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Research On Thermal Management of Non-uniform Thermal Characteristics and Environmental Coupling Wound Batteries

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ABSTRACT

Thermal safety remains a critical challenge for lithium-ion batteries (LIBs) in electric vehicles and energy storage systems, especially under extreme temperatures. Existing thermal models often fail to adequately capture the coupled effects of internal non-uniform heat generation and environmental thermal loads. In this paper, a battery thermal management design method based on electro-thermal coupling modeling and multi-parameter collaborative optimization is proposed. By integrating COMSOL Multiphysics multi-physics field simulation and MATLAB optimization algorithms, a numerical model that can accurately describe the non-uniform heat generation and heat dissipation characteristics of the battery is established. It comprehensively considers multiple physical source terms and actual heat dissipation boundary conditions, and uses linear stretch mapping to achieve equivalent flattening modeling of the winding structure, balancing computational efficiency and accuracy. Experimental and optimization results show that there is a significant current and heat aggregation effect in the electrode tab area, which clearly identifies this area as the core sensitive region for thermal management. Further research reveals that low-temperature conditions (-10°C) can lead to intensified internal temperature rise and deteriorated temperature distribution in the battery, which poses an important need for revision of traditional thermal management strategies. Ultimately, the key thermal parameters obtained through multi-objective optimization exhibit good robustness and can be used for accurate prediction of battery thermal behavior under different operating conditions.

KEYWORDS

Thermal management of lithium-ion batteries; Electro-thermal coupling modeling; Parameter optimization; Thermal aggregation at the tab; Low-temperature thermal behavior

1 Introduction

Lithium-ion batteries are the core components of electric vehicles and energy storage systems, and their thermal safety directly determines the performance, lifespan, and reliability of the entire system. With the accelerated development of lithium-ion batteries towards high energy density and high-rate applications, wound-type batteries are widely used in energy storage and vehicle applications due to their advantages in processing efficiency and adaptability. However, the non-uniform heat generation caused by their spiral structure, combined with complex thermal responses under extreme environmental conditions, makes accurate thermal modeling and environmental coupling a central challenge for improving thermal management and ensuring operational safety.

In recent years, research on the thermal behavior of lithium-ion batteries has grown significantly. Many scholars have focused on developing accurate thermal models and effective thermal management strategies. For instance, Jindal et al [1]. systematically validated the applicability of the Bernardi equation under real-world driving pulse conditions and found that it significantly overestimates heat generation, highlighting the limitations of traditional methods in practical EV operating scenarios and underscoring the need for corrective approaches. Wu Bin et al [2]. conducted systematic studies on thermal parameter estimation, simulation, and design for laminated lithium-ion power batteries. They identified thermal conductivity anisotropy and heat exchange between tabs and the cell as major factors affecting temperature distribution and proposed a thermal-based method for determining capacity limits. Although their work offers valuable insights into thermal characteristics, it does not address the intrinsic non-uniformity in wound cells or environmental coupling.Qu Jie et al [3]. established a detailed finite element model including all microscopic layers for a prismatic wound pouch battery and progressively simplified it using a representative volume element approach. They demonstrated that the simplified model could reduce computational cost while accurately predicting mechanical deformation and failure under load, making it suitable for full-vehicle or electronics simulations. Nonetheless, their model does not explicitly incorporate non-electro-thermal coupling or environmental thermal interactions. Safdari et al [4]. numerically investigated the thermal performance of three phase change material encapsulation structures in a hybrid passive-active thermal management system. They found that a circular structure performed best under high temperatures, while a rectangular layout promoted more uniform airflow during active cooling. However, their study primarily focuses on system-level optimization rather than internal battery thermal mechanisms.Zhu et al [5]. designed four cooling channel configurations for an immersion cooling system (BICS) and used orthogonal experiments and multi-objective optimization to improve

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temperature uniformity and cooling efficiency of the battery pack. While effective for external thermal management, their approach does not consider internal electro-thermal non-uniformity within the cell. Similarly, Feng et al [6]. proposed and validated a global optimization strategy for liquid cooling under extreme temperatures, achieving improvements in temperature uniformity and energy consumption. Yet, their energy-saving strategy does not account for internal heat generation variability or its interaction with environmental conditions.

Although notable progress has been made in thermal modeling and management strategies, current studies often overlook the internal non-uniform heat generation in wound batteries and its coupling with non-uniform heat dissipation under real environmental conditions. In particular, there is a lack of research on simulating non-uniform surface-environment heat exchange or quantifying the impact of extreme seasonal conditions on internal temperature distribution.

In summary, this study employs a multidisciplinary approach combining multi-physics modeling and system optimization to address these research gaps. The main contributions are as follows:

Develops a high-fidelity 3D electro-thermal model for wound LIBs that incorporates realistic environmental coupling.

Proposes a novel linear stretch mapping method for efficient and accurate simulation of flattened battery geometry.

Identifies and quantifies current and heat aggregation effects at the tabs as a critical thermal risk.

Reveals exacerbated thermal non-uniformity under low-temperature conditions (-10°C).

Establishes a robust multi-parameter optimization framework for key thermal parameters.

Firstly, based on the COMSOL Multiphysics platform, a high-fidelity electro-thermal coupled model of the wound battery is developed. This model incorporates non-uniform joule heating, overpotential, and entropic heat effects, and introduces non-uniform heat exchange boundaries to simulate typical winter and summer environmental conditions. Subsequently, a parameter optimization framework is implemented in MATLAB. Through co-simulation and empirical data, key thermal parameters including thermal conductivity and convection coefficients are inversely identified, significantly improving the model ' s predictive accuracy and robustness.

2 Model construction and simulation of wound battery

2.1 Thermal model and heat transfer theory of lithium-ion batteries

The heat generation during battery operation is the core driving factor for temperature changes. To quantify this fundamental heat source, this study employs the classic Bernardi heat generation formula to calculate the volumetric heat generation rate at various locations within the battery.

Bernardi [7] derived the expression for the heat generation of a battery based on the first law of thermodynamics as：

$$q = -IV - \sum_l I_l T^2 \frac{d \frac{U_{l,avg}}{T}}{dT} + \sum_j \frac{d}{dt}\Big[\int_{\upsilon_j} \sum_i c_{i,j} RT^2 \frac{\partial}{\partial T} \ln\Big(\frac{\gamma_{i,j}}{\gamma_{i,j}^{avg}}\Big) d\upsilon_j\Big] + \sum_{j,j\neq m} \sum_i \Big[\Big(\Delta H_{i,j\to m}^0 - RT^2 \frac{d}{dT} \ln \frac{\gamma_{i,j}}{\gamma_{i,j}^{avg}}\Big) \frac{dn_{i,j}}{dt}\Big]$$

The Bernardi heat generation model can be simplified to, after ignoring the mixing heat and phase change heat.

$$q = I(U - V) - I\Big(T \frac{\partial U}{\partial T}\Big)^{[2]}$$

In the formula, I represents current, V represents voltage, U represents equilibrium potential, and T represents temperature. The first term on the right side of the formula indicates the sum of Joule heat and reaction heat, while the second term represents entropy heat, which is related to the change in entropy during the electrochemical reaction.

However, heat generation is not evenly distributed and strongly depends on the local electrochemical reaction rate within the battery. To describe the speed of the charge transfer reaction at the electrode-electrolyte interface, this study introduces the Butler-Volmer kinetics equation for electrode reactions:

$$i = i_0 \Big[\exp\Big(\frac{\alpha_a F}{RT}\eta\Big) - \exp\Big(-\frac{\alpha_c F}{RT}\eta\Big)$$

The equation quantitatively characterizes the nonlinear relationship between the local current density and the electrochemical overpotential, determines the magnitude and distribution of the overpotential in the heat generation formula, and serves as the basis for calculating the local polarization heat and reaction heat.

On the other hand, the reaction rate and heat generation distribution are restricted by the internal electric field and ion field of the battery. The migration process of lithium ions in porous electrodes and separator electrolytes follows the law of conservation of ion charge, and the electrolyte potential equation can describe this process:

$$\nabla \bullet (\sigma_{eff} \nabla \varphi_l) = 0$$

The distribution of the electrolyte phase is solved in the equation, which can calculate the voltage drop caused by ion transport, and thereby accurately obtain the real potential distribution inside the battery and precisely calculate the local overpotential and current density.

All the heat generated by the aforementioned electrochemical processes leads to the temperature distribution and evolution of the battery as a whole. This study simulates the macroscopic result of this heat transfer through the solid heat conduction equation:

$$\rho_b c_{p,b} \frac{\partial T}{\partial t} = \nabla \bullet (k_b \nabla T) + q_b \text{ [8]}$$

This equation embodies the law of conservation of energy and serves as the ultimate carrier for all thermal field simulations. It integrates all heat generation and dissipation mechanisms and ultimately outputs the observable temperature field.

2.2 Research ideas and methods

First, key model parameters were determined through a comprehensive literature review and experimental data collection. Subsequently, a three-dimensional electro-thermal coupled model of a wound battery was developed, incorporating non-uniform heat generation and dissipation effects. The model parameters were then optimized and calibrated using multi-source data. Finally, the model's accuracy and reliability were validated by simulating its performance under two typical operating conditions (summer and winter). This methodology effectively overcomes the limitations of traditional thermal models, enabling more accurate predictions of battery thermal behavior.

2.3 Model construction and simulation settings

2.3.1 Geometric modeling

This study established a simplified three-dimensional model of a wound battery based on the COMSOL Multiphysics 6.3 platform. Compared with the traditional complex helical geometry, the flattened geometry representation, although ignoring the local curvature effect of the layers, can significantly reduce the number of mesh elements and improve computational efficiency. Moreover, by comparing the temperature and potential distribution maps, it was found that this flattening transformation can reproduce the results of the original cylindrical wound battery to a certain extent, proving that the impact of the transformation on the results is limited.

In this study, each layer in the roll and the tabs are drawn as rectangular prisms. The layers are divided into two parts: centered on the positive and negative current collectors, the length of each part is based on the corresponding current collector. Each separator is divided into two domains at the middle thickness, located respectively in the negative and positive parts. Finally, the geometry is defined as an assembly, with assembly interfaces located between the separators and electrodes, facilitating meshing and boundary condition setting.

Table 1 Model geometric parameters

Component	Length (cm)	Thickness (□)	Material
Positive electrode current collector	20.581	200	NMC 111, LiNi0.33Mn0.33Co0.33O2
Negative electrode current collector	22.835	200	Graphite, LixC6 MCMB
Positive electrode	20.581	10	Aluminum
Negative electrode	22.835	10	Copper
Diaphragm	—	30	LiPF6 in 3:7 EC:EMC
Negative electrode tab	0.4	100	Nickel

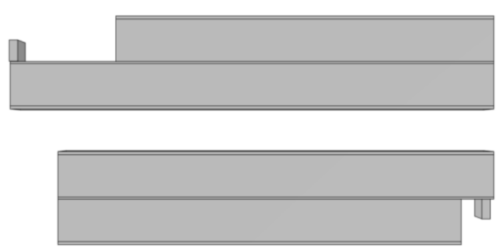

Figure 1 Schematic diagram of lithium battery structure

2.3.2 Selection of physical fields and boundary conditions

This study selected two physical field interfaces: secondary current distribution (cd) and solid heat transfer (ht). The secondary current distribution interface is used to simulate the current distribution and electrode reactions in the battery, while the solid heat transfer interface is used to simulate the temperature distribution of the battery. The two physical fields are coupled through the electrochemical heat node in the multiphysics coupling, which transmits the heat source calculated in the current distribution model to the heat transfer model.

The boundary conditions are set by integrating the actual heat dissipation environment and structural characteristics of the battery. In the current distribution model, an electrical ground condition is applied at the negative terminal, and a total current of 1C is applied at the positive terminal. In the heat transfer model, convective cooling boundary conditions are applied to the external area of the battery. Based on the geometric features and cooling conditions of different regions on the battery surface, three independent convective cooling boundaries are set: side cooling, end cooling, and tab cooling, with different convective coefficients. By reflecting the actual working conditions, it is possible to accurately capture the non-uniform temperature distribution caused by the structure.

Furthermore, to achieve equivalent coupling between the flat geometry and the real spiral winding structure, a linear stretching operator was introduced at the middle boundary of the separator, mapping each point on the source boundary to the corresponding position on the target boundary to ensure the continuity of temperature and electrolyte potential.

2.4 Parameter optimization and model verification based on MATLAB

To ensure the prediction accuracy of the electro-thermal coupling model and address the issue that key physical parameters are difficult to be precisely determined through experiments directly, this study has established a data processing, parameter inversion and model validation system with MATLAB as the core platform.

2.4.1 Collaborative simulation and data analysis framework

Firstly, read the multi-physics simulation data output by COMSOL, including the temperature field, current density field, heat generation field, etc. Based on the battery's geometric structure, define the coordinates of key feature points. By calculating the spatial distance, automatically extract the simulation temperature values of these points.

Then, multi-physics field data analysis was conducted, with independent statistical analysis and spatial distribution visualization of heat generation power, positive and negative electrode current density, etc., to reveal the non-uniformity of heat generation and current distribution inside the battery, and to provide target constraints for parameter optimization.

2.4.2 Parameter inversion optimization model

The optimization objective of this study is to minimize the difference between the simulation results and the reference data, and the core is to construct a parameter inversion problem.

Firstly, six key physical parameters that are most sensitive to the temperature field are selected as optimization variables, including: the thermal conductivity of the positive electrode, negative electrode, and electrolyte, as well as the convective heat transfer coefficients at the side surface, end surface, and tab of the battery.

Then, a weighted cost function centered on the temperature of the feature points is constructed. Considering the absolute temperature, temperature rise, and temperature gradient under summer/winter conditions comprehensively, and introducing parameter rationality constraints and relationship constraints, the sequential quadratic programming algorithm is selected. The optimization takes the current parameter settings in the COMSOL model as the initial point and conducts an efficient search within the given physically reasonable parameter range to obtain the global optimal solution.

Table 2 Optimize reference data

Parameter Name	Value	Material
Radial thermal conductivity of NMC [9]	1.13	$W/(m\bullet K)$
Axial thermal conductivity of NMC	23.16	$W/(m\bullet K)$
The convective heat transfer coefficient on the surface of the battery cell [2]	3.5	$W/(m^2\bullet K)$
The convective heat transfer coefficient of the surface of the tab	2.8—3.4	$W/(m^2\bullet K)$

2.4.3 Model validation strategy

After the optimization was completed, the generalization ability of the model was verified using the independent working condition validation method.

With the optimized parameter set fixed, the thermal behavior of the model under conditions not involved in the optimization is simulated and calculated. The temperature distribution, total voltage response, and proportion of heat generated by the tab are compared and verified to comprehensively evaluate the model performance from multiple perspectives. The prediction accuracy of the model is quantified through statistical indicators such as the mean absolute error (MAE) and the coefficient of determination (R^2). Finally, the optimization process can automatically generate comprehensive diagnostic charts, including comparison diagrams before and after parameter optimization, temperature distribution curves, and detailed optimization result reports.

Through the above systematic parameter inversion and verification process, this study significantly reduced the model's reliance on artificially assumed parameter values and enhanced its predictive confidence under complex and variable operating conditions.

3 Experimental results and analysis

3.1 Key achievements and discussions

3.1.1 Temperature distribution characteristics

To investigate the impact of summer and winter temperatures on the thermal management system, this study conducted simulation comparisons of the battery under different temperature conditions at 25℃ and -10℃ respectively through COMSOL. The results indicated that there was a significant maximum temperature difference within the battery, with the highest temperature occurring in the core area of the battery and the lowest temperature in the area with better surface heat dissipation conditions.

Under summer conditions, the ambient temperature is set at 25°C, and the overall temperature range of the battery is from 38.04° C to 39.40° C, with a maximum temperature difference of 0.8° C. The high-temperature area is mainly concentrated in the core part of the battery, which is due to the fact that the heat generated internally is difficult to be rapidly transferred to the surface for dissipation. From the temperature cross-section diagram of the Y-Z plane, it can be seen that the temperature is symmetrically distributed and gradually decreases from the core to the surface.

Under winter conditions, the ambient temperature is set at -10° C. The overall temperature of the battery drops significantly, ranging from -1.71°C to 2.90°C, with a maximum temperature difference of 8.5°C. Compared with summer, the temperature gradient under winter conditions is more pronounced. This is because the lower ambient temperature causes the battery surface to dissipate heat more rapidly, resulting in a greater temperature difference between the core and the surface.

By comparing the two working conditions of winter and summer, it is found that the ambient temperature has a significant impact on the thermal behavior of the battery. In the high-temperature environment of summer, the overall temperature of the battery is relatively high, but the temperature difference is small; while in the low-temperature environment of winter, the overall temperature of the battery is relatively low, but the temperature difference is large. That is to say, in summer, the overall heat dissipation should be mainly considered to prevent the battery from overheating; in winter, insulation and heating should be mainly considered to reduce the temperature difference inside the battery and avoid local overcooling.

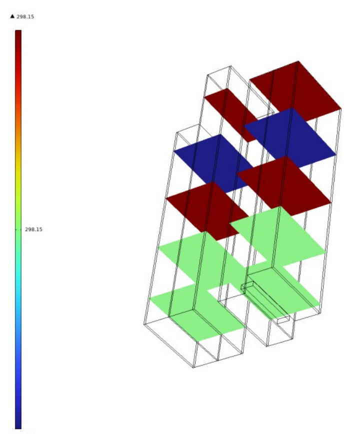

Figure 2 Temperature distribution on the Y-Z cross-section under summer conditions (25°C)

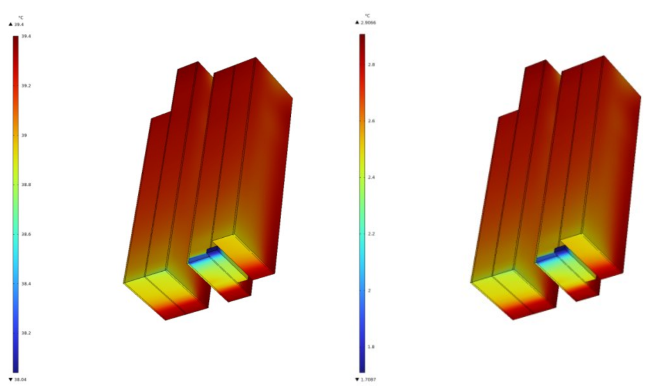

Figure 3 Summer temperatures(25°C) and winter temperatures(-10°C)

3.1.2 Current density distribution

The current density distribution inside the battery is uneven, with a significantly higher current density in the areas close to the tabs. As shown in the figure, the current density reaches its maximum near the tabs and gradually decreases as it moves away from them.

This uneven current distribution will cause uneven heat generation inside the battery, further exacerbating the non-uniformity of the temperature distribution. During high-rate charging and discharging, more heat will be generated in the area near the tabs, which may lead to local overheating and accelerate battery aging. Therefore, in the battery structure design, the position and number of tabs should be optimized to improve the uniformity of current distribution.

This study employed a pseudo-steady-state model and did not take into account the redistribution process of lithium within the battery. If the battery operates for a long time, the distribution will adapt to the changes in the local equilibrium potential, and the current distribution will become more uniform. However, batteries that are cycled for a short time at a fixed state of charge will suffer more electrochemical wear in the areas close to the terminals, which may lead to accelerated aging.

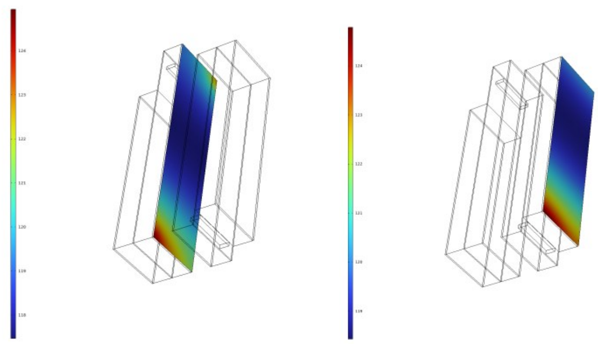

Figure 4 Summer electrolyte current density, diaphragm(25°C)

3.1.3 Potential distribution

Near the negative terminal, the potential is the lowest; near the positive terminal, the potential is the highest. The potential gradually decreases from the terminals towards the interior of the battery, forming a potential gradient.

The non-uniformity of potential distribution can lead to uneven reaction rates within the battery, thereby affecting its performance and lifespan. In regions with higher potential, the electrochemical reaction rate is faster and the utilization rate of active materials is higher; while in areas with lower potential, the electrochemical reaction rate is slower and the utilization rate of active materials is lower. This uneven utilization rate can cause local aging of the battery and reduce its overall lifespan.

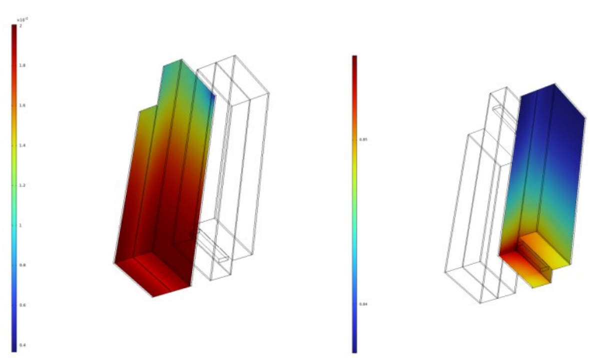

Figure 5 Summer negative and positive electrode potential distribution(25°C)

3.1.4 Heat generation power distribution

Heat generation mainly comes from ohmic heat, reaction heat and polarization heat. Ohmic heat is produced by current passing through the internal resistance, reaction heat is generated by electrochemical reactions, and polarization heat is produced by electrode polarization. The distribution of heat generation power is closely related to the distribution of current density. In areas with higher current density, the heat generation power is also higher. The heat generation power near the tabs is significantly higher than in other areas, which is consistent with the results of the current density distribution. In addition, the simulation results show that the total heat generation power is 2.4340 W under summer conditions and 2.1802 W under winter conditions. This difference is mainly due to the influence of temperature on the battery's internal resistance and reaction rate.

It is worth noting that the heat generated by the tab accounts for 1.01% and 1.13% in summer and winter respectively. Although the proportion is small, due to the poor heat dissipation conditions in the tab area, local hotspots are prone to form, posing a threat to battery safety. Therefore, in the design of the battery thermal management system, special attention should be paid to the heat dissipation of the tab area.

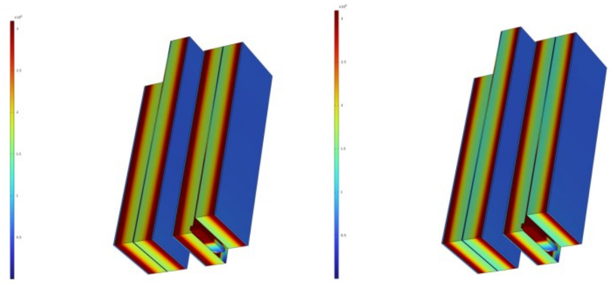

Figure 6 Summer(25°C) and winter(-10°C) heat generation power distribution

3.2 Parameter optimization and thermal management characteristics analysis based on MATLAB

To deeply analyze the thermal behavior of batteries and verify the reliability of model parameters, this study systematically processed and multi-dimensionally analyzed the simulation data based on the MATLAB platform, and formed a complete analysis system from thermal behavior characterization to design parameter verification.

3.2.1 Seasonal temperature characteristics

Based on the MATLAB platform, systematic processing and multi-dimensional analysis of simulation data were carried out. The analysis process strictly followed the set environmental temperature conditions (25°C in summer and -10°C in winter). Temperature data were extracted at four key geometric feature points: the tab, the end, the side, and the core. The heat generation distribution, current density, and thermal physical parameters were comprehensively optimized and verified, forming a complete thermal characteristic analysis system.

The analysis of temperature characteristics shows that the battery exhibits significant thermal behavior differences in different seasons. The temperature range of characteristic points in summer is 37-39°C, with a maximum temperature rise of 14.2°C; in winter, the temperature range is 2-4°C, and the maximum temperature rise is 12.8°C. Although the average temperature rise in summer is higher than that in winter, the temperature rise fluctuation at the core point in winter is more significant, which reflects the problem of decreased thermal conduction efficiency inside the battery in a low-temperature environment. The influence of environmental temperature difference on the average temperature rise is 1.4°C, confirming that the model has the correct response characteristics to environmental boundary conditions.

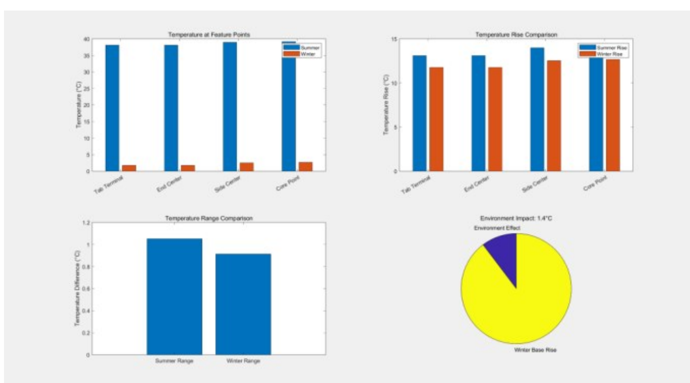

Figure 7 Seasonal temperature comparison chart

3.2.2 Heat production distribution

Analysis of the heat generation distribution pattern reveals the hot spot distribution characteristics inside the battery. The statistics of heat generation density show that the high heat generation areas are mainly concentrated in the side areas close to the tabs. This spatial distribution feature is highly consistent with the subsequent current density analysis results, confirming the physical correlation mechanism of "high current density → high heat generation density".

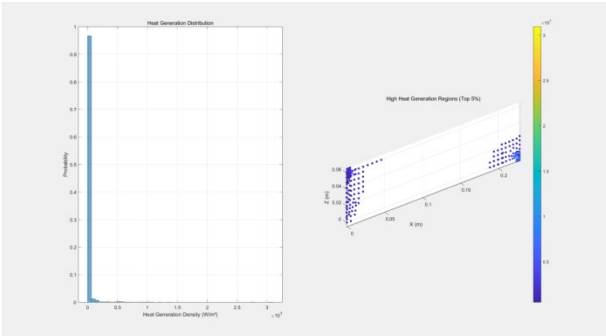

Figure 8 Thermal production distribution analysis map

3.2.3 Current density distribution

The analysis of current distribution characteristics explains the formation mechanism of thermal behavior from an electrochemical perspective. The study quantitatively evaluated by introducing the current crowding factor, finding that the positive electrode crowding factor is approximately 1.4 and the negative electrode crowding factor is approximately 1.2, indicating a more pronounced current concentration phenomenon in the positive electrode region. The spatial distribution analysis further confirmed the aggregation effect of current density near the tabs, which is completely coincident with the aforementioned hot spot area, clearly demonstrating that the uneven current distribution is indeed related to the local heat generation difference.

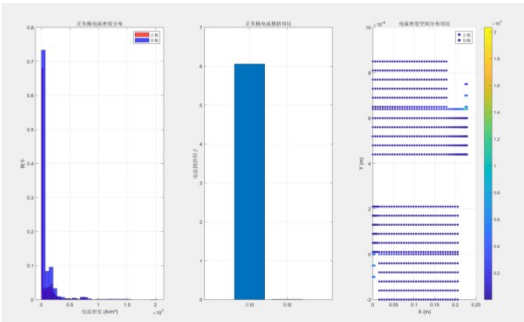

Figure 9 Current density of positive and negative electrodes

3.2.4 Parameter optimization

The parameter optimization verification analysis confirmed the rationality of the initial parameter settings. The results of the optimization algorithm operation showed that the key thermal physical parameters and convective coefficients had no significant changes before and after optimization, with the parameter change percentage approaching zero. This result indicates that the initial parameters already met the temperature control requirements for both winter and summer conditions, namely, the maximum temperature in summer ⩽ 45℃, in winter ⩽ 5℃, and the temperature gradient ⩽ 5℃. It verified the reliability of the parameter settings and provided a reliable parameter basis for the engineering application of the thermal management system.

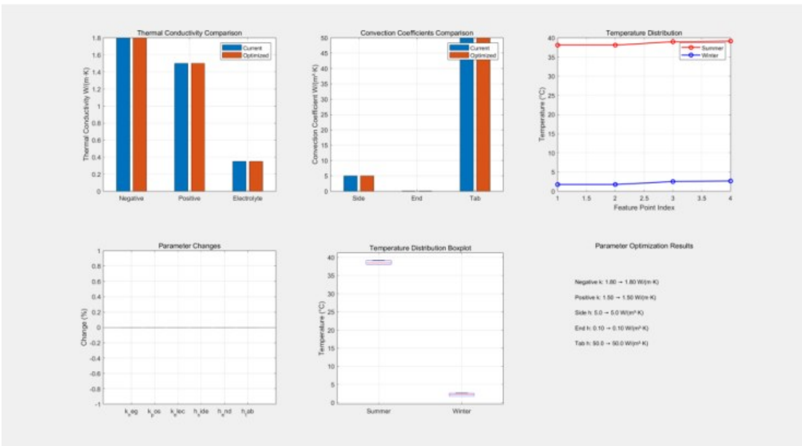

Figure 10 Parameter optimization verification map

4 Conclusion

This study systematically investigated the thermal management issues of wound lithium-ion batteries through multi-physics field modeling and simulation as well as multi-source data collaborative optimization. A high-fidelity electro-thermal coupling model capable of accurately predicting the thermal behavior of batteries under complex operating conditions was constructed. It was found that there is a significant thermal-electrical aggregation effect in the tab area, which is a key area that requires focused attention in thermal management. Additionally, low-temperature conditions exacerbate the internal temperature rise and uneven temperature distribution of the battery, necessitating the development of specialized thermal optimization strategies for this condition. Through a multi-parameter collaborative inversion method, key thermal physical parameters with good robustness were obtained. Multi-condition verification demonstrated that the model has high prediction accuracy and reliability.

Although the research has achieved phased results, there are still limitations brought by model simplification, parameter uncertainty, the absence of aging and mechanical effects, and insufficient validation data. Future research will focus on developing dynamic coupling models, conducting multi-scale experimental verification, and coupling aging and mechanical effects to provide more comprehensive theoretical support and technical means for the precise design and control of battery thermal management systems.

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