

A Review on Battery Thermal Management Systems in Electric Vehicles: Techniques, Challenges, and Machine Learning Advances

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Abstract – Due to the emergence of electric vehicles (EVs) and as an increasing number of applications rely on lithium-ion batteries, the efficient battery thermal management system (BTMS) has not been as important as now. In this paper, a detailed survey is done with regard to the different BTMS techniques, challenges, and also the recent developments of the field. It points out the major challenges encountered by EV batteries, especially the thermal problems that occur when they are driven at high-performance, rapid charging, and extreme weather. These include both the conventional and novel cooling technologies e.g. air cooling, liquid cooling, phase change materials (PCMs), as well as the new systems such as direct refrigerant cooling and hybrid systems which are compared in details. Also, the topic of the combination of machine learning (ML) and those of artificial intelligence (AI) into BTMS optimization is discussed, with the emphasis put on real-time optimization and predictive maintenance as well as fault detection. The relevance of the use of sustainable processes in the development of BTMS is also outlined in the paper along with focus on environmental friendly materials and chillers. Lastly, the directions of the future are given, where the increased efficiency, flexibility, and sustainability of the systems are needed to address the changing needs of the electric vehicle industry.

Keywords – Artificial Intelligence, Battery Thermal Management Systems, Cooling Techniques, Electric Vehicles, Machine Learning, Phase Change Materials, Sustainability.

I. INTRODUCTION

Due to a global focus on sustainability, electric vehicles (EVs) are leading the way when it comes to new car innovations. Major to these cars' performance, safety, and ability to last long be the lithium-ion cell battery packs [1]. Yet, lithium-ion batteries have to face big problems caused by their thermal properties. If the temperature rises too quickly when using high power on the battery, it can lessen the battery's performance, shorten its life, and in the worst-case scenario, result in a potentially hazardous situation [2]. Because of this, regulating

the battery's temperature to within safe and ideal specifications matters a lot. As a result, managing the thermal conditions of batteries is crucial, which is where battery thermal management systems (BTMS) becomes important [3].

A well-designed BTMS allows battery cells to operate within a temperature range of 20°C to 40°C, with a goal for equal temperatures of no higher than 5°C across the cells [4]. The best electrical performance and least amount of degradation are achieved with lithium-ion batteries in this specified range. Should the battery temperature rise, the internal resistance increases, the battery wears down faster, and risks of an explosion become higher. By contrast, low temperatures can cause difficulties for the vehicle's battery by reducing its ability to accept and release charge.

Experts have designed different BTMS systems to face the issue of thermal management. Generally, the systems include air cooling, liquid cooling, PCM-based systems, and certain also use heat pipes or thermoelectric elements [5]. It is common for modern EVs to use liquid-cooling because it works better and fits well inside the vehicle. These systems help with ensuring batteries work well in all kinds of weather because they are capable of efficiently taking in and releasing heat.

Although it's a challenge in engineering, building a good BTMS is costly and reliable. The system should handle changes in driving situations, different road and weather conditions, as well as how the battery is used, all the while ensuring high efficiency and stability [6]. Typically, traditional approaches to design and optimization use empirical and thermodynamic models that mandate running a lot of experiments and complex simulations — making them less suitable for many practical uses.

In recent times, using ML for BTMS development has turned out to be a promising trend. With ML techniques, engineers can model and control thermal systems using data, allowing them to optimize those systems much faster [7]. Despite the main focus on

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usual and mixed BTMS technologies, the latest machine learning advances are also explained in the review, mainly found in the literature review section.

This paper looks to provide a summary of the most recent developments in battery thermal management systems for electric vehicles. It goes over the main thermal issues that affect EV batteries, looks into different BTMS designs, and talks about how they can be integrated into EV powertrains. Another part of this review discusses the recent technologies and models based on AI in BTMS to explain the progress of research. This review strives to contribute by pulling together existing knowledge and calling out gaps that can help build better, more advanced battery systems for electric cars.

II. BATTERY THERMAL MANAGEMENT TECHNIQUES FOR ELECTRIC VEHICLES

The performance of an EV's battery is greatly influenced by how well it is managed in terms of temperature. Lithium-ion batteries suitable for EVs should be kept between 20°C and 40°C. Extreme temperatures can notably impair the effectiveness of batteries, contribute to deterioration, or even lead to devastating thermal runaway. BTMS are put in place to regulate the heat generated within the battery and ensure that every cell experiences the same temperature [8].

A. Air Cooled Systems

Air-cooling was one of the first ways to manage the heat produced by batteries in vehicles. Both passive and active methods of air circulation can be used to cool down batteries. Their effectiveness is often suitable only for batteries in moderate-use vehicles. They are often chosen for frugal EVs and initial models of hybrid cars since they're inexpensive, easy to install and lightweight [9].

Nonetheless, their disadvantage is also pronounced. Using air to cool a battery pack is inadequate when the battery pack has a very large capacity. Batteries can heat up too much during accelerated charging or while driving up steep inclines, amplifying their risk of damage and wearing out quickly in air-cooled setups. Based on this reason, low-cost EVs are among the rare applications where air-cooled BTMS are still employed.

B. Liquid Cooled Systems

Most manufacturers are adopting liquid-cooled BTMS for EVs because they offer better heat dissipation compared to other types of cooling systems. The coolant is pumped through channels that border or pass through battery modules. The heat is transferred from the battery to the radiator, which then ensures it releases the heat into the

surroundings. Communication systems make use of mechanical components such as devices, apparatuses, or devices.

Immersion cooling involves submerging the battery cells in a non-conductive liquid. It provides optimal cooling distribution by ensuring the maximum amount of contact between the material and the battery.

Liquid cooling performs well but increases complication. They rely on pumps, sensors, valves and a control system for regulating temperature. Still, attention must be given to preventing coolant leakage and the developing of safety features. Still, many EV makers find it worthwhile to dedicate extra resources to ensuring optimal battery cooling in vehicles that require such performance [10].

C. Phase Change Material (PCM) Based Systems

Passive phase change materials are used in battery systems to control sudden changes in temperature. While transforming from solid to liquid, these materials gain a considerable amount of heat without a substantial rise in temperature [7]. It absorbs additional heat, helping prevent the battery from overheating when power output is at a maximum.

The battery pack is frequently fitted with PCMs to shield the individual cells from effect. Being passive is their main advantage since they don't incorporate mechanisms or draw electricity. PCMs are capable of absorbing a limited quantity of heat. They can no longer moderate temperature unless the surrounding device is cooled down. As a result, PCMs are commonly incorporated into dual-thermal-management systems.

D. Heat Pipe Systems

The heat pipe system is a viable option for passive thermal management. A heat pipe consists of a closed cylinder with a portion of a fluid enclosed inside. As the battery produces heat, the liquid inside the pipe changes state from a gas to a liquid at the hot end before moving to the cold end. From there it reverts back to its initial gaseous state due to capillary action. This loop of the fluid greatly enhances the transfer and dissipation of heat [6].

Heat pipes don't actively extract heat from a battery pack. Consequently, they spread heat across the entire battery pack to eliminate hot spots. They also work exceptionally well when combined with other types of cooling systems. This also makes heat pipes a good choice for systems that require enduring performance. The performance of these systems may be affected by different orientations and gravitational forces [11].

E. Direct Refrigerant Cooling (Chiller Systems)

Some advanced BTMS feature the integration of refrigerant into the cooling system. The refrigerant from the vehicle's HVAC system is circulated through the chiller or evaporator that come into contact with the battery modules. Eliminating the second coolant path boosts efficiency in rapid charging and performance modes.

Controlling pressure and temperature is demanding in a system that uses refrigerants directly in cooling. They are more difficult to design and operate and even a small leak could harm the battery and the cabin heating/cooling systems. Regardless, these techniques are the preferred choice during climatic conditions or when thermal characteristics are critical in electric vehicles [9].

F. Hybrid Systems

As a result, combining several different cooling methods in a single BTMS layout has gained popularity. Two or more approaches are utilized to optimize the thermal capability of these systems. When the vehicle is being driven at high speed, a PCM quickly absorbs extreme heat waves and leaves longer-lasting cooling to be managed by an active liquid system [12].

Hybrid systems with both passive and active components are able to effectively manage heat over a wide variety of operation scenarios. Nonetheless, advanced expertise and additional investments are needed for their development and implementation. Hybrid systems are expected to become increasingly important in designing BTMS for highly capable and long-range electric vehicles of the future.

G. Comparative Summary

Every BTMS technology has its own advantages and disadvantages. While fairly simple and inexpensive, air-cooled systems are not suitable when substantial cooling power is required. Liquid cooling delivers excellent results while being scaled to various levels, but both its cost and complexity are greater than for other systems. PCM and heat pipes can be used in combination with other methods as a backup solution. For applications where thermal stability is a priority at all times, direct refrigerant systems and hybrid schemes are generally the best choice.

The best option for BTMS will vary according to the demands of a given implementation. BTMS designs are expected to undergo valuable enhancements in response to the evolving nature of EV technology and increasingly stringent demands placed by regulators on performance and safety.

Table 1: Comparative Analysis of Battery Thermal Management Techniques

Technology	Cooling Efficiency	Cost	Complexity	Thermal Uniformity	EV Suitability
Air Cooling	Low	Low	Low	Poor	Entry-level EVs
Liquid Cooling	High	Medium	High	Excellent	High-performance EVs
PCM	Moderate (initial)	Medium	Low	Moderate	Supplementary systems
Heat Pipe	High (localized)	Medium	Medium	Good	Hybrid or compact EVs
Direct Refrigerant	Very High	High	High	Excellent	Integrated thermal systems
Hybrid Systems	Very High	High	Very High	Excellent	Premium & performance EVs

Table 1 provides a comparative analysis of various Battery Thermal Management Techniques (BTMS) used in electric vehicles (EVs). It evaluates the cooling efficiency, cost, complexity, thermal uniformity, and suitability for different types of EVs. Air cooling, which is low in cost and complexity, is suitable for entry-level EVs but has poor thermal uniformity and low cooling efficiency. Liquid cooling offers high cooling efficiency and excellent thermal uniformity, making it ideal for high-performance EVs despite its higher complexity and cost. Phase Change Materials (PCM) provide moderate cooling efficiency initially, moderate thermal uniformity, and are often used in

supplementary systems. Heat pipe systems, offering high localized cooling efficiency and good thermal uniformity, are best suited for hybrid or compact EVs. Direct refrigerant systems provide very high cooling efficiency and excellent thermal uniformity but come with high complexity and cost, making them suitable for integrated thermal systems. Finally, hybrid systems combine multiple techniques, offering very high cooling efficiency and thermal uniformity, making them perfect for premium and performance EVs, though they are costly and complex.

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Website: www.ijdacr.com (Volume 13, Issue 07, February 2025)**III. RECENT ADVANCES IN MACHINE LEARNING FOR BATTERY THERMAL MANAGEMENT SYSTEMS (BTMS)**

Recent developments in battery thermal management systems (BTMS) have seen a significant shift towards the integration of machine learning (ML) and artificial intelligence (AI). These technologies have become critical in addressing the complexities of managing thermal issues in electric vehicle (EV) batteries. Lithium-ion batteries, commonly used in EVs, are highly sensitive to temperature variations, which can drastically affect their performance, lifespan, and safety. As a result, optimizing BTMS has become a priority for automakers, with ML emerging as a key tool in enhancing thermal management.

ML algorithms have proven particularly effective in predicting and controlling the temperature dynamics within EV battery systems, providing real-time optimization. One of the most significant advantages of using ML is its ability to adapt to changing conditions in the battery's environment, including variations in external temperatures, charging cycles, and vehicle usage. According to Chen et al. [13], ML-based real-time optimization has demonstrated its capacity to predict battery temperature fluctuations and adjust cooling strategies proactively. This approach enhances the overall thermal uniformity of the battery, ensuring that temperatures remain within the ideal range (20°C to 40°C), even during high-demand conditions such as rapid charging and long-distance driving.

In addition to real-time optimization, ML is being applied to predictive maintenance of BTMS. Deep learning models, such as convolutional neural networks (CNNs), are increasingly used to analyze temperature data and forecast thermal issues before they occur. This predictive capability is crucial in preventing thermal runaway, which could lead to dangerous situations such as battery fires or explosions. Luo et al. [14] highlighted how deep learning algorithms have been utilized to forecast thermal behavior under different operational scenarios, helping to mitigate the risk of battery failure. These predictive models can analyze large datasets from sensors within the EV, detecting subtle patterns that may indicate early signs of thermal stress, thereby allowing for timely interventions.

The integration of machine learning with hybrid BTMS has also gained momentum. Hybrid systems combine passive and active cooling methods, such as liquid cooling, air cooling, and phase change materials (PCM), to optimize battery temperature management. ML models can analyze real-time data from these systems and adjust the cooling process

dynamically to maintain optimal thermal conditions across the entire battery pack. Arora and Patel [15] discussed the role of ML in enhancing hybrid BTMS, explaining how machine learning algorithms help select the most efficient combination of cooling techniques based on the battery's operating conditions. The ML-driven optimization of hybrid systems has proven effective in managing heat across a broad range of EV models, from entry-level vehicles to high-performance EVs.

Another exciting development in this field is the application of reinforcement learning (RL), which allows BTMS to learn from their interactions with the environment and improve over time. Unlike traditional ML models, which rely on pre-labeled data, RL models can continuously adapt to new conditions. This makes them ideal for managing the dynamic thermal behavior of EV batteries, where environmental and operational conditions can vary significantly. Srinivasan et al. [16] explored the use of RL in BTMS, demonstrating how the system could autonomously adjust its cooling strategies in response to thermal events, optimizing both battery performance and energy consumption. This level of adaptability is essential for EVs that operate in varying climates or under different driving conditions.

Moreover, the use of ML in BTMS has extended to thermal fault detection and mitigation. Zeng et al. [17] implemented a machine learning-based model for fault detection in BTMS, particularly focusing on the early detection of cooling system failures that could lead to overheating. This is crucial for ensuring the safety and reliability of electric vehicles, especially as battery capacities increase and the demands on cooling systems become more critical. The model developed by Zeng et al. leverages real-time data from temperature sensors to predict cooling system failures and suggest preventive measures, such as activating backup cooling systems or adjusting the cooling cycle.

The advent of AI-powered BTMS has also opened up new possibilities for energy efficiency. By optimizing the interaction between battery cooling and power consumption, AI models can reduce the overall energy consumption of the vehicle, leading to longer driving ranges. According to Huang et al. [18], AI-enhanced BTMS can significantly reduce the need for active cooling by predicting when the battery will be exposed to high temperatures and preemptively managing the temperature rise. This predictive capability allows for energy-efficient cooling, which is essential for extending the driving range of EVs and improving their energy efficiency.

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In addition to improving thermal management, machine learning and AI are also playing a crucial role in enhancing the safety of EVs. Machine learning models are being integrated into battery management systems (BMS) to monitor the health of the battery pack and predict potential failure points. These systems work in conjunction with the BTMS to ensure that any anomalies in battery temperature are detected early, minimizing the risk of thermal runaway. Fan et al. [19] demonstrated that AI models could predict and prevent thermal runaway events by analyzing battery performance and temperature data in real time. Their study emphasized the importance of integrating AI with traditional thermal management methods to create safer, more reliable EVs.

Looking ahead, the future of machine learning in BTMS appears promising. As EVs become more sophisticated and the demand for efficient, long-range vehicles grows, the role of ML in thermal management will continue to evolve. The integration of ML with emerging technologies, such as solid-state batteries, will further enhance the capabilities of BTMS, providing even more efficient and reliable cooling systems. Moreover, the increasing availability of high-performance computing and sensor technology will enable more accurate and real-time predictions of battery thermal behavior, making ML an indispensable tool in the development of next-generation EVs.

IV. EMERGING TRENDS AND INNOVATIONS IN BATTERY THERMAL MANAGEMENT SYSTEMS (BTMS)

Battery thermal management systems (BTMS) have evolved significantly over the past few years, especially as electric vehicle (EV) technology advances at a rapid pace. With the increasing demand for longer driving ranges, faster charging times, and higher energy densities in batteries, thermal management has become one of the most critical aspects of EV development. This section delves into the latest trends and innovations in BTMS, with a particular focus on the application of advanced materials, cooling techniques, and the integration of AI-driven solutions.

A. Advanced Materials for Efficient Thermal Management

In recent years, there has been a growing emphasis on the development and use of advanced materials for BTMS. The performance of conventional thermal management systems often falls short when applied to next-generation batteries, such as solid-state batteries, which offer higher energy densities but also present unique thermal challenges. To

address these challenges, researchers have focused on improving the thermal conductivity of materials used in BTMS, including phase change materials (PCMs), graphene-based composites, and carbon nanotubes.

Graphene and carbon nanotubes, known for their exceptional thermal conductivity, are being increasingly integrated into battery thermal management systems. These materials offer a high surface area and superior heat transfer properties, enabling more efficient thermal regulation. Zhang et al. [20] demonstrated the use of graphene-based composites in the development of novel heat sinks for EV batteries, significantly improving heat dissipation efficiency. By incorporating these materials into battery packs, manufacturers can achieve more efficient thermal management, thereby enhancing battery performance and safety.

In addition to these high-conductivity materials, PCMs have seen a resurgence in BTMS design. PCMs are materials that absorb heat as they undergo phase transitions from solid to liquid, providing passive cooling without the need for external energy input. Recent studies have shown that the integration of PCMs with liquid cooling systems can offer a more energy-efficient solution for temperature regulation. Wang et al. [21] explored the combined use of PCMs and heat pipes to create hybrid cooling systems that offer both active and passive cooling solutions, optimizing thermal regulation in varying environmental conditions.

B. Next-Generation Cooling Techniques

While traditional cooling methods such as air cooling and liquid cooling have been widely used, newer and more advanced cooling techniques are being developed to meet the increasing demands for EV battery systems. Among these techniques, immersion cooling and direct refrigerant cooling have emerged as promising solutions.

Immersion cooling involves submerging the battery cells in a dielectric liquid that absorbs and removes heat directly from the battery. This technique provides excellent thermal uniformity across the battery pack and is particularly effective in managing the heat generated during high-power charging and discharging cycles. A study by Li et al. [22] highlighted the significant advantages of immersion cooling in managing heat dissipation in high-performance EVs, demonstrating that it can maintain optimal battery temperatures while minimizing system complexity.

Direct refrigerant cooling, on the other hand, involves circulating refrigerant through the cooling system to absorb and transport heat from the battery. This method offers very high cooling efficiency and

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is particularly suited for high-performance EVs that require rapid charging capabilities. According to Liu et al. [23], the integration of direct refrigerant cooling with heat exchangers can significantly improve the efficiency of the BTMS, allowing EV batteries to maintain a stable temperature during high-load operations. However, challenges remain in designing systems that are both energy-efficient and cost-effective, particularly for mass-market EVs.

C. Machine Learning and AI Integration for Real-Time Optimization

The integration of artificial intelligence (AI) and machine learning (ML) into BTMS has revolutionized the way thermal management is approached. Machine learning algorithms are increasingly being used to predict and optimize the temperature of batteries in real-time, allowing for adaptive and more efficient cooling solutions. These systems are capable of adjusting cooling strategies based on real-time data from temperature sensors, battery state-of-charge, and environmental conditions.

Recent advancements in AI and ML have focused on improving the accuracy and responsiveness of thermal management systems. Chen et al. [24] developed an AI-driven thermal management model that uses reinforcement learning to optimize the cooling process dynamically. This model allows the BTMS to adjust cooling parameters based on both current battery conditions and predictive algorithms, resulting in improved overall system performance. By integrating AI with thermal management, the system can anticipate potential thermal issues before they arise, reducing the risk of battery damage and enhancing safety.

Another promising trend is the use of deep learning techniques for fault detection and thermal runaway prevention. Zeng et al. [25] implemented a deep learning-based system to detect abnormal thermal behavior and predict potential failures in BTMS. Their model was trained on large datasets collected from EV batteries and demonstrated a high level of accuracy in identifying early signs of thermal issues, enabling preventative actions to be taken before the failure occurs.

D. Sustainability and Environmental Considerations in BTMS Design

As the global automotive industry shifts towards electric mobility, sustainability has become a critical focus in the development of BTMS. The environmental impact of thermal management systems, particularly in terms of energy consumption and the use of refrigerants and other cooling fluids, is an ongoing concern. The transition

to more sustainable BTMS involves not only improving the efficiency of cooling techniques but also incorporating eco-friendly materials and refrigerants into system design.

Researchers are exploring alternative cooling fluids with lower global warming potential (GWP) to replace traditional refrigerants. For example, natural refrigerants such as CO₂ and ammonia are being investigated as potential substitutes for synthetic refrigerants. Zhang et al. [26] reviewed the use of CO₂ as a cooling fluid in BTMS, emphasizing its low environmental impact and excellent heat transfer properties. The adoption of sustainable refrigerants could play a crucial role in reducing the carbon footprint of EVs, making them even more environmentally friendly.

Furthermore, the recyclability of BTMS components is another key consideration. As EV adoption grows, the demand for sustainable and recyclable materials in cooling systems will rise. Researchers are focusing on designing modular BTMS that can be easily disassembled and recycled at the end of their lifecycle, reducing the environmental impact of these systems. Liu et al. [27] proposed a circular economy approach to BTMS design, where components are reused or recycled, ensuring that EVs remain a sustainable mode of transportation throughout their lifecycle.

E. Future Directions in BTMS Research

Looking to the future, the development of next-generation BTMS will focus on several key areas:

- **Solid-State Batteries:** As solid-state batteries become more widely used, the need for innovative thermal management solutions that address their unique thermal properties will increase.
- **AI-Enhanced Optimization:** The continued integration of AI and machine learning will further enhance the performance of BTMS by allowing for real-time optimization and predictive fault detection.
- **Sustainable Design:** Future BTMS will prioritize sustainability by incorporating eco-friendly materials, refrigerants, and energy-efficient technologies.
- **Integration with Vehicle Systems:** BTMS will increasingly be integrated with other vehicle systems, such as energy management systems and battery management systems, to optimize overall vehicle performance and energy consumption.

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V. CHALLENGES AND FUTURE DIRECTIONS IN
BATTERY THERMAL MANAGEMENT SYSTEMS
(BTMS)

Battery thermal management systems (BTMS) play a crucial role in maintaining the performance, safety, and longevity of electric vehicle (EV) batteries, particularly as the demand for high-performance EVs continues to grow. However, several challenges persist in the development of BTMS, especially when operating under extreme conditions. One of the primary obstacles is ensuring effective cooling when EV batteries are subjected to rapid charging, high-speed driving, or harsh environmental temperatures. Under these conditions, traditional cooling methods, such as air and liquid cooling, can struggle to dissipate the significant amount of heat generated by high-capacity batteries, leading to thermal stress. This can compromise battery performance, shorten its lifespan, and in extreme cases, pose safety risks, such as thermal runaway or battery fires.

As battery capacities increase, the need for more efficient and advanced cooling technologies becomes more critical. Traditional methods often become inadequate as they fail to maintain thermal uniformity across the entire battery pack, especially during high-demand situations. As a result, there is growing research into integrating advanced materials and innovative cooling techniques that can enhance the thermal performance of BTMS. Materials like graphene and carbon nanotubes, which possess exceptional thermal conductivity, are being explored to improve heat transfer efficiency. These materials allow for better heat dissipation, thus reducing thermal hotspots and improving the overall stability of the battery during high-performance use. Additionally, innovations in phase change materials (PCMs) and hybrid cooling systems that combine active and passive cooling methods are gaining traction as they offer more energy-efficient and cost-effective solutions for EVs.

Looking towards the future, one of the most promising trends is the incorporation of artificial intelligence (AI) and machine learning (ML) into BTMS. AI and ML models can optimize the cooling process in real-time by dynamically adjusting cooling parameters based on data collected from temperature sensors, battery state-of-charge, and external environmental conditions. This level of real-time optimization would allow the BTMS to anticipate thermal fluctuations and take preventative measures before issues arise. As ML algorithms become more advanced, they will enable BTMS to learn from historical data and improve the system's

response to varying operational scenarios. This would not only enhance the efficiency of the cooling process but also prevent potential failures such as overheating and thermal runaway.

In parallel with these technological advancements, sustainability will be a critical consideration for the future of BTMS. With growing concerns about the environmental impact of synthetic refrigerants and cooling fluids, there is a push towards the development of more eco-friendly materials for BTMS. Natural refrigerants like CO₂ and ammonia, which have lower global warming potential (GWP), are being considered as alternatives to conventional refrigerants used in direct refrigerant cooling systems. Furthermore, research is focusing on designing cooling systems that use recyclable or biodegradable materials, reducing the overall environmental footprint of the system. These sustainable innovations will be essential in meeting stricter environmental regulations and ensuring that EVs remain an environmentally friendly transportation solution.

The future of BTMS is therefore marked by continuous advancements in materials science, AI integration, and sustainability. As these systems evolve, the focus will be on achieving higher levels of energy efficiency, cost-effectiveness, and adaptability. By overcoming the current limitations and integrating the latest technological innovations, BTMS will play a pivotal role in improving the performance, safety, and sustainability of electric vehicles.

VI. CONCLUSION

Battery thermal management systems (BTMS) play a key role in providing the best handling, security and life of electric car (EV) batteries. The paper has covered the recent developments on the BTMS technologies with focus on challenge of higher battery capacities, need of charging within a short time and the threats in extreme environmental conditions. Although the classical cooling solutions (air and liquid cooling) continue to receive widespread adoption, hybrid and relatively sophisticated systems that include both passive and active techniques of cooling have increasingly become popular in terms of improving thermal control. Furthermore, machine learning and artificial intelligence have a great potential of enhancing the efficiency of BTMS because it should allow performing real-time optimization and predictive maintenance, thus minimizing the risks of overheating and thermal runaway of batteries. In perspective, advanced material, such as graphene and carbon nanotubes, and more sustainable cooling liquids and parts will be important in addressing the

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constraints of the future EV battery systems. With the developing future of the EV industry, upcoming BTMS will have to comply with the new battery technology including the solid-state battery, as well as consider the question of sustainability so that EVs could remain a safe and environmentally-friendly mode of transportation.

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