Experimental Analysis on the Thermal Characteristics of the Lithium-ion Battery During the Aging Cycles

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Abstract

This paper investigates the thermal characteristic and heat generation mechanism of the lithium-ion battery during the aging cycles. The surface temperature distribution and the thermal characteristic of the battery were analyzed based on the infrared images. Results indicated that the surface temperature distribution of the battery is greatly dependent on the state of charge (SOC). The endothermic peak caused by the entropy heat coefficient of the reversible reaction heat gradually disappears as the increase of the discharge rate. The negative electrode has the highest temperature during the discharge process. The temperature rise of the battery gets higher as the battery ages, that is, the total heat output of the battery increases. However, the reversible reaction heat of the battery has little change with the increase of the aging cycles. The results of thermal behaviors analysis are conducive to understand the safety management and build a reliable thermal model for high energy density lithium-ion battery.

Keywords: Lithium-ion battery, temperature distribution, infrared images, heat generation

1. Introduction

Due to the chemical energy crisis, electric vehicles (EVs) have been vigorously promoted and prevalent all over the world. The lithium-ion batteries featured as large-capacity and high-energy density have been widely used as the main energy storage components of EVs [1]-[3]. However, they still suffer from some disadvantageous properties, for example, the risk of the thermal runaway at a high discharging rate and aging cycles. Therefore, it is imperative to obtain accurate knowledge and analyze the heat generation and temperature variation of the battery during the discharge process. It is essential to ensure the safety and reliable operation of lithium-ion batteries according to the proper thermal management design based on the thermal behavior of lithium-ion batteries. Currently, the research on the thermal behavior of lithium-ion batteries is mainly about the safety, the thermal behavior variation, and heat generation mechanism during the whole operation cycle of the battery. To predict the thermal behavior of Lithium/Polymer battery (LPB) for a single cell and a cell stack, Pals and Newman presented a one-dimensional battery model [4]. Verbrugge [5] modelled the three-dimensional current and temperature distributions in LPB modules. Ui Seong Kim [6, 7] investigated the thermal behavior of a lithium-ion battery during charge using the finite element method. The total heat generations are derived from the surface temperature change during electrochemical Li+ insertion/extraction in adiabatic surrounding. The reversible heat is determined by the entropic coefficients, which are related with open-circuit voltage at different temperatures, while the irreversible heat is determined by the internal resistance [8]. Furthermore, Lu and Prakash [9] investigated MCMB/Li coin cells and found that the reversible heat takes the main part of heat generation using slow charge/discharge rates and the irreversible heat is prominent at high charge/discharge rates.

Thermal issues of large cell are increasingly critical for the scaling-up and integrated deployment of laminated lithium-ion batteries. Therefore, we propose to apply the infrared imaging technology to investigate the thermal characteristics of the lithium-ion battery in this paper. The temperature distribution is investigated at different discharge rate, depth of discharge, and at different aging cycles.
2. Experiments

To study the thermal characteristics and mechanism of the lithium-ion battery during aging process, a test bench was established as shown in Figure 1. It consists of a host computer, a programmable temperature chamber, a battery tester, and an E60 hand-held infrared thermal imager. The battery performance and temperature evolution at different discharge rates, i.e., 0.5C, 1C, 1.5C and 2C were analyzed. The surface temperature distribution of the battery was acquired by the infrared thermal imager. Meanwhile, temperature data are collected by thermocouples attached to the positive and negative ears, as well as the center of the battery with a sampling frequency of 10 s. The lithium-ion battery used in this paper is the soft-packaged ternary polymer lithium-ion batteries with rated capacity of 11Ah produced by Shenzhen Tianjin Co., Ltd. The battery size is 9.5 mm x 80 mm x 130 mm.

![Figure 1](image1.png)

Figure 1 Thermal imaging analysis system for lithium-ion batteries.

To analyze the surface temperature distribution of the battery at different discharge rates and the changes of surface temperature under different aging cycles, the following experiments were carried out:

1. Charge the battery to the upper cut-off voltage by constant current and constant voltage (CCCV) with current of 0.5C rate. The discharge rates of 1C, 1.5C and 2C are used to discharge the batteries respectively. After each discharge, the battery was shelved for half an hour. Current and voltage waveforms are shown in Figure 2. The thermal images of the battery were acquired by the hand-held infrared thermal imager every 10% SOC during the discharging process.

2. Charge and Discharge the battery with 1C current rate until 200 cycles. After each cycle, the battery was shelved for half an hour. The capacity of the battery was reduced to 80% of the rated capacity after 200 cycles.

![Figure 2](image2.png)

Figure 2 Discharge cycles of 1C, 1.5C and 2C rates of batteries: (a) current; (b) voltage.

3. Results and discussion

3.1 The endothermic peak effect

According to the classical Newman’s theoretical model of heat generation, there are four main types of heat generation in the electrochemical reaction of the battery, namely reaction heat generation, polarization heat generation, ohmic heat generation and side-reaction heat generation. These four kinds of heat production can be classified into two categories: reversible heat reaction and irreversible impedance heat. The reversible reaction heat is the exothermic and endothermic process of the battery in electrochemical reactions. The irreversible impedance heat is mainly caused by the Joule heat generated by the internal resistance of the battery. Bernardi’s simplified heat production model [10] has been widely used to assess the heat generation. As shown in equation (1), the
reversible heat and the irreversible heat are considered separately in the model.

\[ q = q_{oc} + q_{irr} = (U_{oc} - U_{t}) - IT \frac{dU_{oc}}{dT} = IT - IT \frac{dU_{oc}}{dT} \]  

(1)

where \( q \) is the total heat production, \( q_{irr} \) is the irreversible impedance heat, \( q \) is the reversible heat of reaction, \( U_{oc} \) is the open-circuit voltage, \( U_{t} \) is the terminal voltage, \( I \) is the current, \( T \) is the temperature, and \( \frac{dU_{oc}}{dT} \) is the entropy heat coefficient.

In Equation (1), the value of the entropy thermal coefficient in the reversible reaction heat term can be positive or negative throughout the discharging process, so there may be an endothermic peak [11]. The temperature changes at the center of the cell surface during the discharge cycle with the 0.5C rate are shown in Figure 3. A small peak and valley can be observed before the first peak appears. According to the Bernardi's simplified heat production model in Equation (1), the peak and valley are caused by reversible reaction heat, called as endothermic peak, which is also the turning point of endothermic effect. It occurs just in the middle process of the battery discharge, followed by a steep downhill peak in the static region of the battery. Then, the temperature rises again with the discharging, and there is a temperature rise peak at the end of the charging process. It can also be found that the decrease of battery temperature during the middle period of discharge is related to the reversible heat of reaction under the condition of small discharge rate. Reversible reaction heat has a significant effect on the change trend of the battery temperature in the middle period of discharge.

![Figure 3](image3.png)

**Figure 3** The temperature curve at center surface of the battery with 0.5C discharge rate.

Figure 4 shows the temperature changes at the center of the cell surface with the discharge rate of 0.5C, 1C, 1.5C and 2C. The four peaks from left to right are 0.5C, 1C, 1.5C and 2C respectively. It can be seen that, with the increase of the discharge rate, the endothermic peak gradually disappears. At 2C discharge rate, the peak of discharge cycle has been completely unaffected by the endothermic peak.

![Figure 4](image4.png)

**Figure 4** The temperature curve at center surface of the battery with different discharge rates.

### 3.2 Effects of SOC on the temperature rise

Infrared thermal imager was used to analyze the changes of temperature field on the surface of the battery with different SOC values at 0.5C, 1C, 1.5C and 2C discharge rates. Figure 5 shows the thermal images of the battery in 50% SOC at discharge rates of 0.5C, 1C, 1.5C and 2C, while Figure 6 presents the thermal images at 10% SOC. The results indicate that both the temperature and uneven temperature distribution increase with the increase of the discharge rate. Besides, the temperature difference between 0.5C and 1C is less than that between 1.5C and 2C. Furthermore, lower SOC leads to higher temperature rise.

![Figure 5](image5.png)

**Figure 5** Thermal images of the battery surface with different discharge rates at 50% SOC.
3.3 Effect of aging on the heat generation

Figure 7 shows the thermal images of the battery discharged from 100% SOC to 0% SOC at 2C rate after 80 aging cycles. It is clear that the surface temperature of the battery is greatly dependent on the SOC, and a lower SOC causes a higher temperature. The temperature rise from 100% SOC to 0% SOC nearly reaches to 30 degrees Celsius. In addition, at the initial discharging stage, the surface temperature on the side of the pole of the negative electrode is higher than the other area, and then the surface temperature of the battery gradually performs uniform. Finally, the temperature distribution in the central region is high and the temperature around the battery is low.

Figure 8 shows the temperature profile at the center of the battery at different aging cycles. It can be seen that as the battery ages, the temperature of the battery is higher and higher during the discharge process, that is, the total heat output of the battery increases. However, the reversible reaction heat of the battery has little change during the aging cycle. The main reason for the increase in temperature of the battery during aging is that the increase in the internal resistance leads to an increase in the irreversible impedance heat.

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Figure 8 The temperature curve of the center point of the battery at different aging cycles.

4. Conclusions

In this paper, a simplified thermal model was introduced to analyze the surface temperature characteristics of the lithium-ion battery. Infrared thermal images of the battery during charging and discharging processes with different current rates were acquired to obtain the surface temperature distribution of the battery. From the temperature curve at the surface center of the battery, it can be seen that there is an endothermic peak due to the reversible reaction heat as the battery is discharged with a low current rate. Generally, the temperature decrease of the battery in the middle period of discharge is related to the reversible reaction heat at small discharge rate, however, the effect of the reversible reaction heat on the temperature rise of the battery is not significant at high discharge rate. Therefore, the endothermic peak gradually disappears as the increase of the discharge rate. In addition, the battery surface temperature is highly sensitive to SOC, and a lower SOC leads to a higher temperature rise, because the internal resistance of the battery gets larger at low SOC, generating more irreversible impedance heat. Finally, thermal imaging analysis of batteries with different aging cycles was
carried out. The results showed that the reversible reaction heat of the battery has little change during aging cycles. The main reason for the increase of temperature during aging is the increase of internal resistance, which leads to the increase of irreversible impedance heat.

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Reference


