Simulation and Experimental Verification of Temperature Field for Square Lithium-ion Power Battery

Biao Jin\textsuperscript{1*}, Qiang Fei\textsuperscript{1}, Yanning Wang\textsuperscript{1}, Yingshun Wang\textsuperscript{1} and Wuyuan Zou\textsuperscript{2}

\textsuperscript{1} Guangdong University of Science & Technology, Dongguan, 523000, China
\textsuperscript{2} Dongguan Tafel New Energy Technology Co., Ltd, Dongguan, 523128, China
E-mail: 53340450@qq.com

Abstract. Lithium-ion power battery will produce a large amount of heat during working process, which will lead to its temperature increase, and then has an important impact on its performance and safety, enhance, in order to investigate temperature field change in the discharge process, its internal resistance experiment and temperature rise experiment under discharging rates were carried out to obtain the battery time-varying internal resistance and entropy heat coefficient. Based on heat production mechanism of lithium-ion battery, its temperature simulation under different discharging rates was carried out, and compared with the experiment. The results show that the simulation values of temperature change are in good agreement with the experiment, and the battery model can well simulate the temperature change of it, which has important guidance for the analysis of its temperature rise and the control of its thermal management process.

Keywords: Lithium-ion Power Battery; Heat Production Model; Entropy Heat Coefficient; Internal Resistance

1. Introduction
Lithium-ion battery has become the first choice of power battery because of its advantages with high energy, high rated voltage and low self-discharging rate, etc. As one of the key components of electric vehicles, battery thermal safety is one of the important factors to measure electric vehicles [1].

In the process of discharge, the lithium-ion power battery will produce large amounts of heat, which causes the temperature rise, which has influence not only on the battery cycle charge-discharge efficiency, capacity, power, reliability, longevity, thermal safety, working conditions, but also the reliability and safety in the process of electric cars on the road, so controlling the working temperature of lithium ion battery within a certain range can effectively avoid the occurrence of spontaneous combustion, explosion and other dangerous situations [2]. The establishment of thermal model for lithium-ion battery can effectively monitor and predict the battery in different working conditions, which is an important tool to simulate the battery temperature field. Many scholars have carried out in-depth research and analysis on the mechanism and model of battery heat generation, but the transient heat generation of battery under different discharge rates is rarely involved, which has important guiding significance to analyze the heat dissipation and temperature change of battery in discharge process. In general, according to its heat production mechanism, electrochemical-thermal coupling model is one of lithium-ion battery heat generation models, which describes the heat produced by its electrochemical reaction [3].
At present, the widely used heat generation theory of battery was proposed by Bernardi et al [4], who thought that battery heat generation was made up of reversible reaction heat (entropy heat) and irreversible heat caused by over-voltage, which includes battery polarization heat and ohmic internal resistance heat. Many scholars have studied and analyzed Bernardi’s heat generation theory and constructed heat generation models of different dimensions, such as concentrated mass model, one-dimensional model, two-dimensional model and three-dimensional model. The ohmic internal resistance heat generation and polarization heat in Bernardi’s battery heat generation theory formula can be obtained by internal resistance test and calculation, but it is difficult to determine the reversible reaction heat, and the entropy heat coefficient affects the change of reversible reaction heat. Many scholars [5-6] have analyzed and studied the entropy-thermal coefficient of lithium batteries, most of which adopt the method of direct measurement, that is, by testing the open-circuit voltage under different ambient temperatures and different states of charge (SOC), the coefficient is calculated.

In this paper, based on the battery temperature rise experiment, a heat generation model with the constant change of heat generation rate with time and ambient temperature was established according to the relationship between battery internal resistance and ambient temperature and the relationship between entropy heat coefficient and SOC, to simulate the temperature change under different discharge rates.

The temperature simulation results agree well with the experimental results, which indicates that the simulation method can simulate the temperature field change of the battery in the discharge process, and gives a good guide for the battery thermal simulation and thermal management control.

2. Experiment

2.1. Model Introduction
The square lithium-ion power battery manufactured by Dongguan Tafei New Energy Technology Co., Ltd is taken as the research object, whose length, width and height are 173.6 mm, 47.5 mm and 131.9 mm respectively, and its capacity is 135 Ah. The experimental equipment includes power battery test system, high and low temperature experimental box, and multi-channel temperature measuring instrument, etc. The battery model is shown in figure 1.

![Geometric model of battery.](image)

Figure 1. Geometric model of battery.

2.2. Experiment
Battery internal resistance measurement methods mainly include DC discharge and AC voltage drop internal resistance measurement method. Hybrid pulse power characterization (HPPC) in the DC discharge internal resistance measurement method can be used to measure the battery's DC internal resistance, which is simple and fast, and compared with other methods, it has obvious advantages. The method can be used to obtain the ohmic resistance and polarization resistance from the voltage response curve of a single cell, and can be used as a function of the charged state [7-8]. In short, HPPC has enough resolution to reliably establish the voltage response of the cell during discharging, laying-out and regenerative charging.
In this experiment, the HPPC was used to test the battery internal resistance of discharge at different ambient temperature, ranging from 25 ℃ to 55℃, and the experimental process was recorded once every 1s. The measurement results are shown in figure 2.

Figure 2. Change curve of internal resistance with SOC at different temperature.

Figure 2 shows that the battery internal resistance decreases with the increasing ambient temperature, the lowest value of which reaches 0.446 mΩ. From the overall measured data, the ambient temperature has a significant effect on its internal resistance, whose value directly affects its capacity and efficiency for charge-discharge. Therefore, it is very important to control the reasonable ambient temperature for the battery performance. According to the test value of internal resistance, the relationship among internal resistance denoted by R, ambient temperature denoted by T and SOC was rationally fitted, and the fitting relation is as follows:

\[
1000R=-425+7.6T-1.87T^2+1.50e-2T^3+(27210-1705T+36T^2-0.267T^3)SOC+(-186026+11207.3T-230T^2+1.69T^3)SOC^2+(629450-37200T+770T^2-5.5T^3)SOC^3+(-1085290+63710T-1320T^2+9.6T^3)SOC^4+(903550-53080T+1110T^2-8.1T^3)SOC^5+(-287790+16980T-360T^2+2.6T^3)SOC^6-0.45
\]

In the same time, the relation surface was obtained as shown in figure 3. According to the fitting surface contour, higher temperature and SOC indicate lower battery internal resistance.

Figure 3. Fitting surface of battery internal resistance, SOC and ambient temperature.
To measure the battery’s temperature rise during discharging process, T-type Thermocouple gages were arranged on the its surface to record its temperature change under different discharging rates such as 1C, 2C and 3C in this experiment.

3. Battery Thermal Model

3.1. Battery Heat Model

According to the battery’s heat generation, heat transfer, heat dissipation and energy conservation law, the following mathematical equation of heat generation of single square battery can be obtained:

$$\rho C_p \frac{dT}{dt} = \lambda \nabla^2 T(i = x, y, z) + \sum Q$$

$$\sum Q = Q_{\text{ear}} + Q_{\text{core}}$$

Where, $$\lambda \nabla^2 T$$ is the energy increased by surface heat transfer (diffusion term), the second term is the heat production rate (source term) in the formula above, where, $$\rho$$, $$C_p$$ and $$\lambda$$ represent the battery’s density, specific heat capacity and thermal conductivity respectively, and $$Q$$ represents the heat production rate, while $$Q_{\text{ear}}$$ represents the joule heat of the battery electrode ears.

The battery heat generation model is based on Bernardi’s basic theoretical formula of heat generation, assuming uniform heat generation of internal substances, and the formula of heat generation rate could be simplified as follows:

$$Q_{\text{core}} = \frac{I}{V_{\text{core}}} \left[ (E - U) - T \frac{dE}{dT} \right] = (I^2 R - I R \frac{dE}{dT})/V_{\text{core}}$$

where, $$Q_{\text{core}}$$ is the battery’s heat generation rate, I indicates the the battery working current, positive when discharging and negative when charging, and E, U, T represents the battery open circuit voltage (OCV) in the equilibrium state, its terminal voltage and its thermodynamic temperature respectively, while $$V_{\text{core}}$$, R is its core volume and internal resistance. In the above formula, $$dE/dT$$ is the battery’s entropy heat coefficient, $$I(E-U)$$, $$-ITdE/dT$$ indicates the heat generated by its internal resistance and its reversible reaction heat respectively.

3.2. Thermophysical Parameters

The density, specific heat capacity and thermal conductivity of the battery core can be obtained directly through experiments, but in this paper, to calculate the above parameters, the thermal physical properties of each component of square lithium battery core, which is composed of layers of material and its thermal conductivity is anisotropic, were weighted. According to the material information provided by the enterprise and the calculation formula in related theoretical literature, the thermal characteristic parameters of the battery can be obtained, as shown in table 1.

| Material          | Density kg/m³ | Specific heat capacity J/kg·K | Heat conductivity coefficient W/K·m |
|-------------------|---------------|-------------------------------|-------------------------------------|
| Composite material (core) | 2364          | 1140                          | 17.1 (vertical), 0.9 (in plane)    |
| AL 3003 H14       | 2770          | 875                           | 170                                 |
| AL 1060 O         | 2702          | 903                           | 238                                 |
| Cu                | 8933          | 385                           | 398                                 |
| PPS               | 1360          | 1190                          | 0.3                                 |
3.3. Entropy Heat Coefficient
From the above analysis, it can be known that entropic heat represents the reversible heat produced by the battery chemical reaction, and $\ln \Delta E/\Delta T$ is the expression of entropic heat from the above bernadi’s heat production theory formula. After measuring the battery OCV and SOC at different temperature, the entropy heat coefficient can be calculated. Figure 4 shows the coefficient change process with SOC, in the figure, positive value represents reversible reaction heat as endothermic process, and negative value represents exothermic process. We can also see that $\frac{dE}{dT}$ varies from 0.15 to 6.075 mV/K, and the coefficient fluctuates with SOC. At the end of discharging, $\frac{dE}{dT}$ decreases sharply and the reaction heat release increases rapidly.

![Figure 4. Changing curve of entropy heat coefficient with SOC.](image)

4. Comparison of Results
Based on the relationship among the battery internal resistance, environment temperature and SOC, its temperature was simulated at 1C, 2C and 3C discharging rate respectively, considering the relationship between the entropy coefficient and SOC, and then the simulation values were compared with the temperature test values. The temperature monitoring points of the simulation and test at different discharge rates are its large surface geometric center, and the initial and ambient temperature are 36°C, 40°C and 44°C, respectively. Figure 5 shows comparison curve of the battery temperature rise.

![Figure 5. Battery temperature field comparison curve between simulation and test.](image)
AS can be concluded from the figure above, the difference value between simulation and experimental of battery temperature rise becomes smaller and smaller with the increasing discharge rate, and the change curves of simulation value and experimental value are basically consistent, which can simulate the temperature change process of it in the discharge process and provide guidance for the process analysis of battery temperature change and the process control of battery thermal management.

5. Conclusions
In this paper, transient entropy heat coefficient and internal resistance values of batteries were obtained by temperature rise experiment and HPPC experiment at different discharge rates respectively. Then, temperature simulation was conducted based on the battery heat generation model, and compared with the experiment for verification. We can conclusion that the battery model could well simulate its temperature changes under different discharging rates.

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