Energy Consumption and Efficiency Analysis of Electric Vehicle Battery Heating Strategy

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Abstract: This paper focuses on the heating strategies for electric vehicle batteries in low-temperature environments, analyzing the energy consumption and efficiency characteristics of different heating methods. Through theoretical analysis, we will establish a mathematical model to compare the advantages and disadvantages of constant current heating, constant voltage heating, and phase change material heating. The empirical study designed an experimental scheme and collected data to verify the actual performance of each strategy. The experimental results show that different heating strategies exhibit significant differences under varying temperature conditions, with bottlenecks in energy loss and efficiency. This study proposes optimization recommendations aimed at improving battery performance and vehicle energy efficiency. The conclusion points out that future research can further explore intelligent control and material improvements to enhance heating efficiency.

Keywords: Electric Vehicle; Battery Heating; Energy Consumption Efficiency; Experimental Analysis; Strategy Optimization

1. Introduction

1.1 Development and Application Prospect

In the context of the continuous advancement of electric vehicle technology, the power battery, as one of the core components, directly determines the overall range, power output characteristics, and even safety reliability. It is worth noting that among various environmental factors, low-temperature conditions pose the most significant constraint on the performance of lithium-ion batteries. As the temperature decreases, the viscosity of the electrolyte increases, resulting in a slowed lithium-ion migration rate, higher internal resistance, and a significant decrease in available capacity. More critically, the risk of lithium dendrite formation also intensifies. Case studies indicate [1] that maintaining an appropriate operating temperature for battery packs in low-temperature environments has become a core issue for enhancing the environmental adaptability and operational reliability of electric vehicles. Research on battery heating strategies conducted under this background holds both theoretical exploration value and engineering practical significance.

Multiple heating methods have been applied in practical engineering fields: external electric heating film, internal AC heating technology, phase change material-assisted heating solutions, and integrated thermal management systems, among others, each with distinct features. These methods exhibit clear characteristics in terms of thermal response speed, energy consumption performance, and system architecture complexity, enabling them to adapt to different application scenarios. Internal AC heating technology achieves significant rapid temperature rise through internal heat generation, but it imposes stringent requirements on the precision of the battery structure. Phase change materials, on the other hand, demonstrate unique advantages—they can cyclically regulate heat release and absorption during charge and discharge processes, making temperature control functionality crucial. It is evident that a thorough analysis of the differential performance of various heating strategies in terms of energy consumption characteristics and thermal efficiency indicators plays a decisive role in developing an efficient and energy-saving battery management system.

The energy consumption control during the battery heating process significantly impacts the vehicle's durability performance, particularly in winter conditions or colder regions, where heating energy losses reduce the proportion of available energy. Case studies show that one of the current research focuses has shifted to: how to minimize heating process energy consumption while ensuring battery performance recovery [2]. A thermodynamic and electrochemical coupled model has been established, incorporating experimental data, to evaluate heating strategies under different parameter conditions. These parameters include initial temperature, target temperature, and heating rate. It is clear that this model not only elucidates the intrinsic mechanisms of energy transfer and loss but also provides necessary theoretical support and technical pathways for optimization design.

1.2 Research Status at Home and Abroad

Domestic and international research institutions and automotive companies have conducted extensive and in-depth research on improving electric vehicle battery heating strategies, achieving a series of valuable results. In one research project on heating methods, researchers at Pennsylvania State University proposed a fast-charging technology similar to that of smartphones. They first heated the battery for 10 minutes, then rapidly cooled it, allowing the electric vehicle's battery to be fully charged in 10 minutes while driving 300-500 kilometers. The technology employs thin nickel foil with temperature sensors as rapid heating material to heat the battery, controlling the current passing through the metal foil, and finally relies on the vehicle's cooling system to rapidly cool the battery. Due to the risk of battery damage and reduced battery lifespan, this technology cannot be mass-produced in the short term. However, it provides new insights for the research and optimization of battery heating strategies.

The research approach of the team from the Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences is to explore the optimization path of material heating performance. By heating the lithium-rich manganese-based cathode material, they successfully repaired the aging of battery-related structures, restored the battery voltage to near its initial level, and extended the cycle life by nearly 1000 times. This achievement not only addresses the issue of material aging but also pioneers a new paradigm of "material-electrochemistry-thermodynamics," bringing new directions for improving battery heating technology strategies to solve cell aging problems.

Meanwhile, Tesla has adopted battery preheating features in its vehicles, preheating the battery during driving before charging to enhance charging efficiency. The patent application by Zhejiang Geely Holding Group Co., Ltd., titled "Battery Heating Control Method, Device, Equipment, Storage Medium, and Program Product," demonstrates a deep consideration of the impact on the cathode potential, innovating related methods to ensure the anode potential of the cell remains within a safe range during pulse heating, effectively reducing the risk of lithium precipitation in the cell, thereby improving the safety and lifespan of the battery.

2. Concept Overview

Electric vehicle power batteries, as the core energy supply units of vehicles, directly constrain the durability and operational safety of the vehicle. Lithium-ion batteries are the most mainstream energy storage devices in electric vehicles. Their working principle relies on the transfer of lithium ions between the anode and cathode materials to achieve the storage and release of electrical energy. Under low-temperature conditions, the ionic conductivity of the electrolyte shows a declining trend, increasing the internal resistance of the battery and significantly reducing its charge and discharge capacity. More critically, it may also lead to the growth of lithium dendrites, which could threaten the safety of the battery and even the related system. Therefore, to maintain the normal operation of the battery under low-temperature conditions, heating strategies have become one of the key methods for improving battery management systems.

For the differences in heating objects and battery characteristics, the currently common battery heating methods mainly include external heating and internal heating. External heating typically uses two typical solutions: liquid circulation heating or PTC heating elements, transferring heat directly to the battery module through heat conduction while regulating the battery's operating temperature. This method provides uniform heating and is easy to control, but has a long heat conduction path, low heating efficiency, complex system structure, and increases the vehicle's mass and energy consumption. On the other hand, internal heating methods apply current inside the battery or utilize the Joule heat generated during the battery's own charging and discharging process, offering fast response speed and high thermal utilization, but require precise control of current parameters to prevent local overheating from damaging the battery structure. The pulse self-heating technology developed in recent years, which introduces metal foils between electrode layers as heating elements, achieves efficient heating in a short time and has become a research hotspot.

In the design process of heating strategies, energy consumption indicators and heating efficiency parameters constitute the core elements of system performance evaluation. The amount of energy consumed is primarily reflected in the key parameter of the ratio of energy consumed during heating to the total energy of the battery, while the ability to convert input energy into effective thermal energy determines the level of heating efficiency. With various heating methods differing in energy conversion paths and heat loss mechanisms, their energy efficiency performance varies in practical application scenarios. Liquid heating methods exhibit high temperature control accuracy, but the additional energy consumption brought by circulation pumps and pipeline systems cannot be ignored, as case studies show that their overall energy efficiency is often at a low level. Although internal heating methods have advantages in thermal conversion efficiency, improper implementation of control strategies can lead to the generation of local thermal stress, significantly affecting the battery's service life. Therefore, when formulating specific heating plans, multiple dimensions must be comprehensively considered, including heating rate parameters, energy consumption level indicators, temperature field uniformity, and potential influencing factors on battery life.

Dedicated to achieving the dual goals of ensuring battery performance and reducing energy consumption while improving overall system efficiency, researchers have proposed several optimization strategies. The introduction of intelligent control algorithms enables the establishment of a real-time monitoring system for battery temperature status, and the implementation of dynamic adjustment mechanisms effectively suppresses thermal runaway phenomena and unnecessary energy loss. Practical applications of new high-conductivity interface materials demonstrate that innovative designs such as phase change energy storage materials significantly enhance heat conduction efficiency and reduce energy loss. The implementation of vehicle thermal management system collaborative optimization strategies also reflects significant value: the scheme of preheating using grid power during charging is highly feasible; utilizing motor waste heat for auxiliary heating during operation has also shown good practical effects. These technical approaches provide practical solutions and methodological guidance for constructing battery heating systems with high efficiency and low energy consumption characteristics.

3. Theoretical Analysis

In the research field of battery heating strategies, the core theoretical analysis is based on thermodynamic principles and electrochemical properties. The reduction in ion diffusion rate in the electrolyte and the deterioration of electrode material dynamics are the main reasons for the limitations of lithium-ion battery performance at low temperatures. This leads to an increase in internal resistance, significantly affecting charge-discharge efficiency and safety. The input of external energy raises the temperature of the battery body, and the improvement of internal reaction dynamics is achieved through this process [4]. In constant-current heating methods, the carrier of work is current, and the energy loss phenomenon follows the rules described by Joule's law—positively correlated with the square of the current, the internal resistance value, and the heating time. Heating processes conducted under constant voltage conditions exhibit dynamic characteristics: the current size adjusts with the battery state, causing the energy utilization efficiency to fluctuate. Phase change materials show unique advantages when applied to heating—the absorption and release of energy during the phase change process are fully utilized. Case studies indicate that while this method has a high energy utilization rate, its dynamic response speed is relatively slow.

Table.1 Experimental Parameters and Performance of each Heating Strategy Type

Types of Heating Strategies	**Case Studies**	**Ambient Temperature (°C)**	**Time required to heat to target temperatur**	**Energy consumption (kJ)**	**Temperature difference (°C)** (Record the effects of	**Applicability**	**Pros and Cons**

			e (s)		waste heat recovery under three environmental temperatures, comparing and analyzing energy consumption and temperature rise rate with traditional PTC heating methods)		
Waste Heat Recovery System	Heating the battery pack to 15°C at environmental temperatures of 0°C, -5°C, and -10°C	0,-5,-10	1,667 1,784 1,956	Reducing 460.7, 406.4, 209.5	≤5	Waste heat recovery technology can make full use of the heat recovery in the electric drive circuit, indirectly achieving the reduction of PTC energy consumption, suitable for low temperature conditions(-10°C~0°C)	This strategy type is suitable for low-temperature conditions, greatly reducing unnecessary energy loss of PTC heaters in thermal management systems
Thermoelectric element heating type	Establish a predictive model for the maximum allowable discharge current of the battery based on its electrochemical characteristics	-40	330	4.7%	≤2	Suitable for ultra-low temperature start-up(-40°C~-20°C)	This strategy type consumes only 4.7% of the battery's rated capacity, while being able to heat the battery pack from -40°C to -20°C within 330s
Wide-line metal film heating	Construct a transient three-dimensional finite element model for the $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ battery based on the electrode microstructure and thermal conduction characteristics	-20	12.5	1766	3.44	Suitable for fast thermal response scenarios	12.5 seconds after initiating heating, the maximum temperature gradient difference of the battery reaches 34.4K
Trapezoidal heating strategy	Experimental and simulation results of the trapezoidal heating strategy	-20	906	3722	≤3	Suitable for low temperature slow charging scene	The battery can heat from -20°C to 10°C within 906 seconds, with an average temperature rise of 1.99°C/min
Variable/Fixed Frequency AC Heating	Comparing the energy conversion efficiency and temperature control differences between variable frequency AC heating and fixed frequency AC heating	0	372/301	1573	≤2	Conventional low temperature(-10°C~10°C)	Variable frequency AC heating circuit topology is complex, making its implementation more difficult, but the heating effects of the

							two methods tend to be the same
Pulse current heating	Calculate the pulse current frequency that maximizes the heat generation rate of the battery at different temperatures, with a unit temperature of 1℃	-20	369	981	1.1	Rapid preheating(-20℃→5℃)	This heating scheme takes 369s to heat the battery from -20℃ to 5℃, while keeping the maximum temperature difference within a range of 1.1℃, effectively avoiding local temperature imbalance.
Lithium-ion battery high-current self-discharge	Use lithium-ion batteries for high-current self-discharge, and utilize their own electrochemical process to complete energy conversion for low-temperature heating.	-15	442	Consumes 7 % of battery capacity	≤4	Parking thermal insulation scene	By controlling the switch to adjust the self-discharge conditions, effectively avoid the risk of uncontrolled heating
All-weather battery	For the prismatic lithium-ion battery, insert a 50μm thick nickel foil internally to construct an all-weather battery, utilizing the high conductivity and low impedance characteristics of the nickel foil to optimize the temperature adaptability of the battery.	-30	262	Consumption of 2 % battery capacity	11.3	Extremely cold environment (Below -25℃)	In low-temperature environments, the switch between the start terminal and the battery positive terminal closes, current flows through the nickel foil to form a circuit, generating Joule heat to heat the battery, and the heat output per unit time is stable.
Air-based heating system	Using the battery to power the fan and the resistive heater	-20	85	Consumption of 6 % battery capacity	≤8	Emergency heating scenario	This solution can heat the battery from -20℃ to 20℃ in just 85s, but it consumes a significant amount of battery power, requiring energy conservation considerations.

The establishment of mathematical models helps quantify the performance differences among various heating strategies. The relationship between energy input and temperature response can be described using an electro-thermal coupling model, and the heating rate and uniformity of temperature distribution can be analyzed by combining heat conduction equations. For phase change material heating, parameters such as phase change latent heat, thermal conductivity, and thermal convection systems should be introduced, and a multi-physics field coupling model should be established to predict heating and insulation performance. As shown in Table 1, according to experimental data, constant current heating can rapidly increase temperature in low-temperature environments, but due to its high energy consumption and large temperature difference, such as pulsed current heating, the battery can heat up to 20°C within 369 seconds in an environment of -5°C, with a maximum temperature difference of only 1.1°C, but energy control remains challenging. In contrast, waste heat recovery systems can effectively reduce the energy consumption of PTC heating from 0°C to -10°C in the environment and improve the overall efficiency of the thermal management system. Air heating systems heat up quickly, but their high energy consumption limits their application in extremely cold environments. As shown in Fig.1, the heating energy consumption of phase change materials is the lowest, which is significantly lower than that of constant current and constant pressure heating at each temperature point. For example, its energy consumption at-20℃ is 31, which is only about 59.6 % of that of constant current heating (52), reflecting the advantages of phase change materials to achieve efficient energy utilization through latent heat regulation. The energy consumption of constant current heating is the highest, especially at -20 ℃ and -15 ℃, which is 15.5 % and 4.8 % higher than that of constant voltage heating, respectively, which is related to the additional Joule heat loss caused by the increase of internal resistance caused by constant current. The energy consumption of constant voltage heating is between the former two, and the gap between constant current heating and constant voltage heating is gradually narrowed at medium and low temperatures (-10 ℃ to 0 ℃). Due to the dynamic adjustment of current with the change of internal resistance under constant voltage, some invalid energy consumption is reduced.

Overall, different heating strategies have unique characteristics in terms of energy consumption, efficiency, and applicability, and must be optimized based on specific application scenarios, as shown in Figure 1.

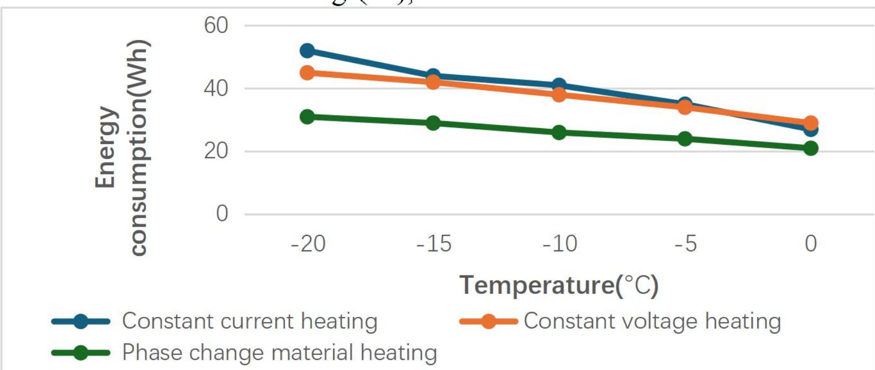

Figure 1. Energy Consumption Comparison of Battery Heating Strategies

4. Empirical Study Design

4.1 Construction of Experimental System

This experimental design aims to explore the energy consumption characteristics and energy conversion efficiency of the low-temperature heating strategy of electric vehicle batteries, and is committed to building a scientific and repeatable experimental research system. The establishment of this system aims to provide solid experimental support for the subsequent data analysis of the system, the optimization iteration of the heating strategy and the verification of related theoretical models.

In the selection of heating methods, in order to ensure the representativeness and comparative value of the experimental results, four typical heating methods in the current industry are selected, including positive temperature coefficient (PTC) heating, waste heat recovery heating, pulse current heating and alternating current heating device based on metal-oxide-semiconductor field effect transistor (MOSFET) control [5]. Through the comparative analysis of these mainstream heating methods, the performance differences of different technical paths in low temperature environment can be fully revealed.

In order to strictly control the experimental variables and ensure the high precision and lateral comparability of the experimental data, all tests were carried out in a standardized low temperature environment chamber. The experimental ambient temperature was accurately set to three gradients of − 10℃, −

5 ℃ and 0 ℃ to simulate different degrees of low temperature conditions. During the experiment, the battery pack needs to be continuously heated from the initial temperature to the target temperature of 15 ℃ [6]. The test object adopts a standardized lithium-ion battery module. High-precision temperature sensors are installed on the surface and key internal positions of the module, and a high-frequency energy consumption acquisition system is equipped to accurately capture the dynamic changes of battery temperature and real-time energy consumption data during the heating process.

4.2 Experimental Equipment and Operation Method

In terms of experimental equipment, a PTC heater with a maximum output power of 7kW was selected as a representative of traditional heating methods. The control strategy was dynamically adjusted according to the environmental temperature, operating at full power below -10°C and gradually reducing output in higher temperature ranges. The waste heat recovery system was based on a thermal management model constructed using KULI software, combining simulation and measurement, and utilizing waste heat from motor controllers, three-in-one components, and other components to heat the battery pack. For electric heating methods such as pulsed current heating and AC heating fixtures, circuit modules that convert DC power into high-frequency AC power or pulsed current were used to change the current form and improve heating efficiency. All experiments were conducted under the same initial charge state (SOC) to eliminate the influence of the battery's own state on the heating process [7].

As shown in Table 2, the PTC heater operates at full power (7kW) below − 10°C and decreases to 0 ~ 5kW above − 10°C. This strategy can be further refined: combined with the energy consumption reduction data at 0°C, − 5°C, and − 10°C (460.7 kJ, 406.4 kJ, 209.5 kJ), the power is reduced in advance when it is close to the target temperature (15°C), and the overshoot energy consumption is reduced. The waste heat recovery system can reduce energy consumption at all temperatures, and the model error rate is ≤ 6.7 %, and the reliability is high. The waste heat coupling time with the motor controller and the three-in-one component can be optimized, and the waste heat is preferentially utilized in the WLTC cycle condition to reduce the PTC start frequency. The efficiency of pulse current heating (369 s from-20 ℃ to 5 ℃, temperature difference 1.1°C) and MOSFET controlled AC heating (132 s from-20 ℃ to 0 ℃, energy consumption 5.4 %) is significant, which can be preferentially used for extremely cold environments (below-20°C). At the same time, the proportion of battery energy consumption is reduced by circuit optimization. In the low-temperature start-up stage (such as below-20°C), pulse heating is used to heat up rapidly, and waste heat recovery is used to maintain the temperature in the middle stage, so as to avoid PTC continuous high-power operation.

Table 2. Experimental Contents and Results

Experimental Content	Specific Parameters or Results
Energy consumption reduction when the battery pack is heated from -10°C, -5°C, and 0°C to 15°C	Reduced by 209.5kJ, 406.4kJ, and 460.7kJ respectively
PTC Heater Control Strategy	The Conditions of -10°C and below enable maximum power 7kW heating, when the ambient temperature rises above -10°C to heat with 0~5kW
PTC Heater Parameters	This device is rated at 7kW, with physical dimensions of 160mm×141mm×105mm, compatible with cooling fluid temperature -40~80°C, self-operating temperature 40~110°C, and a weight of 2.21kg
Heat recovery thermal management system model	Built in KULI software
Model validation	The model error rates of the motor controller, three-in-one component, servo motor, radiator, and battery pack are all controlled within 6.7%

Simulation results	Transient simulation under 0°C, -5°C, and -10°C, with the simulation condition being WLTC cycle condition 2
Dynamic response characteristics of the correlation curve between battery pack cell temperature and proportional valve opening	Under 0°C, -5°C, and -10°C, the time difference for the two methods to raise the minimum temperature of the battery pack cell to 15°C is 91s, 79s, and 214s respectively.
Power and energy consumption curve of PTC heater	Compared with traditional methods, the energy consumption of PTC heaters in the waste heat recovery system is reduced by 460.7 kJ, 406.4 kJ, and 209.5 kJ, respectively
Battery self-heating method	Heating from -20℃ to -10℃ is completed within 442s, with a temperature rise of 1.36℃/min
Resonant LC Converter AC Heating Device	Converting DC current to sinusoidal current to increase heating rate
Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) Control Strategy	Heating the battery from -20℃ to 0℃ within 132s, consuming 5.4% of the battery energy
Pulse current heating	Heating the battery from -20℃ to 5℃ takes only 369s, with a maximum temperature difference of 1.1℃
Circuit module that can convert DC current to pulse current	Heating the battery from -10℃ to 10℃ takes 173s
Method for Low-Temperature Heating of Lithium-Ion Battery High-Current Self-Discharge	By controlling the switch to adjust self-discharge conditions, avoid uncontrollable heating

4.3 Experimental Data Acquisition

In the composition of the data acquisition system, the experimental platform adopts the modular design concept and integrates the multi-dimensional parameter synchronization measurement unit, which specifically covers the temperature sensing module, the voltage acquisition module, the current monitoring module and the power metering module. Each module realizes timing synchronization through a high-precision data acquisition card (sampling frequency is set to 1kHz) to ensure the timestamp consistency of multi-dimensional parameters [8]. Among them, the platinum resistance temperature sensor (Pt1000) with an accuracy of ± 0.1℃ is selected as the temperature sensing module. It is arranged on the key points of the battery module, such as the cell surface, the tab area and the geometric center of the module, to form a spatial distributed temperature monitoring network, which provides micro-scale data support for quantifying the uniformity of the temperature field during the heating process.

The implementation process of parameter measurement follows the standardized process: the voltage acquisition adopts the differential measurement method, and the total voltage of the cell and the module is obtained by the high-precision ADC chip (16-bit resolution), and the sampling interval is set to 0.5s; current monitoring relies on a Hall effect current sensor to achieve non-contact measurement, and its measurement range covers from -100 A to 100 A, ensuring that the current signal is not distorted under special conditions such as pulse heating. Based on the principle of instantaneous power integration, the power metering module records the active power and reactive power of the heating device in real time, and obtains the total energy consumption (unit: Wh) and the effective heating time (unit: s) by time integration operation. The quantification of the heating rate uses the time span when the minimum temperature of the cell reaches the preset threshold (15℃) as the core index. The selection of this index not only conforms to the critical temperature characteristics of battery activity recovery, but also facilitates the horizontal comparison between different heating strategies [9].

In order to improve the statistical significance and reliability of the experimental data, the study used multiple sets of repeated experimental design: under the three initial temperature conditions of-10℃, -5℃ and 0℃, each heating strategy was tested independently and repeatedly for 3 times, and a total of 9 groups of effective data samples were obtained. By calculating the mean and standard deviation of the three repeated experiments, the degree of dispersion of the data can be quantified, which provides a statistical basis for the subsequent significance test. The experimental results are presented in a multi-dimensional form, including temperature-time dynamic curve, power-energy consumption relationship curve and key parameter summary table. The key parameters include heating time, cumulative energy consumption, average heating rate (℃ / min) and temperature standard deviation (reflecting uniformity). These data not only provide a quantitative basis for energy consumption characteristics and efficiency evaluation of different heating strategies, but also lay a data foundation for constructing a mathematical model of the heating process [8,10].

5. Experimental Results and Analysis

The experimental data presented in Table 3 are the differences in energy consumption characteristics and efficiency dimensions of different battery heating strategies. PTC heating device, which is widely used in external heating strategy, has the advantages of simple structure and convenient control, but it is accompanied by high energy consumption level and limited heat transfer efficiency. When the 45 ℃ heating scheme is implemented under -30 ℃ environmental conditions, the observation result of the system energy consumption value reaching 2.52 kWh is recorded, accompanied by a temperature difference fluctuation of 11.5 ℃. The example shows that when the setting value of the target water temperature is lowered by 10 ℃, the energy consumption index can be reduced by 9.9 %, and the temperature difference data is only 0.6 ℃. It can be proved that the moderate adjustment of the heating temperature parameters can indeed improve the energy utilization efficiency. In the experimental scenarios below-10 ℃, the energy consumption reduction of 209.5 kJ compared with the traditional method is observed, and the heating time control target within 1956 seconds is realized. These examples together prove the significant advantages of the strategy for energy reuse.

Table 3. Parameters of Various Heating Strategies under Different Conditions

Strategy Type	Ambient Temperature (℃)	Heating Time (s)	Rising rate of temperature (℃/min)	Changes in energy consumption	Changes in temperature difference	Remarks
PTC heater control strategy	-10	5835	0.27	Energy consumption 1.7kWh	25	Table 3 Parameters of various heating strategies under different conditions Battery pack inlet temperature must be below 45℃, PTC module temperature must not exceed 110℃
Waste heat recovery system	0	1,667	0.54	Reduce 460.7 kJ	15	Compared with traditional methods
Waste heat recovery system	-5	1,784	0.67	Reduce 406.4 kJ	20	Compared with traditional methods
Waste heat recovery system	-10	1,956	0.77	Reduces 209.5kJ	30	Compared with traditional methods
Pulse heating test	-30~0	369	5.8℃/min (Increase by 20 % ~ 49 %)	Energy consumption 0.8 kWh	1.1	Improvement of more than 4 times compared to WTC heating rate
Battery self-heating	-20~-10	442	1.36	Energy consumption 0.51 kWh	Reduce 0.5	Compared to external heating methods
Change target water temperature	-30	463	Decrease 15%	Reduce 3%	Increase by 0.2	Fast charging time increases, energy consumption decreases
Set target water temperature to 45℃	-30	4307.2	1.04	Energy consumption 2.52 kWh	11.5	Comparison with different target water temperature
Set target water	-30	4105.7	0.95	Decrease	Decrease	Compared with the target

temperature to decrease by 10℃				9.9%	0.6	water temperature of 45 ℃
Set target water temperature to increase by 10℃	-30	4610.9	1.11	Decrease 3.2%	Increase 0.9	Compared with the target water temperature of 45 ℃

Internal heating mechanisms such as battery self-heating and pulse heating demonstrate superior heating performance and lower energy loss during experiments [9]. Taking self-heating mode as an example, test data in the -20℃ to -10℃ low-temperature range show that a heating rate of 1.36℃/min can be maintained, with a heating duration control effect within 442 seconds significantly outperforming external heating methods. Pulse heating technology exhibits more rapid thermal response characteristics within the -30℃ to 0℃ operating range, with its heating rate exceeding traditional WTC methods by four times, with values above 5℃/min being stably measured. This strategy also significantly reduces fast charging time, with experimental records showing a reduction in charging duration from 20% to 49%. These examples collectively indicate that internal heating strategies not only optimize thermal management efficiency but also make substantial contributions to improving battery charging performance.

The experimental data demonstrates the differences in energy consumption characteristics and efficiency among various battery heating strategies. The PTC heating devices, widely used in external heating strategies, though advantageous in structural simplicity and control convenience, are accompanied by high energy consumption levels and limited heat transfer efficiency. When implementing a 45℃ heating scheme under a -30℃ environmental condition, the system's energy consumption value reaches 2.52kWh, a recorded observation that is accompanied by a 11.5℃ temperature difference fluctuation phenomenon. Examples show that when the target water temperature setpoint is reduced by 10℃, the energy consumption index can achieve a 9.9% reduction, with the temperature difference data being only 0.6℃, thereby proving that appropriately lowering the heating temperature parameter can indeed improve energy utilization efficiency. In experimental scenarios below -10℃, an observed reduction of 209.5kJ in energy consumption compared to traditional methods, along with achieving the heating duration control target within 1956 minutes, collectively substantiate the significant advantages of this strategy in energy reuse.

Through Fig.2, it can be more intuitive to show that the pulse heating energy consumption is the lowest, which is 1.50 kWh at -30°C and 0.70 kWh at 0°C. PTC heating energy consumption is the highest, reaching 2.52 kWh at -30°C and 1.80 kWh at 0°C. The energy consumption of waste heat recovery system and battery self-heating is between the two, and with the increase of temperature, the energy consumption of the four strategies decreases, and the gap trend is stable. This shows that pulse heating has significant energy efficiency advantages in the low temperature range, which provides a basis for the selection of extreme cold environment strategies, as shown in Figure 2.

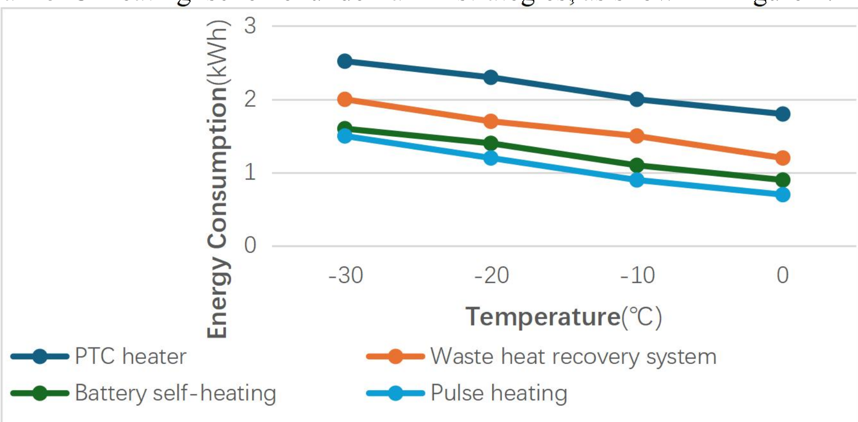

Figure 2. Comparison of Energy Consumption and Efficiency for Difference Battery Heating Strategies

Energy loss primarily stems from insufficient thermal conduction performance, suboptimal system control logic, and the joule heating effect caused by changes in battery internal resistance. During the implementation of the target water temperature strategy, it can be observed that even with limited reduction in heating duration, a 10℃ temperature increase still leads to an observed increase in temperature difference of 0.9℃. The fact that PTC devices can reach high temperatures of up to 110℃ during operation needs to be addressed. If the temperature at the battery pack inlet is not effectively controlled, the thermal management system will face additional energy consumption issues. Research efforts on introducing phase change materials to improve thermal response rates, systematically optimizing thermal conduction paths, and the comprehensive application of dynamic regional heating technology are urgently needed.

6. Conclusion

A systematic examination of the energy consumption and efficiency characteristics of various battery heating strategies has yielded several practical conclusions. Data shows significant differences exist between external heating and internal heating modes, specifically in energy consumption indicators and efficiency parameters. Although external heating methods are relatively mature technologically, their overall heating efficiency remains low, primarily due to significant heat loss and the constraints of complex system architecture [10]. More superior performance is seen in internal heating strategies, particularly in terms of improved thermal utilization and enhanced temperature field uniformity. Metal foil resistance heating and AC heating constitute the two mainstream internal heating implementation paths: the former offers faster heating rates and more precise temperature control, but its structural design complexity and high manufacturing costs are drawbacks; the latter does not require additional heating elements, achieving self-heating through AC excitation that induces internal impedance effects in the batteries, making this technology promising for practical applications.

The factors determining the performance of various heating strategies exhibit diversification characteristics. In the energy consumption process of metal foil resistance heating, the energy consumption is primarily related to two variables: the magnitude of applied power and the duration of action. The energy consumption characteristics of AC heating are closely coupled with the variation relationship between current intensity and frequency values. Examples show that optimizing and adjusting the above parameters can effectively improve thermal conversion efficiency and achieve energy consumption reduction. It is worth noting that the fluctuation of battery internal resistance with environmental conditions has been proven to have a significant impact on heating energy consumption under low-temperature conditions—in the case of ternary lithium batteries, their internal resistance value shows a sharp upward trend under low-temperature conditions, leading to the phenomenon where part of the electrical energy is converted into ineffective heat energy [11]. Therefore, it is necessary to focus on the characteristic curves of battery materials changing with temperature and their corresponding electrochemical reaction laws in practical engineering applications [12].

There are still several limitations in the current stage of research that need to be pointed out. The majority of heating strategies are still in the laboratory verification stage and have not yet been realized in large-scale engineering applications. The phenomenon of excessive loss is often ignored in the energy consumption calculation of traditional models, and the dynamically changing internal resistance of the battery is its root cause, thus affecting the accuracy of actual energy consumption evaluation. The construction of dynamic models for the heating process should become a key direction for future research, and the development of intelligent control strategies should not be overlooked, as both aspects are of significant importance for improving system adaptability and energy efficiency. Examples show that precise heating in key areas can be achieved by combining predictive algorithms with real-time temperature monitoring. The expansion of the application field of phase change materials and the dynamic development of impedance matching technology have created new possibilities for the continuous improvement of heating efficiency [13].

From the perspective of engineering practice, the improvement of overall performance in electric vehicles urgently requires the optimization of battery heating strategies. The goal of refined management has been achieved after the introduction of intelligent control systems, effectively controlling energy waste. The application of new thermal conductive materials shows a positive trend, and the high-level coordination between thermal management systems and battery management systems also demonstrates positive results. If a mechanism for the recovery and utilization of waste heat resources can be established, the energy utilization rate within the system will gain further improvement potential. These technical improvement measures not only directly improve the user experience under low-temperature conditions but also lay a solid foundation for the iterative upgrade of next-generation battery management systems [14].

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