Study on Thermal Runaway Behavior of Lithium Ion Battery under Overcharge Using Numerical Detecting Method

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Abstract—In order to provide support for the early warning model of thermal runaway of lithium-ion battery, the thermal runaway behavior of power lithium battery is studied by analyzing the charging current, voltage and other parameters of lithium-ion power battery under overcharge condition. In addition, the morphological changes of battery before and after thermal runaway are compared. It is found that under the conditions of this study, overcharging for 58 minutes will lead to thermal runaway of full load lithium-ion battery. In the early stage of thermal runaway, the leakage gas in the battery box will continue to increase, which is 1339 ppm in the First Level early warning, 3405 ppm in the Second Level early warning and 8292 ppm in the Third Level early warning.

1. INTRODUCTION
Ensuring the safe use of lithium battery pack is the basic requirement for battery pack of electric vehicle. Since the lithium battery pack of electric vehicle is composed of multiple single batteries in series, when the battery pack without battery management system is directly used, the difference between the single batteries in the battery pack will gradually increase during use and cannot be adjusted. That will be resulting in single overcharge, over discharge a series of faults, such as over-current and high ambient temperature of the battery pack, reduce the service life and performance of the whole battery pack, scrap and explosion in serious cases. In recent years, lithium battery energy storage industry has developed rapidly. Lithium battery energy storage is an energy storage technology that uses electrochemical reaction to realize the mutual conversion between electric energy and chemical energy [1-7]. It is the most rapidly developed energy storage technology at present. In particular, lithium-ion battery is most widely used in various battery energy storage technologies because of its high energy density and long cycle life [8-9]. Lithium iron phosphate has stable crystal structure and is not easy to decompose even at high temperature or overcharge. Therefore, it is commonly used as the cathode material of lithium ion battery and has a good development prospect [10-12].

Some scholars have studied the runaway behavior of lithium-ion battery in different external environments, simulated the thermal runaway behavior of battery under the conditions of extrusion, overcharge, over discharge and heating, and obtained a series of laws and conclusions [13-15]. Some scholars have established relevant thermal models of lithium-ion batteries by using simulation software,
such as ANSYS, FLUENT or COMSOL, to simulate and analyze the thermal behavior of lithium-ion batteries under different abuse conditions [16-21]. The characteristic parameter alarm threshold of most models is lack of sufficient experimental data. Therefore, there are some problems, such as high false positive and false negative rate, lack of wide applicability and so on. In this paper, the behavior of single lithium-ion power battery before, during and after thermal runaway under overcharged condition is studied.

2. EXPERIMENT

Simulate the real situation, place a power battery pack inside the power battery box, overcharge one of the batteries, resulting in battery thermal runaway, simulate the scene of battery thermal runaway in the battery box in practical application, and actually test the early warning and fire control functions of the single power battery fire early warning and control device. The test battery box adopts the standard micro electric vehicle battery box. The dimensions of the battery box are 1100mm long, 800mm wide and 190mm high. 39 battery packs are arranged in the battery box according to the real working state, of which 9 are working battery packs, each consisting of 10 fully charged 12Ah ternary soft packed lithium batteries. One of them is overcharged, and the other 8 groups are arranged close to the periphery of the overcharged battery pack to test the thermal runaway of the overcharged battery pack, which leads to the thermal runaway of the adjacent battery packs and the diffusion of thermal runaway. The remaining 30 groups are battery pack models, which simulate the structure of the real battery box. The battery pack and battery pack models are arranged in 5 rows. The fire early warning control device is arranged in the gap 3 rows apart from the overcharged battery pack to test the early warning effect to the greatest extent. The fire extinguishing device is arranged at the far end from the overcharged battery pack to test the fire extinguishing effect to the greatest extent. The overcharge power supply adopts HT10020 equipment with constant wing energy as the charger, with constant current of 20A and constant voltage of 8V. The overcharge battery pack is charged directly through the charging cable. The monitoring equipment adopts notebook computer, which is connected to the fire early warning control device through the harness, and the communication mode adopts CAN bus to read the monitored status information in real time. A Nikon SLR camera is used for on-site shooting and recording at a fixed position, as shown in Figure 1. The specific physical diagram of the experiment is shown in Figure 2.

![Figure 1. Schematic diagram of experimental system](image-url)
3. RESULTS AND DISCUSSION

In the early stage of the charging process, the voltage rises slowly, as shown in Figure 3. When the overcharged battery pack is charged at constant current for about 58 minutes, the internal heat of individual battery cells is out of control, resulting in gas. The internal pressure increases, the package cracks, and the characteristic gas concentration in the box suddenly increase, triggering a First Level early warning. At this time, the gas smoke data rises rapidly to 1339 ppm, and the temperature does not change significantly, as shown in Figure 4.

After the First Level early warning, due to continuous overcharge, more battery cells were thermally out of control, the battery soft package further burst, the characteristic gas concentration further increased sharply, and the Second Level early warning was triggered after 2 minutes and 20 seconds. The gas smoke data rapidly increased to 3405 ppm, and the temperature did not change significantly, as shown in Figure 5. In this process, it can be seen that the charging voltage decreases, which is in line with the characteristics of thermal runaway of lithium-ion battery. As 10 overcharged batteries are packaged into a group, heat out of control and heat accumulation occurred successively. Even in case of power failure, it is inevitable that the temperature will rise further and burn. About 3 minutes and 30 seconds after the Second Level early warning, more batteries burst and combustion occurred. The Third Level early warning was triggered. The gas smoke data rapidly increased to 8292 ppm, and the temperature did not change significantly, as shown in Figure 6. The fire extinguishing device was automatically started to suppress the fire. The open fire was suppressed, but the heat runaway reaction continued and the heat was still gathering. After 8 minutes, the packaging of other battery cells in the overcharged battery pack burst, releasing a large amount of electrolyte and electrode reaction gas. However, due to the filling of aerosol and inert gas sprayed by the fire extinguishing device, there was no secondary combustion in the battery box.

As the thermal runaway occurs at one end of the battery box, the thermal runaway does not diffuse, and the battery box is flat, which is unfavorable to heat conduction, resulting in temperature imbalance inside the battery box. The ambient temperature on the test day is relatively high, and the temperature in the box before the test has reached 50 degrees. The fire early warning control device is placed in the gap 3 rows away from the overcharged battery pack, which is far away. The temperature change of
thermal runaway fails to cause obvious monitoring temperature change, and the effect of temperature monitoring is not obvious under the specific conditions of the test.

Figure 3. Change of current and voltage during charging

Figure 4. First Level early warning parameter change

Figure 5. Second Level early warning parameter change
Figure 6. Third Level early warning parameter change

After 2 hours, the battery is unpacked and observed. After unpacking, no smoke is observed and there is no sign of re-ignition. The overcharged battery pack has stopped the thermal runaway reaction, the overcharged battery pack has obvious signs of combustion, and the adjacent battery packs have no material damage and no uncontrolled thermal diffusion. The fire extinguishing device has been started, the fire extinguishing agent has been sprayed, and there is no obvious trace of fire extinguishing agent in the box.

It can be seen that the overcharged battery pack is completely burned, the combustion does not spread to the adjacent battery pack, there are burning marks on the appearance of the adjacent battery pack, and the structure is intact.

Figure 7. Battery pack status before and after the experiment

Overcharge causes thermal runaway of the soft pack battery in the battery pack. In the early stage of the thermal runaway, the fire early warning control device sends an early warning signal in time when the observable signs of thermal runaway are not obvious. The continuous overcharge caused the thermal runaway of 10 soft pack batteries in the battery pack and caused combustion. The fire extinguishing device was started in time, successfully suppressed the fire and prevented the thermal runaway from spreading to the adjacent battery pack.

4. CONCLUSION

By studying the thermal runaway behavior of lithium-ion battery under overcharge condition, this paper actually tested the fire early warning and control of the thermal runaway in the battery box with a length of 1100mm, a width of 800mm and a height of 190mm. When the thermal runaway of lithium-ion battery occurs after overcharging for 58 minutes, the leakage gas in the battery box will continue to increase, 1339 ppm in the First Level early warning, 3405 ppm in the Second Level early warning, 8292 ppm for the Third Level early warning. At this time, the temperature does not change rapidly.
Comparing the state of battery pack before and after the experiment, it is found that the state of thermal runaway battery is significantly different from other batteries. The quantitative determination of thermal runaway state is one of the key problems in battery safety research. This paper studies the thermal runaway behavior of lithium ion battery under overcharge quantitatively, which provides a technical basis for relevant research. In the future, more relevant research work should be carried out under other conditions.

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