Current Situation and Application of Internal Temperature Field Estimation in Li-ion Batteries

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Abstract: As a widely used energy storage device today,precise characterization of the internal temperature distribution within lithium-ion batteries is imperative for enhancing battery efficacy and guaranteeing safety.In this paper, the research status of internal temperature field estimation of lithium batteries is introduced and summarized. First, different types of temperature sensors, are discussed and their advantages and disadvantages are compared. Secondly, the thermal characteristics of the lithium battery and the impact of pertinent parameters on the temperature field was systematically examined and analyzed. Then, the modeling methods of temperature field of lithium battery are described in detail, including electrochemical-thermal coupling model, electric-thermal coupling model and thermal abuse model. Finally, different algorithms for the estimation of internal temperature field of lithium battery are discussed, such as extended Kalman filter, recursive least square method, unscented Kalman filter, etc., and their application in the estimation of internal temperature of lithium battery is analyzed with examples. In general, in-depth understanding of the internal temperature distribution of lithium batteries helps to predict the temperature change during charging and discharging, and improve the performance and safety of the battery.

Keywords: *Lithium-ion batteries; temperature monitoring; thermal models; internal temperature estimation*

I. INTRODUCTION

In the era of environmental protection and energy crisis, new energy sources have demonstrated unique advantages in terms of low power consumption and low emissions. Among them, lithium-ion batteries, characterized by high energy density, long cycle life, and low self-discharge, have become the preferred technology for both stationary and mobile applications, attracting widespread attention[1]. However, in practical applications, the heat generated during the battery operation can impact its performance, induce aging, reduce lifespan, and even lead to thermal runaway, causing safety incidents such as fires or explosions under extreme conditions[2].

Under normal circumstances, lithium-ion battery temperatures within the range of -20℃ to 60℃ can maintain good performance and stability[3], with the optimal operating temperature range being 15℃-35℃[4]. In order to guarantee the secure and steadfast operation of the battery pack, maintain optimal performance, and extend the cycle life, effective monitoring of the battery pack is required. Currently, battery pack surface temperatures are mainly monitored through contact [5,6] or non-contact [7–9] measurement methods. However, internal-surface temperature disparities can impede accurate temperature assessment in battery measurements. To obtain more precise battery temperatures, numerous researchers have conducted studies and analyses, covering various approaches such as analyzing heat generation characteristics, constructing battery models, and utilizing algorithms to estimate internal temperatures [10]. These efforts aim to enhance the battery pack's performance, extend its lifespan, and prevent safety incidents.

Therefore, proper management of the operating temperature of lithium-ion battery packs is crucial for both their performance and safety. Obtaining accurate battery pack temperatures is the first step in ensuring the normal operation of the battery, directly influencing subsequent battery pack management and control. This paper aims to offer a thorough exposition on the operational fundamentals of lithium-ion batteries, encompassing heat generation characteristics, model development, and the estimation of temperature fields.

II. COMPOSITION AND WORKING PRINCIPLE OF LITHIUM BATTERY

Typical lithium-ion batteries comprise a positive current collector, positive electrode, separator, negative electrode, and negative current collector, as illustrated in Fig.1. In commercial lithium-ion batteries, aluminum and copper are typically used as materials for the positive and negative current collectors, respectively. The positive electrode is usually made of a metal material composed of cobalt mixed with nickel, manganese, or aluminum in different proportions [11,12]. Typical embeddable material, graphite, is used as the negative electrode material[12,13]. A separator made of polypropylene or polyimide is employed to prevent direct contact between the positive and negative electrode materials, preventing a short circuit between the two electrodes. The electrolyte facilitates the transfer of lithium ions between the positive and negative electrodes, such as with $LiPF_6$.

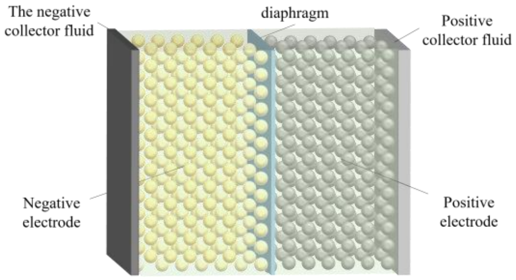


Fig. 1. Components of a lithium battery

The working principle of a lithium-ion battery is illustrated in Fig.2. During charge and discharge cycles, lithium ions undergo insertion and de-insertion, while electrons generated on the electrodes flow through the external circuit. In the charging process, the positive electrode undergoes oxidation, leading to the departure of lithium ions into the electrolyte, while the negative electrode experiences reduction, facilitating the incorporation of lithium ions. Concurrently, electrons generated during oxidation traverse the external circuit from the positive to the negative electrode. In this process, the battery absorbs energy from the external environment, converting electrical energy into chemical energy [14]. The discharge process is the complete reverse of this.

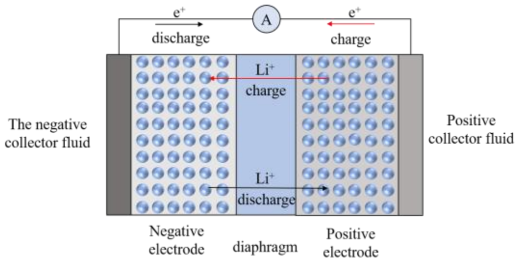


Fig. 2. Lithium battery working principle diagram

Taking a lithium-ion battery with C_6 as the negative electrode and $LiMeO_2$ as the positive electrode as an example, the corresponding partial electrochemical reaction expressions are as follows:

Positive electrode reaction:

$$LiMeO_2 \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{1-x}MeO_2 + xLi^+ + xe^- \quad (1)$$

Negative electrode reaction:

$$C_6 + x\,Li^+ + xe^- \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_xC_6 \quad (2)$$

Overall battery reaction:

$$LiMeO_2 + C_6 \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_xC_6 + Li_{1-x}MeO_2 \quad (3)$$

The working process of a lithium-ion battery involves the de-insertion and insertion of lithium ions into the electrolyte and the migration of electrons in the external circuit.

III. LITHIUM BATTERY TEMPERATURE DETECTION METHODS

The inherent challenge of heat generation in batteries presents a formidable barrier to battery advancement. Ensuring the performance and safety of lithium-ion batteries necessitates the implementation of a resilient temperature monitoring system. Currently, battery temperature monitoring methods can be broadly classified into contact and non-contact measurements[15]. Key characteristics such as measurement range, accuracy, resolution, and cost are crucial for the proper selection of sensors.

A. *Thermistors*

Thermistors are solid-state semiconductor devices whose resistance changes with temperature. A temperature sensor based on thermistors derives the battery temperature from the resistance variation [6]. Thermistors exhibit either a positive or negative temperature coefficient. In the instance of a negative temperature coefficient, resistance diminishes proportionally with rising temperature, demonstrating non-linear characteristics that necessitate calibration for accurate temperature monitoring. Conversely, in the case of a positive temperature coefficient, the resistance increases with temperature, making it suitable for temperature measurement and protective applications.

Thermistors are cost-effective, highly sensitive to temperature changes, and have a broad measurement range, capable of monitoring temperatures from -55℃ to 300℃[16]. Additionally, thermistors can be small in size, with measurement instruments achieving an error of <1mK, and they can maintain long-term stability [17]. In commercial applications, their accuracy is typically ±1℃[18], making them widely used temperature sensors in various applications. In practical applications, thermistors are often attached to the surface or near the battery to quickly obtain battery temperature, as illustrated in Fig.3.

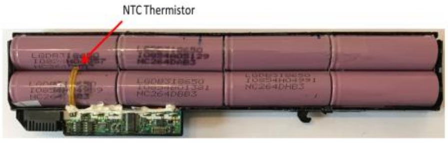


Fig. 3. Thermistors

However, in practical applications, limitations such as space, wiring, and connectivity constraints prevent the extensive deployment of sensors. Only a limited number of sensors can be used for monitoring, especially within lithium-ion battery packs. This constraint impedes the sensors' precision in capturing the battery's peak temperature, thereby potentially giving rise to hazardous circumstances.

B. *Thermocouples*

Thermocouples operate based on the Seebeck effect, measuring the temperature of a battery by detecting the thermoelectric potential difference between two different conductive or semiconductor materials [19]. The measurement principle of a thermocouple is illustrated in Fig.4.

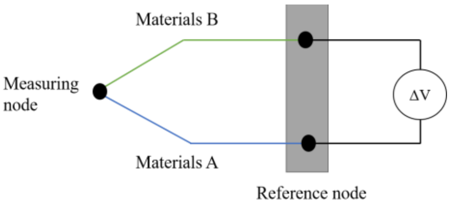


Fig. 4. Schematic diagram of thermocouple measurement

Thermocouples are cost-effective, robust, and have a broad measurement range, making them a standard tool for industrial temperature measurement [20]. With a variety of types available to suit different conditions, thermocouples are widely used in research, accounting for approximately 27% of literature utilizing thermocouples for temperature measurement[21]. However, thermocouple temperature sensors are sensitive to corrosion, requiring regular maintenance. They are not suitable for long-term temperature measurements, and their non-linear relationship with temperature makes obtaining accurate temperature readings more complex [27].

C. *Fiber Bragg Grating (FBG) Sensor*

Unlike thermocouples and thermistors, Fiber Bragg Grating (FBG) sensors acquire temperature information of the battery through changes in wavelength. This is primarily due to the correspondence between the reflective wavelength (λ) of the optical fiber and the grating pitch (Λ) of the FBG [5]:

$$\lambda_B = 2n_{eff}\Lambda \quad (4)$$

where n_{eff} is the refractive index of the optical fiber.When the temperature of the lithium-ion battery changes, it causes a shift in the wavelength of the FBG, as it has a linear relationship with temperature. This temperature information can be rapidly and accurately obtained through demodulation equipment, as shown in Fig.5. Additionally, FBG sensors can achieve multiplexing, requiring fewer materials and simplifying wiring.

Due to its small size, lightweight, strong anti-interference ability, high sensitivity, and long-term reliability, FBG sensors have become a research focus in the field of battery temperature measurement [24]. The monitoring temperature range of FBG depends on the materials used in sensor fabrication, with the material directly determining the monitoring range. Black [25] summarized various fiber and coating materials, providing corresponding temperature ranges. Silicon dioxide is the most standard material, with a temperature range of -273℃ to 1190℃. In comparison, the temperature range of coating materials is smaller. However, between -20℃ and 60℃, the accuracy of FBG sensors can reach ±0.4 to ±0.2℃, with excellent corrosion resistance, making them an ideal choice for internal battery temperature measurement [26,27].

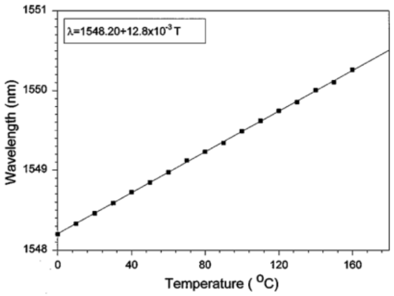


Fig. 5. Temperature and wavelength function diagram

D. Infrared Thermal Imaging

Infrared thermal imaging is commonly used for measuring and displaying the surface temperature of objects. It is a typical non-contact temperature detection method, often employing non-contact devices such as infrared cameras to capture changes in the temperature of batteries. Typically calibrated within the range of 0-120℃, infrared thermal imaging can achieve a thermal sensitivity of 0.03 to 0.09℃ and an accuracy of 2% [28,29]. Using an infrared camera allows real-time monitoring of the entire battery's surface temperature, providing a simple and intuitive measurement method that can validate thermal simulations, as shown in Fig.6.However, the cost of implementing infrared thermal imaging technology is relatively high. Moreover, its measurement accuracy is susceptible to significant external factors such as the surrounding environment, leading to significant measurement errors. Therefore, this technology is not suitable for commercial battery temperature measurement.

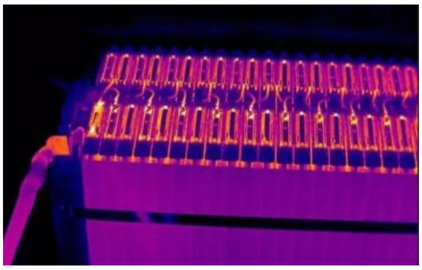


Fig. 6. Infrared Thermal Imaging

IV. THERMAL CHARACTERISTICS ANALYSIS OF LITHIUM BATTERIES

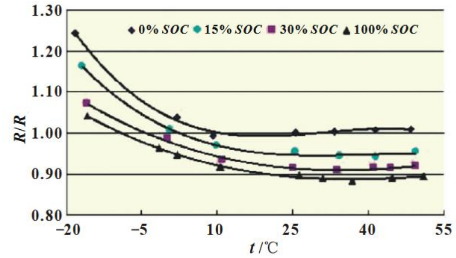
Studying the heat generation of batteries forms the basis of thermal conduction and dissipation research. Understanding the thermal characteristics and the interrelationships between different parts of the battery is crucial for accurately obtaining battery temperature, better utilizing and managing batteries, maintaining their performance, extending their lifespan, and preventing accidents.

In 1985, based on the principle of energy conservation, Bernardi[30] established a formula expressing the heat generation of lithium-ion batteries, describing the general energy balance of the battery system. It summarized that the heat generated by the battery during operation is produced in various ways, including chemical reaction heat, Joule heat, polarization heat, entropy heat, phase change heat, and mixed heat. Although accurate, the expression involves numerous parameters that are not easily measured directly, making the calculation relatively complex. Later, Noboru Sato [31], through thermodynamic experiments and research, confirmed that the heat generated by the battery is mainly related to charge and discharge. He simplified Bernardi's heat generation model, categorizing heat generation factors into reaction heat, polarization heat, and Joule heat, providing valuable insights for further research on the thermal characteristics of lithium-ion batteries.

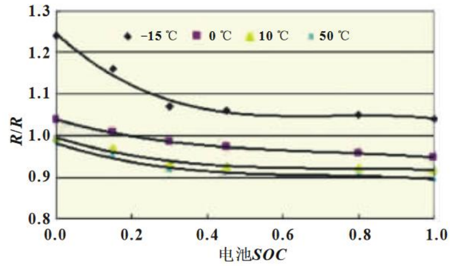
To study the impact of internal resistance on the state of charge (SOC) and temperature of the battery, Zhang Zhijie et al.[32], using lithium manganese oxide batteries as samples, measured the changes in battery internal resistance under different temperatures and operating conditions using a mixed pulse experiment method. The results are shown in Fig.7.

It can be observed that describing the internal resistance value during the battery operation with a variable is more effective than a fixed value, and at the end of discharge, more heat is generated as the resistance increases. Hin Ji Woong [33], through experiments and analysis, concluded that the significant heat generated in the late stage of discharge is due to polarization, leading to an increase in polarization internal resistance.

Yang Yantao[34] studied the influence of capacity, direct current internal resistance, and open-circuit voltage on the battery temperature of pouch-type lithium-ion batteries. It was found that battery capacity and open-circuit voltage have little effect on the heating characteristics of the battery, while direct current internal resistance has a significant impact and is challenging to control.



(1)Variation of Internal Resistance with Temperature Curve



(2)Variation of Internal Resistance with Temperature Curve

Fig. 7. Internal resistance curve

By summarizing the findings, it can be concluded that during the normal operation of the battery, factors such as battery capacity, voltage, and external ambient temperature have little impact on the heating characteristics of the battery. Heat generation is mainly related to the magnitude of charge and discharge currents and the ohmic and polarization heat within the battery. Therefore, in calculations or model construction, simplifying these factors can ensure model accuracy while improving computational efficiency.

V. LITHIUM BATTERY THERMAL MODELING RESEARCH

Lithium-ion battery models are primarily used to describe the thermal behavior states inside and outside the battery and their relationships. They can be broadly categorized into three types: electrochemical-thermal coupling models, thermo-electric coupling models, and thermal abuse models.

A. Electrochemical-Thermal Coupling Model

During the charge and discharge processes of lithium-ion batteries, chemical reactions occur continuously, accompanied by the generation of a considerable amount of heat. The electrochemical-thermal coupling model combines the chemical reactions of the battery with the heat generation to describe the battery's temperature [34].

The team led by John Newman at the University of California, Berkeley, first proposed the electrochemical model[35,36], using theoretical principles such as Fick's law, concentrated solution theory, and Butler-Volmer equation to describe the working process of lithium-ion batteries from a one-dimensional perspective. Subsequently, Bernardi within the same team [30], based on the law of energy conservation, pointed out that the heat generation process of the battery involves multiple heat generation methods, including Joule heat, chemical reaction heat, phase change heat, and mixed heat. They accurately established the heat generation formula for lithium-ion batteries. The Bernardi heat generation rate model is given by:

$$\rho c \frac{\partial T}{\partial t} = \lambda \nabla^2 T + q \tag{5}$$

Where, ρ , c , λ , T and q are the mass density, specific heat capacity, thermal conductivity, temperature gradient, cell resistance, current, temperature, current rate of change, cell voltage, and cell voltage rate of change, respectively.

Weifeng Fang [37] combined the Newman model with the heat generation formula of the battery, establishing a one-dimensional electrochemical-thermal coupling model. Xiao M et al. [38], based on electrochemical and thermal principles, extended the electrochemical-thermal coupling model to two dimensions. Many studies use a simplified version of the Bernardi heat generation rate equation, neglecting the non-uniform heat generation of the battery itself and considering only the main sources of heat generation, i.e., reversible chemical reaction heat and irreversible ohmic heat. This simplification can enhance the model's computational efficiency while ensuring accuracy [41].

The electrochemical-thermal coupling model mainly focuses on the electrochemical reactions inside the battery, allowing for a precise description of lithium-ion batteries. It accurately expresses the heat generation and temperature distribution within the battery. However, the model has lower computational efficiency and faces numerous challenges in practical applications. The primary reason is the need for a large number of parameters, most of which are challenging to measure and calculate directly.

B. Electrical-Thermal Coupling Model

The electrical-thermal coupling model is a type of coupled model that combines the battery circuit with the heat generated by the battery. It aims to quickly obtain the temperature distribution of the battery while ensuring relatively high accuracy.

Park C et al.[42] analyzed the heat generation and dissipation of the battery core and surface based on the law of energy conservation. They established a heat balance expression equation to derive the electrical-thermal coupling model of the battery. However, due to the empirical values of many parameters in the coupling model, the accuracy of the results is relatively poor. Fan He et al.[43] used experimental methods to obtain the required parameter data. They then performed parameter identification through the least squares method to determine the temperature distribution of lithium-ion batteries. The accuracy of the model was verified by measuring surface and internal temperatures as well as temperature changes through experiments. Dong H J et al. [44] constructed a three-dimensional electrical-thermal coupling model for $LiCoO_2$/C batteries. They proposed transient and thermal-electric finite element analysis of cylindrical lithium-ion batteries, studying the temperature changes under different discharge rates. The model considered Joule heat and entropy heat of each battery component, addressing the energy conservation problem and obtaining temperature change curves. Shi Nan [45] identified the first-order RC equivalent circuit parameters for a single 18650 cylindrical lithium-ion battery. They used a thermal imager to collect surface temperatures, calculated battery parameters through the least squares method, established various thermal models for simulating cylindrical lithium-ion batteries to obtain temperature distributions, and experimentally validated surface temperatures.

Compared to the electrochemical-thermal coupling model, the electrical-thermal coupling model simplifies aspects of battery structure design and ignores detailed internal structures and various chemical reactions inside the battery. Although the temperature field distribution obtained is not as precise as that of the electrochemical-thermal coupling model, it still meets practical accuracy requirements. Moreover, it uses fewer computational parameters, resulting in faster computational efficiency, making it more widely used in battery temperature field monitoring.

C. Thermal Abuse Model

The thermal abuse model is an essential tool for studying the safety of lithium-ion batteries. It is primarily used to investigate secondary reactions that occur in batteries under extreme conditions and predict the safety and service life of batteries under abnormal usage scenarios.

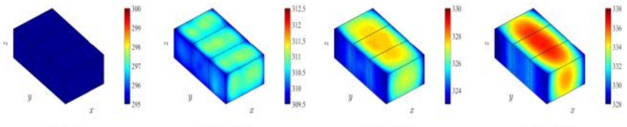
Gi-Heon Kim et al. [46] established a three-dimensional thermal abuse model for lithium-ion batteries to simulate thermal runaway phenomena in a high-temperature environment. By studying the thermal characteristics of batteries with different sizes, they found that larger-volume lithium-ion batteries are more prone to thermal runaway. Coman P T et al. [47] implanted an internal short circuit device into the battery and developed a thermal-electrochemical model based on the Arrhenius equation. They obtained the thermal runaway phenomenon and temperature distribution caused by the internal short circuit. Huang Wencai et al. [48] constructed a three-dimensional layered thermal abuse model, heating lithium-ion batteries to different temperatures. They simulated the variations and heat generation and transfer of lithium-ion batteries under different temperature conditions. The study revealed that the reaction between the positive electrode and the electrolyte is the main source of heat generation when the battery experiences thermal runaway under high-temperature conditions. They also found that the heat transfer coefficient and the initial temperature of the battery are inversely proportional to the time it takes for the battery to experience thermal runaway.

In contrast to the models mentioned earlier that study the thermal characteristics and temperature field distribution of batteries under normal operation, thermal abuse models focus on studying the thermal characteristics of batteries under abnormal conditions, such as high temperatures, short circuits, compression, or puncture. By establishing thermal abuse models, it is possible to predict and analyze parameters such as temperature, voltage, and current under abnormal conditions, understand the safety and lifespan of batteries, and take appropriate measures to ensure the normal operation of batteries and prevent thermal runaway. Moreover, thermal abuse models can provide theoretical references for the design and optimization of batteries.

VI. LITHIUM BATTERY INTERNAL TEMPERATURE FIELD ESTIMATION RESEARCH STATUS

Lithium-ion batteries primarily exhibit two types of temperatures during their operation, namely surface temperature and internal temperature. According to practical experience and existing literature, there exists a significant difference between the internal and external temperatures of lithium-ion batteries. While surface temperature can be directly measured using methods such as attaching temperature sensors, internal temperature cannot be directly measured by sensors. The internal temperature of lithium-ion batteries is a crucial factor in realizing thermal management techniques for these batteries. Therefore, there is a need for research on estimating the internal temperature of lithium-ion batteries to acquire an accurate distribution of the internal temperature field.

Rui Xiong[49] established an equivalent thermal circuit model using the Bernardi heat generation rate model. By discretely expressing the temperature field of the battery using circuit theory, a real-time estimation model for internal temperature and environmental parameters was built using a dual Extended Kalman Filter, achieving online estimation of internal battery temperature. Ping Wang [50], based on the lumped parameter model of lithium-ion batteries, formulated a mathematical model for the internal heat generation resistance concerning temperature, State of Charge (SOC), and cycle counts. They proposed a lithium-ion battery internal core temperature estimation method using a Recursive Least Squares with Forgetting Factor (FFRLS) - Unscented Kalman Filter (UKF) algorithm. Yi Xie[51] and colleagues considered a cylindrical battery as three nodes and developed a one-dimensional heat model. In the temperature estimation process, they identified internal resistance and estimated SOC. They employed a one-dimensional heat model combined with a Dual Kalman Filter algorithm to estimate the internal temperature of lithium-ion batteries. The accuracy of the internal temperature estimation was enhanced by considering the anisotropy of different directional thermal conductivity coefficients, leading to the identification of equivalent thermal conductivity coefficients. Liu Xintian et al. [52] proposed a lithium-ion battery internal temperature estimation method based on a simplified variable parameter model. By identifying the internal heat capacity and external thermal resistance of the battery under different environmental temperatures, a variable internal heat capacity and external thermal resistance estimation model was established. Subsequently, in conjunction with the extended Kalman filtering algorithm, internal temperature estimation of the battery was achieved. Ning Tian et al. [53], based on the Bernardi heat generation model and the thermal conduction relationship of the battery, employed the Kalman filtering algorithm for the first time to reconstruct the temperature field of a three-dimensional square lithium battery pack. The battery was divided into N nodes in a three-dimensional grid, with different divisions for the battery core and casing. Finite difference equations for each node were derived based on the law of energy conservation. The Kalman algorithm was then used to describe the state-space representation equation, ultimately achieving the distributed Kalman estimation of the internal temperature field of the entire battery pack. The results are shown in Fig.8.



(a) $t = 0$ s (b) $t = 240$ s (c) $t = 480$ s (d) $t = 1200$ s

Fig. 8. DKF-based temperature field reconstruction

JiangongZhu[54] focused on the electrochemical equilibrium phenomenon during the short-term relaxation time of batteries and researched an impedance-based temperature estimation method. Through experimental analysis, they found a regularity in the impedance of the battery during short-term relaxation time after discontinuing current excitation. An exponential equation was established to correct deviations caused by measuring phase shifts and relaxation times resulting from electrochemical imbalances. The temperature gradient between the internal and surface of the battery was considered, and a multivariate linear equation coupled with environmental temperature was provided. They established an internal temperature estimation model, predicting the internal temperature of the battery.

Pan Guobing[55], addressing the issue that non-contact infrared temperature measurement methods cannot monitor the internal temperature field of a battery stack, proposed a three-dimensional temperature field reconstruction method based on the surface temperature field and a virtual heat source. This method initially employed a segmentation algorithm to separate the effective area, mapping it into a surface temperature field using calibration, and thus preliminarily reconstructed the three-dimensional temperature field. Subsequently, a virtual heat source was used to correct the temperature of individual subunits, providing an accurate and intuitive reflection of the internal temperature distribution within the battery stack.

By estimating the internal temperature field of lithium-ion batteries, a better understanding of the internal heat distribution of lithium-ion batteries can be obtained. This enables the prediction of temperature variations during charge and discharge processes, as well as the uneven distribution of temperatures. Such insights are valuable for determining the maximum internal temperature of the battery and identifying potential hotspots or local overheating areas. Consequently, appropriate measures can be taken to reduce the operating temperature of the battery, maintain its performance, and enhance the battery's lifespan, safety, reliability, and performance.

VII. CONCLUSION

This article provides a comprehensive overview and summary of the estimation of the internal temperature field in lithium-ion batteries. Through an integrated analysis of existing research findings, the paper elaborates on various aspects related to the estimation of the lithium battery temperature field, including temperature sensors, battery thermal characteristics, thermal models, and internal temperature field estimation.

Firstly, the article introduces the types of temperature sensors used for lithium battery temperature measurement, including contact and non-contact sensors, and compares and analyzes their advantages and disadvantages. Secondly, it discusses the thermal characteristics of lithium batteries, analyzing the impact of relevant parameters on the distribution of battery temperature fields. Then, it introduces methods for modeling the temperature field of lithium batteries, elucidating the strengths and weaknesses of thermal models and their applicable ranges. Finally, the paper provides an exposition on the research into the estimation of the internal temperature field of lithium batteries.

The research indicates that during the charging and discharging processes, lithium-ion batteries generate a significant amount of heat, which may lead to issues such as elevated battery temperatures and thermal runaway, posing safety concerns. Therefore, understanding the distribution of internal temperatures is crucial for enhancing the performance, safety, and reliability of lithium-ion batteries.

In summary, the estimation of the internal temperature field in lithium-ion batteries is a vital direction in lithium-ion battery research. By comprehensively analyzing existing research achievements, this article offers a comprehensive introduction to the key technologies and methods involved in estimating the temperature field of lithium batteries, highlighting their role in improving the performance and reliability of lithium-ion batteries.

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