Thermal Management in Electric Vehicles: A Survey

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Abstract

Thermal management in electric vehicles (EVs) is essential for optimizing battery efficiency, energy efficiency, and overall vehicle performance. This survey paper explores various aspects of thermal management, emphasizing its significance in the context of climate change and the automotive industry's shift towards electrification. The integration of advanced technologies, particularly artificial intelligence (AI), has enhanced the effectiveness of thermal management systems, enabling real-time optimization of cooling strategies to ensure safety and reliability. The paper systematically reviews the relationship between battery efficiency and thermal management, highlighting the impact of temperature fluctuations on lithium-ion batteries and the necessity for sophisticated thermal management strategies. Various heat dissipation techniques, including passive and active cooling methods, are analyzed for their effectiveness in maintaining optimal thermal conditions. The design and implementation of cooling systems are explored, focusing on their integration with vehicle components and the role of advanced technologies in optimizing cooling strategies. The survey identifies current challenges, such as the inadequacy of existing systems to maintain optimal temperatures and the reliance on singular cooling strategies. Future research directions are proposed, emphasizing the potential of innovative materials and emerging technologies to address these challenges. By leveraging these advancements, EVs can achieve enhanced performance, safety, and energy efficiency, supporting their sustainable development and adoption in the global market. The survey concludes by reiterating the importance of effective thermal management in ensuring the long-term success of electric vehicles.

1 Introduction

1.1 Significance of Thermal Management

Thermal management in electric vehicles (EVs) is essential for optimizing vehicle performance and efficiency, particularly in light of global climate change and the need to reduce greenhouse gas emissions from the transportation sector, which significantly contributes to energy-related emissions [1]. The full electrification of the automotive industry is crucial for mitigating these environmental impacts [2]. Effective thermal management ensures optimal battery temperatures, preventing overheating and enhancing both performance and safety [3].

Optimizing battery thermal management (BTM) systems is critical for improving energy efficiency and extending the driving range of EVs. Auxiliary loads, such as air conditioning systems, are the largest energy consumers in light-duty vehicles, significantly impacting the energy efficiency of Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) [4]. Current climate control systems prioritize temperature regulation over overall thermal comfort, often leading to inefficient energy usage and highlighting the necessity for advanced thermal management strategies [5].

The integration of advanced technologies, such as artificial intelligence (AI), into thermal management systems holds the potential to enhance performance and energy management beyond conventional techniques [6]. Furthermore, incorporating battery aging considerations into the optimization of

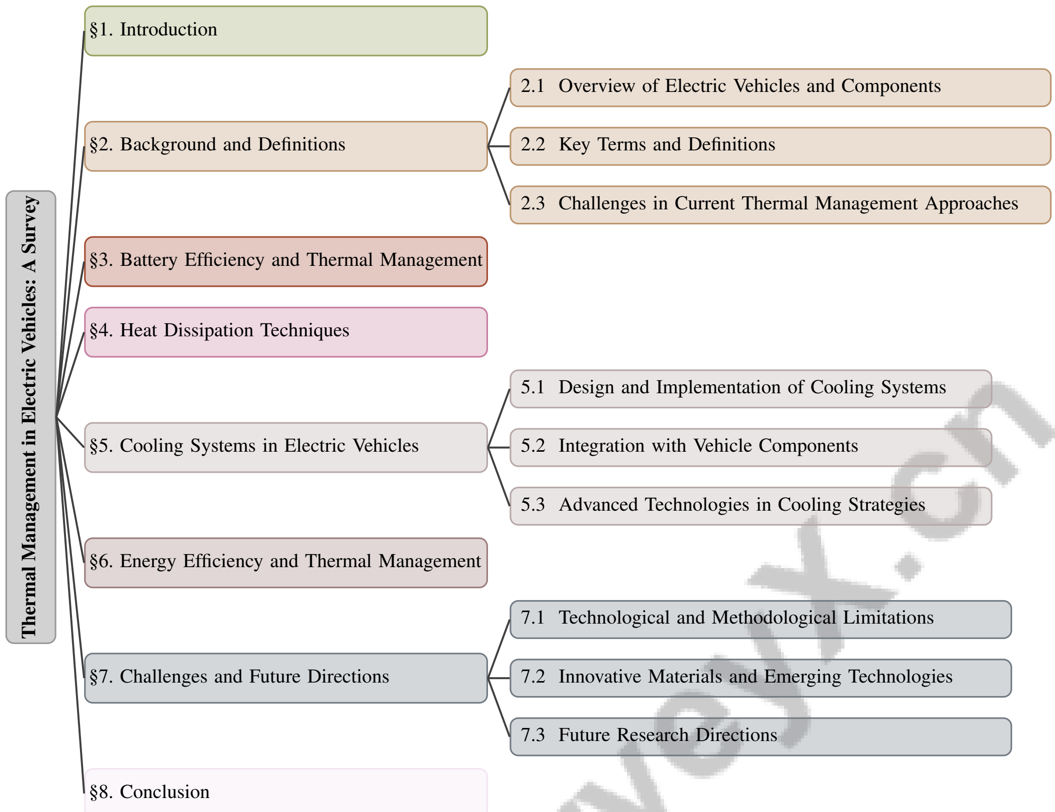

Figure 1: chapter structure

bidirectional charging for EVs is essential, as existing methods frequently neglect battery aging costs, thus requiring a more comprehensive approach [7]. The development and integration of innovative materials and technologies are paramount for advancing thermal management in EVs, ensuring efficient and sustainable operation under varying environmental conditions and demands [8].

1.2 Structure of the Survey

This survey is systematically organized to provide a thorough analysis of thermal management in electric vehicles (EVs). It begins with an introduction that emphasizes the significance of thermal management in optimizing battery and overall energy efficiency, highlighting its critical role in maintaining optimal operating temperatures to enhance the performance and lifespan of EV components. Following the introduction, Section 2 presents the background and definitions, offering an overview of electric vehicles and their components, particularly focusing on battery thermal management needs while defining key terms and elucidating associated challenges.

Section 3 investigates the intricate relationship between battery efficiency and thermal management, emphasizing the impact of temperature on battery performance and exploring strategies for enhancing performance through effective thermal management. Section 4 conducts a comprehensive analysis of various heat dissipation techniques employed in EVs, focusing on both passive and active cooling methods. It evaluates their advantages and limitations, including an in-depth examination of air-cooling battery thermal management systems (BTMS) and their effects on battery performance, safety, and overall powertrain efficiency. Recent advancements in cooling technologies, such as innovative cooling channel designs and advanced thermally conductive materials, are also discussed to address challenges in EV thermal management [6, 9].

The design and implementation of cooling systems are examined in Section 5, which discusses the integration of these systems with other vehicle components and the role of advanced technologies in optimizing cooling strategies. Section 6 highlights the critical role of thermal management in enhancing the overall energy efficiency of EVs. It explores various strategies for optimizing battery

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temperature control, emphasizing the use of supervised learning techniques, particularly artificial neural networks (ANNs), to effectively model and manage thermal management subsystems. The integration of predictive models and AI in developing advanced thermal management strategies is discussed, showcasing their potential to improve energy consumption while maintaining optimal battery temperatures. Case studies illustrate the effectiveness of these AI-driven approaches in reducing total energy consumption while ensuring system performance [6, 10].

In Section 7, the current challenges and future research directions in thermal management for EVs are explored, focusing on technological and methodological limitations that hinder progress. The discussion underscores the importance of innovative materials and emerging technologies, such as AI and physics-informed machine learning, in addressing these challenges. The need for advanced battery thermal management systems (BTMS) capable of ensuring optimal performance and safety of lithium-ion batteries is highlighted, along with the integration of these systems with vehicle thermal management to enhance overall efficiency and reliability [11, 6, 9, 2, 12]. The survey concludes by summarizing the key findings and reiterating the importance of effective thermal management in EVs.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Overview of Electric Vehicles and Components

Electric vehicles (EVs) signify a revolutionary shift from internal combustion engines to electric propulsion, driven by the imperative to reduce pollution and fossil fuel reliance, as endorsed by global initiatives promoting EVs and battery electric vehicles (BEVs) [13, 2, 14]. Key advancements in battery technology, charging infrastructure, and electric motor design are crucial for enhancing EV efficiency, reliability, and safety. The primary EV components include the electric motor, power electronics, and the battery system, which serves as the main energy source. Effective thermal management of these components, especially the battery, is vital for optimizing performance, efficiency, and safety.

EV batteries, predominantly lithium-ion cells, offer high energy density and longevity but are sensitive to temperature variations, affecting their performance and lifespan. Effective thermal management is essential to maintain optimal battery temperatures, as overheating can halve battery lifespan with a 13 °C increase, while also enhancing energy efficiency [15, 8, 11, 16, 12]. Advanced battery thermal management systems (BTMS) adapt to varying environmental conditions, ensuring efficient cooling in high temperatures and thermal insulation in colder climates, crucial for extending operational range in extreme environments.

Thermal management systems in EVs dissipate heat generated during charging and discharging cycles using passive methods like heat sinks and thermal pads, and active systems employing liquid cooling or air conditioning [17, 18, 6, 19]. Integrating these systems with vehicle architecture enhances thermal performance and energy efficiency. Coordinated control of power split, engine thermal management, and cabin heating can significantly save fuel in hybrid electric vehicles (HEVs) and connected automated vehicles (CAVs) by optimizing energy consumption using real-time traffic data and sophisticated control strategies, such as model predictive control.

Thermal management is also crucial for the electric motor and power electronics to prevent performance degradation and ensure reliability. The electric motor, converting electrical to mechanical energy, generates heat that must be dissipated efficiently [5]. Similarly, power electronics, which control the electrical energy flow to the motor, require robust thermal management solutions [6].

2.2 Key Terms and Definitions

Understanding key terminologies is vital for comprehending the complexities of thermal management systems in EVs, crucial for optimizing battery performance and vehicle efficiency. This involves insights into battery management systems (BMS), thermal control mechanisms, and advanced technologies like artificial neural networks (ANNs) for optimal temperature regulation, impacting energy consumption and operational effectiveness [8, 13, 10].

Thermal Management: In EVs, thermal management involves technologies and strategies to regulate temperatures of critical components, such as lithium-ion batteries, electric motors, and power electronics. This regulation is essential due to lithium-ion batteries' sensitivity to temperature fluctuations affecting efficiency, safety, and lifespan. Advanced thermal management systems (TMS) utilize cooling methods like liquid, air, and phase change materials to maintain optimal conditions. Innovations include integrating ANNs for real-time optimization, enhancing battery temperature control, and contributing to energy efficiency by minimizing energy consumption during operation [8, 12, 10, 9].

Battery Efficiency: Battery efficiency refers to the ability of the battery system to effectively convert stored chemical energy into electrical energy while minimizing losses. Lithium-ion battery efficiency is significantly influenced by thermal management, as temperature fluctuations can lead to performance and lifespan variations. High temperatures can accelerate degradation, reducing battery life by 50

Cooling Systems: EV cooling systems dissipate excess heat generated by the battery, electric motor, and power electronics. These systems are classified into passive methods, using materials like phase change materials (PCM) to absorb and dissipate heat without external power, and active methods, involving mechanical systems like liquid cooling or nanofluid technologies requiring energy input to enhance heat transfer [6, 20, 21].

Battery Thermal Management (BTM): BTMS are specialized systems for regulating lithium-ion battery temperature, crucial for new energy vehicles (NEVs) due to high energy and power density. These systems ensure optimal battery performance, safety, and longevity, as lithium-ion batteries are sensitive to temperature fluctuations. BTMS are categorized by cooling medium: phase change materials (PCMs), liquid cooling, and air cooling. Effective thermal management enhances battery efficiency and mitigates risks like thermal runaway, contributing to EV and HEV safety and performance. Recent advances include integrated systems utilizing vehicle heat sources, innovative cooling designs, and new materials for improved efficiency and lifespan [15, 22, 9, 21, 12].

Thermal Runaway: Thermal runaway is a hazardous condition where battery temperature rises uncontrollably, potentially leading to catastrophic failure. Effective thermal management is crucial for mitigating this risk by ensuring safe battery operation within temperature limits [8].

These definitions establish a foundation for understanding thermal management in EVs, emphasizing the necessity of optimal thermal conditions for enhancing vehicle performance and safety, particularly regarding lithium-ion batteries sensitive to temperature fluctuations. Effective TMS are essential for battery efficiency and security, with various cooling mediums—phase change materials, liquid, and air—playing significant roles. Advanced strategies, including supervised learning for optimal thermal control, underscore the complexity and importance of managing battery temperatures to reduce energy consumption while ensuring safety [12, 10].

2.3 Challenges in Current Thermal Management Approaches

Thermal management in EVs faces challenges that impede battery performance optimization, safety, and energy efficiency. A major issue is the inadequacy of current BTMS in maintaining optimal temperatures across diverse conditions, leading to safety risks and performance degradation [3]. This is worsened by reliance on singular cooling strategies that fail to address temperature variations and prevent thermal runaway during high discharge rates [23], with thermal anomalies posing persistent concerns [24].

The non-linear relationship between state of charge (SOC) and temperature complicates estimation processes, affecting thermal management algorithm reliability [25]. This is compounded by inefficient energy consumption and prolonged charging times in current BEV technologies, especially in extreme climates where battery performance is compromised [8]. Despite advancements, fast charging still exceeds 30 minutes for 80

Ineffective management of heat generation and thermal runaway risks in battery systems limits EV and electric aircraft performance and safety [22]. Existing methods struggle to balance thermal and structural performance, resulting in increased mass and inadequate thermal management [26].

Conventional onboard BMS lack computational power for advanced algorithms necessary for accurate SOC and state of health (SOH) estimations [27]. The neglect of battery aging leads to inaccurate EV operating cost assessments and V2G service profitability [7]. In connected HEVs, optimizing thermal management while managing power-split between engine and battery presents further complexities [18].

These challenges highlight the need for innovative thermal management approaches addressing inefficiencies of existing models, limitations of current cooling technologies, and high costs of developing advanced systems. Advancements are crucial for ensuring efficient and safe EV operation [13].

3 Battery Efficiency and Thermal Management

The relationship between battery efficiency and thermal management is pivotal, especially as lithium-ion batteries (LIBs) are highly susceptible to temperature changes that affect their capacity, lifespan, and functionality, particularly in extreme conditions [25, 12, 16, 11]. Understanding these effects is essential for optimizing battery performance in electric and hybrid vehicles. Figure 2 illustrates the hierarchical structure of battery efficiency and thermal management, categorizing the impact of temperature on battery efficiency alongside various thermal management strategies. This figure highlights the effects of temperature variations on lithium-ion battery performance and longevity, while also outlining innovative cooling strategies and technological enhancements that are crucial for optimizing battery performance in electric and hybrid vehicles.

3.1 Impact of Temperature on Battery Efficiency

Temperature variations critically influence the performance and longevity of lithium-ion batteries in electric vehicles (EVs) and hybrid electric vehicles (HEVs). Effective thermal management is crucial to prevent overheating and thermal runaway, which can compromise safety and efficiency. Elevated temperatures accelerate degradation, reducing capacity and posing safety risks [8], while low temperatures increase internal resistance, reducing energy efficiency and extending charging times [25].

Accurate estimation of battery states, such as state of charge (SOC), state of health (SOH), and internal temperature, is complicated by temperature variability, affecting SOC estimation precision and overall optimization [13, 25]. Factors like road conditions, driving behaviors, and high-current fast charging exacerbate temperature fluctuations, impacting battery lifespan [27]. Addressing these fluctuations is crucial for optimizing energy management strategies, often neglected despite their significant implications for performance and longevity [14]. Advanced thermal management systems are essential for maintaining optimal operating temperatures, enhancing battery reliability [22].

Maintaining optimal battery temperatures is indispensable for improving LIB performance and lifespan in EVs and HEVs, highlighting the need for innovative thermal management solutions to mitigate adverse temperature effects [8].

3.2 Thermal Management Strategies for Battery Performance

Enhancing battery performance in EVs and HEVs requires sophisticated thermal management strategies to regulate temperature amidst fluctuations. Integrating active and passive cooling methods leverages the strengths of both for enhanced thermal regulation [23], allowing dynamic adjustments based on real-time conditions.

To illustrate these concepts, Figure 3 presents a figure that represents the hierarchical categorization of thermal management strategies for battery performance, highlighting key cooling methods, control techniques, and AI-driven optimizations. This visual representation underscores the complexity and interconnectivity of various strategies employed to optimize battery performance.

Optimizing cooling system designs is critical for effective thermal management. Advanced battery thermal management systems (BTMS), such as J-type BTMS incorporating features from U-type and Z-type structures, exemplify innovative designs facilitating real-time cooling adjustments [3]. Multi-objective model predictive control (MPC) frameworks optimize fast charging while adhering to thermal management constraints, ensuring efficient charging without compromising thermal stability [28].

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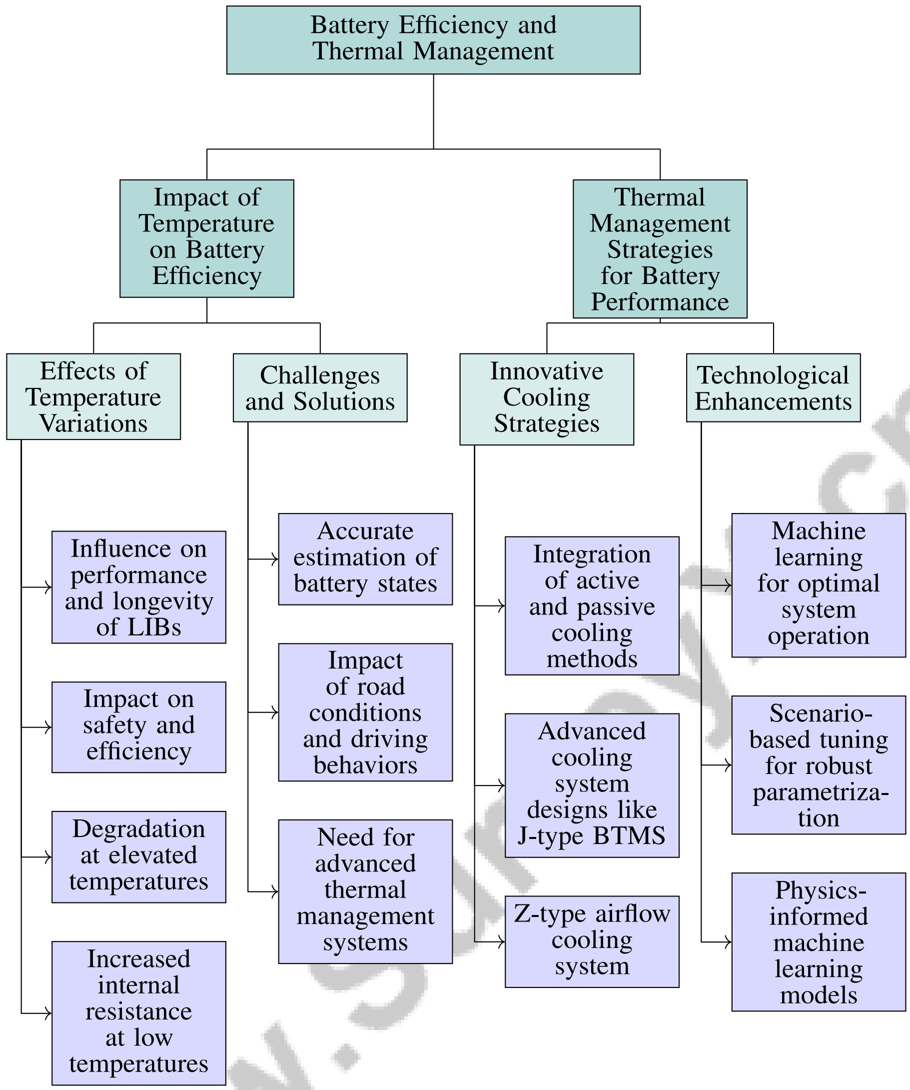


Figure 2: This figure illustrates the hierarchical structure of battery efficiency and thermal management, categorizing the impact of temperature on battery efficiency and various thermal management strategies. It highlights the effects of temperature variations on lithium-ion battery performance and longevity, and outlines innovative cooling strategies and technological enhancements for optimizing battery performance in electric and hybrid vehicles.

Machine learning techniques, particularly supervised learning, create artificial neural network (ANN)-based models for optimal thermal management system operation, utilizing physical relationships within subsystems for precise control [10]. Scenario-based tuning enhances this by employing automated scenario generation for robust parametrization of thermal management controllers [29].

Innovative cooling strategies, such as the Z-type airflow cooling system, aim to minimize temperature extremes and differences [30]. Optimizing the spatial arrangement of heat-generating devices within battery packs using multi-split configuration designs for fluid-based cooling addresses inefficiencies in manual design methods [20].

The integration of physics-informed machine learning models, like convolutional neural networks (CNNs), enhances temperature distribution estimation in battery packs by incorporating physical laws into the training process, improving thermal management efficacy [11]. Additionally, level-set topology optimization facilitates battery pack designs that satisfy thermal and structural requirements while minimizing weight [26].

Artificial intelligence (AI) techniques, including machine learning and deep learning, provide significant advantages over traditional methods in thermal management, enabling adaptive and efficient systems that ensure safety, efficiency, and reliability across varying operational conditions [6]. The integration of advanced algorithms and cloud computing, as proposed in the Battery Cloud, enhances battery performance, safety, and economic viability through improved data collection and analysis [27].

Thermally modulated charging protocols (TMCP) are explored to retain battery heat during charging, enhancing performance and mitigating lithium plating [31]. The combination of the Extended Kalman Filter (EKF) and Coulomb Counting (CC) methods aims to improve SOC estimation across varying temperatures, addressing challenges posed by temperature variability [25].

Integrating advanced thermal management strategies, including liquid, air, and phase change materials, is crucial for optimizing LIB performance in EVs and HEVs. These strategies enhance efficiency, mitigate thermal runaway risks, and ensure reliable operation under diverse environmental conditions, contributing to energy conservation and emissions reduction in the automotive sector [8, 19, 9, 14, 12].

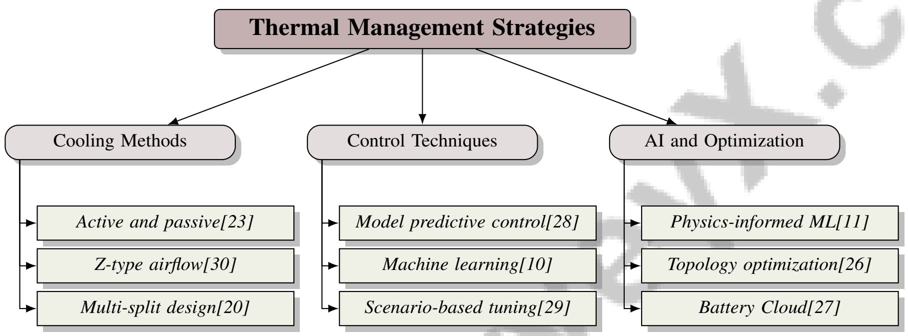


Figure 3: This figure represents the hierarchical categorization of thermal management strategies for battery performance, highlighting key cooling methods, control techniques, and AI-driven optimizations.

4 Heat Dissipation Techniques

Category	Feature	Method
Overview of Heat Dissipation Techniques	Integrated Cooling Solutions	HBTMS[21]
	Optimization and Control	HBPA[32]
	Dynamic Thermal Regulation	PTMD[33], TMCP[31]
Passive and Active Cooling Methods	Combined Cooling Techniques	MBTMS[23]
Innovative Heat Dissipation Techniques	Airflow Optimization	Z-BTMS[30]
	Intelligent Control Systems	TMLSTO[26]

Table 1: This table provides a comprehensive summary of various heat dissipation techniques employed in electric vehicle thermal management systems. It categorizes these techniques into integrated cooling solutions, optimization and control, dynamic thermal regulation, passive and active cooling methods, and innovative heat dissipation techniques, highlighting the specific features and methods associated with each category. Key references are cited to support the methodologies discussed, underscoring their relevance in advancing thermal management capabilities in electric vehicles.

Effective thermal management is crucial in electric vehicles (EVs) to ensure the safety, efficiency, and longevity of lithium-ion batteries. With the rising demand for EVs, innovative solutions for addressing heat generation and dissipation challenges are becoming increasingly important. This section explores various heat dissipation techniques, categorizing them into active and passive cooling methods, which are fundamental to thermal management in EV systems. Table 1 presents a detailed summary of heat dissipation techniques, categorizing them into distinct approaches and methods relevant to electric vehicle thermal management. Additionally, Table 3 presents a comprehensive comparison of various cooling methods employed in electric vehicle thermal management, elucidating their respective features, advantages, and limitations.

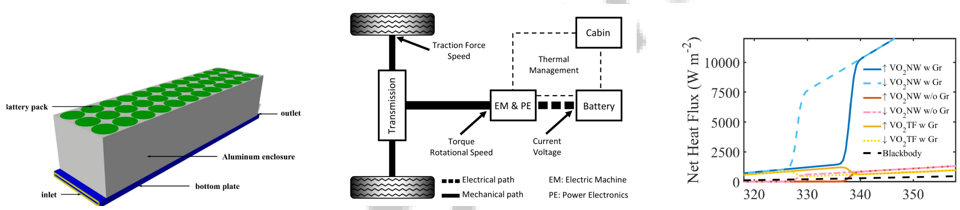
4.1 Overview of Heat Dissipation Techniques

Maintaining thermal stability in EVs, particularly for lithium-ion batteries susceptible to thermal fluctuations, requires effective heat dissipation strategies. Both active and passive cooling methods have been developed to optimize thermal performance. Air-based, liquid-based, and phase change material (PCM)-based systems are prominent, each offering distinct advantages depending on the application context [12]. Air-cooling systems are valued for their simplicity and cost-effectiveness, yet they may require optimization to enhance heat transfer efficiency [9].

Liquid-based systems excel in thermal conductivity and heat transfer, making them suitable for intensive cooling applications. For instance, the J-type battery thermal management system (BTMS) employs a dual outlet system with adjustable valves to optimize cooling efficiency [3]. PCM-based systems utilize materials with high latent heat capacities to absorb and release thermal energy during phase transitions, maintaining stable temperatures without mechanical components [12]. However, their effectiveness can be limited by PCM thermal conductivity, necessitating enhancements such as high-conductivity additives.

Advanced methods like Thermo-Mechanical Level-Set Topology Optimization offer comprehensive approaches to optimizing battery pack design for thermal performance and structural integrity [26]. Thermally modulated charging protocols (TMCP) introduce active thermal switching to manage thermal conductance during extreme fast charging, addressing thermal challenges associated with rapid energy transfer [31].

The integration of artificial intelligence (AI) into thermal management systems marks a significant advancement, enabling adaptive and efficient control of thermal conditions [6]. AI-driven approaches facilitate real-time optimization of cooling strategies, enhancing the safety, efficiency, and reliability of EVs.



(a) Battery Pack with Aluminum Enclosure and Bottom Plate[21]

(b) Electric Vehicle System Components and Interactions[32]

(c) Comparison of Net Heat Flux between VO2 NW and VO2 TF with and without Gr[33]

Figure 4: Examples of Overview of Heat Dissipation Techniques

As illustrated in Figure 4, effective heat dissipation techniques are vital for optimizing the performance and longevity of technological systems. The first subfigure highlights a battery pack in an aluminum enclosure, showcasing material choice and structural design's role in heat dissipation. The second emphasizes the interactions between components in an EV system, where efficient thermal management is crucial for maintaining system integrity. The third subfigure compares net heat flux between VO2 nanowires and thin films, with and without a graphene layer, underscoring the influence of material properties on heat dissipation. Collectively, these examples provide a comprehensive understanding of heat dissipation strategies and their significance across applications [21, 32, 33].

4.2 Passive and Active Cooling Methods

Method Name	Cooling Methods	Energy Efficiency	Operational Challenges
MBTMS[23]	Water Channels	Improved Cooling Performance	Thermal Runaway
TMLSTO[26]	Passive, Active	Significant Improvements	Transient Conditions

Table 2: Comparison of cooling methods in electric vehicle thermal management, detailing their energy efficiency and operational challenges. The table highlights the methods MBTMS and TMLSTO, illustrating their respective cooling techniques and associated issues.

Thermal management in EVs relies on both passive and active cooling methods, each presenting unique advantages and limitations for maintaining optimal battery temperatures. As illustrated in Figure 5, which classifies cooling methods in electric vehicle thermal management, these approaches can be distinguished into passive, active, and hybrid categories, highlighting their respective techniques and challenges. Additionally, Table 2 provides a comparative analysis of various cooling methods used in electric vehicle thermal management, focusing on their energy efficiency and operational challenges. Passive cooling methods, such as heat sinks, thermal pads, and phase change materials (PCMs), utilize natural heat dissipation mechanisms without external energy input [12]. These methods are simple, cost-effective, and energy-efficient but may struggle under high thermal loads or rapid temperature changes [9].

Conversely, active cooling methods employ mechanical systems to enhance heat removal, including liquid cooling, air conditioning, and thermoelectric coolers. Liquid cooling systems circulate a coolant to absorb heat from the battery, dissipating it through a heat exchanger, thereby offering superior thermal conductivity and effective temperature control [3]. While effective for intensive cooling, these systems can be complex and costly. Air-based active cooling systems, utilizing fans or blowers, enhance airflow over heat-generating components, balancing efficiency and cost [23].

Integrating PCMs into active cooling systems can further improve thermal management by utilizing latent heat for temperature stabilization [26]. This hybrid approach combines the benefits of passive and active methods, ensuring robust thermal management across varying operational conditions.

Despite their effectiveness, active cooling methods often demand significant energy input, impacting overall vehicle energy efficiency. The complexity and cost of these systems may hinder widespread adoption, emphasizing the need for optimized cooling strategies that leverage both passive and active methods to advance thermal management in EVs [6].

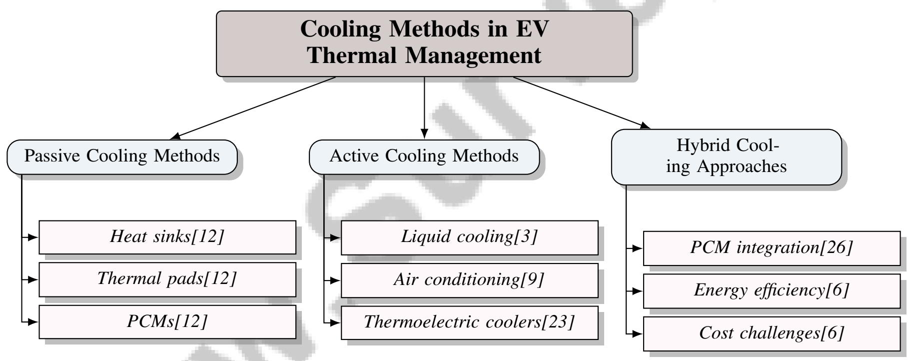


Figure 5: This figure illustrates the classification of cooling methods in electric vehicle thermal management, distinguishing between passive, active, and hybrid approaches, highlighting their respective techniques and challenges.

4.3 Innovative Heat Dissipation Techniques

Emerging heat dissipation techniques are pivotal for enhancing the thermal management capabilities of EVs, addressing traditional cooling methods' limitations and improving overall vehicle performance. One promising approach is integrating phase change materials (PCMs) with enhanced thermal conductivity, significantly boosting passive cooling performance through efficient heat absorption and release during phase transitions [12]. Incorporating high-conductivity additives into PCMs represents a key innovation for improved heat distribution and battery temperature stabilization.

Advanced thermal interface materials (TIMs) enhance heat transfer between battery cells and cooling systems by minimizing thermal resistance, thereby improving both passive and active cooling strategies [26]. The use of TIMs alongside liquid cooling systems can lead to more efficient thermal management, particularly in high-performance applications.

Novel airflow designs, such as the Z-type airflow cooling system, exemplify innovation in optimizing heat dissipation through enhanced airflow management. This system minimizes temperature gradients within battery packs, ensuring uniform cooling and preventing localized overheating [30].

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The integration of artificial intelligence (AI) and machine learning (ML) into thermal management systems signifies a substantial advancement. AI-driven models can predict thermal behavior and optimize cooling strategies in real-time, adapting to varying operational conditions and enhancing EV safety and efficiency [6]. These models utilize sensor data and predictive algorithms to dynamically adjust cooling parameters, ensuring optimal thermal performance.

The incorporation of advanced materials and AI-driven methodologies in innovative heat dissipation techniques underscores their transformative potential for improving thermal management systems in EVs. Recent advancements in AI, particularly deep learning, have addressed complexities in thermal management, enhancing traditional numerical techniques. AI applications enable more effective battery thermal management systems, crucial for maintaining optimal temperature control and ensuring lithium-ion battery performance and safety. Furthermore, supervised learning strategies utilizing interconnected artificial neural networks have been developed to optimize thermal management operations, accurately estimating battery temperatures and reducing energy consumption, thereby significantly advancing overall thermal management capabilities in EVs [6, 12, 10, 11]. These innovations not only enhance battery performance and safety but also contribute to the energy efficiency and reliability of electric vehicles, supporting their continued adoption in the automotive industry.

Feature	Air-based Cooling	Liquid-based Cooling	PCM-based Cooling
Cooling Type	Passive	Active	Passive
Key Advantage	Cost-effective	High Thermal Conductivity	Stable Temperature Maintenance
Main Limitation	Efficiency Optimization Required	Complex And Costly	Limited BY Conductivity

Table 3: This table provides a comparative analysis of three distinct cooling methods used in electric vehicles: air-based, liquid-based, and PCM-based cooling. It highlights the primary characteristics, advantages, and limitations of each method, offering insights into their applicability and effectiveness in thermal management systems.

5 Cooling Systems in Electric Vehicles

5.1 Design and Implementation of Cooling Systems

In electric vehicles (EVs), effective thermal management is paramount for optimizing battery performance and extending vehicle lifespan. Recent advancements in cooling systems incorporate various mediums—air, liquid, and phase change materials (PCM)—to enhance Battery Thermal Management Systems (BTMS) within the broader Vehicle Thermal Management Systems (VTMS) framework [12]. A significant innovation is the multi-split configuration design for fluid-based cooling, which optimizes the layout of heat-generating devices using dynamic physics modeling to improve cooling efficiency [20].

Dynamic control strategies, such as Scenario-based Thermal Management Parametrization (STMP), employ deep reinforcement learning to autonomously adjust feedback controllers, optimizing performance under diverse thermal loads [29]. Shape memory alloys (SMA) further enhance cooling efficiency by adapting mechanical properties with temperature changes, significantly impacting thermal conductance [16]. Cooling-guided diffusion models also optimize battery cell arrangements by progressively denoising inputs with classifier guidance, enhancing cooling efficiency [34].

The hierarchical categorization of cooling systems and strategies for electric vehicles is illustrated in Figure 6. This figure highlights key cooling techniques, innovative strategies, and integration approaches, emphasizing the importance of air, liquid, and PCM cooling methods, as well as advanced designs like multi-split and STMP with deep reinforcement learning (DRL). Furthermore, it showcases integration approaches such as dynamic programming and smart charging, which are critical for enhancing the overall efficiency of thermal management systems.

Integration of dynamic programming for energy management, which considers battery temperature and State of Charge (SOC), demonstrates the synergy between thermal and energy management, particularly in Plug-in Hybrid Electric Vehicles (PHEVs) [14]. Model-based optimization approaches that incorporate detailed battery models into smart charging processes are crucial for optimizing battery performance and longevity [7]. The iPTM strategy, which integrates power and thermal management through model predictive control, further enhances system efficiency [18].

These innovations in EV cooling systems leverage advanced technologies, adaptive controls, and novel materials to address lithium-ion batteries' temperature sensitivity, thereby optimizing cooling efficiency and ensuring safety and reliability across various operational scenarios [12, 2, 9].

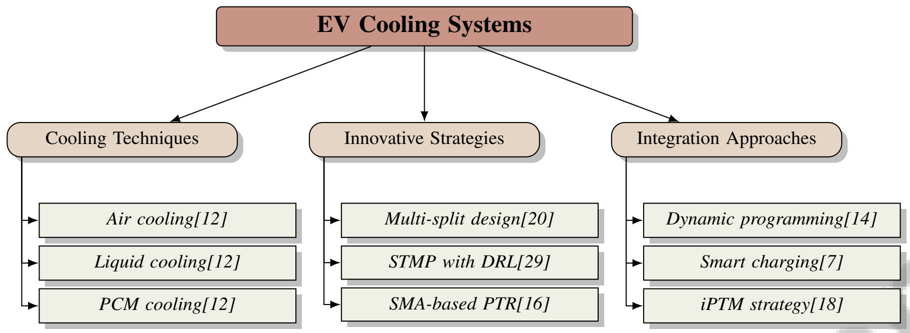

Figure 6: This figure illustrates the hierarchical categorization of cooling systems and strategies for electric vehicles (EVs), highlighting key cooling techniques, innovative strategies, and integration approaches. It emphasizes the importance of air, liquid, and PCM cooling methods, innovative designs like multi-split and STMP with DRL, and integration approaches such as dynamic programming and smart charging.

5.2 Integration with Vehicle Components

The integration of cooling systems with vehicle components is essential for effective thermal management in electric vehicles (EVs), ensuring optimal operating temperatures for enhanced performance and durability. This integration requires a comprehensive understanding of thermal interactions among components such as batteries, electric motors, and power electronics [12].

Advanced thermal interface materials (TIMs) play a crucial role in this integration, facilitating efficient heat transfer and minimizing thermal resistance, especially in high-performance applications [26]. Strategic placement of TIMs enhances thermal coupling, optimizing the overall thermal management system.

Dynamic control strategies, including STMP, further enhance integration by utilizing deep reinforcement learning to fine-tune feedback controllers, adapting to varying thermal loads during different driving scenarios [29]. Additionally, multi-split configuration designs for fluid-based cooling systems optimize the spatial distribution of heat-generating devices, improving cooling efficiency [20].

Artificial intelligence (AI) and machine learning (ML) models enable real-time predictions of thermal behavior and optimize cooling strategies based on sensor data, allowing for adaptive control of thermal conditions across all vehicle components [6]. The integration of these advanced technologies is vital for addressing challenges related to lithium-ion battery temperature sensitivity, ultimately enhancing vehicle functionality and longevity [12, 2].

5.3 Advanced Technologies in Cooling Strategies

Advanced technologies, particularly artificial intelligence (AI) and machine learning (ML), have revolutionized cooling strategies in electric vehicles (EVs), leading to innovative solutions that enhance efficiency and reliability. The combination of convolutional neural networks (CNNs) with finite element method (FEM) simulations improves the efficiency and reduces costs associated with modeling the thermal properties of composite phase change materials (CPCMs) [1].

Reinforcement learning (RL) is employed to dynamically balance energy efficiency and thermal comfort, allowing controllers to adjust the trade-off between these factors based on environmental interactions [5]. Model predictive control (MPC) methods effectively manage the nonlinear dynamics of thermal management systems, while stochastic model predictive control (SMPC) enhances these strategies by incorporating disturbance predictions for proactive responses [35, 36].

Physics-informed machine learning models integrate physical laws into the learning process, enabling precise predictions with limited training data, thus providing robust thermal management solutions

[11]. Supervised learning models further optimize thermal management systems by accurately reflecting operational characteristics without complex physics-based models [10].

Innovative multifaceted battery thermal management systems (MBTMS) combine active and passive cooling methods to synergistically reduce maximum temperatures and improve uniformity, effectively preventing thermal runaway [23]. Data-driven methods for thermal anomaly detection in battery management systems (BMS) enhance early detection capabilities, ensuring timely interventions and improving safety and reliability [24].

The iPTM strategy exemplifies the integration of predictive thermal management with engine aftertreatment co-optimization, leveraging both short-term and long-term predictions to manage slow thermal dynamics effectively [18]. The incorporation of AI and ML in cooling strategies signifies a pivotal shift in thermal management practices, enhancing efficiency and improving battery safety across diverse operating conditions. These innovative approaches are crucial for addressing the complexities of thermal management in EVs, ultimately contributing to their overall performance and longevity [11, 6, 9, 17, 10].

6 Energy Efficiency and Thermal Management

6.1 Impact of Thermal Management on Energy Efficiency

Thermal management plays a crucial role in enhancing the energy efficiency of electric vehicles (EVs), significantly affecting the performance and reliability of components like lithium-ion batteries. Advanced systems, such as the J-type Battery Thermal Management System (BTMS), have demonstrated a 31.18% improvement in thermal regulation over conventional designs, essential for maintaining optimal battery temperatures and minimizing energy losses [3]. Incorporating strategies like two-layer Model Predictive Control (MPC) can lead to energy savings of up to 7.9

Supervised learning (SL) in thermal management has shown to reduce total energy consumption by 48.5

The Enhanced Kalman Filter-Coulomb Counting (EKF-CC) method significantly improves State of Charge (SOC) estimation accuracy across varying temperatures, crucial for optimizing energy management strategies [25]. The Battery Cloud system exemplifies the integration of advanced algorithms for improved battery management, achieving high accuracy in SOC estimation and effective thermal anomaly detection, enhancing energy efficiency through real-time data analysis and predictive maintenance [27].

Effective thermal management is integral to optimizing energy efficiency in EVs, enhancing the efficiency and reliability of essential components, and facilitating sustainable operation under diverse conditions. Key advancements include enhanced battery management systems, advanced charging technologies, and intelligent powertrain management, contributing to the overall reliability and effectiveness of electric vehicles [18, 13, 31, 2].

6.2 Predictive Models and AI in Thermal Management

The integration of predictive models and artificial intelligence (AI) in thermal management systems represents a significant advancement in optimizing EV performance and efficiency. AI-driven approaches, including machine learning and deep learning, enable adaptive control of thermal conditions, enhancing safety and reliability [6]. Predictive models using machine learning algorithms forecast thermal dynamics by leveraging extensive datasets from vehicle sensors, improving temperature estimation accuracy and facilitating timely detection of thermal anomalies [24, 10, 11].

Future research should focus on integrating AI with robust physical models to enhance the reliability and accuracy of thermal management systems. Hybrid approaches combining data-driven models with physics-based simulations can provide comprehensive insights into thermal behavior, enabling precise control over thermal management processes. Addressing limitations like reliance on extensive training data and computational resources is essential for advancing AI applications in thermal management. Innovations like physics-informed machine learning offer promising alternatives by incorporating physical laws into surrogate models, reducing data requirements and computational burdens while improving accuracy [11, 6]. These AI-driven systems can achieve greater efficiency and adaptability, supporting sustainable EV operation under diverse conditions.

The integration of predictive models and AI in thermal management systems is crucial for enhancing energy efficiency and performance in EVs. Advanced techniques, such as supervised learning and physics-informed machine learning, enable precise control of battery temperatures and optimize thermal management subsystems, including fans, pumps, and heat exchangers. These AI-driven approaches improve temperature estimation accuracy and reduce total energy consumption, ensuring batteries operate within safe temperature ranges. Model predictive control frameworks optimize fast charging performance while maintaining thermal stability, underscoring AI's significant role in developing efficient thermal management solutions for EVs [19, 28].

6.3 Role of HVAC Systems in Energy Efficiency

Heating, ventilation, and air conditioning (HVAC) systems are pivotal in the energy efficiency of EVs, significantly consuming energy, particularly under extreme climate conditions. Integrating advanced HVAC systems is essential for optimizing thermal comfort while minimizing energy consumption, enhancing overall vehicle efficiency [8]. In light-duty vehicles, HVAC systems are among the largest auxiliary energy consumers, impacting the energy efficiency of Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs). Traditional HVAC systems often prioritize temperature regulation without considering overall thermal comfort, leading to inefficient energy usage [5].

Applying model predictive control (MPC) methods in HVAC systems enhances energy efficiency by dynamically adjusting operations based on real-time conditions [35]. These systems optimize energy usage by predicting future thermal loads and adjusting HVAC operations accordingly, reducing unnecessary energy expenditure while maintaining occupant comfort. AI and machine learning integration further improves energy efficiency through adaptive control strategies, allowing HVAC systems to operate more efficiently by predicting future thermal demands [6]. This predictive capability is particularly beneficial during peak demand periods, ensuring HVAC systems contribute positively to overall vehicle energy efficiency.

7 Challenges and Future Directions

7.1 Technological and Methodological Limitations

The advancement of thermal management technologies for electric vehicles (EVs) is impeded by several technological and methodological constraints. A significant challenge is the reliance on predictive models like stochastic model predictive control (SMPC), which often fail to account for real-world disturbances under unpredictable driving conditions, compounded by the variability of long-term speed predictions impacting model predictive control (MPC) strategies [18]. Innovations such as the J-type Battery Thermal Management System (BTMS) present manufacturing and implementation complexities, potentially limiting their widespread adoption [3]. Thermal runaway remains a critical risk in systems using phase change materials (PCMs), especially when improperly integrated, resulting in elevated temperatures in adjacent cells [23].

Data-driven approaches face challenges like data loss, asynchronous sampling, and the need for extensive datasets, which hinder real-time anomaly detection and model performance [24]. AI-driven solutions are often limited by dataset quality, where imbalanced data can negatively impact classifier performance [6]. Material degradation, notably in systems utilizing shape memory alloys (SMA), poses a threat to the long-term reliability of thermal regulators [16]. Existing methods frequently lack validation across diverse real-world applications, restricting their effectiveness [13].

The high costs of liquid cooling systems, the weight of PCM systems, and challenges in maintaining consistent temperature management across battery packs further constrain current strategies [12]. Air cooling methods, while cost-effective, often underperform under extreme conditions, such as high discharge rates or elevated temperatures [9]. The EKF-CC method's dependency on accurate initial state of charge (SOC) values and potential cumulative errors in Coulomb Counting highlight limitations in battery management systems [25]. Although the TMCP method shows promise for extreme fast charging, it requires additional components like thermal switches, which introduce complexity and safety concerns [31].

Addressing these limitations is crucial for developing robust and adaptable thermal management systems. Enhancing battery thermal management systems (BTMS), particularly in air-cooling technologies, is vital for improving efficiency and reliability, preventing issues such as thermal runaway and aging, and supporting the sustainable growth and adoption of EVs. Innovations in design, computational simulations, and vehicle thermal management system integration are essential for these advancements [12, 9].

7.2 Innovative Materials and Emerging Technologies

Advancements in thermal management for electric vehicles (EVs) increasingly rely on innovative materials and emerging technologies. A promising research area is the optimization of Battery Thermal Management System (BTMS) designs through hybrid approaches that combine air cooling with other technologies, enhancing thermal management capabilities by leveraging air cooling's cost-effectiveness while addressing its heat transfer limitations [9]. Exploring advanced battery chemistries and integrating Heating, Ventilation, and Air Conditioning (HVAC) systems with BTMS are critical for improving energy efficiency and safety across vehicle components [22].

Data-driven methods resilient to data loss and requiring minimal reference data offer advantages in thermal anomaly detection, ensuring timely interventions that enhance battery system safety and reliability [24]. Integrating machine learning algorithms into State of Charge (SOC) estimation methods could improve accuracy and efficiency, optimizing battery management [25]. The Battery Cloud exemplifies innovation by providing a platform for refining algorithms, enhancing data security, and exploring applications like battery recycling, extending battery system lifecycle and utility [27].

The potential of innovative materials and technologies, including artificial intelligence and advanced modeling techniques, is substantial in transforming thermal management systems, enhancing efficiency, safety, and performance through improved thermal conductivity and temperature control [6, 1, 37, 11]. Focusing on these areas can significantly enhance EV efficiency, safety, and sustainability, supporting their development and adoption.

7.3 Future Research Directions

Future research in thermal management for electric vehicles (EVs) should focus on enhancing system efficiency, safety, and adaptability. Developing robust models that adapt to varying conditions is essential, with an emphasis on optimizing charging strategies to balance efficiency and safety while exploring new battery technologies [13]. Incorporating online learning capabilities to update artificial neural network (ANN) models with new data can improve optimal scheduling strategies [10].

Improving speed prediction robustness and integrating advanced data classification algorithms are vital for addressing cold-start operations in hybrid electric vehicles (HEVs), thereby enhancing predictive model accuracy under dynamic conditions [18]. Refining design and control strategies for the J-type Battery Thermal Management System (BTMS) under dynamic driving conditions is necessary for practical applications, ensuring effective thermal regulation [3].

Integrating expert knowledge within deep reinforcement learning (DRL) frameworks and improving scenario generation processes can optimize learning curricula in thermal management systems, enhancing strategy adaptability across diverse conditions [29]. Exploring speed optimization and eco-driving strategies could further enhance energy efficiency and reduce trip times, contributing to sustainable transportation solutions [8].

These research directions highlight the potential for significant advancements in thermal management technologies, supporting sustainable EV development and adoption. By integrating advanced computational techniques, such as artificial intelligence, and optimizing coordination between thermal management and powertrain control, future research can markedly improve efficiency, safety, and adaptability in electric and hybrid vehicles. This will enhance battery performance and longevity while contributing to energy savings and greenhouse gas reduction, supporting the automotive industry's shift towards sustainable practices [6, 12, 17, 9].

8 Conclusion

Effective thermal management is integral to the performance, energy efficiency, and reliability of electric vehicles (EVs). The deployment of advanced technologies, especially artificial intelligence (AI), significantly enhances these systems by enabling the development of predictive models that optimize cooling strategies in real-time, thus maintaining vehicle safety and reliability across diverse

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operational scenarios. The integration of battery aging considerations into smart charging strategies is crucial, as neglecting this aspect can lead to a significant underestimation of EV operating costs. Addressing battery degradation is essential for enhancing both the lifecycle and cost-effectiveness of EVs. Furthermore, innovations such as the Thermally Modulated Charging Protocol (TMCP) have demonstrated the capability to achieve extreme fast charging, marking a substantial advancement in charging technologies. This survey underscores the transformative potential of innovative materials and emerging technologies in overcoming existing challenges, thereby promoting the sustainable evolution of the automotive industry. By leveraging these advancements, EVs can achieve superior performance, safety, and energy efficiency, facilitating their wider adoption and success in the global marketplace.

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