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A Review of Low-Temperature Heating Technologies for Lithium-Ion Batteries in New Energy Vehicles

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Abstract

With prominent features such as high specific power, low self-discharge rate, high energy density, and long cycle life, lithium-ion batteries have become the core energy storage components supporting the operation of power systems in new energy vehicles. However, in environments with low temperatures, this leads to a notable decrease in maximum power output and energy availability, and it also readily initiates lithium plating on the negative electrode during such charging, drastically reducing the battery's capacity retention and lifespan. Consequently, the effective preheating of lithium-ion batteries in environments with low temperatures has emerged as a key technical aid for the consistent and dependable functioning of new energy vehicles in colder areas. This paper systematically sorts out the low-temperature heating technology of lithium-ion batteries and analyzes the applicable scenarios and limitations of various technologies. In closing, this study systematically delineates the pressing technical bottlenecks demanding immediate breakthroughs within the domain of low-temperature heating technologies for lithium-ion batteries, and presents an outlook on their future evolution pathways and practical application prospects.

Keywords

New Energy Vehicles; Lithium-ion Batteries; Low-temperature Heating; External Heating; Internal Heating; Thermal Management System.

1. Research Background

1.1 Application Status of Lithium-Ion Batteries in New Energy Vehicles

Power batteries serve as the core power supply components for new energy vehicles, and their performance is directly linked to critical vehicle metrics including driving range, power delivery capacity, as well as safety and stability during operation. Bolstered by their exceptional electrochemical properties, lithium-ion batteries have steadily superseded conventional energy storage batteries like lead-acid batteries and nickel-metal hydride batteries, emerging as the dominant category in the current power battery sector for new energy vehicles.

1.2 Impact of Low-Temperature Environments on the Performance of Lithium-Ion Batteries

The comprehensive performance of lithium-ion batteries will decline significantly when in a low-temperature environment. The specific manifestations can be summarized into the following four core aspects:

Deterioration of electrolyte performance: Low-temperature environments will significantly increase the viscosity of the electrolyte in lithium-ion batteries, directly slowing down the movement speed of ions in the electrolyte and reducing the conductivity accordingly.

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Increase in battery impedance: Low-temperature conditions will cause the ohmic impedance, charge transfer impedance, and diffusion impedance of lithium-ion batteries to increase to varying degrees, ultimately leading to a decrease in battery output power.

Attenuation of available energy and peak power: The charging and discharging capabilities of lithium-ion batteries in low-temperature environments are severely constrained, driven by the combined impacts of reduced electrolyte conductivity and elevated total battery impedance.

Negative Electrode Lithium Plating and Associated Safety Hazards: When charging takes place under low-temperature conditions, the rate of lithium ion intercalation into the negative electrode's active material lags behind the rate of lithium deposition on the electrode's surface. Surplus lithium ions that fail to embed into the active material will precipitate as metallic lithium on the negative electrode surface, gradually forming needle-shaped lithium dendrites. Unchecked lithium dendrite growth not only depletes the lithium ions available for electrochemical reactions inside the battery, resulting in irreversible loss of battery capacity, but also carries the risk of puncturing the battery's internal separator structure, triggering an internal short circuit within the cell.

1.3 Importance and Research Significance of Low-Temperature Heating Technologies

In low-temperature environments, lithium-ion batteries will experience significant performance degradation. Preheating the battery before charging and discharging operations can effectively increase the battery temperature, optimize the fluidity and conductivity of the electrolyte, reduce the internal impedance of the battery, thereby restoring the normal charging and discharging functions of the battery.

2. Research Status of Low-Temperature Heating Technologies for Lithium-Ion Batteries

Lithium-ion battery low-temperature heating technologies are categorized into external and internal heating systems, based on the heat source's location and the heating device type. Technologies for external heating create heat within the battery's outer area and convey it to the battery via heat transfer techniques like conduction, convection, or radiation, thereby raising the battery's temperature; conversely, internal heating systems directly produce heat within the battery and ensure even heating via internal heat conduction.

2.1 External Heating Technologies

External heating is the earliest technical path, with the significant advantages of simple structure and easy practical application, and has been practically applied in some new energy vehicle models. Common implementation forms of such technologies mainly include: electric heating plate or heating film heating, fluid circulation heating, Peltier effect-driven heating, and phase change material-assisted heating.

2.1.1 Electric Heating Plate/ Film Heating

The working method of electric heating plate/film heating technology is to directly attach the electric heating plate or electric heating film to the outer surface of the battery, and use the heating effect of the heating element when energized to transfer heat to the inside of the battery through heat conduction to achieve battery preheating. Currently, the commonly used heating elements in the industry mainly include two types: PTC heating plates and wide-line metal films.

PTC heating plate is a semiconductor heating element with positive temperature coefficient characteristics. Its resistance will increase significantly with the increase of ambient temperature. JIN et al. conducted a related experiment: embedding PTC resistance strips into aluminum plates with grooves, and then placing the aluminum plates in the side gaps of the battery cells. Using the heating effect of the PTC resistance strips when energized, the heat is quickly transferred to each battery cell through the aluminum plates. The final experimental data show that this composite heating scheme considering both internal and external can make the battery temperature rise uniformly, and the

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temperature difference inside the battery can be controlled within 5℃[1]. However, this heating scheme has obvious shortcomings: the energy required for heating is provided by the battery's own power, which will reduce the overall operating efficiency of the battery system.

Wide-line metal film heating is another widely used electric heating film heating technology. The experimental idea of ZHANG et al. is to install a wide-line metal film on the side of the battery: this film is composed of two layers of copper film, one takes the form of a full rectangular flat copper sheet, while the other is a continuous copper conductor with a predefined width; electrical connections from a power source are made to the two terminals of the copper conductor, and insulating, wear-resistant coatings are applied to the exterior surfaces of both copper components. When current passes through the copper wire, the copper wire will generate heat due to the Joule heating effect, and then these heats will be uniformly transferred to the battery body through the complete copper film plane on the other side [2]. The prominent advantage of wide-line metal film heating is the fast heating rate, but due to the need for multi-level heat transfer from the outside to the inside, it is easy to cause temperature differences among individual battery cells in the battery pack, and some areas may experience overheating, which will affect the charging and discharging balance of the battery pack and shorten the battery life.

2.1.2 Fluid Circulation Heating

At the heart of fluid circulation heating lies a mechanism that leverages a non-stop circulating fluid medium to carry heat generated by an external thermal source to the battery’s outer surface, finally raising the battery’s temperature through convective heat exchange. Based on the category of circulating fluid deployed, this heating technique falls into two primary branches: air heating and liquid heating.

Air heating is an external heating technology boasting a simple structure and low implementation cost. Its working process is: an external power supply activates the electric heating wire to heat the air, after which a fan propels the resulting hot air flow to the battery pack area, and the battery thus achieves temperature rise through the convective heat transfer effect of the hot air. WANG et al. developed an electric heating wire heating box and conducted heating tests on single batteries under the low-temperature condition of -15℃. The experimental data show that when the battery temperature rises from -15℃ to 0℃, it takes an average of 87 seconds to increase by 1℃, and the overall heating rate is relatively slow [3]. The advantages of this type of technology are: simple structure and easy construction, low investment cost, convenient daily maintenance, and no pollution to the battery body; however, its shortcomings are also very prominent: the specific heat capacity of air itself is limited, the heat transfer efficiency is not high, which directly leads to a slow battery heating rate; at the same time, the uneven distribution of hot air inside the battery pack is likely to cause poor temperature consistency among individual battery cells in the pack.

The working principle of liquid heating is roughly similar to that of air heating, with the core difference only being the use of liquid instead of air as the circulating heat transfer medium. Since the specific heat capacity of liquid is much higher than that of air, its heat transfer efficiency is also greatly improved. WANG et al. designed a battery module containing 12 prismatic battery cells, selecting silicone oil as the heat transfer liquid. Not only were gaps reserved between the battery cells for the circulation of silicone oil, but also a distribution pipe was installed at the inlet to achieve uniform distribution of silicone oil, and a collector pipe was added at the outlet to balance the system flow resistance [4]. The experimental results confirm that this heating system can raise the temperature of the battery pack from -28℃ to 25℃ in only 11 minutes, and the heating rate is significantly faster than that of air heating technology. However, liquid heating technology also has certain limitations: due to the certain conductivity and fluidity of the liquid itself, the system has strict requirements on the tightness standard. Once leakage occurs, it may induce safety hazards such as battery short circuits.

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2.1.3 Peltier Effect Heating

The core characteristic of the Peltier effect is: when current passes through a thermocouple structure composed of two different semiconductors, the two ends of the thermocouple will generate endothermic and exothermic physical phenomena respectively; by adjusting the direction and magnitude of the current, the intensity and direction of endotherm and exotherm can be precisely controlled.

Troxler et al. developed a heating device with Peltier elements as the core. The device attaches one side of the Peltier element to the outer surface of the battery through a copper plate, and the other side is directly in contact with the heat dissipation device [5]. When current is passed through the Peltier element, the side connected to the copper plate will continuously generate heat, which is transferred to the battery through the heat conduction of the copper plate to complete the heating of the battery; while the heat absorbed by the other side of the element is discharged to the external environment through the heat dissipation device. However, due to the high cost of Peltier elements themselves, low heat energy conversion efficiency, and high energy loss, this technology is currently difficult to be widely promoted and applied in the field of new energy vehicles.

2.1.4 Phase Change Material Heating

Phase Change Material refers to a category of functional materials that can undergo phase transition reactions such as solid-to-liquid and solid-to-solid transformations and within a specified temperature interval, while absorbing or emitting substantial quantities of latent heat throughout the entire phase change process. The working principle of phase change material heating technology is: during the battery’s routine operational phase, the phase change material absorbs and retains the thermal energy emitted by the battery cell; in scenarios where the surrounding environment temperature drops to a low level, the phase change material triggers a reverse phase transition process, releasing the previously stored latent heat to warm the battery, in turn keeping the battery operating within an optimal temperature bracket.

LUO et al. developed a conductive paraffin/expanded graphite composite phase change material and built a lithium-ion battery thermal management system based on it [6]. Relevant experimental data show that this system can support lithium-ion batteries to achieve full-temperature range thermal management in extreme environments of -40℃~+50℃. Phase change material heating technology also has some shortcomings: such materials are usually large in volume and weight, which will directly increase the curb weight of electric vehicles, occupy more interior space, and thus adversely affect the vehicle's driving range; in addition, phase change materials typically have low thermal conductivity, resulting in slow heat transfer rates, resulting in an insufficiently timely heating response, which often cannot meet the requirements in scenarios requiring rapid preheating.

2.2 Internal Heating Technologies

The core idea of internal heating technology is to directly generate thermal energy inside the battery body to achieve battery preheating. It has the prominent characteristics of high heat conversion efficiency, fast temperature rise speed, and good temperature uniformity in various regions of the battery cell. At present, the widely studied internal heating paths mainly include three types: current excitation heating, Self-Heating Lithium-Ion Battery, and electromagnetic induction heating.

2.2.1 Current Excitation Heating

The technique of current excitation heating leverages the fact that lithium-ion batteries' internal resistance markedly rises in environments with low temperatures. The system proactively administers a distinct kind of current to the battery, creating heat via the Joule heating effect within the battery, aiming for a swift increase in battery temperature. Based on the applied current type, there are three distinct methods for current excitation heating: direct current heating, alternating current heating, and alternating pulse heating.

The core principle of direct current heating is to pass a short-time large current through the battery, triggering the self-discharge process of the battery, and using the large amount of Joule heat generated

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by the ohmic impedance inside the battery to quickly raise the battery temperature. CHEN et al. suggested a rapid, electrically activated self-heating system relying on brief, high-current self-discharge: the power battery pack, by managing the relay's on-off, executes a brief, high-current self-discharge, and the heat emitted during the discharge accelerates the battery's temperature increase [7]. This method has excellent thermal efficiency and can raise the battery temperature to the ideal working range in a very short time; however, the sudden increase in current in a short time will put the battery in a high current density state, which not only makes precise regulation difficult but also may cause excessive temperature differences inside the battery.

The operation mode of alternating current heating is to apply alternating current of a specific frequency and amplitude to the positive and negative electrodes of the battery, and use the comprehensive internal impedance of the battery to generate Joule heat to achieve battery heating. After experimental research. STUART et al. found that low-frequency current of 60Hz, as well as current of 10~20kHz and higher frequencies, can effectively achieve battery heating. The use of low-frequency and high-amplitude alternating current can speed up the heating rate, but such current will exacerbate side reactions inside the battery and accelerate battery aging; while high-frequency current has a relatively small impact on battery aging, but the heating rate will be slightly slower [8]. The advantages of alternating current heating are that temperature control is relatively simple, the heating power and heating rate can be adjusted by adjusting the frequency and amplitude of the alternating current, and the temperature consistency of various parts of the battery is good; however, this method requires a dedicated inverter device to generate alternating current of a specified frequency, which will increase the overall cost and complexity of the system, and the energy consumption during the heating process is also relatively high.

The core approach of alternating pulse heating is to connect the target battery with another energy storage component to form a closed loop, and generate pulse current through repeated charging and discharging between the two, ultimately generating heat inside the battery due to the action of the current. The LI team developed a new type of driving circuit topology. When the vehicle is in a stationary state, it uses the inverter bridge arm to generate high-amplitude pulse current to heat the battery [9]. The technique of alternating pulse heating merges the benefits of both direct and alternating current heating, ensuring rapid heating and even temperature spread across the battery pack, while also reducing battery loss; yet, the logic behind regulating pulse current in this method is quite intricate.

2.2.2 Self-Heating Lithium-Ion Battery

The core of the Self-Heating Lithium-Ion Battery is to adjust the internal structure layout of the battery and embed a dedicated heating component inside the battery cell to achieve the internal self-heating function of the battery. This technology does not require additional external heating equipment, the heating process is more compact and efficient, and the temperature consistency of each part of the battery pack is better.

ZHANG et al. developed an SHLB structure scheme based on nickel foil embedding, integrating a nickel foil with two tabs as a built-in heating element into the battery. When heating is not needed, the control switch remains closed, the nickel foil is not connected to the circuit, and the battery can complete charging and discharging operations in the conventional mode; in situations needing heating at low temperatures, activating the control switch allows current to pass through the nickel foil, creating Joule heat. This directly heats the battery's electrolyte and electrode parts, leading to a swift increase in the battery cell's temperature[10].

Although self-heating lithium-ion batteries have many advantages such as fast heating rate, uniform temperature distribution, and compact overall structure, there are still several urgent problems to be solved. The heating element installed inside the battery will occupy a part of the internal space, which may reduce the energy density index of the battery.

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2.2.3 Electromagnetic Induction Heating

The core principle of electromagnetic induction heating is to use the electromagnetic induction effect to place the battery to be heated in a high-frequency alternating electromagnetic field environment. At this time, the conductive components such as the electrode sheets inside the battery will generate induced current. When the eddy current flows inside the conductive components, it will release heat through the Joule heating effect, thereby realizing the internal heating of the battery.

Scholars such as JIANG proposed a battery temperature rise scheme based on induction heating technology. They wound the pouch battery with the copper coil of the induction module, excited a high-frequency alternating electromagnetic field through the copper coil, and prompted the generation of eddy current inside the battery to generate heat [11]. Relevant experimental data show that when heating a 5mm-thick pouch battery at a working frequency of 100kHz, the heating rate can reach 71.4°C/min, and the standard deviation of the overall battery temperature does not exceed 6°C, showing the prominent advantages of fast heating rate and good temperature distribution uniformity.

However, electromagnetic induction heating technology also has obvious application limitations. This technology has specific requirements on the structure and material of the battery, and is currently only applicable to thin pouch batteries. At the same time, the generation of a high-frequency alternating electromagnetic field requires supporting dedicated high-frequency power supplies and induction coils, which will increase the cost and complexity of the entire system.

3. Comparison of Various Aspects of Heating Technologies

This paper selects five core indicators: cost, energy consumption, heating rate, temperature consistency, and reliability, to conduct a comparative analysis of the external heating technologies mentioned above. The specific performance differences of various technologies are shown as Table 1.

Table 1. Performance Comparison of Various Heating Technologies

Classification of Heating Technology	Specific Heating Method	Cost	Energy Consumption	Heating Rate	Temperature Consistency	Reliability
External Heating	Electric Heating Plate/Film	Low	Relatively Low	Relatively High	Low	Relatively Low
	Air Heating	Relatively Low	Relatively Low	Low	Relatively Low	High
	Liquid Heating	High	Relatively High	Relatively Low	Relatively High	High
	Peltier Effect Heating	High	Relatively Low	Low	Relatively Low	Relatively High
	Phase Change Material Heating	Relatively High	High	Relatively Low	Relatively High	Relatively High
Internal Heating	Direct Current Heating	Relatively Low	Relatively Low	Relatively High	Relatively High	Relatively Low
	Alternating Current Heating	Relatively High	Relatively High	Relatively High	Relatively High	Relatively High
	Alternating Pulse Heating	Relatively High	Relatively High	Relatively High	Relatively High	Relatively High
	Self-Heating Lithium-Ion Battery	High	Relatively High	High	Relatively Low	Relatively Low
	Electromagnetic Induction Heating	Relatively High	Relatively High	High	Relatively Low	Low

4. Challenges and Prospects

4.1 Challenges Faced by Existing Technologies

At present, the research on low-temperature heating technologies for lithium-ion batteries has made breakthrough progress, but there are still many urgent problems to be solved in practical application:

Balance between heating efficiency and energy consumption: Current mainstream heating schemes often generate high energy loss to achieve efficient temperature rise.

Precise control of temperature consistency: For battery systems used in groups, the temperature difference between different individual batteries will seriously affect the working performance and service life of the entire battery pack.

Improvement of safety and reliability: During low-temperature heating, once there is a deviation in temperature control, it may cause abnormal conditions such as battery overheating and intensified lithium plating reaction, which may induce safety hazards.

Optimization of cost and integration level: Some efficient heating technologies, including self-heating lithium-ion batteries and electromagnetic induction heating, are difficult to achieve large-scale mass production due to high costs.

Impact on battery life: Heating technologies such as direct current heating and low-frequency high-amplitude alternating current heating may cause irreversible damage to core components such as the battery's electrode structure and electrolyte during the heating process, thereby accelerating the aging speed of the battery.

4.2 Future Development Trends

The future development of low-temperature heating technologies for lithium-ion batteries mainly focuses on the following directions:

Innovative breakthroughs in efficient and low-consumption heating schemes: With the core goals of improving energy conversion efficiency and reducing energy consumption, focus on the research and development of new heating materials and structures.

Refined optimization of intelligent temperature control strategies: Realize precise sensing and dynamic regulation of battery temperature with the help of cutting-edge sensor technology and control algorithms.

This integrated approach not only enhances the efficiency of the heating system but also optimizes energy consumption, contributing to improved overall vehicle performance. By minimizing redundant components and ensuring seamless interaction between the systems, the vehicle achieves a more compact design without compromising on thermal control. Moreover, such innovations can extend the lifespan of both the battery and the heating components.

In-depth development of heating technologies under multi-field coupling scenarios: Conduct in-depth research on the battery heating mechanism under the coupling effect of multiple fields such as electricity, heat, and magnetism, and develop a multi-field synergistic heating technology system.

Research and development of long-life heating technologies: Reduce the damage to battery structure and performance during heating by optimizing heating parameters;

Environmentally friendly and sustainable development paths: Develop environmentally friendly heating materials and working media to reduce the environmental pollution caused by the heating system.

5. Conclusion

To meet the demand for stable operation of new energy vehicles in cold regions, low-temperature heating technology for lithium-ion batteries is one of the core supporting technologies. This paper systematically summarizes ten mainstream low-temperature heating schemes for lithium-ion batteries.

From the perspective of technical characteristics, the prominent advantages of the external heating lie in simple structure layout and low overall investment cost, but such technologies generally have the shortcomings of low energy conversion efficiency and uneven temperature distribution of the battery cell group; while the internal heating can achieve faster heating rate, higher energy utilization efficiency, and excellent temperature consistency among battery cells. However, some subdivision technologies have limitations such as high research and development and application costs, complex structural design, and potential indirect impact on the cycle life of battery cells. At the current stage of technological development, there is no single heating scheme that can fully meet all performance requirements of new energy vehicles under actual working conditions.

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