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Simulation of electrical abuse of high-power lithium-ion batteries

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Abstract

A numerical study is performed to analyze the temperature variation and distribution of high-power prismatic Li-ion batteries in excess duration and high-rate current abuse scenarios. With an adiabatic condition at the bottom of the cuboid battery, the highest temperature point is located at the center of the bottom surface, and the lowest is located at the cathode lead at the beginning and then moves to the corner near the cathode during the charging/discharging processes. The rising rate of battery temperature and maximum temperature difference decrease gradually with time, meanwhile the temperature difference of leads increases at first then decreases. With the same current rate, the heat generation rate and temperature difference of discharging are higher than those of the charging processes.

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Keywords: high-power lithium-ion battery, electrical abuse, numerical simulation

1. Introduction

Lithium-ion batteries with characteristics of high energy storage efficiency, high cycle life and low self-discharge rate are widely used in areas of portable devices, transport and energy storage. However, thermal safety is a major concern of the battery in long-duration and high-current usages such as in unintentional electrical abuse cases. Battery thermal safety is directly associated with the temperature variations and distributions inside the battery cells and modules, which affect the battery materials and the integrity of cells and modules. Both experimental and numerical studies have been used to study battery safety. The thermostability of different battery materials was investigated in numerical studies [1-4] to explore the reactive mechanism of thermal run-away. Pesaran et al. [5] measured the heat

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capacity of several electrical vehicle (EV) and hybrid electrical vehicle (HEV) cells by a calorimeter. Forgez [6] et al. measured the temperature at the cell center by inserting a thermocouple to the axis of LiFePO4 cylindrical cell, and a prediction model of cell center temperature was built. Feng et al. [7] measured the thermal runaway critical parameters of Li(NixCoyMnz)O_2(NCM) prismatic battery. Jeon et al. [8] applied the porous electrode and transient thermal models to calculate the temperature of the 18650 battery in discharging/charging processes. Ling et al. [9] analyzed the battery thermal management system performances with different phase-change materials (PCM) by numerical methods for selecting the best PCM to achieve temperature uniformity. Park et al. [10] analyzed the effects of different coolants and cell layouts on the temperature distribution of battery module, and compared the power consumption of different cases. However, the studies on electrical abuse of high-power Li-ion battery are scarce in the literature. The maximum continuous current rate of high-power battery can be as high as 7C in abused scenarios, compared with the rate of 1C normally considered in existing standards. Therefore, there is a need to study battery performances under such conditions. In an abused case, the batteries charge/discharge by current or working time over the tolerated range. Because of its configuration, the non-uniform temperature distribution of prismatic cell is more prominent. It is therefore investigated in this study, which is focused on predicting the temperature variation and distribution using a heat generation theoretical model for the high-power prismatic Li-ion battery.

2. Heat generation theoretical model

The sources of Li-ion battery heat generation consisted of the irreversible resistance heat, reversible entropy heat, mixed heat and phase change heat. Normally, the resistance heat and entropy heat are the primary sources of battery heat generation. The mixed heat can be neglected when the internal material is homogenous. The phase change heat can be neglected when no gas is generated. The heat generation model can be derived from electrochemistry and thermodynamics by considering the differential form of Gibbs-Helmheltz equation $\Delta G=\Delta H-T\Delta S$:

$$d(\Delta G)=d(\Delta H)-dT\Delta S-Td(\Delta S) \tag{1}$$

According to the first and second laws of thermodynamics, entropy and enthalpy have the following relationship:

$$Td(\Delta S)=d(\Delta H)-vdp \tag{2}$$

No gas is generated when the battery charges/discharges properly, so dp=0. For a reaction system, the reduction of Gibbs free energy equals to the non-volumetric work from the system to the surrounding. The non-volumetric work present as electrical work from battery reaction. The battery electromotive E is the anode potential minus the cathode potential, then $\Delta G=nFE$, where nF represents the charge migration of reaction. Accordingly,

$$\Delta H = nFE - nFT\frac{\partial E}{\partial T} \tag{3}$$

The enthalpy-change of reaction corresponds to the battery heat generation and effective electrical work:

$$\Delta H = Q + IVt \tag{4}$$

where Q designates the battery total heat generation, I the reaction current, and V the working voltage. Considering that the charging current is positive and discharging current is negative, then $I=nF/t$. In addition, $E=V+IR_r$. where R_r designates the internal resistance of battery.

Combining the equations above and designating V_b as the battery volume, the battery heat generation rate of per unit volume can be simplified as follows:

$$q=\frac{Q}{V_b t}=\frac{1}{V_b}\left(I^2R_r - IT\frac{\partial E}{\partial T}\right) \tag{5}$$

where the coefficient of entropy heat $k_S=\partial E/\partial T$ can be measured by experiment and can even be considered as constant in the normal temperature range. In this study, the 1868110 prismatic Li-ion battery is considered with its capacity 13.5Ah, internal resistance 1.3mΩ and coefficient of entropy heat k_S 0.00001V/K.