Analysis on Thermal Runaway of Lithium Ion Battery

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Abstract: The power battery is composed of a plurality of batteries, and a single battery plays an important role in the safety of the whole battery pack. In this paper, the lithium-ion batteries with LiCo1/3Ni1/3Mn1/3O2 as cathode material was stimulated by overcharge, and analyzes apparent regularity of battery explosion from explosion combustion temperature, explosion pressure and battery deformation. Test results show that thermal runaway duration of lithium ion battery pack is longer than that of all single cells combined; firstly, the lithium ion battery going through thermal runaway will deformation; secondly, the pressure wave of a single cell’s explosion is not enough to cause the explosion of the battery pack.

Introduction

Lithium ion battery is being developed to large power battery used in aviation, hybrid electric vehicle, and electric vehicle, etc. However, the capacity of a single cell cannot meet the power requirements of large mechanical equipment. In recent years, battery accidents have occurred frequently. In January 2014, a Boeing 787 had to carry out an emergency landing at Takamatsu Airport due to smoke emission out of failing battery during the flight. The possible reason is that the battery is overheated due to overcharge, which leads to overflow of battery inner liquid [1]. In September 2016, Samsung Electronics Co. Ltd. has recalled 2.5 million Galaxy Note7 phones across the world, due to a barrage of explosions happened in this type of mobile phone. In order to study the safety of lithium ion batteries, a lot of researches on them have been done by many scholars in China and beyond. Chil-Hoon Doh [2] and some other researchers have studied explosion and combustion of LiCoO2 pouch cell under conditions of squeeze, acupuncture and impact. Zhang, Jhu and some other researchers have compared the anode material of Li(Ni1/3Co1/3Mn1/3)O2 (NCM) to that of conventional lithium ion batteries, namely, LiNiO2, LiMn2O4 and LiCoO2, and found out that it has better thermal stability [3,4]. Research group of Wang Singsong [5,6] has analyzed combustion behavior of lithium ion battery from mass loss rate, temperature and heat release rate in detail, and thermal runaway behavior and mechanism of lithium ion battery (NCM) under different charging statuses. To ensure battery safety, the United States and Japan have pioneered the issuance of evaluation criteria for the safety of lithium ion battery [7,8]. In 2015, China also issued the first mandatory standards on lithium ion battery and the pack [9]. In order to better simulate the actual situation, the battery pack is tested in an enclosed space, and analysis of the impact of a single battery explosion on the entire battery pack will be made, minimizing the explosion harm to people.

Test

Test Material

The lithium ion battery is composed of anode and cathode, electrolyte, separator, and aluminum shell. NCM and graphite are used as materials for anode and cathode. The battery is rectangular. The size of the battery is 50×20×40mm, and the separator material is PP. LiPF₆ is a lithium salt electrolyte, using EC, DMC and other lipid mixtures as the organic solvent. Rated capacity of the lithium ion battery is 20Ah. The test battery is to be charged and discharged for 3 times by 0.2C in a loop, using for the overcharge test of battery pack.
**Test Condition**

The battery pack is composed of three identical lithium ion batteries which are bundled together, placed in a non-fully enclosed box (the volume is 170x70x70mm). Two lugs on the upper lid of the box are connected with the inner battery’s electrodes, and the upper lid is fastened to the box body by bolts. Pressure sensor (the model is 211B6 from Swiss company KISTLER) is installed in the middle of upper lid. In the air control test, the pressure sensor is installed on both sides of the battery, and the distance between the battery and the battery level is 10cm. When the ambient temperature is at (20 ± 5) °C, overcharge the battery with the overcharging rate of 2C, until the battery explodes or burns. In the course of test, put two K-type thermocouples on the surface of batteries respectively to collect temperature data. One is placed in the middle of the bottom of the overcharged battery and the other is placed 10cm above the battery.

**Results and Discussion**

**Temperature of Thermal Runaway.** Figure 1 and Figure 2 show the temperature curve of lithium-ion battery pack and single lithium-ion cell that are overcharged to the explosion under the same conditions. In overcharging stage, the battery temperature stayed stable for a long time in a certain range (temperature stable zone), this is because the chemical reaction in this stage is the positive and negative electrode Li\(^+\) on the insertion/de-insertion, then, it rose slowly and entered the second stage of thermal runaway (temperature rise zone), this is because the battery positive and negative Li\(^+\) insertion/de-insertion close to the limit, the battery cannot be in the storage, and the current has been overcharged, making the battery inside the SEI membrane, electrolyte, electrodes and other active substances decomposition reaction with each other to release heat\([10]\). For the battery pack, as shown in Figure 1 (a), the explosion critical moment is the 580th second. The violent reaction inside battery caused that the surface temperature rose faster than in the stage of overcharging. From the 484th second to the 754th second, the battery temperature continued to rise and reached the maximum of 470°C at the 754\(^{th}\) second. From the 754th second to 1998th second, the battery temperature decreased at a certain rate, which indicated the thermal runaway reaction inside battery was weakening. After 1998s, the temperature curve suffered "a cliff-like drop", which indicated the reacting injection in the battery pack ends. The thermal runaway time of the battery pack was 1514s from the 484th second to 1998th second. Combustion cannot occur unless there was enough fuel and air which jointly form a combustible mixture\([11]\). The batteries did not come into fire because there is no enough air in the box due to large smoke concentration.

![Figure 1. Incompletely Enclosed Test of battery pack.](image)

**Battery Deformation.** A deformed cell in a battery pack squeezes the surrounding because of the close contact among the cells. As a consequence, as the Figure 3 (b) shows, the aluminum shell of
the battery is damaged and the interior of the battery is exposed to the air due to the squeeze from the thermal runaway cell. The active substances in the cells exposed to the oxygen in the air greatly raise the potential risk of the battery pack. Furthermore, a thermal runaway cell will not be able to deform freely due to the constraining force from surrounding cells, which leads to the crack of the battery shell under internal and external pressure. Space for the deformation of each cell should be provided in order to possibly reduce its influence to surrounding cells.

![Figure 3. Exploded Cells.](image)

**Figure 3. Exploded Cells.**

**Explosion Pressure**

**A Single Battery Explodes.**

![Figure 4. Single cell explosion pressure curve.](image)

*Figure 4. Single cell explosion pressure curve.*

In order to better study the explosion pressure of the battery pack, a single battery was charged test. As shown in Figure 4, No. 1 sensor and No. 2 sensor pressure curve trend is basically consistent, Because NO. 1 sensor curve is more obvious, with the NO. 1 sensor as a reference. When the battery exploded at 2s, the pressure rose rapidly. Circled in blue, the pressure wave is generated when the battery case burst, about 20KPa. Then, the battery jet out a large amount of combustible gas, and accompanied by the burning of the battery, The battery reaches the peak value at 4.76s and 9.93s respectively. This is because the battery combustion process is unstable, a battery may be burned into several times to ignite, extinguish, and then ignite the process.

**Battery Pack Exploded in the Air.** In order to compare the influence of the enclosed box, the battery pack was charged in the air environment. The batteries in the battery pack part explode, however, in the closed box, the battery pack all the explosion, that the battery shell sympathetic detonation had great effect. This is due to the existence of the shell, making the battery generated high temperature flue gas is not easy to spread, so that heat can be a long time to pass around the battery heat. Although the battery burning in open space, the higher the temperature, but because of...
the uncertainty of the flame direction, making the heat transfer around the battery is not stable, causing some of the surrounding battery did not explode. The highest pressure in the air at 0.21MPa, compared to the pressure of the battery pack in the enclosed box, there is no big change in the pressure. But there are many pressure peaks in the pressure diagram, and the peak is not like the "sudden hop" of the explosion pressure wave. This is because the battery exploded and caught fire, battery burning caused by intense pressure wave fluctuations.

![Figure 5. Explosion pressure curve of battery pack in open space.](image)

Conclusion
In an enclosed space, the lithium-ion battery pack did not burn due to the insufficiency of air in the box after the explosion. The measured highest temperature was 470°C; a thermal runaway cell in a battery pack seriously squeezes the surrounding cells; after the explosion, heat tends to accumulate in the enclosed space, which leads to the reduction of explosion interval of other cells. What’s more, other cells explode after the previous pressure wave generated by cell explosion disappeared, and the pressure wave generated by a cell will not lead to the sympathetic explosion of the surrounding full-charged cells.

Reference


