Modeling and Experimental Verification of Heat Dissipation Model for Test System of Li-ion Battery Test-bench

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Abstract. In order to develop a test-bench which can accurately test the mechanical signal of lithium-ion battery under various working conditions, the finite element model of heat dissipation simulation is established for different test systems designed in the mechanical system of the test-bench. At the same time, pulse excitation experiments are used to verify the simulation results, and the bulk force experiments are carried out to verify the optimal test system structure chosen according to the simulation results. The mechanical structure of a test system is composed of a lithium-ion battery and upper/lower spacer. In its finite element model, the finite element model of the lithium-ion battery is established by the actual measurement after cutting lithium-ion battery by a diamond cutter, and spacers are established according to their actual design. The heat dissipation simulation finite element model can simulate the heat dissipation of an actual test system, which is conducive to the design and selection of an optimal test system, so as to improve the accuracy of test data measured through the test-bench and provide a reliable data basis for the development of the battery management system coupling temperature-current-voltage-swell-force.

Keywords: Lithium-ion Battery, Test System, Natural Convection Model, Pulse Period Experiment

1. Introduction

Lithium-ion battery is not only widely used in various portable electronic devices in daily life, but also used as a reversible power supply system for electric vehicles because of its advantages of high energy storage density, high power output density, environmental protection, low self-discharge rate and low cost [1]. However, their performance also suffers from aging, degradation, thermal runaway, and incorrect state of charge prediction.

Therefore, in order to find more accurate and efficient methods to solve the above problems, in recent years, more and more researchers began to focus on the relationship between the mechanical signal and the performance of lithium-ion battery. Daniel et al. introduced a novel method of using a mechanical rather than electrical signal in the incremental capacity analysis (ICA) method in their paper, which derives the incremental capacity curves based on measured force (ICF) instead of voltage (ICV) [2]. A novel method of SOH/SOC determination using mechanical measurements has been
proposed by John et al. which offer potential utility for the improvement of existing battery management systems [3]. Besides, Shankar et al. developed a phenomenological model of the bulk force exerted by a lithium-ion battery during various charge, discharge, and temperature operating conditions and proved that the bulk force model can be very useful for a more accurate and robust SOC estimation based on fusing information from voltage and force (or pressure) measurements [4].

To sum up, existing researches focus on the internal relationship between the performance of lithium-ion battery and its mechanical signal, and pay less attention to the test-bench for measuring mechanical characteristic signal of lithium-ion battery and the accuracy of the data measured by the test-bench. Therefore, in order to more accurately measure the mechanical signal during the process of charging and discharging, so as to more accurately and comprehensively study the correlation between the performance of lithium-ion battery and the mechanical signal of battery, the finite element model of heat dissipation simulation of the test system for test-bench is established, and the simulation results are verified by experiments. Based on the established finite element model, it can provide a reference for the design of a test system of a lithium-ion battery test-bench and improve the accuracy of the data measured by the test-bench. Thus, it is conducive to more accurately and comprehensively study the relationship between lithium-ion battery performance and battery mechanical signals.

2. Development of Heat Dissipation Simulation Model

2.1. Mechanical Structure of Test System
The lithium-ion battery test-bench in this paper is mainly composed of mechanical system and measurement-control system (Fig. 6). The core part of the mechanical system that affects the accuracy of data measurement is the test system, which is composed of lithium-ion battery and upper/ lower fixed spacer. The function of the spacer is to simulate the constrained conditions of lithium-ion battery in the battery pack, and transfer the bulk force and displacement of lithium-ion battery in the process of charging and discharging to the sensor. At the same time, it also plays the role of heat dissipation, insulation and easy to measure the surface temperature and strain of the battery. Therefore, according to the function of the spacer, in this test-bench, two mechanical structure schemes of spacers constituting the test system are designed to select an optimal structure, as shown in Fig. 1. Besides, the geometry of lithium-ion battery is modeled to simulate heat model by using detailed information of battery aluminum case and jellyroll configurations (obtained after cutting the lithium-ion battery with a diamond cutter as show Fig. 2.)

![Figure 1. Mechanical structure of different spacers](image)

Under various test conditions of a lithium-ion battery, if the heat dissipation performance of a test system is not well, the temperature of the test system will be higher, which is not conducive to safety test, but also affects the accuracy of the test data. Therefore, it is necessary to establish a heat dissipation simulation model for the above two structural schemes to compare their heat dissipation performance, so as select an optimal test system structure.
2.2. Modeling of Simulation Model

In order to predict the heat dissipation of the testing system of the test-bench, this paper establishes a three-dimensional model based on CATIA, and then uses the preprocessing software HyperMesh for geometric cleaning and mesh generation. For the components with simple structure, hexahedral elements are used, and the rest are mixed hexahedral and tetrahedral elements. The number of elements finally divided reaches 8.16 million (Fig. 3). Finally, it is imported into fluent to establish the natural heat convection model and solve it.

![Figure 2. Cutting diagram of the lithium-ion battery](image)

![Figure 3. Finite element model](image)

During the actual test, the test system is placed in the thermal chamber maintaining a constant ambient temperature. At the same time, the thermal chamber here regulates the ambient temperature rather than heat flow, because higher heat flow is needed to cool the battery faster to keep the battery surface temperature unchanged, so the natural convection heat dissipation model can be used to simulate the heat dissipation of the test system under the actual test conditions. The components included in the natural convection heat dissipation model are air, battery case, jellyroll and spacer, in which the fluid region air is in contact with the solid region battery case and spacer, and the solid region battery case is in contact with the solid region spacer and jellyroll. It should be noted that, from the cutting Fig. 2, there is still a small gap of about 0.1 mm on both sides of the contact area between the jellyroll and the battery case. According to the contact region pairs, we can clearly know that there are heat conduction and heat convection in the model, that is to say, the model also belongs to the category of coupled fluid-solid model. In this case, the contact region is coupled to calculate. At the same time, in order to save the calculation time, all components are simplified to homogenization model, especially for lithium-ion battery. If each thin electrode layer of the jellyroll is modeled separately, it not only needs extremely heavy modeling work, but also increases the number of elements and the number of contacts between the electrode layers, which greatly increases the calculation cost and time. According to references [5,6,7], the material properties of each component in the model are shown in Table 1.
Table 1. Material properties of components

| Volume | Case    | Spacer | Jellyroll |
|--------|---------|--------|-----------|
| Material name | Aluminium | PBT | Composites |
| ρ (kg·m⁻³) | 2770 | 1620 | 2550 |
| C_p (J·(kg·K)⁻¹) | 871 | 1500 | 1222.2 |
| K (W·m⁻¹·K⁻¹) | 150 | 0.34 | x: 22.2 | y: 22.2 | z: 9.8 |

In the heat dissipation finite element model of the test system, the lithium-ion battery exists as a volume heat source. Consequently, in the steady-state calculation process of the heat dissipation model, it is necessary to set the volume heating power according to the actual test, which is equivalent to simulating the actual test process as the process of reaching the heat balance state under the condition of natural heat dissipation and constant volume heating power. Then according to the actual heating principle of lithium-ion battery in the test, the actual volume heat generation rate can be calculated by the following equation:

\[ P_V = \frac{I^2 R}{V} \]  

(1)

In formula (1), I is the test current, R is the ohmic resistance of the lithium-ion battery, \( V \) is the volume of the lithium-ion battery jellyroll and \( P_V \) is the volume heating power of the lithium-ion battery jellyroll under one actual test condition. Where \( R \) can be calculated through the voltage response curve obtained from HPPC test of lithium-ion battery and these equations (2) and (3). In formula (2), \( R_{oi} \) represents the ohmic internal resistance of the battery in each SOC state. Its calculation principle is that the terminal voltage of the battery drops linearly at the beginning of discharging and rises linearly at the beginning of charging [8-9]. It can be considered that it is caused by the existence of ohmic internal resistance \( R \) of the battery. Therefore, \( R_{oi} \) in all SOC states can be calculated according to the voltage response curve in Fig. 4. Finally, the final calculated average value of 0.077864 is the internal resistance value of the lithium-ion battery jellyroll.

\[ R_{oi} = \frac{(V_{1i} - V_{2i}) + (V_{4i} - V_{3i})}{I} \]  

(2)

\[ R = \frac{\sum_{i=1}^{20} R_{oi}}{20} \]  

(3)

Figure 4. Voltage response curve of HPPC test
3. Model Validation

3.1. Pulse Period Experiment to Verify
During the process of charging and discharging, it is accompanied by two heat sources of Joule heat and entropy heat [10]. Among them, Joule heat is generated due to the internal resistance of the battery and is irreversible. It is always exothermic during the charging and discharging process. The entropy heat is due to the chemical reaction heat of the lithium-ion battery in the charge and discharge process, so it is reversible, dissipates heat during charging and absorbs heat during discharge. Therefore, short pulse period experiments can be used to simulate the Joule heat source in the heat transfer model to verify the simulation results [11], because the total heat generated by entropy heat during the test is approximately zero.

![Figure 5. Location of temperature measuring point](image)

In this paper, during the actual short 4A pulse period experiment, 18 measuring points (Fig. 5) are arranged in the testing system to measure the temperature change of the test system in real time. At the same time, the temperature of 18 measuring points is also monitored in the heat dissipation simulation model. In this way, the accuracy of the simulation of the model can be verified through the test results. The experimental site is shown in Fig. 6.

![Figure 6. Picture of the experimental site](image)

![Figure 7. Experimental temperature and simulated temperature curve of rectangular spacers](image)

For the first test system composed of rectangular spacers, the temperature curves of the corresponding 18 measuring points obtained from the actual test and simulation results are shown in
Fig. 7. According to these curves, it can be seen that the trend of temperature change curve of the 18 measuring points of the simulation result and the temperature value when the final thermal equilibrium is reached are consistent with the actual test result within the error range. Therefore, it can be proved that the model can well simulate the heat distribution of a test system during the actual test, so that the heat dissipation performance of a test system can be quantitatively compared.

In the same way, for the second test system composed of spherical spacers, according to the Fig. 8, it is further proved that the model can well simulate the heat distribution of different test systems of the test-bench during the actual test. So as to realize the quantitative comparison of the heat dissipation performance of different testing systems. These curves in Fig. 7 and Fig. 8 also show that the temperature of the test system composed of rectangular spacers is lower during the test, which indicates that its heat dissipation performance is better, so it should be selected for the actual test.

**Figure 8.** Experimental temperature and simulated temperature curve of spherical spacers

3.2. Bulk Force Experiment to Verify

In order to further verify whether the optimal test system selected according to the simulation results is reliable and reasonable, and whether the corresponding test data can be accurately measured, the actual bulk force test was carried out on the two test systems. The bulk force test is to measure the bulk force of a preloaded lithium-ion battery from 0 SOC to full charge at a constant rate and the obtained bulk force curve is shown in Fig. 9. It can be seen from the curve that the bulk force measured by the first type of testing system is obviously greater than that of the second one, so the testing system composed of the rectangular spacer structure should be selected. This is because the measurement of the bulk force is transmitted through the spacer, and there will be a small loss of force, so the actual measured bulk force will always be smaller than the real one. At the same time, the higher the temperature in the testing system, the more obvious the softening of the spacer, which causes more force loss. Therefore, the larger the bulk force actually measured through the testing system is, the better and more reliable it is, and the more accurate the actual mechanical signal response can be measured by it. This also further proves the validity of the model, so when the mechanical structure of the different test system is designed for the same test-bench, the calculation results of the simulation model can be used to help the selection.

**Figure 9.** Bulk force comparison curve
4. Conclusion
In this paper, based on the measuring information of a lithium-ion battery cut by a diamond cutter, the natural convection heat dissipation simulation finite element model of test systems of the test-bench including battery jellyroll, battery case, spacer and air is established. Then, these pulse period experiments and bulk force experiments verify that the model can accurately simulate the heat distribution of test systems reaching the thermal equilibrium state in the actual test, so that the heat dissipation performance of different test systems can be compared quantitatively. Therefore, the established model is conducive to accelerate the development speed of a lithium-ion battery test-bench and improve the accuracy of the measured data of a developed test-bench, so that researchers can more easily and accurately study the inherent law between the performance and mechanical signal of a lithium-ion battery.

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