A Review on Thermal Management Techniques for Lithium-Ion Batteries in Electric Vehicles

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Abstract-Electric vehicles are becoming an important solution for reducing greenhouse gas emissions and fossil fuel consumption. However, the performance, safety, and lifespan of lithium-ion batteries strongly depend on effective thermal management. Excessive temperature rise may lead to battery degradation, reduced efficiency, and thermal runaway. Therefore, battery thermal management systems (BTMS) play a critical role in maintaining optimal operating temperatures. This paper reviews various thermal management techniques used in electric vehicles, including air cooling, liquid cooling, phase change materials, heat pipes, immersion cooling, and hybrid cooling methods. The advantages, limitations, and performance characteristics of each technique are discussed based on recent studies. Furthermore, recent advancements such as nanofluids, artificial intelligence-based control, and hybrid thermal systems are highlighted. Finally, the research gaps and future directions for improving EV battery thermal management are presented.

Keywords-Electric vehicles, Lithium-ion battery, Thermal management system, Cooling techniques, Phase change materials, Heat pipes

1. Introduction

The rapid growth of transportation demand and the increasing concern over environmental pollution have accelerated the development of electric vehicles (EVs). Conventional internal combustion engine vehicles contribute significantly to greenhouse gas emissions and air pollution, leading to global climate change and health hazards. As a result, many countries are promoting the adoption of EVs as a sustainable transportation solution. EVs offer several advantages such as zero tailpipe emissions, higher energy efficiency, and reduced dependence on fossil fuels.

The performance and reliability of electric vehicles largely depend on the efficiency of their energy storage systems. Among various battery technologies, lithium-ion batteries have become the most widely used energy storage devices in EVs due to their high energy density, long cycle life, and lightweight characteristics. However, lithium-ion batteries are highly sensitive to temperature variations during operation. During charging and discharging processes, electrochemical reactions and internal resistance generate a significant amount of heat inside the battery cells. If the generated heat is not properly dissipated, the battery temperature may rise beyond the safe operating range.

Generally, lithium-ion batteries perform optimally within a temperature range of approximately 20–40 °C. When the battery temperature exceeds this range, several problems may occur, including capacity degradation, reduced cycle life, uneven temperature distribution within the battery pack, and potential safety risks such as thermal runaway. Thermal runaway is a critical safety issue that may lead to battery failure, fire, or explosion. Therefore, maintaining the battery temperature within an appropriate range is essential to ensure the safety, efficiency, and durability of electric vehicle battery systems.

To address these challenges, Battery Thermal Management Systems (BTMS) are employed in EVs to regulate battery temperature and maintain uniform temperature distribution across the battery pack. A well-designed BTMS can effectively remove excess heat generated during battery operation and prevent overheating. In addition, it helps to enhance battery lifespan, improve charging performance, and maintain consistent power output.

Various thermal management techniques have been proposed and implemented for EV batteries. These techniques can be broadly classified into active cooling methods and passive cooling methods. Active cooling methods include air cooling, liquid cooling, and refrigerant-based cooling systems, which use external energy sources such as fans or pumps to dissipate heat. Passive cooling techniques include phase change materials (PCM) and heat pipe systems, which rely on natural heat transfer mechanisms. In recent years, hybrid thermal management systems combining multiple cooling techniques have been developed to improve thermal performance and reliability.Although significant progress has been made in the development of battery thermal management technologies, several challenges still remain. Issues such as high system complexity, increased energy consumption, uneven temperature distribution, and high implementation cost continue to limit the effectiveness of existing BTMS solutions. Therefore, further research is required to develop advanced cooling techniques that can provide efficient thermal control while maintaining system simplicity and cost-effectiveness.

This review paper provides a comprehensive overview of battery thermal management techniques used in electric vehicles. Various cooling methods, including air cooling, liquid cooling, phase change material cooling, heat pipe systems, and hybrid cooling approaches, are discussed in detail. In addition, recent advancements such as nanofluid cooling and intelligent thermal management strategies are examined. Finally, the research gaps and future directions for improving EV battery thermal management systems are highlighted.

2. Literature Review

Battery thermal management is one of the most critical aspects influencing the performance, safety, and durability of electric vehicle battery systems. Numerous researchers have investigated different cooling techniques to maintain the optimal operating temperature of lithium-ion batteries.Several studies have focused on air-based cooling systems due to their simplicity and low cost. Zhao Chenghao and co-authors analyzed air cooling configurations for EV battery packs and reported that optimized airflow design can reduce the maximum battery temperature and improve temperature uniformity. However, the cooling capability of air systems is limited, particularly for high-power batteries used in modern electric vehicles. Therefore, air cooling is generally suitable only for small or low-power EV applications.

To overcome the limitations of air cooling, many researchers have explored liquid cooling systems. Yang Shiming and colleagues investigated liquid cooling techniques for lithium-ion batteries and demonstrated that liquid-based systems provide better heat removal and uniform temperature distribution compared with air cooling. Liquid cooling uses coolant fluids such as water-glycol mixtures to transfer heat from the battery pack. Despite their high efficiency, these systems increase system complexity and may introduce issues such as coolant leakage and higher energy consumption.

Another promising approach is the use of phase change materials (PCM) for passive thermal management. Ling Zhi Yi studied PCM-based cooling systems for EV batteries and reported that PCM can absorb a large amount of heat during the phase transition process, thereby limiting the temperature rise of battery cells. However, the main drawback of PCM is its relatively low thermal conductivity, which restricts heat dissipation under high heat generation conditions. To improve PCM performance, researchers have proposed composite PCM materials combined with high-conductivity additives such as graphite or metal foams.

In addition to PCM cooling, heat pipe-based thermal management systems have also attracted considerable attention. Wang Qi investigated the application of heat pipes in EV battery packs and found that heat pipes can efficiently transfer heat from battery cells to cooling surfaces through evaporation and condensation mechanisms. This method provides high thermal conductivity and passive operation. Nevertheless, the design and integration of heat pipes into compact battery packs remain challenging.

More recently, researchers have proposed hybrid battery thermal management systems that combine multiple cooling techniques to enhance performance. Lyu Yabin demonstrated that combining PCM with liquid cooling can significantly improve temperature control and reduce peak battery temperature. Hybrid systems provide better heat dissipation and temperature uniformity compared with single-method cooling approaches. However, hybrid systems may increase system weight, cost, and design complexity.

Apart from conventional cooling methods, emerging technologies such as nanofluid cooling and artificial intelligence-based thermal control have also been investigated. Nanofluids contain suspended nanoparticles that enhance the thermal conductivity of conventional coolants. AI-based thermal management systems utilize machine learning algorithms to predict battery temperature and optimize cooling strategies in real time. These advanced techniques show promising potential for improving the efficiency and reliability of EV battery thermal management systems.

Although numerous studies have contributed to the development of battery thermal management technologies, several challenges remain. Many existing systems still suffer from high energy consumption, uneven temperature distribution, and complex system design. Furthermore, most studies focus on individual cooling techniques rather than integrated hybrid solutions. Therefore, further research is required to develop efficient, compact, and cost-effective thermal management systems for next-generation electric vehicles.

3.Thermal Issues in EV Batteries

Thermal management is a critical aspect of electric vehicle battery systems because lithium-ion batteries generate heat during operation. In electric vehicles, batteries are subjected to continuous charging and discharging cycles, which result in internal heat generation due to electrochemical reactions and internal resistance. If this heat is not properly dissipated, the temperature of the battery pack may rise beyond the safe operating limit. Excessive temperature can lead to reduced battery efficiency, faster degradation, and potential safety hazards. Therefore, maintaining an optimal thermal environment inside the battery pack is essential to ensure reliable performance, longer battery life, and safe operation of electric vehicles.

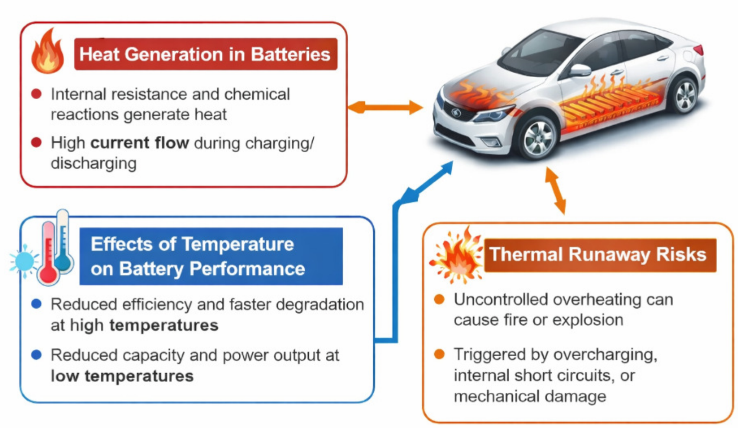

Fig.1. Thermal issues in Batteries

(i)Heat Generation in Batteries

Heat generation in lithium-ion batteries mainly occurs due to internal resistance, electrochemical reactions, and high current flow during charging and discharging processes. When current passes through the battery, resistive losses produce heat, which increases with higher current levels. Additionally, chemical reactions inside the battery cells also contribute to heat production. During rapid charging or high-power operation, the heat generation rate increases significantly, causing a rise in battery temperature. If the generated heat is not effectively removed, it can accumulate within the battery pack and affect the overall performance of the system.

(ii)Effects of Temperature on Battery Performance

Temperature plays a significant role in determining the performance and lifespan of lithium-ion batteries. At low temperatures, the internal resistance of the battery increases, which reduces its capacity and power output. On the other hand, high temperatures accelerate chemical reactions within the battery, leading to faster degradation of electrode materials and electrolyte. Prolonged exposure to elevated temperatures can reduce the cycle life of the battery and decrease its overall efficiency. Therefore, maintaining the battery temperature within the optimal operating range, typically between 20 °C and 40 °C, is necessary to achieve stable performance and long service life.

(iii)Thermal Runaway Risks

Thermal runaway is one of the most serious safety concerns associated with lithium-ion batteries. It occurs when the heat generated inside the battery exceeds the heat dissipated to the surroundings, leading to a rapid increase in temperature. This condition can trigger uncontrolled chemical reactions inside the battery, resulting in excessive heat generation, gas release, and possible fire or explosion. Thermal runaway may be initiated by factors such as overcharging, internal short circuits, mechanical damage, or poor thermal management. Therefore, effective battery thermal management systems are required to monitor battery temperature and prevent conditions that may lead to thermal runaway.

4.Battery Thermal Management Systems

The block diagram in fig 2 illustrates the working principle of a Battery Thermal Management System (BTMS) used in electric vehicles to maintain the battery temperature within a safe operating range.The electric vehicle battery system is the primary energy source that supplies electrical power to the vehicle's motor and other components. Most modern EVs use lithium-ion batteries due to their high energy density, long cycle life, and lightweight characteristics. However, during charging and discharging operations, heat is generated inside the battery pack.The battery pack consists of multiple lithium-ion cells arranged in modules to provide the required voltage and capacity. These cells generate heat due to internal resistance and electrochemical reactions. If the generated heat is not properly dissipated, it may cause temperature rise and affect battery performance.

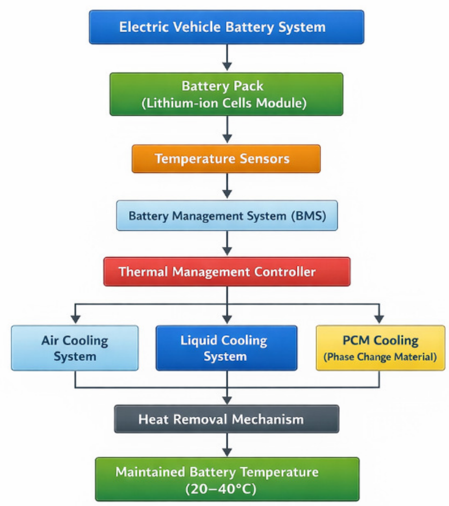

Fig.2. Block diagram for Battery Thermal Management systems

Temperature sensors are installed at different locations within the battery pack to continuously monitor the battery temperature. These sensors send real-time temperature data to the control system. Accurate temperature sensing is important to prevent overheating and maintain uniform temperature distribution.

The Battery Management System is an electronic control unit responsible for monitoring and protecting the battery pack. It collects data from temperature sensors, voltage sensors, and current sensors. Based on this information, the BMS determines whether the battery temperature is within the safe operating range.

The thermal management controller processes the temperature information received from the BMS. If the temperature exceeds the allowable limit, the controller activates appropriate cooling mechanisms to remove excess heat from the battery pack.

4.Cooling Systems

Different cooling techniques can be used to regulate battery temperature

AirCoolingSystem

Air cooling uses fans or airflow channels to remove heat from the battery pack. It is simple and inexpensive but has lower cooling efficiency.

LiquidCoolingSystem

Liquid cooling uses coolant fluids such as water-glycol mixtures to absorb heat from the battery cells. It provides better heat transfer and temperature uniformity compared to air cooling.

PCMCooling(PhaseChangeMaterial)

Phase change materials absorb heat during phase transition (solid to liquid), helping to maintain a stable battery temperature. PCM cooling is a passive cooling method that does not require external energy.

Heat Removal Mechanism

The cooling systems transfer heat away from the battery pack and dissipate it into the surrounding environment. Effective heat removal helps maintain uniform temperature distribution among battery cells.

Maintained Battery Temperature (20–40 °C)

The final objective of the thermal management system is to maintain the battery temperature within the optimal operating range of 20–40 °C. Maintaining this temperature range improves battery efficiency, extends battery lifespan, and enhances safety by preventing thermal runaway.

Table 1. Cooling Method Comparison

Cooling Method	Cooling Efficiency	Cost	System Complexity	Advantages	Limitations
Air Cooling	Low	Low	Simple	Easy design, low maintenance	Limited heat removal
Liquid Cooling	High	Medium	Moderate	Better heat transfer, uniform temperature	Leakage risk
PCM Cooling (Phase Change Material)	Medium	Medium	Simple	Passive cooling, good temperature stability	Low thermal conductivity
Heat Pipe Cooling	High	High	Complex	High heat transfer capability	Expensive design
Hybrid Cooling	Very High	High	Complex	Best temperature control	High system cost

Cooling efficiency comparison

Comparison of different battery cooling techniques used in electric vehicles based on cooling efficiency is shown in figure 3.

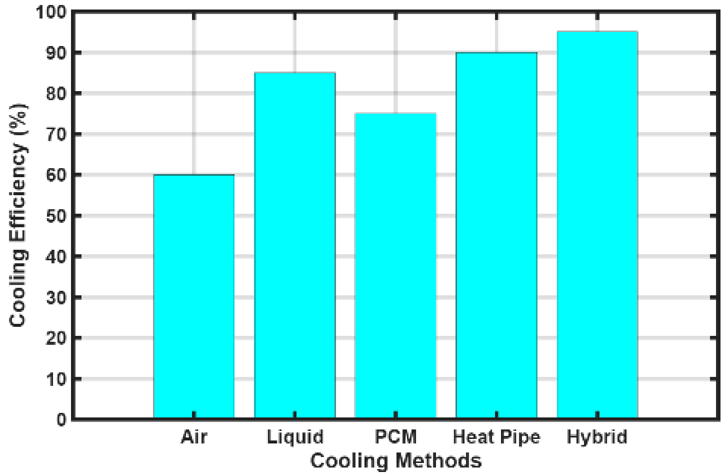

Figure 3. Comparison of different battery cooling techniques used in electric vehicles based on cooling efficiency.

The comparison chart illustrates the cooling efficiency of various battery thermal management techniques used in electric vehicles. Among the different methods, air cooling shows the lowest efficiency of approximately 60%, as it relies on airflow to remove heat from the battery pack and has limited heat transfer capability. Liquid cooling demonstrates higher efficiency, around 85%, due to the use of coolant fluids that effectively absorb and transfer heat away from the battery cells. Phase change material (PCM) cooling provides moderate efficiency of about 75%, as PCM absorbs heat during its phase transition and helps maintain a stable temperature. Heat pipe cooling achieves a higher efficiency of nearly 90% because it transfers heat rapidly through evaporation and condensation processes. Hybrid cooling systems exhibit the highest efficiency of approximately 95%, as they combine multiple cooling techniques such as liquid cooling and PCM to enhance heat dissipation and maintain uniform temperature distribution. Therefore, hybrid cooling methods are considered the most effective solution for maintaining optimal battery temperature in modern electric vehicles.

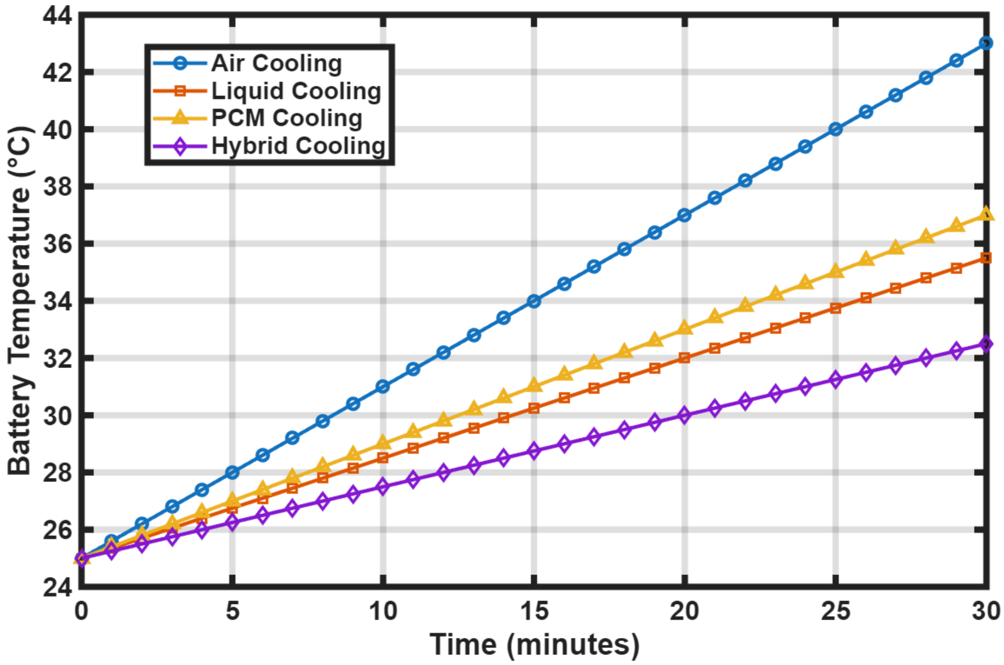

Figure 4. Variation of battery temperature with time under different cooling techniques.

The graph 4 illustrates the variation of battery temperature with time for different cooling techniques used in electric vehicle battery thermal management systems. The horizontal axis represents time in minutes, while the vertical axis represents battery temperature in degrees Celsius. Four cooling methods are compared: air cooling, liquid cooling, PCM cooling, and hybrid cooling. As time increases, the battery temperature rises for all methods due to continuous heat generation during battery operation. However, the rate of temperature increase differs among the cooling techniques. Air cooling shows the highest temperature rise, reaching approximately 43 °C after 30 minutes, indicating its limited heat dissipation capability. Liquid cooling performs better, maintaining the temperature around 35–36 °C due to improved heat transfer through coolant circulation. PCM cooling provides moderate performance by absorbing heat during the phase change process, maintaining the temperature near 37 °C. Hybrid cooling demonstrates the best thermal performance, keeping the battery temperature around 32–33 °C after 30 minutes. This indicates that combining multiple cooling methods significantly improves heat dissipation and maintains a more stable battery temperature, making hybrid cooling a promising solution for advanced electric vehicle battery thermal management systems.

Conclusion

Battery Thermal Management Systems (BTMS) play a crucial role in ensuring the safe and efficient operation of electric vehicle batteries. Lithium-ion batteries generate a significant amount of heat during charging and discharging processes, which can negatively affect battery performance, lifespan, and safety if not properly controlled. This review discussed various thermal management techniques such as air cooling, liquid cooling, phase change material (PCM) cooling, heat pipe cooling, and hybrid cooling methods. Among these techniques, liquid cooling and hybrid cooling systems demonstrate superior thermal performance due to their higher heat dissipation capability and better temperature uniformity within the battery pack. PCM and heat pipe systems also provide promising solutions for passive thermal regulation. Proper thermal management helps maintain the battery temperature within the optimal operating range, thereby improving efficiency, extending battery life, and reducing the risk of thermal runaway. Therefore, the development of advanced thermal management systems is essential for the reliable and sustainable growth of electric vehicle technology.

Future Scope

Future research on battery thermal management systems should focus on the development of more efficient, compact, and cost-effective cooling technologies for electric vehicle batteries. Advanced materials such as high thermal conductivity phase change materials and nanofluids can be explored to enhance heat transfer performance. Hybrid cooling systems that combine multiple cooling techniques may provide improved temperature control and better thermal uniformity across battery cells. In addition, the integration of intelligent control strategies using artificial intelligence and machine learning can enable real-time temperature monitoring and adaptive cooling management. Further research is also required in thermal modeling and simulation to accurately predict battery temperature behavior under different operating conditions. These advancements will contribute to improving battery safety, increasing energy efficiency, and supporting the widespread adoption of electric vehicles in the future.

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