Research Article

Research on the Early Warning Mechanism for Thermal Runaway of Lithium-Ion Power Batteries in Electric Vehicles

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Lithium-ion power batteries are critical to the macrostrategy of new energy vehicles, and safety concerns such as thermal runaway remain a major bottleneck in the productization and industrialization of lithium batteries. Based on COMSOL Multiphase, an electrochemical-thermal coupling model for lithium-ion power batteries is created, as well as a thermal model for thermal runaway. A comparative study on lithium-ion power batteries was conducted using this model under on-board conditions, high rate cyclic charging and discharging conditions, and thermal abuse conditions. The results show that the temperature rise rate can significantly characterize the occurrence of thermal runaway, and when the temperature rise rate exceeds 1 °C/s, the lithium-ion power battery has a high probability of thermal runaway. In addition, when the average temperature exceeds 80 °C, there is a potential risk of thermal runaway in Li-ion power batteries. The results of the study show that high temperatures take longer to trigger thermal runaway, and the battery is slower to warm up. The time it takes for thermal runaway to occur, the maximum temperature reached, and the maximum voltage are all strongly connected to the overcharge flow under overload abuse conditions. The shorter the time it takes for thermal runaway to occur and the greater the maximum temperature and voltage attained, the larger the overcharge current.

1. Introduction

The new energy vehicle industry needs to upgrade battery safety technology, and the government needs to develop relevant industry standards. As a core component of new energy vehicles, the safety of lithium-ion power batteries has received widespread attention, especially the common safety issue of thermal runaway, which needs to be addressed urgently [1]. The new energy vehicle industry needs effective thermal runaway prevention and control solutions and relevant simulation models to guide the safety design of power battery systems, and the government needs effective testing and simulation solutions to develop relevant industry standards in order to reduce the risk of thermal runaway in commercially available products and to protect people’s lives and property. The significance of the research is described below in two specific aspects [2].

To ensure national energy security and effectively reduce carbon emissions [3], new energy vehicles have become one of the strategic emerging industries that various countries are vigorously fostering and developing [4, 5]. Power battery is an important source of power for electric vehicles, and the safety of power battery is the first issue to be considered and solved during the development of electric vehicles [6, 7].

However, safety incidents of lithium-ion battery systems characterized by thermal runaway have occurred from time to time, limiting the large-scale application of electric vehicles. In the case of lithium-ion battery smoke, when thermal runaway occurs, the internal chemical reaction of the battery will produce a large amount of gas, which will rush out of the battery safety valve or break through the case, and subsequently bring out the active material inside the battery, which will be manifested as battery smoke [8].

For the case of fire, the fire in an accident is usually caused by the ignition of the electrolyte and its decomposition products inside the battery. From the three elements of the combustion reaction (combustible, oxygen, and ignition), the combustible material is the electrolyte and its
decomposition products; there is a shortage of oxygen inside the battery, so the electrolyte needs to leak out of the battery's encapsulated shell before a fire can occur; the ignition material can come from the arc generated by the short circuit outside the battery or from the sparks generated by the friction between the high-speed gas ejected and the safety valve body during thermal runaway [9, 10].

In the case of an explosion, the impact is usually caused by the rapid diffusion of high-pressure gas [11]. The safety valve is the key to releasing the high-pressure gas build-up in a timely manner since the battery has internal conditions for high-pressure gas build-up. If the safety valve can be opened before the battery case ruptures and releases enough of the high-pressure gas generated during thermal runaway, the battery will not explode; if the safety valve is not opened in time, an explosion may occur [12–14].

Both fires and explosions are a concern. As a new thing, electric vehicles have high expectations and public concern in the event of an accident [15]. Thermal runaway is the root cause of smoke, fires, and explosions, and thermal runaway accidents can undermine the public’s confidence in accepting electric vehicles and hinder their popularity [16]. The safety management of lithium-ion power battery systems with the primary objective of preventing thermal runaway is an issue that still needs to be addressed in the development and application of electric vehicles [17]. The new energy vehicle industry is in urgent need of effective thermal runaway prevention and control solutions and establishment of relevant simulation models to guide the safety design of power battery systems [18–20].

The paper’s organization paragraph is as follows. The related work is presented in Section 2. Section 3 analyzes the thermal runaway warning system for lithium-ion power batteries. Section 4 discusses the Li-ion power battery thermal runaway warning system solution. Section 5 discusses the experiments and results. Finally, in Section 6, the research work is concluded.

2. Related Work

Thermal runaway is the main object of research on improving the safety of lithium-ion batteries [21]. When the battery shell is deformed or punctured by external forces causing mechanical abuse of the battery or not used in accordance with the requirements of the battery’s own electrical characteristics parameters, resulting in overcharging, overdischarging, external short circuit causing electrical abuse of the battery, or due to external factors, battery by-reaction heat generation causes local overheating of the battery resulting in thermal abuse of the battery and will make the lithium-ion battery in a very short period of time to occur exothermic chain reaction, causing battery temperature to rise sharply, further developing into thermal runaway, eventually leading to smoke, fire, and combustion or even explosion accidents [22]. Lithium-ion batteries lead to smoke, fire, and combustion, and explosion accidents have posed a great threat to the safety of public life and property. Particularly in the field of large-scale energy storage applications, the entire energy storage power plant will be destroyed, and the surrounding environment of the power plant and the public safety and property have certain negative effects. The realization of large-scale distributed energy storage and reliability applications is the main approach of the current international energy strategy deployment [23].

Studying the thermal runaway behavior of lithium-ion batteries and using the battery temperature, voltage, current, and the gas components released by side reactions as fault identification and diagnostic parameters to achieve early warning of thermal runaway of batteries are necessary and feasible, thereby improving the safety of lithium-ion batteries and protecting people’s lives and property. Based on this, researchers have successively proposed thermal runaway early warning technology based on battery management system (BMS) real-time monitoring of battery voltage, current, battery surface temperature, and other signals [24], thermal runaway early warning technology based on battery internal state prediction, lithium-ion battery thermal runaway early warning technology based on gas detection, and early warning technology based on gas detection. The early warning technology of thermal runaway based on battery internal state prediction and the early warning technology of lithium-ion battery thermal runaway based on gas detection have been verified through laboratory tests and practical field applications [25].

2.1. Thermal Runaway Warning Technology Based on Internal State Prediction. Modern BMSs rely on monitoring external parameters (such as voltage, current, and cell surface temperature) to ensure safe and reliable battery operation. However, for lithium-ion batteries, which are completely closed systems, monitoring of external parameters does not allow for a fully accurate simulation of them, nor does it accurately reflect their internal electrochemical changes, making it impossible for modern BMSs to fully assess the potential thermal runaway risk of a single cell. Reference [14] proposes that monitoring the internal state of the battery improves the identification parameters required for state estimation in modern BMS, allowing for a more accurate assessment of the battery’s thermal runaway risk, which is critical in the early detection of thermal runaway in Li-ion batteries. In [15], a simulation study of the thermal characteristics of a LiFePO4 Li-ion battery with a capacity of 20 A-h found that the temperature difference between the internal and surface temperature of the battery could reach up to 20°C in the large multiplier discharge state and concluded that it was difficult to truly reflect the true state of the Li-ion battery by measuring the surface temperature of the battery. In order to solve the challenge of monitoring the internal core temperature of Li-ion batteries, [16] established an internal battery temperature tracking model based on heat transfer analysis according to the thermal characteristics of Li-ion batteries and the kinetic characteristics of chemical reactions during thermal runaway. Reference [17] proposed a lithium-ion battery internal state monitoring scheme based on embedded foldable Bragg fiber optic
sensors. When the internal stress or temperature of the battery changes, the refractive index and wavelength of the refracted light of the Bragg fiber change accordingly, then by measuring the change of the wavelength of the refracted light, the internal stress and temperature of the battery are judged, and then with a modern BMS, the lithium-ion battery fault identification parameters are monitored in real time. This enables real-time prediction of the battery’s state of charge and health and early warning of thermal runaway in Li-ion batteries.

2.2. Early Warning Technology for Thermal Runaway Based on Gas Detection. Early warning of thermal runaway of Li-ion batteries is theoretically feasible using gas detection sensors as the characteristic identification parameters such as battery temperature, discharge voltage, and discharge current change very slowly and cannot be monitored early by modern BMSs, while the internal electrochemical reactions of the battery produce large amounts of gaseous substances.

Reference [19] monitored the temperature and gas generation behavior of a Li-ion battery type 26650 in real time from normal condition overcharge to thermal runaway stage using a high-resolution gas detection instrument. In [20], by performing infrared spectroscopy of the organic electrolyte of the Li-ion battery, it was found that the ester functional group has a more intense and sharp absorption peak at 1760 cm$^{-1}$ and that the specific ester species can be determined by the fingerprint absorption region of the ester functional group at 1300 to 1000 cm$^{-1}$. Reference [21] shows a patent for the invention of a lithium-ion battery thermal runaway automatic alarm and its monitoring method based on gas detection, consisting of a gas collection device, a gas detection device, a control device, and an alarm device. Reference [22] confirms that gas detection sensors are practical for application to lithium-ion battery thermal runaway early warning technology.

3. Thermal Runaway Warning System for Lithium-Ion Power Batteries

In this section, we discussed the research on a thermal runaway warning system for lithium-ion power batteries and the theoretical basis of thermal runaway warning systems for lithium-ion power batteries in detail.

3.1. Research on Thermal Runaway Warning System for Lithium-Ion Power Batteries. The lithium-ion power battery thermal runaway warning device is necessary and missing for new energy vehicles. Some studies at home and abroad have explored the thermal runaway process of lithium-ion power batteries, laying the foundation for the establishment of an early warning system in this paper. To establish a thermal runaway warning system, it is first necessary to determine when thermal runaway will occur in the battery and at what temperature thermal runaway will occur in the battery. In [23], three cylindrical batteries arranged side by side were baked on a stove to explore the inflection point temperature change and thermal runaway evolution law of the battery thermal runaway under the same temperature environment. The inflection point temperature and thermal runaway progression of the same type of battery under the same abusive working environment are different, as shown in Figure 1.

The lack of a fixed and obvious temperature inflection point for thermal runaway of Li-ion batteries makes it very difficult to determine thermal runaway of Li-ion power batteries. Without being able to determine whether thermal runaway has occurred in a battery, the challenge of early warning cannot be solved. In order to give a standard for determining thermal runaway of batteries, [24] conducted a pinprick experiment on cylindrical 18650 batteries to investigate the correlation between pack voltage and thermal runaway of batteries. Figure 2 shows the voltage change curve of the battery after a pinprick. As can be seen from the figure, when the steel needle was inserted into the battery pack, the voltage of the battery inserted by the steel needle immediately dropped to 0 V, but the voltage of the pack of the battery became irregular. Therefore, it is not appropriate to use voltage as a characterization parameter for the battery, the change in voltage of the pack is complex, and the change in voltage during thermal runaway of the battery caused by other conditions is even more complex.

A simulation study of the thermal runaway inflection point temperature of the battery was carried out, and batteries with different diaphragm melting temperatures were subjected to high-temperature tests. The local temperature rise of the battery will cause the decomposition reaction of the internal materials of the battery in a small area, and the decomposition reaction of the battery will release heat, resulting in a further increase of the battery temperature, so that when the battery temperature reaches the melting temperature of the diaphragm, the temperature of the battery will rise sharply. As a result, the temperature inflection point of the battery’s thermal runaway and the diaphragm melting temperature have a specific relationship. The warning system’s goal is to alert the driver and passengers when the battery is ready to experience thermal runaway. Knowing the temperature at which thermal runaway occurs can determine if thermal runaway has occurred, but it cannot predict when it will occur.

3.2. Theoretical Basis of Thermal Runaway Warning Systems for Lithium-Ion Power Batteries. In this section, we defined the necessary conditions for an established early warning system and the theoretical foundations of the early warning system established.

3.2.1. The Necessary Conditions for an Established Early Warning System. The association between the parameters of battery voltage, current, temperature, and temperature increase rate and battery thermal runaway is researched in order to determine the characterization parameters and parameter thresholds of battery thermal runaway. Because the battery voltage and current parameters change in a complex and irregular manner when thermal runaway occurs and the correlation between thermal runaway and the current and
voltage of the battery is weak, the current and voltage of the battery are excluded as characterization parameters of thermal runaway of the battery. In the BMS of new energy vehicles, there are only current, voltage, and temperature probes to detect the current, voltage, and temperature of the battery. Therefore, the temperature and temperature rise rate of the battery is used as the standard parameter for thermal runaway of the battery.

3.2.2. Theoretical Foundations of the Early Warning System Established. After a pinprick, the battery temperature rises rapidly within a short period of time, and the battery voltage drops to 0 V. This is due to the fact that when the battery is pinpricked, the steel needle pierces the battery and at the same time punctures the diaphragm that separates the positive and negative terminals in the battery, making the positive and negative terminals of the battery come into direct contact and short-circuiting the battery. After the battery short circuit, the current in the battery is extremely high, and because of the internal resistance of the battery, the battery puts out a huge amount of heat after the short circuit, and the battery’s heat capacity is called small; the battery temperature rises after causing other areas of the diaphragm to melt, further increasing the short circuit area. The battery short circuit makes the battery temperature continue to rise. The internal structure of the battery is destroyed; after the temperature rises, the battery material begins to decompose, further heat releases, and the battery then fires or explosion.

4. Li-Ion Power Battery Thermal Runaway Warning System Solution

The thermal runaway warning system for pure electric vehicles is an embedded system based on the BMS of the vehicle. The input parameters are the temperature, voltage, and current detectors in the BMS, and the output parameters provide the driver with thermal runaway warning information for the lithium-ion power battery.

Based on the above findings, this paper presents the framework of the Li-ion power battery thermal runaway warning scheme as shown in Figure 3.

The data flow of a lithium-ion power battery thermal runaway warning system is as follows:

1. Vehicle BMS monitors temperature, current, voltage, and other parameters.
2. Input the monitored parameters into the lithium-ion power battery thermal runaway warning system, and the system will judge whether the lithium-ion power battery is in danger of thermal runaway; if the battery temperature exceeds 80°C, the battery is judged to be in danger of thermal runaway and the system is turned on; if the battery temperature does not exceed
80°C, the battery is judged to be in a safe state, the thermal runaway warning system is turned off, and the vehicle runs normally.

(3) After the system is switched on, continue to monitor the battery temperature and speed up the frequency of data monitoring and uploading. If the battery temperature rises at a rate of more than 1°C/s, the battery is judged to be in thermal runaway, and a warning message is immediately given to instruct the driver and passengers to escape and take fire-fighting measures. If the battery is not experiencing thermal runaway as a consequence of the test, the system selects a model to compute when the battery is about to experience thermal runaway and sends an early warning message to the driver, instructing him on what to do next. The system chooses which calculation model’s voltage determination parameter to use in this phase. In the case of thermal runaway caused by a pinch, the battery voltage drops to 0 V quickly, in the case of thermal runaway caused by an overcharge, the battery voltage is greater than the rated voltage, and in the remaining cases, thermal runaway is caused by high temperature.

The input parameters for the early warning system are temperature $T$, temperature rise $dT/dt$, and voltage $v$. The instrument panel displays the battery temperature detected by the BMS while the driver is driving, which serves as an indicator to the driver. When the battery is approaching 80°C, the driver can adjust the driving strategy, either by switching on the pack forced cooling system to prevent the pack temperature from rising too quickly or by quickly applying cooling measures to the battery to avoid thermal runaway. When the instrument panel shows that the battery pack temperature exceeds 80°C, the battery is in danger of thermal runaway, and there is a risk of a thermal runaway at any time, at which point the thermal runaway warning system is activated. The instrument panel will show when the battery will experience thermal runaway and other indications of the pack’s condition. If the parameters calculated by the warning system indicate that thermal runaway of the battery pack is imminent, the driver should stop the vehicle immediately, instruct the passengers to leave the vehicle quickly, and find a way to extinguish the fire quickly to ensure that thermal runaway of the battery does not cause injury or death.

Figure 4 shows the calculation model of the battery warning system. After the system has selected the model by voltage $V$, the temperature parameter $T$ is input to the warning system, and the BMS system completes the calculation process. Based on the time displayed on the dashboard, the driver of the vehicle can choose to adjust the driving strategy or open the doors and assist the passengers in abandoning the vehicle.

The collected parameter signals are fed to the filter circuit system through an amplification circuit and converted into

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**Figure 3:** Li-ion power battery thermal runaway warning system solution.
electrical signals, which are then converted into digital signals by an analogue-to-digital conversion circuit. After processing the electrical signal into a digital signal by the analogue-to-digital conversion circuit system, the signal enters a discriminatory comparison circuit. If the battery voltage rises, the system selects the overcharge calculation model shown in Figure 4; if the battery voltage drops to 0 V, the system selects the pinprick calculation model, and the pinprick process occurs quickly in the thermal runaway process, so if the battery selects the pinprick calculation model, a warning alarm should be given soon, and the driver should take fire-fighting measures as soon as possible or abandon the car to escape; if the battery voltage gradually drops while driving, the system will select the hot box calculation model; at this time, the battery thermal runaway time will be strongly related to the battery temperature, and the battery thermal runaway time point, the temperature of the thermal runaway inflection point, and whether the battery fires and explodes after the occurrence of thermal runaway are all highly sensitive to real-time temperature.

According to the thermal runaway warning scheme and model, the thermal runaway warning system model was established in the simulation platform Simulink, and high-temperature thermal runaway warning simulations were carried out. Table 1 shows the simulation data of the high-temperature thermal runaway warning system. As can be seen from Table 1, when the battery temperature is below 80°C, the thermal runaway warning system does not show up on the instrument panel. When the battery temperature exceeds 80°C, the warning system starts to work and calculates the time at which thermal runaway will occur. As the battery temperature gets higher and the temperature rise rate gets faster, the time displayed on the dashboard decreases sharply, which is consistent with the pattern of thermal runaway of the battery.

5. Experimental Tests

In this part, we define the lithium-ion power battery overcharge abuse test temperature, overcharge abuse test voltage for Li-ion power batteries, and lithium-ion power battery high-temperature abuse test in detail.

5.1. Lithium-Ion Power Battery Overcharge Abuse Test Temperature. During the lithium-ion power battery overcharge test, Figure 5 illustrates the battery temperature and temperature rising rate. The battery temperature grew from 20°C to 30°C over the first 2000 s of the battery overcharge test, a 10°C rise. The battery temperature rise rate was extremely low, and during this time, the battery maintained charging, and the lithium ions in the battery continued to
move from the positive to the negative electrode; although the battery charge state reached 100% at this time, the concentration of lithium ions in the porous structure of the negative electrode of the battery was still not saturated, so the lithium ions in the battery moving from the positive to the negative electrode had little resistance, so the battery temperature rise rate was small. As the lithium-ion concentration in the negative electrode rises after 2000s, the resistance to lithium-ion transport from the positive electrode to the negative electrode rises, and the battery temperature rise rate accelerates.

5.2. Overcharge Abuse Test Voltage for Li-Ion Power Batteries.
Figure 6 shows the temperature and voltage variation curves of the battery during the battery overcharge test. As can be seen from the graph, first, this is due to the fact that, at 2500 s, the SEI film starts to decompose, causing damage to the cell structure, but as charging proceeds and the SEI film is formed, the voltage will continue to rise after the drop. By 2800 s, the lithium-ion concentration in the negative terminal of the battery reaches saturation, and the battery voltage rises sharply.

After completing the 2C overcharge test, the original intention of this paper was to investigate the temperature and voltage variation of a battery under different charging currents as a result of thermal runaway. However, due to the limitations of the test conditions and test funds, this paper could not complete the test. In [24], the performance pattern of the thermal runaway of the battery in the overcharge test under different charging current conditions was studied. Figure 7 shows the temperature and voltage curves for the overcharge test at different rates. The charging current of the overcharge test has a strong influence on the time required for the thermal runaway to occur and the maximum temperature and voltage reached by the thermal runaway. The higher the charging current, the shorter the time required for the thermal runaway to occur and the

5.3. Lithium-Ion Power Battery High-Temperature Abuse Test.
Figure 8 shows the temperature variation curve of the high-temperature abuse test for Li-ion power batteries. After 800 min, the ARC stopped heating, the battery temperature continued to rise, the rate of temperature rise increased, and at 880 min, the battery thermal runaway occurred and the battery temperature rose sharply, reaching a maximum temperature of 450°C. The internal component materials are used within 10 minutes of the rapid increase in battery temperature, the thermal runaway process ceases, and the battery temperature begins to drop.

In order to study the effect of different working conditions on the thermal runaway of Li-ion power battery, several sets of working conditions were simulated in this paper, and finally, five working conditions with a
A temperature gradient of 20°C were selected: 140°C, 160°C, 180°C, 200°C, and 220°C. Figure 9 shows the temperature change of thermal runaway of the battery under different temperature conditions in the numerical simulation of high-temperature abuse.

6. Conclusions

The thermal runaway of lithium-ion power batteries and its warning mechanism are investigated in depth in this work. The findings of this work can be used to develop a theoretical foundation for a thermal runaway warning model and system. A number of simulations of high-temperature abuse conditions are carried out for Li-ion power batteries to study the influence of the abuse temperature on the inflection point temperature, the inflection point moment, and the maximum temperature of the battery during the rapid temperature rise. The findings reveal that the greater the abuse temperature, the higher the battery’s inflection point and maximum temperature and the quicker the time it takes for the battery to reach thermal runaway. Furthermore, the results reveal that the battery’s temperature change characteristics are identical under various working settings [26–28].

Data Availability

The dataset used in this paper is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding this work.

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