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# *Thermal Management Optimization of New Energy Vehicles under Extreme Temperatures*

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***Abstract.*** Aiming at the problem that -30 ℃ to 50 ℃ extreme temperatures restrict the engineering application of power batteries for new energy vehicles, this paper analyzes the electrochemical and thermal performance degradation mechanism of power batteries in harsh extreme environments, and summarizes latest research progress of battery material optimization, integrated thermal management architecture and AI-driven intelligent control strategies. It points out four critical industrial bottlenecks including insufficient system coordination, lack of unified standard test data, imperfect reliability verification system and foreign core patent barriers. The results show that extreme temperatures significantly deteriorate battery performance and safety, and thermal management systems need to effectively balance temperature, energy and power output efficiently. Finally, three key development trends including multi-energy coordination, digital twin simulation verification and low-cost practical engineering are prospected systematically. This study can provide solid theoretical support and practical technical reference for the research and engineering application of power battery thermal management in wide extreme temperature regions worldwide.

***Keywords:*** New energy vehicles, Power battery, Thermal management, Extreme temperatures, Optimization

## 1. Introduction

New energy vehicles are accelerating toward full-climate and full-scenario large-scale applications. With the continuous expansion of application scenarios and the improvement of user demands, vehicles are required to maintain stable and efficient operation in various complex climate conditions, including severe cold, high temperature, large temperature difference and other harsh environments. Among all technical constraints, the poor adaptability in -30 ℃ to 50 ℃ extreme environments has become a core bottleneck that restricts further industrialization and market popularization.

At present, the global new energy vehicle industry maintains fierce competition, and foreign leading enterprises have long taken extreme-temperature battery thermal management as a key research and development direction. They have invested a lot of resources in material research, system design and algorithm optimization, and have formed relatively mature technical systems and patent layouts. China ranks first in the world in terms of production and sales volume of new energy

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vehicles, and has formed a complete industrial chain covering battery manufacturing, vehicle assembly and supporting parts. However, most vehicles are still equipped with traditional thermal management systems that are designed for conventional temperature environments. Compared with international top enterprises, China still has a certain gap in battery temperature control accuracy, operational stability and long-term durability under extreme working conditions.

As the core energy storage component of new energy vehicles, power batteries suffer obvious performance degradation under extreme temperature conditions. The working efficiency and service life of power batteries are closely related to the external ambient temperature, and extreme temperature will directly destroy the internal electrochemical balance of the battery. Low-temperature environments raise electrolyte viscosity and reduce ion transmission efficiency, leading to capacity attenuation, increased internal resistance and unstable power output. High-temperature environments accelerate internal side reactions, aggravate battery aging and improve the possibility of thermal runaway, which brings serious hidden dangers to vehicle safety. Therefore, stabilizing battery temperature, maintaining energy retention and ensuring constant power output have become key research objectives in the field of new energy vehicle power battery technology.

Traditional passive thermal management solutions can hardly meet the requirements of extreme working conditions, because they rely on natural heat dissipation or simple heating, with slow response speed and poor control accuracy. AI-based intelligent thermal management technology provides a feasible way to solve the application problems under harsh environments. By introducing intelligent algorithms and real-time condition perception, the thermal management system can adjust the working mode dynamically and adapt to the changes of external temperature. This paper focuses on the control optimization of power battery temperature, energy retention and power stability in -30℃ to 50℃ environments. It reviews the technologies of battery material improvement, integrated thermal management design and AI-driven regulation. Contents unrelated to battery thermal management and purely theoretical researches are excluded. The paper is arranged in the order of research status, core challenges and development trends, so as to provide support for related research and engineering practice.This analysis can also provide a reference for the improvement of relevant national standards and the coordinated development of the industrial chain, so as to further enhance the international competitiveness of China's new energy vehicle industry in extreme temperature adaptation technologies.

## 2. Basic characteristics of power battery thermal management in extreme temperature environments

The temperature range from -30℃ to 50℃ has become a key index that limits the full-scenario application of new energy vehicles [1]. In actual road operation, vehicles often encounter sudden temperature changes and long-term extreme temperature exposure, which puts forward higher requirements for the adaptability of thermal management systems. From the perspective of electrochemical mechanism, low temperature increases the viscosity of electrolyte and reduces the transport efficiency of lithium ions. The migration speed of lithium ions between positive and negative electrodes is greatly reduced, which directly affects the charge and discharge efficiency of the battery.

Under low-temperature conditions, batteries usually suffer more than 30% capacity loss and 2–3 times internal resistance growth, resulting in unstable power output and obvious decline in vehicle dynamic performance. High temperature accelerates the decomposition of SEI film and the growth of lithium dendrites, which shortens the cycle life by 20%–30% and increases thermal runaway risks

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[2]. The continuous deterioration of internal structure will not only reduce the service life of the battery, but also lead to safety accidents such as fire and explosion in severe cases.

In engineering applications, the core goal of extreme-temperature thermal management is not simple temperature control. It should realize the coordinated balance of temperature stability, energy retention and constant power output, which provides a clear direction for technical research and development [1]. Different from conventional temperature control, extreme-temperature thermal management needs to take into account energy consumption, control accuracy and system reliability at the same time, so as to ensure that the battery can work in the optimal temperature range under any harsh conditions.This integrated control concept has become an important basis for the design and iteration of wide-temperature thermal management systems in the global automotive industry.

## 3. Research progress of power battery thermal management technology under extreme temperatures

### 3.1. Wide temperature range optimization of battery cells

Researchers at home and abroad have made obvious breakthroughs in material improvement and structural design of battery cells. By optimizing the formula of key materials and improving the manufacturing process, the wide-temperature adaptability of single batteries has been significantly improved. Foreign enterprises mainly adopt fluoro-carbonate electrolytes to enhance low-temperature conductivity, but such materials have poor high-temperature stability, which limits their full-temperature application. This kind of electrolyte can perform well in low-temperature environment, but it is easy to decompose and fail in high-temperature environment, so it cannot meet the needs of full-temperature range use.

Chinese companies have developed composite lithium salt systems, which can maintain more than 85% capacity at -30°C, but they are restricted by high cost and mass production difficulties [3]. The preparation process of composite lithium salt is complex, and the raw material cost is high, which makes it difficult to realize large-scale promotion in the short term. Foreign high-nickel ternary materials support stable operation at 60℃, but their low-temperature performance declines rapidly. The energy density of high-nickel ternary materials is outstanding, but the low-temperature conductivity is insufficient, and the capacity attenuation is serious in alpine regions.

Domestic modified lithium iron phosphate materials improve low-temperature performance and thermal stability effectively, but their energy density is 10%–12% lower than that of ternary materials [2]. Modified lithium iron phosphate has obvious advantages in safety and service life, but the lower energy density affects the endurance mileage of vehicles, which is a problem that needs to be balanced in engineering design.

### 3.2. Integrated thermal management architecture

The industrial technical route has shifted from single heat dissipation to integrated systems combining liquid cooling, heating and waste heat recovery. The integrated design can make full use of the waste heat generated by the vehicle, reduce the energy consumption of the thermal management system, and improve the overall energy efficiency of the vehicle. Tesla's eight-way valve system realizes efficient whole-vehicle waste heat recovery and shortens preheating time by 40% at -30℃ [4]. The system integrates multiple heat sources such as motor, electric control and battery, realizing multi-directional heat distribution and utilization.BMW iX uses phase change materials to control the temperature difference within 2°C at 50°C, but the system structure is highly

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complex [5]. Phase change materials can absorb and release a lot of heat during the phase change process, keeping the battery temperature stable, but the matching with the battery pack is difficult and the installation cost is high. NIO ET7 adopts heat pump and PTC hybrid heating, which can heat the battery to 25℃ within 15 minutes at -30℃, but its long-term reliability needs further verification [6]. The hybrid heating system combines the advantages of high efficiency of heat pump and rapid response of PTC, but the failure rate and durability under long-term use need to be tested by actual working conditions.

### 3.3. AI-driven scenario-based regulation

AI path planning and condition prediction can identify extreme environments in advance and activate preheating or cooling strategies. Through the collection and analysis of big data such as road conditions, weather and vehicle speed, the system can predict the temperature changes that the battery will face, and carry out proactive regulation to avoid performance degradation. Foreign algorithms integrate road and weather data with high prediction accuracy, while domestic systems have better real-time performance, but the accuracy is 5%–8% lower in extreme weather [1].The MPC+RL fusion algorithm reduces thermal management energy consumption by more than 10%. Model Predictive Control (MPC) has good stability, and Reinforcement Learning (RL) has strong adaptive ability, and the combination of the two can optimize the control effect. Tsinghua University's lightweight MPC algorithm achieves precise temperature control under limited on-board computing resources, but its robustness in complex scenarios needs to be improved [7]. The lightweight design reduces the computing pressure of the vehicle controller, but it is still difficult to adapt to the complex and changeable actual road conditions.Continuous optimization of algorithm structure and training data will help to further improve the stability and adaptability of intelligent thermal management systems in real vehicle applications.

## 4. Existing core problems, challenges and future development trends

### 4.1. Core challenges

At present, the engineering application of extreme-temperature thermal management technologies is restricted by four major industrial bottlenecks. These bottlenecks exist in material research, system design, standard formulation and patent layout, which together affect the large-scale promotion of related technologies.

1. The coordination between battery cells and thermal management systems is insufficient. Material optimization for a single temperature interval is not synchronized with system-level design, which easily causes unbalanced energy distribution and higher energy consumption under wide-temperature conditions [2]. The research and development of battery materials and thermal management systems are often carried out separately, lacking unified design standards and collaborative mechanisms.

2. The standardized test database for extreme scenarios is incomplete. Intelligent regulation algorithms depend highly on real working condition data. The lack of unified and standard test data in China leads to weak generalization ability of most algorithms [6]. There is no unified test specification for extreme temperature environments, and the data from different institutions are not comparable, which affects the training effect of algorithms.

3. The wide-temperature reliability verification system is not perfect. Existing standards and test methods fail to fully cover the full range of -30 ℃ to 50 ℃, resulting in a deviation between

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laboratory performance and actual road performance [8]. Most of the existing tests are carried out under ideal laboratory conditions, which cannot restore the real complex road environment.

4. Foreign core technology patent barriers are relatively high. Domestic enterprises lag about 1-2 years in high-temperature early warning, low-temperature heating and other key links, which restricts the speed of industrial upgrading [1]. Foreign enterprises have applied for a large number of core patents in advance, and domestic enterprises need to carry out innovative research to break through the restrictions.

## 4.2. Future development trends

Combined with industrial development demands, future technologies will develop toward three core directions. These directions are based on the current technical bottlenecks and market demands, and are the key to promoting the development of extreme-temperature thermal management technology.

1. The first direction is multi-energy collaborative integration.

The complementary cooperation of heat pumps, photovoltaics, fuel cells and other systems can significantly reduce energy consumption in extreme temperature scenarios [2]. The multi-energy collaborative system can realize the efficient utilization of various energy sources, reduce the dependence on single energy, and improve the energy efficiency of the whole vehicle.

2. The second direction is digital twin simulation verification.

The construction of full-range virtual test models can restore real working conditions, shorten R&D cycle and reduce verification costs [6]. Digital twin technology can build a virtual model consistent with the actual battery pack, simulate various extreme temperature environments, and accelerate the research and development progress.

3. The third direction is low-cost engineering implementation.

Material localization and architecture modularization can reduce system cost by 20%–25%, promoting the application of advanced thermal management technologies in mid-to-low-end models [1]. Reducing the cost of key materials and simplifying the system structure are important ways to realize the popularization of advanced technologies.

## 5. Conclusion

Extreme temperatures from -30℃ to 50℃ damage the electrochemical stability of power batteries by increasing electrolyte viscosity, accelerating SEI film decomposition and lithium dendrite growth. These changes directly lead to capacity attenuation, rapid increase of internal resistance, shortened cycle life and higher thermal runaway risks. The core of extreme-temperature thermal management is not simple temperature control, but the collaborative balance of temperature stability, energy retention and power constancy.

Battery material modification, integrated thermal management architecture and AI-driven intelligent regulation have become three mainstream technical routes. Domestic and foreign researches have made phased breakthroughs in electrolyte optimization, multi-source heat recovery and fusion algorithm control. However, the technologies still face practical problems such as cost trade-off, structural reliability and algorithm robustness. These problems need to be solved through continuous technological innovation and engineering optimization.

Insufficient coordination between battery cells and thermal management systems, lack of standardized extreme-scenario test databases, imperfect wide-temperature reliability verification systems and foreign patent barriers are the four core constraints that restrict the large-scale

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application of power battery thermal management technologies in extreme temperature ranges. These constraints are interrelated and need to be addressed systematically from the industrial level.

This study systematically reviews the basic characteristics and research progress of power battery thermal management in extreme temperatures, and clarifies the core technical logic and key performance constraints. The results can provide theoretical support and technical reference for the optimization and engineering application of wide-temperature thermal management technologies. It helps new energy vehicles break through regional climate restrictions and supports the high-quality development of the industry toward high performance, high reliability and low cost.

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