Comprehensive Analysis of Low-Temperature Heating and Thermal Runaway Management in Lithium-Ion Batteries for New Energy Electric Vehicles

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Abstract: This paper conducts an in-depth study on the challenges of low-temperature heating and thermal runaway management in lithium-ion batteries for new energy electric vehicles (NEEVs). First, the current research status of low-temperature heating for lithium-ion batteries is reviewed, analyzing the principles and practical effectiveness of existing heating methods, followed by a comprehensive synthesis of research findings. Subsequently, the control strategies for lithium-ion battery thermal runaway are systematically examined, including the mechanisms and hazards of thermal runaway, as well as the principles and practical performance of various mitigation approaches. Building on this foundation, the interplay between low-temperature heating and thermal runaway management is explored, and optimized measures for integrated management are proposed. Finally, the research outcomes are summarized, providing theoretical foundations and practical guidance for ensuring the safe operation of lithium-ion batteries in NEEVs under low-temperature conditions.

Keywords: New Energy Electric Vehicles (NEEVs); Lithium-Ion Batteries; Low-Temperature Heating; Thermal Runaway; Integrated Management

1. Introduction

Under the global backdrop of energy transition and sustainable development, new energy electric vehicles (NEEVs), as a pivotal representative of green mobility, are reshaping transportation patterns and lifestyles. Among their components, lithium-ion batteries (LIBs), serving as the core of NEEVs, directly determine vehicle performance and user experience through their efficiency and safety.

The development of NEEVs has not been achieved overnight but has evolved through prolonged technological accumulation and innovative breakthroughs. With increasing emphasis on environmental protection and the urgent demand for sustainable energy utilization, NEEVs have transitioned from conceptual frameworks to practical realities, achieving remarkable success in the market [1]. However, LIBs face significant challenges in practical applications. Notably, performance degradation under low-temperature conditions and thermal runaway risks have emerged as critical barriers to the widespread adoption and performance enhancement of NEEVs. Low temperatures lead to increased internal resistance and reduced discharge capacity in LIBs, severely impairing driving range and power output. Meanwhile, thermal runaway may trigger catastrophic safety incidents, such as fires or explosions, posing substantial threats to life and property [2].

Therefore, conducting an in-depth study on low-temperature heating and thermal runaway management for LIBs in NEEVs is of paramount importance. By comprehensively analyzing these two critical challenges, we can better understand the operating mechanisms and performance characteristics of LIBs, thereby providing theoretical support and practical guidance for developing safer and more efficient battery technologies.

2. Analysis of Low-Temperature Heating for Lithium-Ion Batteries in New Energy Electric Vehicles

2.1 Current Research Status of Low-Temperature Heating for Lithium-Ion Batteries

The rapid advancement of new energy electric vehicles (NEEVs) has placed significant emphasis on lithium-ion batteries (LIBs), whose performance largely determines the overall capabilities of these vehicles. However, LIB performance is notably compromised in low-temperature environments, making research on low-temperature heating technologies critically important.

Current research on low-temperature heating for LIBs has achieved notable progress. At the material level, researchers are dedicated to developing electrode materials and electrolytes with enhanced low-temperature performance to improve ionic conductivity and electrochemical reactivity. Novel nanomaterials, such as carbon nanotubes and nano-metal oxides, have been incorporated into electrodes, significantly enhancing low-temperature conductivity [3]. In terms of heating methods, two primary approaches dominate: external heating and internal heating. External heating methods, including resistive wire heating and hot air circulation, are straightforward but suffer from uneven heat distribution and low efficiency. Internal heating methods, such as alternating current (AC) heating and pulsed current heating, achieve more uniform heating but require sophisticated battery management systems (BMS).

Concurrently, theoretical research on low-temperature heating for LIBs continues to deepen. By establishing mathematical models and conducting simulation analyses, researchers can more accurately predict temperature distribution and performance variations during heating processes, thereby providing theoretical support for optimizing heating strategies.

2.2 Principles and Practical Effectiveness of Low-Temperature Heating Methods

The development of NEEVs demands higher battery performance, with low-temperature heating being a critical technical challenge. Multiple methods have been proposed and applied in this field, each with distinct principles and practical effectiveness.

External Heating:

This method transfers heat to the battery via external devices, such as resistive wires or ceramic heaters. While simple in principle, it faces challenges such as uneven heating and high energy consumption. In practical applications, precise control of heating power and duration is essential to avoid battery damage and mitigate adverse impacts on vehicle range.

Internal Heating:

However, due to the non-uniform distribution of current, the internal heating efficiency of large-scale batteries tends to decrease. Utilizing the battery's internal resistance or electrochemical reactions to generate heat, this method leverages inherent battery properties for efficient and uniform heating. However, it imposes stringent requirements on battery materials and structures, and achieving precise control remains technically challenging. With optimized control, internal heating can significantly reduce heating time and enhance low-temperature performance.

Thermal Fluid Heating:

This approach circulates high heat-capacity fluids (e.g., hot oil or water) through or around the battery. While it ensures uniform heating, the system complexity, additional components (e.g., pumps and pipelines), and associated costs limit its practicality [4].

Microwave Heating:

Emerging as a promising technique, microwave heating exploits the penetration and selective heating properties of microwaves to directly warm the battery. Although rapid, this method risks localized overheating and requires rigorous optimization to ensure uniform radiation distribution and safety. If these challenges are addressed, microwave heating could become a highly efficient solution for low-temperature applications.

3. Analysis of Thermal Runaway Management in Lithium-Ion Batteries for New Energy Electric Vehicles

3.1 Current Research Status of Thermal Runaway Control

Significant progress has been made in controlling thermal runaway of lithium-ion batteries (LIBs). At the material level, researchers are developing more stable and heat-resistant electrode materials and electrolytes to reduce the risk of thermal runaway. Novel cathode materials and electrolyte formulations continuously emerge, which enhance both battery performance and thermal stability [5]. In terms of structural design, optimizing battery encapsulation and thermal dissipation structures has become a research focus. Rational encapsulation minimizes external impacts on batteries, while effective heat dissipation structures promptly remove internally generated heat, thereby reducing the likelihood of thermal runaway. Advanced sensors and monitoring systems have also been developed for real-time tracking of battery parameters (e.g., temperature, voltage, current), enabling immediate intervention upon detecting anomalies.

The continuous advancement of battery management systems (BMS) plays a critical role in thermal runaway mitigation. By precisely evaluating and controlling battery states, BMS ensures balanced charging and discharging, preventing overcharging or overdischarging, which reduces the probability of thermal runaway. However, despite progress, challenges remain. For instance, the stability and reliability of new technologies and materials in practical applications require further validation, and the synergistic effects among different control methods demand deeper investigation [6].

3.2 Principles and Practical Effectiveness of Thermal Runaway Control Methods

As new energy electric vehicles (NEEVs) evolve rapidly, controlling thermal runaway in LIBs, their core component, is paramount. This section examines the principles and practical performance of various control strategies.

Cooling Technology:

Liquid cooling or air cooling systems rapidly dissipate heat from batteries to slow temperature rise. Liquid cooling offers higher heat exchange efficiency but involves complex systems and higher costs. Air cooling is simpler but may exhibit limited efficacy under extreme conditions [7].

Thermal Insulation:

High-performance insulation materials are used to wrap batteries, reducing heat transfer to the surroundings and delaying thermal runaway propagation. However, material selection must balance insulation performance, weight, cost, and impacts on battery performance.

Chemical Suppression:

Specific chemical additives are introduced to inhibit exothermic reactions during the early stages of thermal runaway. While effective in altering the internal chemical environment, their performance depends on dosage, reaction conditions, and other factors.

Battery Management System (BMS):

BMS monitors real-time parameters (temperature, voltage, current) and triggers protective actions (e.g., circuit disconnection, cooling activation) upon detecting abnormalities. The accuracy and response speed of BMS are decisive for practical effectiveness.

In practical applications, hybrid approaches are often employed to achieve optimal thermal runaway control. For example, high-performance electric vehicles may combine liquid cooling, insulation materials, and advanced BMS, while cost-sensitive models may prioritize air cooling and simplified chemical suppression [8]. Additionally, the effectiveness of control methods is influenced by usage environments (e.g., high temperatures, heavy loads) and driving habits, necessitating higher demands on control strategies under extreme conditions.

4. Integrated Considerations for Low-Temperature Heating and Thermal Runaway Management

In the development of new energy electric vehicles (NEEVs), integrated management of low-temperature heating and thermal runaway in lithium-ion batteries (LIBs) is critical. The research and implementation of optimization measures hold profound significance.

Battery Design:

Advanced materials and structures should be adopted to enhance low-temperature resistance and thermal stability. For example, selecting electrode materials with superior low-temperature conductivity and optimizing encapsulation structures can minimize heat loss and thermal runaway risks.

Intelligent Thermal Management Systems:

Real-time monitoring of battery parameters (e.g., temperature, voltage) via sensors, combined with advanced algorithms, enables precise control of heating and cooling processes. In low-temperature environments, heating functions are activated promptly to restore optimal operating temperatures, while rapid cooling mechanisms are triggered under high-temperature or thermal runaway-prone conditions to ensure safety [9]. Due to sensor latency, the Battery Management System may fail to address instantaneous thermal runaway effectively.

Charging-Discharging Strategy Optimization:

Controlling charging currents and voltages to avoid overcharging and rapid discharging reduces internal heat accumulation. Dynamic adjustment of charging-discharging strategies based on environmental and operational conditions further mitigates risks.

Safety Protections:

Measures such as installing safety valves and explosion-proof devices allow timely pressure release upon early signs of thermal runaway, preventing catastrophic escalation.

System Integration:

Integrating low-temperature heating and thermal runaway management with vehicle control systems ensures synergistic operation. Effective data exchange with powertrain and energy recovery systems enables intelligent adjustment of battery operation modes based on vehicle status and environmental conditions [10].

Monitoring and Early Warning Mechanisms:

Establishing comprehensive systems for real-time monitoring of battery health and performance indicators, coupled with data analysis and predictive modeling, facilitates early detection of potential issues. Timely warnings to users enable proactive countermeasures.

5. Conclusion

In the development of new energy electric vehicles (NEEVs), research on low-temperature heating and thermal runaway management for lithium-ion batteries (LIBs) is of paramount importance. Through the in-depth exploration in preceding chapters, a comprehensive and systematic understanding of these two critical areas has been established.

Low-Temperature Heating:

Current research progress, principles, and practical effectiveness of various heating methods have been thoroughly analyzed, providing robust theoretical and practical support for enhancing LIB performance under low-temperature conditions.

Thermal Runaway Management:

The mechanisms, hazards, and control strategies of thermal runaway have been clarified. Mastery of diverse mitigation methods and their practical outcomes lays a foundation for ensuring the safe operation of LIBs.

Future Directions:

To achieve superior integrated management, the following actions are imperative:

Technological Innovation: Increase investment in R&D to explore more efficient, safe, and reliable low-temperature heating and thermal runaway control technologies. System Design Optimization: Balance vehicle performance and user demands in system design, ensuring coordinated integration of battery management with overall vehicle functionality. Enhanced Monitoring and Early Warning: Strengthen real-time monitoring of LIB operating states, enabling timely detection and resolution of potential issues through predictive analytics.

Research on low-temperature heating and thermal runaway management for LIBs in NEEVs is an ongoing process. Continuous summarization of experience and innovative advancements are essential to adapt to evolving market demands and technological trends, thereby injecting strong momentum into the sustainable growth of the new energy automotive industry.

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