Available online ***www.jsaer.com***

***Journal of Scientific and Engineering Research*, 2023, 10(3):63-69**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Experimental Study on Effects of Penetration on Thermal Runaway Characteristics of Lithium-Ion Battery

DONG yuan-jin*, MENG jian, SUN xiao-mei, ZHAO pei-dong, ZHENG bin

*College of Transportation and Vehicle Engineering, Shandong University of Technology, China

Abstract The use of lithium-ion battery electric vehicles is one of the important ways to achieve carbon neutrality. The harm caused by lithium-ion battery thermal runaway is huge. The research on thermal runaway has attracted much attention. The experimental system of battery thermal runaway was set up. Effects of penetration on thermal runaway characteristics of lithium-ion battery were studied. The battery internal temperature, battery surface temperature, battery voltage and eruption time were analyzed in the process of battery thermal runaway. The results showed that the thermal runaway of the battery shows a trend of spreading from the needle position to both ends, and the area of thermal runaway inside the battery is an irregular semicircle before the overall thermal runaway of the battery. The battery voltage is slowly reduced from 4.2 V to 3.5 V, and then drops to 0 V. The maximum temperature of the battery surface in the nail-triggered thermal runaway experiment reached 774 °C, the highest temperature inside is 1005 °C, and the eruption time was only 22 s.

Keywords Penetration, thermal runaway, lithium-ion battery, triggering mode

1. Introduction

In recent years, many countries have successively proposed ' zero carbon ' or ' carbon neutral ' climate goals, which have risen to national strategies [1]. Countries around the world have increased their investment in the new energy industry, promoting the high-quality development of the new energy vehicle industry. The power source of automobiles is shifting from traditional fossil fuels to electrochemical energy storage systems [2]. Lithium-ion batteries are widely used in new energy industries due to the significant advantages of high energy density, long cycle life, and low self-discharge rate, and are gradually becoming the mainstream of the automotive power battery market [3-5]. However, the high energy density, flammable electrolyte and poor diaphragm stability of lithium batteries will inevitably lead to thermal runaway and other safety problems in extreme abuse situations [6-8]. The thermal safety of the power battery has become the focus of attention, and to a certain extent, has hindered the development of electric vehicles [9-11]. Therefore, during the development and application of electric vehicles, the prevention of thermal runaway is an issue that still needs to be addressed.

A common feature of battery thermal safety accidents is battery thermal runaway, which is commonly triggered by the following three ways: mechanical abuse, electrical abuse and thermal abuse [12]. Experts and scholars have conducted numerous experimental studies on the thermal safety of $LiFeO_4$, $LiCOO_2$ and $LiMnO_4$ lithium batteries. The experiments are conducted to reveal the mechanism of thermal runaway [13], behavioral characteristics [14-15], influencing factors [16-17], and thermal runaway extension blocking mechanism [18-20] as well as for the validation of thermal abuse models, etc.

In summary, in this paper, a lithium-ion soft pack battery with a capacity of 53 Ah is used as a research object. The experiments of thermal runaway triggered by acupuncture was carried out. The thermal runaway characteristics of the battery under penetration abuse condition is analyzed based on monitoring data. The research results can provide reference for the safety design of lithium battery thermal management system.

2. Thermal runaway experiments under penetration triggering methods

2.1 Experimental objects and systems

The cell is $268\ mm \times 102\ mm \times 11.5\ mm$ in size, and the capacity is 53 Ah lithium-ion battery, as shown in Fig. 1. The battery is placed in the thermal runaway experimental system, and the thermal runaway of the battery is triggered by penetration.

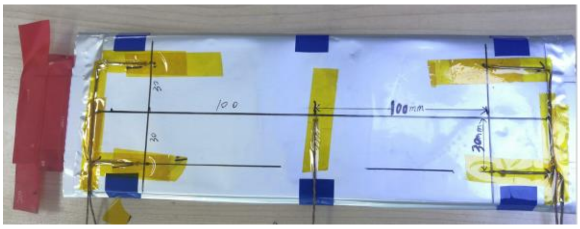
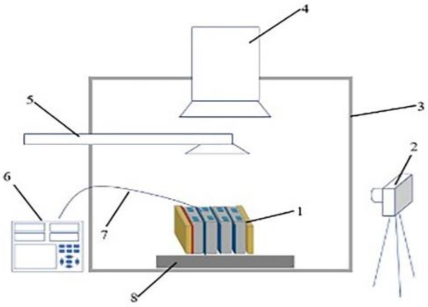


Figure 1: Experimental battery samples

The thermal runaway experimental system is shown in Fig. 2, which is composed of experimental battery device, video recorder, explosion-proof box, exhaust device, spray device, data acquisition device, heat insulation device and sensor. Firstly, the thermal runaway of the battery is triggered by penetration.



1-Battery device;2-VCR;3-Explosion-proof box;4-Exhaust device;
5-Spraying device; 6-Data collector; 7-Thermocouple and voltage line;
8-Insulation device

Figure 2: Battery thermal runaway test system

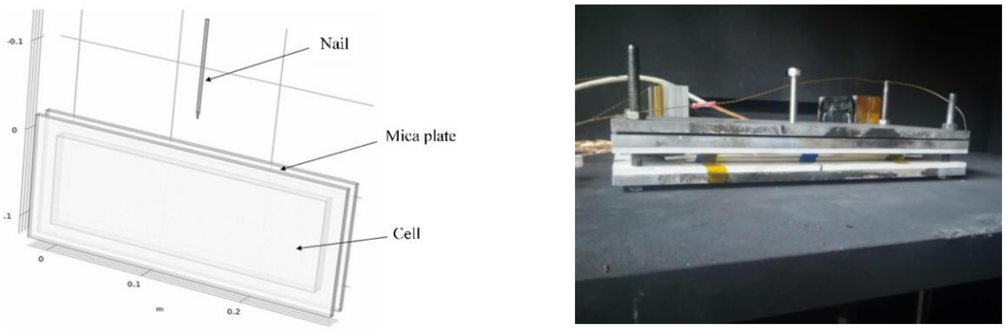
2.2 Experiment content

The mechanically induced thermal runaway of power battery is usually caused by chassis piercing and collision accidents. In experiments, acupuncture experiments are often used to simulate mechanically induced conditions.

2.2.1 Nail penetration experiment

The nail-triggered battery thermal runaway experiment is called the most stringent battery thermal safety experiment. Considering that different nail positions have different damage forms to the battery, and the nail position of most nail experiments is the front center of the battery, the nail-triggered thermal runaway experiment at the side center of the battery was carried out in this experiment. In this paper, a steel nail with a diameter of 3mm is selected. The angle of the needle is 30°, At a speed of 80 mm/s, it pierces into the battery from the center of the battery side, causing the battery to thermal runaway.

Fig. 3(a) and Fig. 3(b) are the schematic diagram and physical diagram of the acupuncture experimental device, respectively. The device consists of a needle, a mica plate, a battery and a steel fixture. During the assembly, the battery is first clamped in the middle by two mica plates, and then the steel fixture clamps the mica plate and the battery as a whole to provide a certain preload for the battery.



(a) Schematic diagram of nail experimental *(b) Physical view of the side of the battery*

Figure 3: Lateral center pinning thermal runaway test

Fig. 4 shows the layout scheme and name of temperature measuring points on the surface of the battery in the side nail experiment. Real-time monitoring and recording of voltage and temperature changes during thermal runaway of the battery under mechanical abuse conditions.

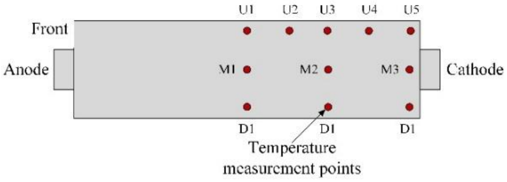


Figure 4: Side center temperature measurement point layout scheme

2.3 Experimental evaluation index

During the experiment of penetration thermal runaway trigger modes, the input energy before the thermal runaway of the battery, the maximum surface temperature, and the duration of the spray valve were used as indicators to evaluate the degree of thermal runaway hazard.

The temperature changes of the surface and internal key parts of the battery during the thermal runaway process were monitored. $T_{i,j\ (t)}$ were used to represent the temperature changes of each position in the battery with time, where i ∈(penetration) represents the trigger mode of thermal runaway, j represents the position of the battery surface temperature measuring point in each experiment, and t represents the moment of the thermal runaway experiment. At the same time, the experimental phenomena of battery thermal runaway under different trigger modes were recorded by video equipment.

Input energy experiment evaluation index:

$$E_{\text{nail}} = 0 \tag{1}$$

Where E_{nail} is the nail input energy.

Battery thermal runaway injection duration:

$$D_{\text{nail}} = t_{1,\text{nail}} - t_{0,\text{nail}} \tag{2}$$

Where D_{nail} is the duration of thermal runaway injection under different trigger modes. $t_{1,\text{nail}}$ is the end time of injection, $t_{0,\text{nail}}$ is the start time of injection.

3. Experimental phenomena and analysis of results

3.1 Analysis of experimental phenomena under penetration triggering methods

The thermal runaway process of side acupuncture is shown in Fig. 5. When the needle is inserted from the side, a small amount of smoke is ejected from the needle position and the side position. Subsequently, the ejected combustible gas was ignited and burned rapidly, and the needle position changed from smoke to violently burning flame. The thermal runaway of the battery gradually intensified, and flames were ejected and burned violently on both sides of the battery. The battery is completely thermally out of control, and there are flames around the battery, accompanied by high-temperature particles and a large amount of smoke. Finally, the material inside the battery is exhausted, the flame eruption ends, and a small amount of flame exists around the battery.

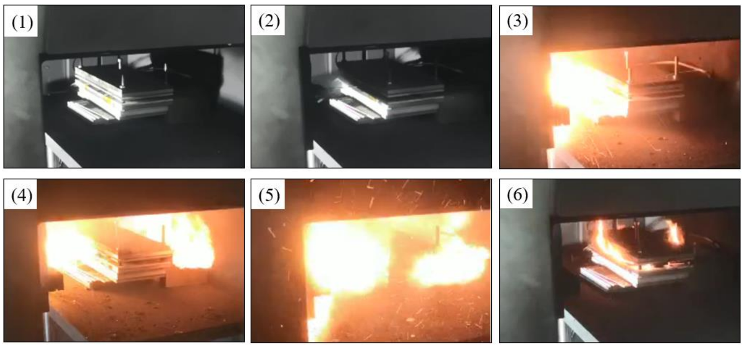


Figure 5: Lateral pinprick experimental phenomenon

3.2 Analysis of temperature change under penetration triggering methods

The thermal runaway time of the acupuncture trigger battery is short, so the experimental results of the first 100 s are analyzed emphatically. As shown in Fig. 6, the temperature change of the temperature measurement point on the lower side of the battery surface. The battery temperature increases in the order of down 1, down 2 and down 3, and the heat spread takes 4 s. It is shown that the thermal runaway of the battery shows a trend of spreading from the needle position to both ends after the needle insertion, and the maximum temperature of the three temperature measurement points on the lower side reaches 774.6 °C. The temperature curve of the temperature measurement point in the middle of the surface with time is shown in Fig. 7, and the maximum temperature is 736 °C. The temperature rise of the battery is also carried out in the order of middle 1, middle 2 and middle 3, which indicates that the spread of thermal runaway spreads from the center to both sides, and the spread time is 4s. As shown in Fig. 8, during the thermal runaway process, the temperature of the five temperature measuring points on the upper side of the battery changes with time, and the highest temperature of 716 °C appears in the ' upper 5 ' position. However, the spreading order of the upper side of the battery is not the same as that of the middle and lower sides, spreading from the middle to both sides. This shows that after the needle is inserted into the side of the battery, the needle position first triggers thermal runaway, and then the thermal runaway spreads to other areas without thermal runaway inside the battery with the needle position as the origin. Since the material inside the battery is not absolutely uniform, the area of thermal runaway inside the battery is an irregular semicircle before the overall thermal runaway of the battery.

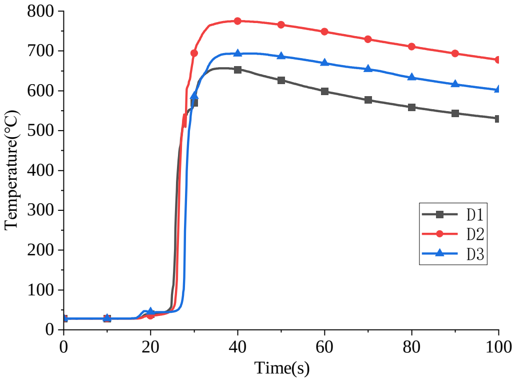


Figure 6: Temperature on the lower side of the battery surface

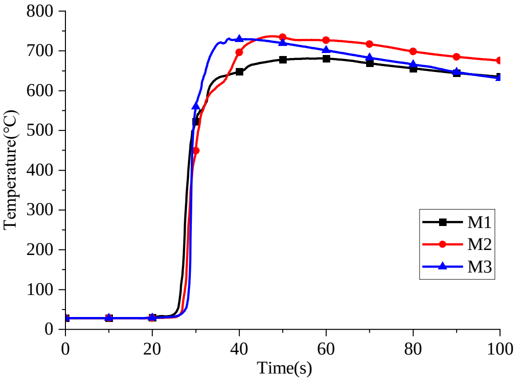


Figure 7: Temperature in the middle of the cell surface

Fig. 9 shows the curve of battery internal temperature and battery voltage with time. When the needle triggers thermal runaway, the battery voltage first fluctuates from 4.2 V to 3.5 V. At this time, a local internal short circuit occurs inside the battery, so the battery voltage only decreases slowly and does not directly change to 0 V. At the same time, the local internal short circuit and chemical exothermic reaction of the battery lead to a rapid increase in temperature. When the battery temperature rises to about 950 °C, a large area of internal short circuit occurs in the battery, the voltage drops rapidly from 3.5 V to 0 V, and the internal temperature of the battery further rises to 1005 °C at this time.

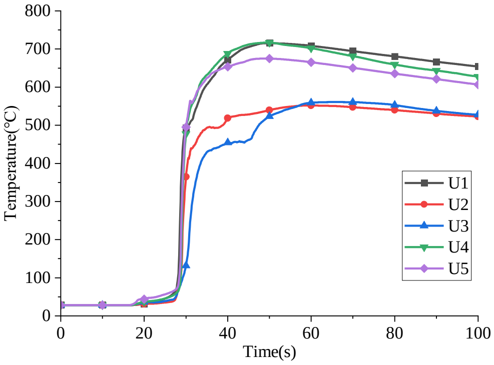


Figure 8: Temperature change curve on the upper side of the cell surface

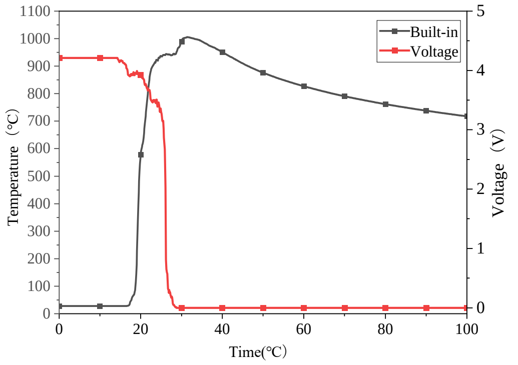


Figure 9: Battery temperature vs battery voltage curve

According to Fig. 10, it can be seen that the surface temperature of the battery is mostly between 650 °C-750 °C during the thermal runaway process, and it is cooled to 400 °C-600 °C after about 200 s of the end of the thermal runaway. The highest temperature on the surface of the battery is 774 °C, and the highest temperature inside is 1005 °C. The temperature rise of the built-in thermocouple is much earlier than that of the surface temperature measurement point. It shows that the inside of the battery is first out of control after acupuncture, and then spreads from the inside to the surface of the battery.

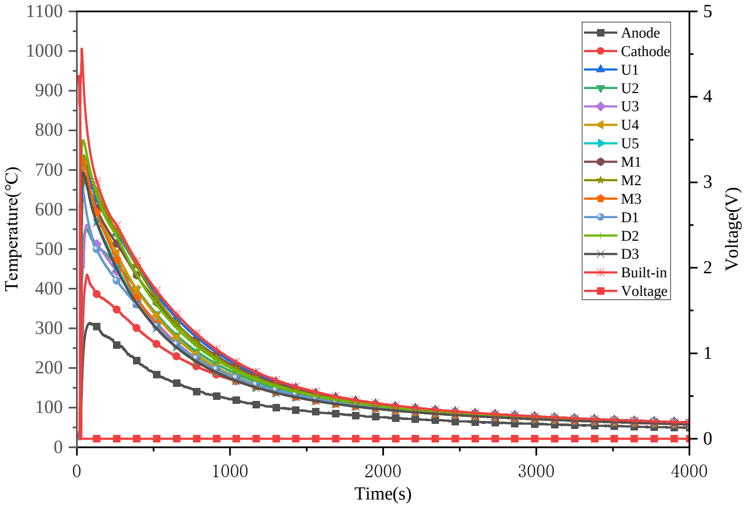


Figure 10: Temperature change curve of lateral pinprick cell temperature measurement point

4. Analysis of thermal runaway of batteries with penetration triggering methods

The experimental phenomena and experimental data of battery thermal runaway experiments under penetration trigger mode is analyzed. From the perspective of injection and ignition phenomena, the thermal runaway injection duration of the side acupuncture trigger battery is 22 s. Battery ejection is the most severe stage of battery thermal runaway, so the length of the ejection process can reflect the danger of battery runaway to a certain extent.

The mechanism of thermal runaway triggered by acupuncture is local internal short circuit caused by acupuncture penetration. The energy input of the needle-triggered thermal runaway battery is 0J. When the battery is thermally runaway, the chemical energy and electrical energy inside the battery are converted into thermal energy in a short time. Therefore, the more the input energy is, the higher the temperature is when the battery is thermally runaway. The maximum surface temperature of the thermal runaway battery triggered by acupuncture is 774 °C.

5. Conclusion

In this paper, the thermal runaway experiments of the battery triggered by penetration were carried out, and the effects of penetration trigger methods on the thermal runaway of the power battery were studied.

(1) The maximum temperature of the battery surface in the penetration-triggering thermal runaway experiment is only 774 °C, and the eruption time is was only 22 s. When the penetration triggers thermal runaway, the battery voltage first fluctuates from 4.2 V to 3.5 V, the battery temperature rises to about 950 °C, a large area of internal short circuit occurs in the battery, the voltage drops rapidly from 3.5 V to 0 V, and the internal temperature of the battery further rises to 1005 °C at this time.

(2) According to the temperature change curve of the temperature measurement point, it can be seen that the thermal runaway spreads from the needle position to other areas without thermal runaway inside the battery. Because the material inside the battery is not absolutely uniform, the area of thermal runaway inside the battery is an irregular semicircle before the overall thermal runaway of the battery.

(3) According to the voltage change curve before thermal runaway, it can be seen that the abnormal change of voltage sudden rapid decline can be used as a condition to judge whether the overcharge thermal runaway occurs.

References

[1]. IEA. World energy outlook 2019[R]. Paris, France: International En-ergy Agency, 2019.

[2]. Kalair, A., Abas, N., Saleem, M. S., Kalair, A. R., & Khan, N. (2021). Role of energy storage systems in energy transition from fossil fuels to renewables. Energy Storage, 3(1), e135.

[3]. Dai, H., Wang, Y. (2020). Study on Thermal Characteristics of Battery Modules of Electric Vehicle Based on Electrochemical Thermal Coupling Model. Automotive Engineering, 42(5), 665-671.

[4]. Lai, X., Yi, W., Cui, Y., Qin, C., Han, X., Sun, T et al. (2021). Capacity estimation of lithium-ion cells by combining model-based and data-driven methods based on a sequential extended Kalman filter. Energy, 216, 119233.

[5]. Liu, L., Xu, J., Wang, S., Wu, F., Li, H., & Chen, L. (2019). Practical evaluation of energy densities for sulfide solid-state batteries. eTransportation, 1, 100010.

[6]. Ma, R., Liu, J., Wang, S., Rao, Z., Cai, Y et al. (2020). Progress on thermal runaway propagation characteristics and prevention strategies of lithium-ion batteries[J]. Journal of Inorganic Materials, 66(23), 2991-3004.

[7]. Chombo, P. V., & Laoonual, Y. (2020). A review of safety strategies of a Li-ion battery. *Journal of Power Sources*, *478*, 228649.

[8]. Sun, J., Mao, B., & Wang, Q. (2021). Progress on the research of fire behavior and fire protection of lithium ion battery. *Fire Safety Journal*, *120*, 103119.

[9]. Ji, C., Wang, B., Wang, S., Pang, S., Qi, p. (2020). A review of the thermal safety issues of lithium-ion batteries Used in Electric Vehicles. Journal of Beijing University of Technology, 46(6), 630-644.

[10]. Feng, X., Ren, D., He, X., & Ouyang, M. (2020). Mitigating thermal runaway of lithium-ion batteries. Joule, 4(4), 743-770.

[11]. Lai, X., Jin, C., Yi, W., Han, X., Feng, X., Zheng, Y., & Ouyang, M. (2021). Mechanism, modeling, detection, and prevention of the internal short circuit in lithium-ion batteries: Recent advances and perspectives. Energy Storage Materials, 35, 470-499.

[12]. Chen, J., Liu, M., Zhou, Y., Lan, F., Luo, Q. (2020). Experimental Study on the Safety of Automotive NCM Batteries Under Different Abuse Conditions. Automotive Engineering, 42(01), 66-73.

[13]. Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y., & He, X. (2018). Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. Energy Storage Materials, 10, 246-267.

[14]. Fu, Y., Lu, S., Li, K., Liu, C., Cheng, X., & Zhang, H. (2015). An experimental study on burning behaviors of 18650 lithium ion batteries using a cone calorimeter. Journal of Power Sources, 273, 216-222.

[15]. Lopez, C. F., Jeevarajan, J. A., & Mukherjee, P. P. (2015). Characterization of lithium-ion battery

thermal abuse behavior using experimental and computational analysis. Journal of The Electrochemical Society, 162(10), A2163.

[16]. Zhao, R., Liu, J., & Gu, J. (2016). Simulation and experimental study on lithium ion battery short circuit. *Applied Energy*, *173*, 29-39.

[17]. Guo, L. S., Wang, Z. R., Wang, J. H., Luo, Q. K., & Liu, J. J. (2017). Effects of the environmental temperature and heat dissipation condition on the thermal runaway of lithium ion batteries during the charge-discharge process. Journal of Loss Prevention in the Process Industries, 49, 953-960.

[18]. Wilke, S., Schweitzer, B., Khateeb, S., & Al-Hallaj, S. (2017). Preventing thermal runaway propagation in lithium ion battery packs using a phase change composite material: An experimental study. Journal of Power Sources, 340, 51-59.

[19]. Shah, K., Chalise, D., & Jain, A. (2016). Experimental and theoretical analysis of a method to predict thermal runaway in Li-ion cells. Journal of power sources, 330, 167-174.

[20]. Chen, M., Bai, F., Song, W., Lv, J., Lin, S., Feng, Z., ... & Ding, Y. (2017). A multilayer electro-thermal model of pouch battery during normal discharge and internal short circuit process. Applied thermal engineering, 120, 506-516.