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Temperature rise prediction of lithium-ion battery suffering external short circuit for all-climate electric vehicles application

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HIGHLIGHTS

- External short circuit of lithium battery is experimented at three ambient temperatures.
- The impacts of SOC and ambient temperature on maximum temperature rise are analysed.
- The heat generation caused by external short circuit is proved having two modes.
- An online prediction approach of ESC-caused maximum temperature rise is proposed.
- The presented algorithm can achieve the precise prediction 22.3 s ahead of time.

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ABSTRACT

External short circuit (ESC) is a severe fault that can cause the large current and high temperature of lithium-ion batteries (LiBs) immediately. Temperature rise prediction is crucial for LiB safety management in an all-climate electric vehicles application because many disastrous consequences are caused by high temperature. This study mainly investigates the ESC-caused temperature rise characteristics of LiB, and proposes an online prediction approach of the maximum temperature rise. Three original contributions are made: (1) Abusing tests of LiBs under ESC are conducted at varying ambient temperatures, and the influences of battery state of charge (SOC) and ambient temperature on the maximum temperature rise are revealed. (2) Characteristics of temperature rises are analysed, therein finding that the heat generation of LiBs caused by ESC presents two modes: Joule heat-dominant mode and reaction heat/Joule heat blended mode; leakage is an external manifestation of the latter. (3) Two heat generation modes are proved to be linearly separable at temperature rise discharge capacity plane, and then a two-step prediction approach of maximum temperature rise is proposed based on support vector machine. Finally, the presented approach is validated by the experimental data. The maximum temperature rise can be predicted up to 22.3 s ahead of time and very precise prediction results are obtained, where the mean prediction error for the eight test cells is 3.05%.

1. Introduction

Enhancing battery safety is of great significance for the lithium-ion batteries (LiBs) utilization in all-climate electric vehicles (AEVs) and other applications, and is necessary to be taken into account in battery management [1–3]. LiB has potential hazards of fire and explosion caused by sorts of field failures, like overheat, overcharge, and short circuit. Up to now, various safety installations, such as pressure release valves, shutdown separators, positive temperature coefficient elements, and one-shot fuses, etc., have been developed for battery safety concerns [4]. However, despite these achievements, severe battery faults have been reported continuously in many applications, some of which even result in catastrophic consequences [5]. How to improve the battery safety remains a technique challenge. In AEV applications, higher requirements for battery safety are put forwards due to the complex application environments in vehicle and possible serious consequences.

Till now, publications of battery management studies are mainly directed against the battery state estimation, namely state of charge (SOC) [6–11], state of health (SOH) [12–14], state of power (SOP) [15], etc., without enough concern of battery safety issue [16,17]. There are several safety faults that may happen on the battery. Exploring the specific characteristics of LiBs under fault conditions is quite essential for designing an effective fault detection and diagnosis system. A few

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researchers have carried on relevant studies pointedly. To name a few, Sahraei et al. [18] proposed a set of internal short circuit (ISC) abusing tests for 18,650-type cylindrical cells under mechanical abusing conditions; Maleki and Howard [19] investigated the effects of ISC by three experimental methods and used accelerating rate calorimeter (ARC) to measure the heat generation of the battery, this study indicated the location of ISC is critical in ISC events; Shah et al. [20] proposed an experimental study on thermal runaway of LiB cells while Mohmmadian and Zhang [21] investigated the prevention of thermal runaway using microchannels; Greve and Fehrenbach [22] proposed a finite element (FE) crash model based on various mechanical abusing tests of nickel cobalt oxide (NCA) LiB to predict the ISC occurrence location during the deformation process.

However, in the literatures, there is a lack of investigation on the external short circuit (ESC) fault of LiBs. ESC is a dangerous battery failure and often occurs during the vehicle collisions, which usually causes the large current and high temperature. The expectation of this study is to propose an approach for online predicting the possible maximum temperature rise of the LiB under ESC fault based on the experimental analysis. Three original contributions are made:

(1) **ESC abusing tests:** ESC abusing tests of lithium cells are conducted at three ambient temperatures. Cells with five different SOC values are short-circuited under each ambient temperature condition. Based on the test results, the variation characteristics of the cell temperature rise are explored. The impacts of SOC and ambient temperature on the maximum temperature rise are disclosed.
(2) **Heat generation mode analysis:** The manner of ESC-caused heat generation within the LiB is analysed based on a lumped parameter thermal model and found to fall into two modes; these two modes are linearly separable and are possible to be detected online.
(3) **Prediction of temperature rise:** A novel two-step prediction approach of the maximum temperature rise for the lithium cells in ESC fault is proposed based on support vector machine (SVM) classifier. The presented algorithm can be implemented in online battery management applications.

The remainder of the paper is organized as follows: the experimental study of lithium cells under external short circuit, thermal model, and analysis of heat generation mode are conducted in Section 2; the SVM-based heat generation mode discrimination algorithm and temperature rise prediction algorithm are proposed in Section 3; the effectiveness of the presented approach is evaluated by experiments in Section 4 while the conclusions are summarized in Section 5.

2. External short circuit of lithium cells

ESC abusing tests are conducted with the commercially available 18650-type cylindrical NMC lithium cells. The specifications of the tested cell are listed in Table 1, where the internal resistance is a mean value in the usable SOC range. In this test, the internal electrochemical thermal characteristics are not investigated; the lithium cells are seen as black boxes, being studied only in terms of their equivalent circuit model. The external input and output characteristics of cells that can be directly measured (the currents, voltages and temperatures) are utilized to implement the online prediction of temperature rise of the LiB during the ESC.

Table 1
Specifications of the test cell.

Specification parameters	Value
Dimension	ϕ18.6 × 65.2 mm
Mass	45.5 g
Operating temperature range	−20 to +60 °C
Nominal voltage	3.6 V
Charge cut-off voltage	4.2 V
Discharge cut-off voltage	2.5 V
Internal resistance	35 mΩ
Nominal capacity	2.0 Ah

2.1. Experimental setup

Fig. 1 shows the established ESC abusing test system. As shown in Fig. 1(A), a *Motohawk* controller is linked with the upper computer through a CAN bus to operate the relay module, which connects the positive and negative terminals of the cell and is used to touch off a short circuit fault. Fig. 1(B) shows the connection of the tested cell, where the total external resistance (including the connector and wire) is less than 25 mΩ. A thermal chamber is used to set up the ambient temperature. Cells, sensors, and relay are placed in a steel safety box. The entire short-circuit process can be controlled and clearly observed from the upper computer, as shown in Fig. 1(C). To make the results reliable, an infrared thermal imager and two thermocouple sensors are used to measure the cell temperature. The infrared thermal imager monitors the temperature distribution and is used as redundant device in case of the thermocouple malfunction. The two thermocouples are attached on the surface of the battery, close to positive and negative poles, respectively. The average of the data from two thermocouples is taken as the cell temperature to conduct the analysis.

In this test, three ambient temperature conditions, 20 °C, 30 °C, and 45 °C are adopted. Under each temperature condition, two groups of lithium cells (named as **Group 1** and **Group 2**) are short-circuited repeatedly under the same test conditions. Each group contains five cells with SOCs ranging from 20% to 100% (in increments of 20%). Repeating the tests with two groups of cells ensures that the test data and conclusions are more credible and have generalizability. The cells, along with the safety box, are placed in the thermal chamber for more than three hours before the onset of the test to reach the constant preset temperature. The different initiations of cell SOC and ambient temperature are expected to give insight into the impacts of SOC and onset temperature on the temperature rise of the lithium cells during the ESC process.

The current, voltage, and temperature of the cells are recorded during the test. It should be noted that the so-called ‘cell temperature’ refers to the surface temperature, rather than the internal temperature of the cell. The ESC duration time is set as 90 s. Our previous studies [23] indicate that 90 s is long enough for the current and voltage of an 18650-type lithium cell to drop to zero. After this time period, the ESC is terminated by interrupting the relay module. The cell temperature continues being recorded after the test for more than five minutes to enable observation of the maximum temperature rise.

2.2. Analysis of test results

The test results are summarized in Figs. 2–4. The discharge capacities are calculated from the measured current during the short-circuit process, as shown in the illustrations. It can be noticed that the discharge capacity during the short-circuit process is very different from the initial charged capacity of the cell. Thus, unlike in a normal situation, the heat generation caused by the ESC process cannot be simply inferred from the initial battery energy. The sensors recorded different temperature variations, proving that the cell temperature during ESC is impacted by the initial conditions. Note that the temperature rise value, rather than the temperature value, of the cell surface is investigated to achieve a better comparison of the ESC characteristics under different ambient temperature conditions. The voltage is not plotted because it is not used for the subsequent analysis; the variation of cell voltage of a lithium cell during ESC and its relation with the current can be found in Ref. [23].

After the ESC occurs, the cell instantly produces a high current. Then the current gradually decreases, producing a platform of