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A method to predict the lithium-ion battery internal temperature

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Abstract: The estimation accuracy of lithium-ion battery internal temperature is not high, which may cause thermal runaway fire and other safety problems. In this work, Electrochemical impedance spectrum (EIS) is used to study the variation law of battery temperature. A new battery internal temperature estimation method independent of SOC and SOH is proposed. The law of impedance variation with temperature is studied. The internal relationship between the temperature and the imaginary part of the characteristic quantity is found under different temperatures. The temperature prediction model of lithium-ion batteries is established, and experiments verify its accuracy. The results show that the battery's internal temperature can be accurately predicted even when the SOC and SOH of the battery are unknown. This prediction method has great application prospects in the real-time monitoring of the lithium-ion batteries internal temperature.

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1. Introduction

The lithium-ion battery (LIB) is one of the essential components of new energy vehicles. The state of the LIB needs to be monitored in real-time to ensure the regular operation and safety. Battery internal temperature is one of the most critical parameters in the working process of a battery[1]. The online detection of battery temperature change plays a vital role in battery life and safety. However, external temperature sensors (thermocouple and resistance temperature detector) are usually used to obtain the temperature in the current battery temperature estimation method. These sensors are suitable for surface temperature monitoring but only cover a limited battery surface area. Due to the thermal conductivity varies significantly in all directions of a lithium-ion single battery, the maximum temperature difference in the thickness direction can reach 20 ° C. The traditional method of measuring battery surface temperature is difficult to truly reflect the internal temperature of a LIB[2]. In addition, the thermal inertia of the battery may cause a significant time delay between the surface temperature signal and the internal temperature signal. The hot spots may not be recognized, making it difficult to obtain the real temperature inside the battery. Suppose the battery surface temperature or ambient temperature is directly used for calculation which will lead to a large error in battery state estimation, resulting in the excessive internal temperature of individual batteries and fire[3]. Therefore, real-time detection of internal battery temperature is the key to reducing and eliminating battery safety accidents.

Electrochemical impedance spectroscopy (EIS) is a classical chemical measurement method. In the past 20 years, EIS has been widely used in the research and production of LIB. Some scholars proposed the method to estimate the internal temperature of LIB by using some characteristic quantities of EIS. The method of using EIS has the following advantages: (1) it can maintain the complete structure of the battery without damaging the battery structure such as an embedded thermocouple; (2) the internal temperature of the battery can be obtained in a very short time. Therefore, EIS has attracted more and more attention in estimating the internal temperature of LIB.

In this work, EIS is used to study the variation law of battery with different temperature. A new battery internal temperature estimation method independent of SOC and SOH is proposed. The experiments verify the accuracy of the temperature prediction model. The results show that the battery's internal temperature can be accurately predicted even when the SOC and SOH of the battery are unknown. This study provides an effective strategy for real-time monitoring of the battery's internal temperature.

2. Experimental method

The batteries used in the experiments were assembled in a glove box. The EIS data was obtained at an electrochemical workstation (SP-200, Biologics) with 5 MV AC amplitude and 100 mHz -7 MHz frequency range. The oven controlled the required test temperature. The temperature gradient of the oven was 0°C, 10°C, 20°C, 30°C, 40°C, 50°C, and 60°C. The battery is put in the oven for 2 hours after reaching each temperature gradient. The battery's internal temperature is considered equal to the oven's set temperature at this time. Battey testing system (NEWARE, BTS4000) was used for charge and discharge tests. The schematic diagram of the experimental setup is shown in Fig. 1.

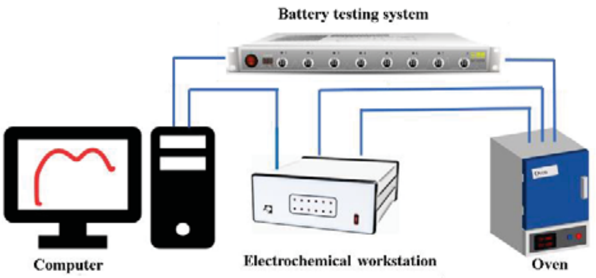

Figure 1. Schematic diagram of the experimental device

3. Results and discussion

3.1 Influence of temperature on EIS

Almost all diffusion processes in lithium-ion batteries are affected by temperature. The self-exothermic heat and ambient temperature in the charging and discharging process of the battery affect the charge transfer and the deintercalation of lithium ions in the electrode active material.

The thermal effect of the battery EIS was studied as shown in Fig. 2(a). The temperature slightly influences the high-frequency impedance but greatly influences the low and middle-frequency impedance in the range of 0 ~ 60°C. It can be found in Fig. 2(b) that the impedance gradually decreases with temperature increase within the normal operating temperature range. This is because the temperature increase will accelerate the lithium-ion transfer rate, and the REDOX reaction rate at the electrode will also increase. The high reactant activity decreases the interfacial impedance and charges transfer impedance. Moreover, high temperature increases the embedding and de-embedding rates of lithium ions. It weakens the influence of concentration polarization caused by battery SOC on the diffusion rate of lithium ions.

The optimal excitation frequency range is determined to be 0 ~ $5x10^4$ Hz to simultaneously exclude the influence of battery SOC and SO. Figure 2(c) obtained the imaginary part value curve of the battery at different temperatures. It can be seen that the imaginary part has an obvious relationship with temperature. The imaginary part changes obviously with the change in the internal temperature of the battery. Therefore, it is feasible to estimate the battery's internal temperature by using the characteristic quantity (imaginary part) of the EIS.

When the excitation frequency exceeds $5x10^4$ Hz, the curves even tend to coincide with each other. Too close to the imaginary part curve is not conducive to determining the mapping relationship between the battery's internal temperature and the imaginary part value. Hence, two characteristic frequencies are selected. When the excitation frequency is $0.5x10^4$ and $1x10^4$ Hz, the difference between the imaginary part values at different internal temperatures of the battery is large. The mapping relationship with the battery's internal temperature is the clearest.

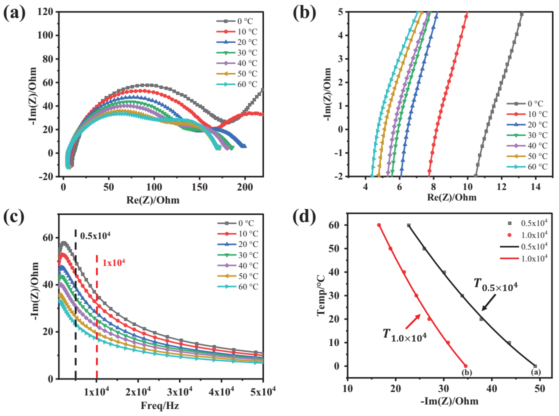

Figure 2. 60% SOC battery at different temperatures: a. Nyquist plot, b. R_b, c. Relationship between imaginary part and frequency, d Fitting curves at different characteristic frequencies

3.2 Model establishment

The imaginary part values are selected at the excitation frequency $0.5x10^4$ Hz and $1x10^4$ Hz. The relationship between the battery's internal temperature and the imaginary part value is fitted by using a polynomial, as shown in Fig. 2(d).

The polynomial expression of the fitting:

$$T_{0.5\times10^4} = 0.0276x^2 - 4.2451x + 141.98 \qquad (a)$$

$$T_{1.0\times10^4} = 0.0539x^2 - 6.0862x + 146.00 \qquad (b)$$

Where $T_{0.5x10}{}^4$ and $T_{1x10}{}^4$ represent the temperature fitting function of the imaginary part of the impedance of $0.5x10^4$ Hz and $1x10^4$ Hz, respectively. The function fitting parameter (determined coefficient) is $R^2(a)= 0.9986$ and $R^2(b)= 0.9991$, respectively. The R^2 is closer to 1 which means better the fitting accuracy. Where T is the final estimated temperature of the battery, and x is the imaginary part value under the characteristic frequency. It can be seen from the fitting curve (Fig. 2(d)) that the mapping relationship between the battery internal temperature and the imaginary part value can be well fitted by using the polynomial.

3.3 Validation of the model

The LIB with unknown SOC and SOH states was selected to verify the estimation model accuracy. In the temperature range of 0~65 ℃, a total of 7 temperature points of 5, 14, 25, 35, 45, 55, and 65 ℃ were tested for verification. Models (a) and (b) were selected to compare the accuracy of the models. The imaginary part values were recorded corresponding to $0.5x10^4$ and $1x10^4$Hz at different temperatures. The internal temperature of the battery is estimated using the resulting mathematical model. The actual temperature, the predicted temperature, and the error value are shown in Tables 1 and 2.

As can be seen from table 1, the estimation error of 65°C exceeds 1°C when using the model (a). All-temperature estimation errors are within 0.8°C when using model (b) in table 2. Overall, temperature model (b) is selected when the battery's internal temperature is 0 ~ 65 ℃, and the estimation error can be kept within 1 ℃. 0 ~ 60 ℃ is a common operating temperature range for lithium-ion batteries. Therefore, this prediction method has good accuracy and practical application significance. Moreover, it's easy to implement. First, offline calibration is performed on the battery internal temperature and imaginary part value data within a suitable temperature range. Then a unique polynomial function expression is determined. A single point excitation of a specific frequency is applied to the battery when it is necessary to obtain the temperature of a battery. Finally, the obtained imaginary part value is brought into the corresponding function expression so that the internal temperature of the single battery can be measured in real-time.

Table.1. Comparison of temperature prediction results of model (a)

-Im/Ohm	Actual temp/ °C	Predicted temp/ °C	Error / °C
46.07781	5	4.97443	0.02557
41.00938	14	14.30792	0.30792
36.03819	25	24.83981	0.16019
31.38053	35	35.94527	0.94527
27.71525	45	45.52652	0.52652
24.04050	55	55.87698	0.87698
21.34391	65	63.94650	1.05350

Table.2. Comparison of temperature prediction results of model (b)

-Im/Ohm	Actual temp/ °C	Predicted temp/ °C	Error / °C
32.55215	5	4.99583	0.00417
29.08087	14	14.59109	0.59109
25.73689	25	25.06284	0.06284

22.65875	35	35.76762	0.76762
20.18840	45	45.09747	0.09747
17.67437	55	55.26773	0.26773
15.56053	65	64.34630	0.65370

4. Conclusions

This work explores the EIS law of lithium-ion batteries at different temperature. Interestingly, the imaginary part is sensitive to temperature change in a specific frequency range. The imaginary part has a good mapping relationship with the battery's internal temperature at the frequency $1\text{x}10^4$ Hz. A method for real-time estimation of the battery's internal temperature based on the imaginary part is proposed. All temperature estimation errors are within 0.8 ℃.

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