

A Review of Fast Charging Technology for Power Batteries in New Energy Vehicles

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ABSTRACT

In the context of the increasingly urgent global transition in energy structure and environmental protection demands, the new energy vehicle (NEV) industry has rapidly emerged with its clean and efficient characteristics. Fast charging technology has become a crucial link in the NEV industry chain, playing a vital role in enhancing the overall performance of vehicles. This paper delves into the current development status and challenges faced by fast charging technology for power batteries in NEVs, with a particular focus on the pivotal role of thermal management technology during the rapid charging process. It provides a detailed analysis of the working principles, performance characteristics, and application environments of mainstream thermal management technologies, including air cooling, liquid cooling, phase change cooling, and heat pipe technology. Additionally, this paper examines the innovative applications of emerging technologies such as composite thermal management systems, microchannel heat pipes, and advanced materials. It points out that thermal management technology for fast charging batteries needs to overcome challenges in economy and reliability, moving towards integration and intelligence. By summarizing existing research achievements and shortcomings, this paper aims to provide theoretical support and practical guidance for the sustainable development of fast charging technology in NEVs, thereby promoting the prosperity and development of the NEV industry.

KEYWORDS

New Energy Vehicles; Power Batteries; Fast Charging Technology; Thermal Management.

1. INTRODUCTION

In the context of the global energy structure transformation and intensifying environmental protection demands, the new energy vehicle (NEV) industry has swiftly emerged as a pivotal force in addressing energy and environmental challenges, leveraging its advantages of zero emissions, low noise, and high energy efficiency. Notably, significant growth in NEV sales has been observed in markets such as China, Europe, and the United States, showcasing immense potential (see Figure 1). Fast charging technology, as the core of the NEV industry chain, has greatly shortened charging times and enhanced vehicle practicality. However, the accompanying heat issues pose severe challenges to battery life and safety, highlighting the importance of thermal management technology. Despite numerous advancements in fast charging technology, research on the role of thermal management during fast charging and optimization strategies remains inadequate. This study aims to deeply analyze the significance of thermal management in fast charging technology, comprehensively evaluate the pros and cons of existing technologies, and propose optimization suggestions to provide a reference for the sustained development of fast charging technology in NEVs.

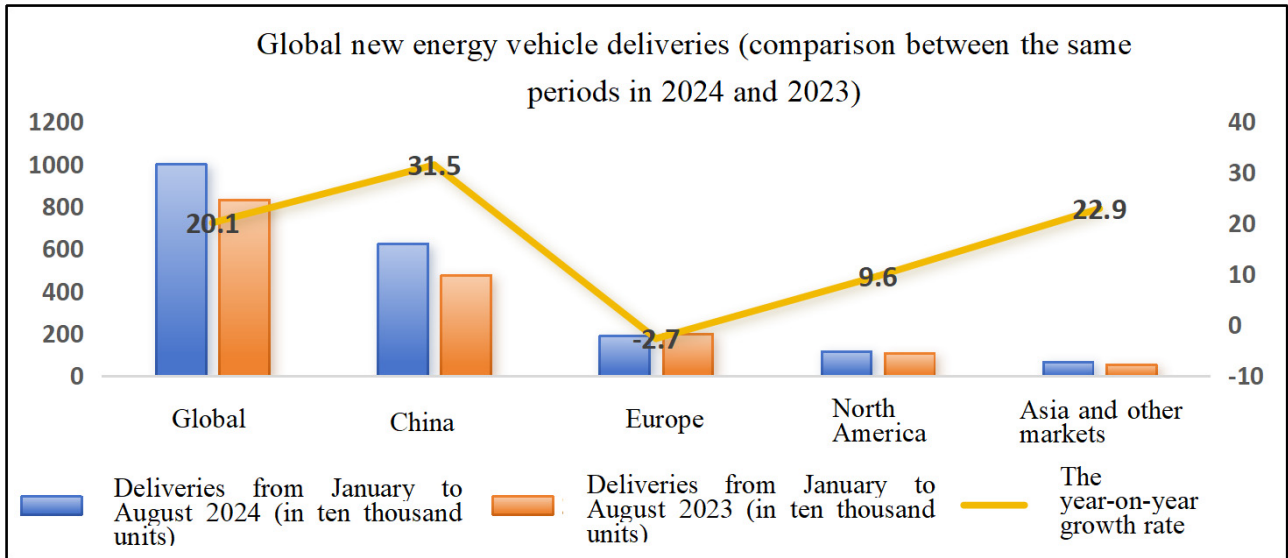


Figure 1. Global new energy vehicle deliveries (comparison between the same periods in 2024 and 2023)

2. THE CURRENT DEVELOPMENT OF FAST CHARGING TECHNOLOGY FOR NEW ENERGY VEHICLES

2.1. Evolution of Fast Charging Technology

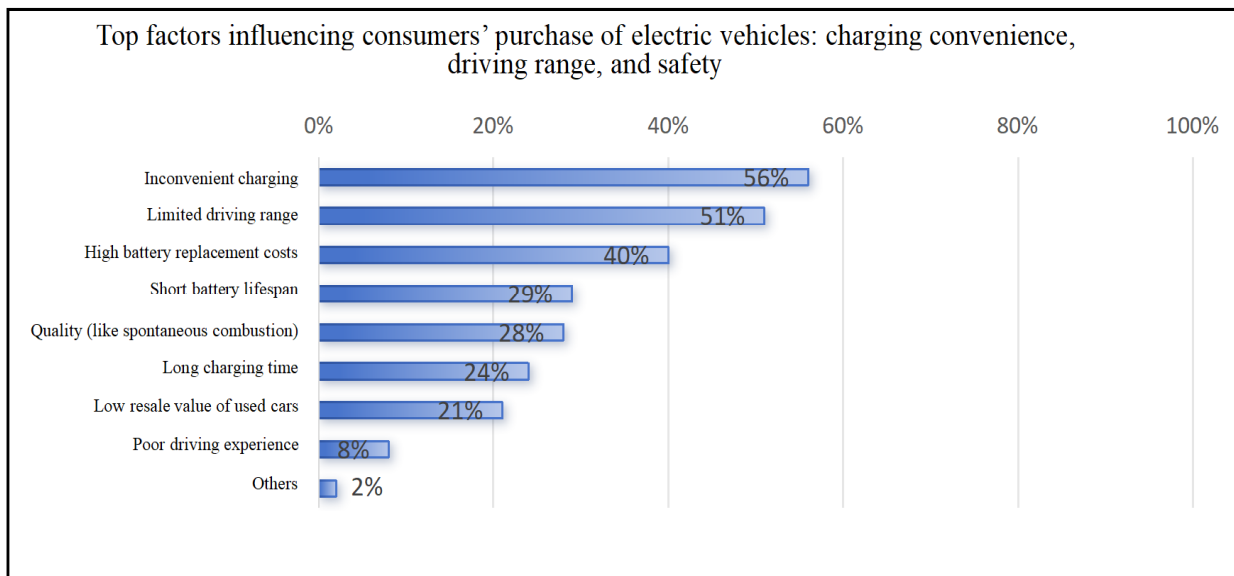


Figure 2. Factors influencing consumers' purchase decisions on electric vehicles

Fast charging technology for power batteries in NEVs has undergone a significant transformation from low to high charge rates. In the early stages, lead-acid batteries had low charge rates of only 0.1C, and high charge rates adversely affected their lifespan. Lithium-ion batteries, marked by high energy density, high discharge voltage, and long cycle life, have been widely adopted in NEVs [1]. With advancements in lithium-ion battery technology and Battery Management Systems (BMS), charge rates have increased significantly. However, AC slow charging solutions still face the issue of long charging time. Technological progress has driven the development of fast charging technology,

particularly with the emergence of supercharging standards that measure charge and discharge rates using the C-rate. A 4C charge rate means that a battery can be charged to 80% capacity within 15 minutes, marking a leap from low charge rates to 3C or even higher, significantly enhancing the practical value and market competitiveness of NEVs (see Figure 2). Fast charging technology also faces challenges such as the need for battery materials and structures to withstand high currents, and the efficient management of heat generation and accumulation requiring advanced thermal management systems. These challenges pose higher requirements for the control strategies and hardware facilities of BMS.

2.2. Challenges Faced by Fast Charging Technology

The fast charging technology for NEV power batteries offers significant convenience to users, but its technical challenges cannot be ignored. Achieving fast charging requires battery materials and structures to withstand high current impacts, posing higher demands on battery design and material selection [2]. Taking Tesla's V3 Supercharger stations as an example, when providing a charging power of up to 250 kW, the battery temperature can rise sharply from room temperature to above 50°C within minutes, highlighting the severity of battery heat generation and accumulation during fast charging. Research shows that for lithium-ion batteries operating between 30°C and 40°C, every 1°C increase in temperature reduces their lifespan by approximately two months, and extreme temperatures can even trigger thermal runaway events, leading to battery damage or explosions [3]. The introduction of an efficient Battery Thermal Management System (BTMS) has become necessary, as it needs to address complex thermal-fluid dynamic issues and achieve precise control over battery temperature. Fast charging also places higher demands on the control strategies and hardware facilities of the BMS, including more accurate voltage and temperature monitoring and faster anomaly response speeds, to ensure that the battery operates safely and efficiently within an appropriate temperature range.

3. FAST CHARGING THERMAL MANAGEMENT TECHNOLOGY FOR POWER BATTERIES

3.1. The Cruciality and Design Functions of Thermal Management Technology

During the fast charging process of NEV power batteries, the sharp increase in current density leads to significant internal heat generation, involving both accelerated electrochemical reactions and resistive heating effects, which rapidly elevate the battery temperature above 50°C [4]. This temperature change not only intensifies the internal thermal stress of the battery, potentially triggering chain reactions such as electrolyte decomposition and active material detachment, thereby affecting battery performance and lifespan, but may also lead to thermal runaway events. Especially when the temperature exceeds 70°C, the internal chemical reactions within the battery may become uncontrollable, generating a large amount of heat and gas, and potentially causing the battery to ignite or explode [5]. Thermal management technology is therefore of paramount importance. The Battery Thermal Management System (BTMS), as the core of rapid charging technology, monitors battery temperature in real-time and employs measures such as liquid cooling, air cooling, or phase change cooling to keep the battery temperature within a safe range, preventing overheating and thermal runaway events, and significantly enhancing battery safety and reliability. A well-designed BTMS can effectively reduce the maximum battery temperature, improve temperature uniformity, and extend battery lifespan. Current BTMS research covers a variety of cooling systems, each with its own working principle, consisting of sensors, controllers, actuators, and cooling media to achieve precise control over battery temperature [6]. For example, Tesla's Model S Plaid and BYD Han EV utilize liquid cooling technology and intelligent temperature control algorithms respectively to ensure the safe and efficient operation of the battery pack during fast charging. The BTMS also features fault

warning and self-protection functions, providing solid technical support for the safe use of NEV power batteries.

3.2. Comparison and Analysis of Mainstream Thermal Management Technologies

The fast charging technology for NEV power batteries relies on efficient thermal management systems. Currently, the mainstream thermal management technologies include air cooling, liquid cooling, phase change cooling, and heat pipe technology. Table 1 provides an intuitive overview of the performance characteristics and application scenarios of these technologies.

Table 1. Performance comparison of mainstream battery thermal management technologies

Type	Heat Exchange Efficiency	Cost	System Complexity	Temperature Control Accuracy	Application Scenarios
Air cooling	Low	Low	Low	Low	Low-power battery packs
Liquid cooling	High	Medium	High	High	High-power intensive applications
Phase change cooling	Medium	Medium	Medium	Medium	High-heat load short-term applications
Heat pipe cooling	High	High	Medium	High	High-end battery application

Air cooling systems, as a traditional technology for thermal management of NEV power batteries, utilize air as the medium to achieve heat exchange through natural convection or forced air circulation driven by fans [7] (see Figure 3). This system boasts a simple structure and low cost, but its heat transfer coefficient is relatively low, making it difficult to meet the cooling demands under high discharge rates. Manufacturers such as Tesla widely adopted air cooling systems in their early models. However, as battery performance requirements have increased, research has shifted towards forced cooling technologies, enhancing cooling efficiency by adding fans to increase air velocity. Despite its limitations, the air-cooling system remains widely used in low-power battery packs due to its absence of leakage risks and high technological maturity [8].

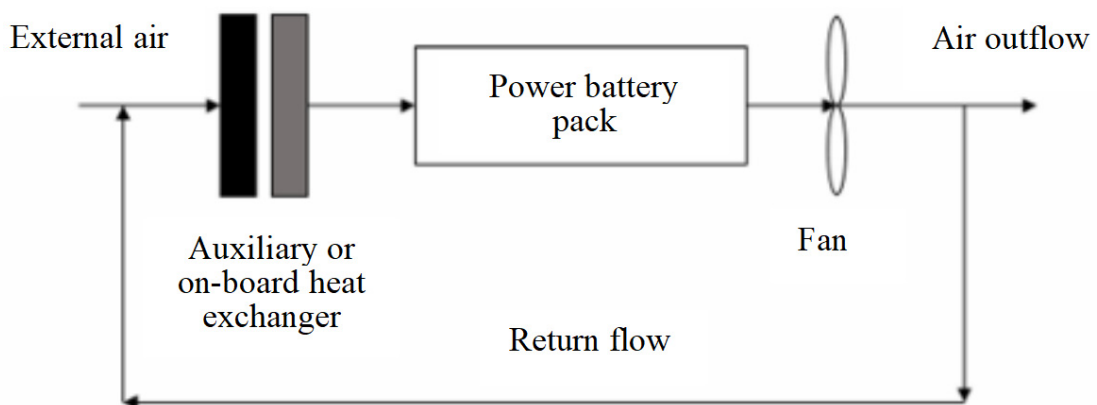


Figure 3. Schematic diagram of air cooling system

Compared to air cooling, liquid cooling technology has become the preferred solution for thermal management in high-performance new energy vehicles due to its high heat exchange efficiency and excellent temperature control capabilities. This technology utilizes the circulation of coolant to effectively absorb and dissipate heat generated by the battery by flowing through cooling pipes near the battery modules. The liquid cooling technology adopted by the Tesla Model S Plaid is an example,

where its coolant circulation system can quickly respond to changes in battery temperature and ensure the safe and stable operation of the battery pack while maintaining optimal coolant parameters. However, liquid cooling systems also face issues of complexity and relatively high costs, including the integration of equipment such as pumps, pipes, and heat exchangers, as well as the potential risk of liquid leakage. These factors need to be fully considered in design and application.

Phase change cooling and heat pipe technology, as two key technologies in high-end battery thermal management, exhibit unique advantages respectively. Phase change cooling technology utilizes the phase change characteristics of phase change materials (PCMs) during endothermic or exothermic processes to achieve precise regulation of battery temperature, balancing the temperature through internal phase changes of the material without external energy [9]. Heat pipe technology, on the other hand, relies on the evaporation and condensation cycle, efficiently transferring heat from the heat source to the cooling area with a thermal conductivity much higher than traditional metals, achieving rapid cooling. Both technologies are particularly suitable for applications with limited space and extremely high temperature control requirements, such as high-end battery applications. Although the costs of phase change cooling and heat pipe technologies are relatively high and the system complexity increases maintenance difficulties, their significant advantages in temperature control accuracy and efficiency, as well as their potential to improve battery safety and performance, make them important research directions in the field of battery thermal management.

Different thermal management technologies have their own advantages and disadvantages, and the selection should take into account specific application scenarios, performance requirements, cost, reliability, and other factors. In the future, with the rapid development of new energy vehicle technology, thermal management systems will tend to be more integrated, intelligent, and efficient to meet the growing market demand and continuously improving performance requirements [10].

4. PRACTICE AND APPLICATION OF EMERGING THERMAL MANAGEMENT TECHNOLOGIES

4.1. Design and Effectiveness of Composite Thermal Management System

The composite thermal management system combines the advantages of heat pipe technology and phase change material (PCM), aiming to improve thermal management efficiency and responsiveness. Heat pipe technology provides a fast heat transfer path to efficiently conduct heat from the heat source to the cooled areas; while PCM balances temperature fluctuations by storing excess heat in these areas and releasing it when demand is low. The system is particularly well suited for electric vehicles and energy storage systems, where it can significantly reduce thermal spikes in batteries during high loads and rapid charging. Studies have shown that battery modules with composite thermal management systems can reduce the maximum temperature rise during fast charging by more than 20% compared to conventional systems [11], while maintaining the battery temperature in a more stable range, effectively extending battery life and improving overall performance.

4.2. Application of Microchannel Heat Pipe in Battery Thermal Management

Microchannel heat pipe, as a technological innovation in the field of thermal management, constructs tiny flow channels by introducing microfabrication technology into the traditional heat pipe, thus realizing efficient heat exchange in a limited space. The significant advantage of this technology is that it can be effectively applied in electronic devices with high-density thermal management requirements, and gradually expanded to the thermal management system of electric vehicle batteries [12]. The microchannel heat pipe shows unique value in battery thermal management due to its excellent heat transfer performance and optimized volume-to-mass ratio. Specifically, it can significantly reduce the temperature of the battery pack and effectively improve the charging

efficiency and safety. Experimental data clearly show that the battery pack with microchannel heat pipe can maintain the temperature in the safe range by 30% under the continuous high rate discharge condition, which is more prominent in its thermal management efficiency compared with the traditional heat pipe technology [13]. This technological breakthrough not only brings new solutions to the field of battery thermal management, but also further promotes the technological innovation and performance improvement in this field. Through the application of microchannel heat pipe, the thermal management problem of EV batteries has been solved more effectively, providing strong support for the safe and efficient operation of new energy vehicles.

4.3. Application of Advanced Materials in Battery Thermal Management

Advanced materials, especially graphene and metal foams, are gradually taking their place in the field of battery thermal management due to their unique thermal conductivity and structural properties. Graphene, with its atomic-level thickness and excellent high thermal conductivity, is considered an ideal material for the preparation of thermal interface materials (TIMs). Such TIMs can significantly reduce the thermal resistance between battery components, thus effectively improving the heat transfer efficiency and ensuring the temperature control of the battery during charging and discharging [14]. At the same time, metal foams, with their large specific surface area and high porosity, show great potential as heat exchange enhancement materials in heat pipe or liquid cooling systems. By optimizing the system structure and integrating the metal foam, the cooling performance of the thermal management system can be significantly enhanced to improve the thermal stability and safety of the battery [15]. The introduction of these advanced materials not only enriches the technical means of battery thermal management, but also promotes the technological progress and innovation in this field. By combining advanced structural design and high-performance materials, the new thermal management technology significantly optimizes the thermal management effectiveness of the battery, providing a solid technical support for the safe and efficient operation of power batteries in new energy vehicles.

5. CHALLENGES AND DEVELOPMENT TRENDS OF FAST-CHARGING BATTERY THERMAL MANAGEMENT TECHNOLOGY

5.1. Economy and Reliability Challenges

Fast charging battery thermal management technology faces the challenges of economy and reliability. Efficient Battery Thermal Management System (BTMS) is crucial for fast charging technology, but it often adopts expensive materials and complex structures, such as pumps, pipelines and heat exchangers for liquid cooling systems, which significantly increase the cost [16]. Under the lightweight requirement of EVs, the BTMS needs to be optimized within a limited mass and volume, which further increases the manufacturing cost and design difficulty. The reliability of the BTMS is also a focus of attention, which needs to maintain stable operation during fast charging to ensure high efficiency performance over the entire life cycle of the battery [17]. However, factors such as ambient temperature changes, system aging, and material degradation all affect system reliability, especially heat pipe performance decay and phase change material cycling stability degradation, which can weaken the heat absorption and release performance. Complex systems are costly to maintain and can lead to high repair costs and specialized support requirements in the event of failure [18]. Improving the economy and reliability of fast-charging battery thermal management technology is a key issue that needs to be addressed nowadays.

5.2. Design and Effectiveness of Composite Thermal Management System

With the rapid development trend of electric vehicles (EVs) and large-scale energy storage systems, fast-charging battery thermal management technology is facing a major challenge of integration and

intelligence. The thermal management system is no longer limited to a single high-efficiency thermal control function, but must be deeply integrated with the battery management system (BMS), vehicle control system and energy recovery system at the system level to fully optimize the energy efficiency and comprehensive performance of the whole vehicle [19]. This integration trend requires the thermal management system to be able to analyze data in real time, accurately predict the thermal state of the battery, and dynamically adjust the cooling strategy accordingly, so as to achieve the purpose of improving system efficiency and safety. The realization of this process is highly dependent on advanced algorithms and powerful data processing capabilities, which significantly increases the complexity of system design and implementation difficulties.

Intelligent regulation, as the core element of a composite thermal management system, requires the use of advanced sensors and controllers to ensure accurate temperature control and efficient energy management. The system also needs to have fast response, high stability and safety performance to adapt to a variety of complex working conditions, to ensure the stable operation of the system and effectively prevent safety accidents. The design and realization of the composite thermal management system is not only an innovation of the current thermal management technology, but also an important support for the intelligent development trend of future new energy vehicles. Through continuous optimization and innovation, the composite thermal management system will further enhance the thermal management efficiency of the battery and lay a solid foundation for the sustainable development trend of new energy vehicles [20].

6. CONCLUSION

Power battery fast charging technology and its thermal management system, as a core component of the new energy vehicle industry, play a crucial role in promoting the rapid development trend of the industry. In the fast-charging process, realizing effective thermal control is a key link to ensure battery performance and safety. Currently, a variety of thermal management technologies, such as air cooling, liquid cooling, phase change cooling and heat pipe technology, each showing unique technical characteristics and application effectiveness. With the continuous progress of science and technology and the continuous expansion of the market, the thermal management system of the battery is being optimized, aiming at better adapting to the needs of new energy vehicles and improving their overall performance and safety.

In the future, the development trend of thermal management systems will be integrated, intelligent and efficient. By deeply integrating the battery management system, vehicle control system and energy recovery system, the thermal management system will realize more efficient energy utilization and more accurate temperature control. With the help of advanced sensors and controllers, the system will be able to dynamically adjust the cooling strategy to adapt to the complex and changing working conditions. The application of new materials such as graphene and metal foam will bring higher heat transfer efficiency and more precise temperature control to the thermal management system. These continuous technological innovations and experimental validations will provide strong support for the sustainable development trend of the new energy vehicle industry and promote it to play a more important role in the global energy structure transformation and environmental protection.

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