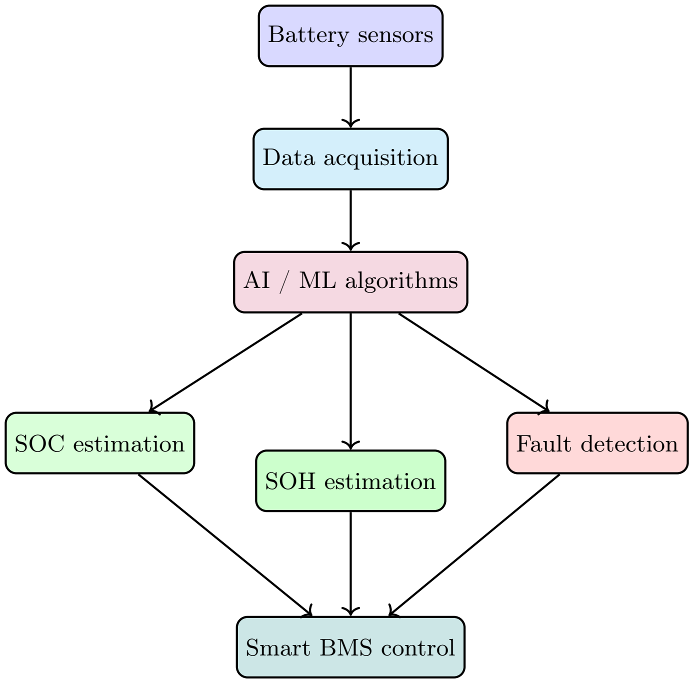


Figure 5: AI-assisted smart BMS architecture.

7. Advanced predictive control strategies for battery thermal management

Figure 6 shows a predictive thermal control architecture for electric vehicle battery systems incorporating thermal prediction, control optimization, cooling actuation, real-time feedback, and performance objectives. Battery thermal management systems have traditionally relied on fixed control rules and threshold-based protection mechanisms. Although these approaches provide acceptable performance under normal operating conditions, they often exhibit limited adaptability under highly dynamic operating environments. Variations in ambient temperature, battery aging, charging rates, and driving conditions require more intelligent control strategies capable of responding proactively rather than reactively [21], [33].

Predictive control techniques have emerged as promising solutions for improving battery thermal regulation. Unlike conventional control systems that react only after temperature deviations occur, predictive controllers estimate future battery thermal behavior and adjust cooling actions in advance. This capability improves thermal stability, reduces energy consumption, and enhances battery safety [24], [42].

7.1. Proportional–Integral–Derivative (PID)-based thermal control

PID controllers remain among the most widely used control techniques in battery thermal management systems. The PID controllers continuously compare measured battery temperature with a desired reference temperature and adjust cooling system operation accordingly. The control signal can be expressed as (3). The PID controllers offer simple implementation and low computational requirements. However, performance may deteriorate under highly nonlinear battery operating conditions and rapidly changing thermal loads [20], [23].

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{3}$$

In (3), $e(t)$ represents the temperature error and K_p, K_i, and K_d are the proportional, integral, and derivative gains respectively.

7.2. Fuzzy logic control

Fuzzy logic controllers have gained attention because they can effectively manage nonlinear battery behavior without requiring detailed mathematical models. These controllers utilize linguistic rules based on expert knowledge and sensor information to determine appropriate cooling actions.

Typical fuzzy control inputs include battery temperature, temperature gradient, and state of charge, while outputs may include cooling fan speed, coolant flow rate, or thermal management system operating mode. Fuzzy logic controllers are particularly useful when battery operating conditions vary significantly and precise system models are unavailable [35], [43].

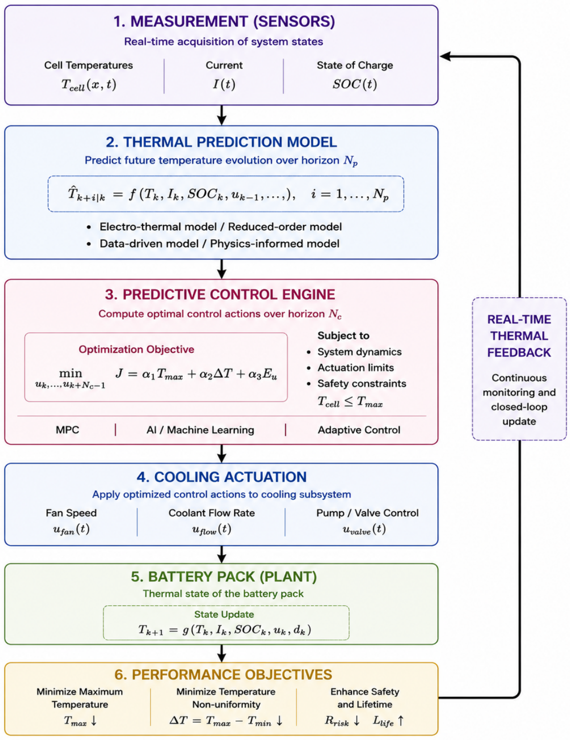


Figure 6: Predictive thermal control architecture for electric vehicle battery systems.

7.3. Model predictive control

Model Predictive Control (MPC) is one of the most advanced thermal management approaches currently under investigation. MPC utilizes mathematical models to predict future battery temperatures over a specified prediction horizon and optimizes cooling actions accordingly.

The primary advantage of MPC is its ability to simultaneously consider multiple operating constraints, including temperature limits, energy consumption, and cooling system capacity. As electric vehicle battery systems become increasingly complex, MPC is expected to play an important role in next-generation thermal management architectures [24], [42].

7.4. Machine learning-based predictive control

Recent advances in artificial intelligence have enabled the development of machine learning-based predictive control systems. These approaches utilize historical battery operating data to learn thermal behavior patterns and predict future temperature evolution.

Machine learning models can estimate temperature rise, detect abnormal thermal conditions, and recommend optimal cooling strategies before safety limits are exceeded. Such predictive capabilities are particularly beneficial during fast charging and high-power driving conditions where thermal dynamics change rapidly [24], [43].

Overall, predictive control strategies represent an important advancement in battery thermal management. By combining real-time sensing, thermal modeling, and intelligent decision-making algorithms, future battery management systems will achieve higher levels of efficiency, safety, and reliability while supporting increasingly demanding electric vehicle applications [25], [48].

8. Thermal challenges during fast charging

The growing adoption of electric vehicles has increased the demand for fast-charging technologies capable of reducing charging time while maintaining battery safety and reliability. Modern charging systems can deliver high charging currents that significantly reduce charging duration; however, these operating conditions introduce substantial thermal challenges. Elevated charging currents increase internal heat generation, accelerate battery degradation mechanisms, and create safety concerns if thermal conditions are not properly controlled [16], [21].

During fast charging, battery cells experience increased electrochemical activity and higher internal resistance losses. According to Joule's law, heat generation rises with the square of charging current, making thermal management increasingly important as charging rates increase. Excessive temperature rise may reduce charging efficiency and negatively affect battery lifespan [14], [38].

8.1. Temperature rise during fast charging

Figure7 shows thermal effects associated with fast charging of lithium-ion batteries. Battery temperature generally increases as charging current increases. Under high C-rate charging conditions, internal heat generation may exceed the cooling capability of the battery thermal management system, resulting in temperature accumulation within the battery pack. Elevated temperatures accelerate electrolyte decomposition, increase side reactions, and promote electrode degradation. Furthermore, non-uniform temperature distribution among cells may lead to unequal aging and reduced pack-level performance. Consequently, maintaining thermal uniformity during fast charging has become a major objective in modern battery thermal management system design [9], [27].

8.2. Lithium plating phenomenon

One of the most significant challenges associated with fast charging is lithium plating. Lithium plating occurs when lithium ions are deposited as metallic lithium on the anode surface instead of being intercalated into the electrode structure. This phenomenon is more likely to occur under high charging currents and low-temperature operating conditions [16], [28].

Lithium plating reduces available battery capacity, increases internal resistance, and may eventually lead to internal short circuits. Repeated plating and stripping cycles accelerate battery aging and compromise long-term performance. Therefore, preventing lithium plating is an important consideration when designing fast-charging strategies and battery management algorithms [28], [30].

8.3. Impact on battery aging

Fast charging can accelerate several battery degradation mechanisms. Elevated temperatures increase side reactions within the electrolyte and electrode materials, leading to gradual loss of active lithium and capacity fade. High charging currents may also contribute to structural damage within electrode materials and increase mechanical stresses during repeated cycling [3], [30].

Numerous studies have shown that batteries subjected to frequent fast-charging cycles generally exhibit faster capacity degradation than batteries charged using moderate charging rates. Consequently, thermal control and intelligent charging management are essential for minimizing degradation while maintaining acceptable charging times [39], [41].

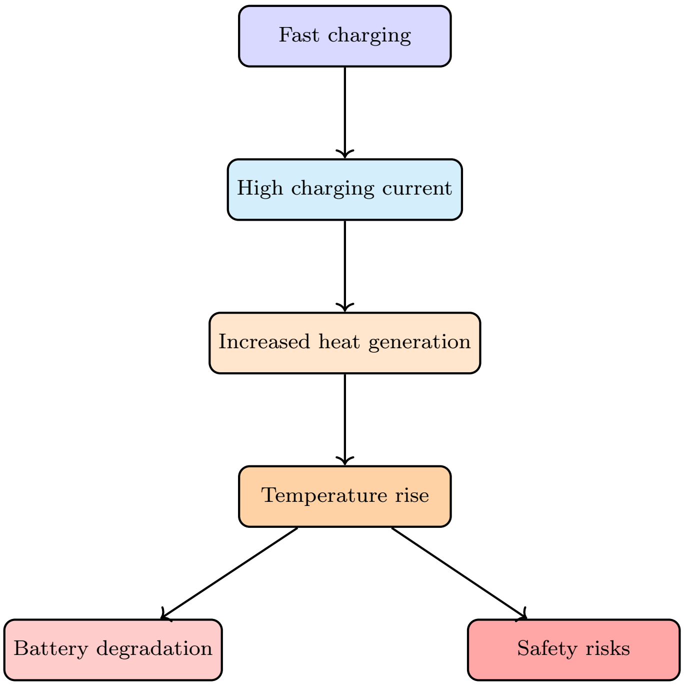


Figure 7: Thermal effects associated with fast charging of lithium-ion batteries.

8.4. Safety considerations

Fast charging increases the probability of thermal instability if heat generation is not adequately controlled. Elevated temperatures may trigger electrolyte decomposition, gas generation, and abnormal electrochemical reactions. Under severe operating conditions, these effects can contribute to thermal runaway initiation and propagation within battery packs [9], [31].

Advanced battery management systems continuously monitor temperature, voltage, current, and state of charge during charging operations. Modern control systems can dynamically adjust charging current based on real-time battery conditions to prevent excessive temperature rise and maintain safe operation [21], [24].

8.5. Future fast-charging technologies

Future electric vehicle platforms are expected to support ultra-fast charging while maintaining battery safety and durability. Emerging solutions include advanced thermal management systems, intelligent charging algorithms, silicon-rich anodes, solid-state batteries, and AI-assisted charging control strategies. These technologies aim to reduce charging time without significantly increasing thermal stress or battery degradation [42], [44], [51].

Although substantial progress has been achieved in recent years, balancing charging speed, thermal safety, and battery longevity remains one of the most important research challenges in electric vehicle battery technology. Continued advancements in battery materials, cooling technologies, and predictive control systems will play a critical role in enabling next-generation fast-charging solutions.

9. Research gaps and future directions

Despite significant advancements in electric vehicle battery technologies, several challenges remain unresolved. Current battery thermal management systems have improved temperature regulation and operational safety; however, increasing battery energy density, fast-charging requirements, and growing demand for longer driving ranges continue to create new thermal management challenges [9], [21].

One major research gap involves the development of accurate real-time thermal prediction models. Most existing thermal models either provide high accuracy with substantial computational requirements or offer simplified calculations with limited prediction capability. Future research should focus on developing computationally efficient models capable of providing reliable temperature predictions under dynamic driving and charging conditions [24], [42].

Another important challenge is the achievement of uniform temperature distribution within large battery packs. Temperature variations between cells remain a significant cause of uneven aging, capacity loss, and safety concerns. Although advanced cooling technologies have demonstrated promising results, further optimization is required to ensure effective thermal balancing while minimizing system complexity and energy consumption [12], [19].

The integration of artificial intelligence into battery management systems has gained considerable attention in recent years. However, many AI-based approaches are still primarily evaluated under laboratory conditions and have not been extensively validated in real-world electric vehicle applications. Future investigations should focus on improving model robustness, interpretability, and reliability under diverse operating environments [39], [44].

9.1. Digital twin and smart battery systems

Digital twin technology is emerging as a promising solution for next-generation battery management systems. By creating a virtual representation of battery behavior, digital twins can continuously monitor battery health, estimate thermal conditions, and predict potential failures before they occur. Although preliminary studies have shown encouraging results, challenges related to computational cost, data synchronization, and large-scale implementation still require further investigation [43], [45].

9.2. Advanced battery materials

Future battery technologies are expected to utilize advanced electrode materials and solid-state electrolytes that provide higher energy density and improved thermal stability. Solid-state batteries, in particular, offer the potential to reduce thermal runaway risks while improving safety and performance. Nevertheless, several technical challenges related to manufacturing, material compatibility, and long-term reliability must be addressed before widespread commercialization becomes feasible [33], [46].

9.3. Sustainable thermal management solutions

Environmental sustainability is becoming an increasingly important consideration in electric vehicle design. Future thermal management systems should not only improve battery performance but also minimize energy consumption and environmental impact. The use of recyclable cooling materials, eco-friendly phase change materials, and energy-efficient thermal control strategies represents a promising direction for future research [18], [47].

9.4. Future scope

The future of electric vehicle battery thermal management will likely involve the integration of advanced cooling technologies, artificial intelligence, digital twin platforms, and next-generation battery chemistries [50], [51], [53]. These developments are expected to improve thermal safety, charging performance, operational reliability, and battery lifespan. Continued collaboration between researchers, industry, and automotive manufacturers will be essential for overcoming existing challenges and enabling the widespread adoption of safe and efficient electric mobility systems [52], [54]–[56].

10. Conclusion

The rapid growth of EVs has increased the importance of BTMS in ensuring battery safety, reliability, efficiency, and long-term performance. Lithium-ion batteries are highly sensitive to temperature variations, and excessive heat or non-uniform temperature distribution can accelerate degradation, reduce efficiency, and increase the risk of thermal runaway. This review examined the thermal characteristics of major EV battery chemistries, including LFP, NMC, NCA, and emerging solid-state batteries. Key heat generation mechanisms, battery aging factors, and thermal safety concerns were discussed. The study also analyzed thermal runaway phenomena and highlighted the importance of early fault detection and effective thermal control strategies. Various battery cooling technologies, including air cooling, liquid cooling, phase change materials, heat pipes, and hybrid cooling systems, were reviewed and compared. Among these approaches, liquid cooling and hybrid thermal management systems provide superior thermal regulation for high-energy-density battery packs. The review further explored the role of artificial intelligence in battery management systems through applications such as state estimation, fault diagnosis, predictive maintenance, and adaptive thermal control. In addition, thermal challenges associated with fast charging were discussed, emphasizing the need for advanced thermal management to ensure safety and extend battery life.

Declarations and ethical statements

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Artificial Intelligence usage statement: During the preparation of this manuscript, the author utilized ChatGPT and Grammarly solely for language refinement and grammatical corrections. The author carefully reviewed and revised the generated content and take full responsibility for the accuracy, integrity, and originality of the final manuscript.

Availability of data and materials: All data and information used in this review were obtained from publicly available published literature and cited sources.

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CRediT authorship contribution statement

Sai Balaji Kamana: Conceptualization, Investigation, Writing – review & editing. **Kenneth E. Okedu** : Data collection & Formal analysis. **Bhanu Pratap Soni** : Data collection & Formal analysis. **Hari Charan Nannam**: Conceptualization, Formal analysis & Visualization. **Chalapaka Veerendra Bharghav Kumar**: Editing & Visualization.

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