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Research on the safety of power lithium-ion batteries

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Abstract:
Lithium-ion batteries (LIBs) have become the core energy storage devices in many fields. With the continuous expansion of its application areas and the continuous growth of installed capacity, ensuring its safe use has become a severe challenge. Reports of fires and explosions make people worried and show why battery safety is critical. Improving safety is essential for protecting users, property, and for people to trust and accept these technologies. Battery safety risks are complex and can come from different sources. Internal problems such as unstable materials, aging effects, and poor manufacturing can lead to short circuits or thermal reactions. External abuse conditions, including overheating and overcharging, can trigger dangerous events like fire or explosion. In recent years, several studies have shown that even small issues can lead to serious failures if not detected early. This review shows the recent research progress to analyse the intrinsic reasons and provide some feasible method for safety improvement.

Keywords: Lithium-ion batteries, safety; failure Mechanism.

1. Introduction

With the rapid advancement of electric vehicles and new energy automobile, Lithium-ion batteries (LIBs) are widely used. And also because of long cycle life, environmental friendliness and high energy storage, they become popular. Despite these advantages, the increase of reports on explosions and fires involving LIBs have attracted the attention of the public. People began to worry about the safety of batteries and it becomes critical to have more technological test for further application [1-3].

Therefore, scientists have increasingly turned their attention to understanding the fundamental causes of LIB failures and try to find methods for prevention. Rather than focusing solely on isolated abuse conditions [4], recent studies mainly pay attention to a more general view that including structural defects, gas evolution and aging effects. they are also working on better ways to test batteries and prevent accidents before they happen.

This review aims to analyse recent advancements in lithium-ion battery safety based on some representative studies published in this year. We will explore emerging safety issues, real-world failure diagnostics, quantitative risk models, and modern strategies for enhancing intrinsic and system-level resilience.

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Our goal is to give a clear view of the main safety issues and suggest useful ways to improve lithium-ion battery systems in the future.

2. LIB working principle

A lithium-ion battery usually has four main parts: the positive electrode (cathode), the negative electrode (anode), the separator, and the electrolyte. During charging and discharging, lithium ions move between the anode and the cathode. Electrons also flow through an external circuit to provide electric power. The separator keeps the two electrodes apart while letting ions pass through. The electrolyte helps the ions move easily [5]. These are the functions of each part.

In the whole reaction, the Li ion play an important role. During charging, Li ion will be oxidated and leave from the cathode materials, diffuses into the electrolyte and move through the salt bridge to the anode half. At the same time, electrons move in the opposite direction through the external circuit. During discharging, Li ion will move back to the cathode half and be reduced.

Although this process works well in normal conditions, problems can happen when the battery is overused [6]. If the separator is damaged, the processes in the lithium-ion battery shift from controlled to uncontrolled electrochemical reactions, leading to substantial heat production [7]. Also, if the battery is overcharged, damaged, heated too much, or has internal defects, it will catch fire or explodes and that's called thermal runaway.

Recent research has shown that different battery materials react differently. For example, lithium iron phosphate (LFP) is more stable than lithium nickel cobalt manganese oxide (NCM) or lithium cobalt oxide (LCO) [8]. The temperature at which risk happened and the maximum temperature reached can also vary. In one study, batteries with LCO reached temperatures over 700 °C, while LFP batteries were much safer under the same test conditions [9].

Thermal runaway is not only a problem in single cells. In battery modules or packs, heat from one cell can spread to others, causing a chain reaction. This is especially dangerous in electric vehicles and energy storage systems where many batteries are connected [10].

3. Battery Safety Issues

Lithium-ion batteries face several safety problems, especially when they are damaged, misused, or aged. Based on recent studies, two major sources of safety problems can be identified. The first one is design and manufacturing defects; the second one is abusing risks that will cause overheating and gas release. These problems can cause battery failure, fire, or even explosion [8, 10-12].

3.1 Design and manufacturing defects

Many battery failures begin with small problems in materials or production. Poor-quality materials can have some certain weaknesses, while mistakes during manufacturing can damage the internal structure.

Thermal runaway is the most serious safety risk. It can start from overcharging, short circuits, or high temperatures. A recent study showed that even small damage to battery parts can lead to local heating and short circuits. For example, in one failed battery module, researchers found missing insulation pads and corrosion near the tab, which caused electrolyte leakage and thermal runaway. This shows that even small internal problems can lead to big safety failures [10].

Manufacturing quality also affects battery safety. Defects such as poor welding, separator misalignment, or uneven electrolyte filling can increase the chance of failure [13]. In a real battery failure case, researchers used X-ray CT to find broken tabs and electrolyte leakage caused by weak seals. These problems are hard to detect but very dangerous. It is important to improve quality control and inspection methods during production [10].

One example of a common design-related failure is separator shrinkage under heat. Many lithium-ion batteries use polyolefin-based separators, which begin to shrink or melt at temperatures above 130 °C [13]. This thermal shrinkage may allow the cathode and anode to come into direct contact, leading to internal short circuits and possibly thermal runaway [14]. This problem has been observed in many fire incidents, especially in cells without reinforced separators. Although ceramic-coated separators have been developed to address this issue, they are not always used due to cost and production limitations.

Another key issue mentioned in the same review is the lack of mechanical protection in some battery designs. During nail penetration or crush tests, cells with weak casings or poor structural support often fail rapidly, releasing heat and gas. In contrast, designs with stronger outer shells or improved internal structures can delay or even prevent thermal runaway under the same conditions. These findings show that beyond material stability and manufacturing quality, structural protection is a necessary part of safe battery design [15].

3.2 Abuse Risk and Gas-Driven Hazards

In the real world, batteries often face more than one kind of stress at the same time. A battery may be exposed to heat, impact, or overcharging together. One study created a model that combines thermal, electrical, and mechanical abuse into one risk score. This method also considers battery aging, which changes how these dangers related to the battery. For example, older batteries may show lower risks in thermal tests but higher gas generation, which increases the chance of fire [11].

During thermal runaway or overcharge, batteries can release dangerous gases. If these gases reach a high concentration, they may catch fire or explode. Researchers found that gas types and amounts depend on the battery material. Some batteries with nickel-rich cathodes release more flammable gases than safer ones like LFP [8]. Aged and swollen batteries tend to produce more gas, which increases explosion risk. Therefore, gas monitoring could be useful for early warning systems [11].

Accidents caused by overcharging have been deeply studied in recent years. When batteries are charged beyond their voltage limit, they begin to produce heat and generate oxygen from cathode decomposition. In the hazard classification study [8], overcharged LCO and NMC cells reached similar runaway conditions as in thermal abuse. Even when the heating rate was lower than thermal abuse and mechanical abuse, the amount of gas produced was higher.

Different abuse types often lead to the same outcome: internal gas generation and possible explosion. The gas typically comes from electrolyte decomposition, cathode breakdown, and SEI layer reactions. Common gases include CO, CO_2, H_2, CH_4, and various hydrocarbons. According to the classification in recent paper, batteries containing NMC or LCO generated more than 200 mL of flammable gas per cell during failure [2]. If this gas accumulates in a closed system like a battery module, the internal pressure can break the casing or trigger an explosion.

In summary, while different abuse methods trigger failure in different ways, they often result in the same dangerous process: heat buildup, gas generation, and risk of fire or explosion. Understanding these cases helps guide safer design and better early detection systems.

4. Safety Improvement Strategies

4.1 Internal Strategies: Materials and Design

Cathode materials play a big role in battery safety [16]. In a recent study, the cells with different cathode were exposed to thermal abuse. The LFP battery started thermal runaway at 270 °C and reached a peak temperature of 400 °C, while the LCO cell triggered at only 210 °C and reached over 700 °C [8]. This shows that LFP is more stable and less likely to catch fire than nickel-rich materials like NMC or LCO. Choosing safer materials helps lower the chance of thermal runaway [8].

Separators are also very important. Traditional separators are polyolefin-based porous membranes which may melt at high temperatures. To solve this, some researchers use heat-resistant polymer separators that stay stable during thermal abuse [17, 18].

Electrolytes can be improved by adding flame retardants or replacing liquid electrolytes with solid-state ones. Adding flame retardants such as trimethyl phosphate (TMP) has been shown to delay ignition by 20–30 seconds during abuse tests. These changes reduce the risk of fire and slow down the spread of heat during failure [19, 20]. Battery structure matters as well. For example, reducing sharp edges, improving tab welding, and preventing gas accumulation can lower the chance of short circuits or swelling [10].

4.2 External Strategies: System-Level Protection

At the system level, Battery Management Systems (BMS) can detect abnormal temperatures, voltages, or swelling. Advanced BMS can shut down charging or discharging before danger happens. Some studies suggest adding gas sensors to detect early signs of failure [11]. Thermal management systems are also key. For example, one study compared air-cooled and liquid-cooled battery packs during high-current charging. The air-cooled system reached 58 °C, while the liquid-cooled system stayed below 40 °C. Lower temperature reduces the chance of thermal runaway [11]. Air cooling and liquid cooling are common, but researchers are also exploring phase-change materials (PCM) and heat pipes [21]. These systems help control battery temperature during use or abuse [11, 13].

Another useful method is cell balancing, which makes sure each cell in a pack has similar voltage and capacity [22]. This prevents overcharging of weak cells, which can be dangerous [13]. Some new strategies also focus on aging detection. Since older batteries behave differently, tracking internal resistance or gas buildup over time can help predict safety risks before they occur [11].

5. Safety Assessment and Testing Methods

To improve battery safety, researchers and engineers must understand how batteries behave under different conditions. Testing and assessment methods are important tools to measure risks, compare battery types, and improve designs. In recent years, new models and standardized tests have been developed for better real-world situations.

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5.1 Abuse Testing Methods

There are three common types of abuse tests: thermal, electrical, and mechanical. In thermal tests, batteries are heated until they fail. This helps identify the temperature at which thermal runaway starts, and how severe it becomes. Electrical tests include overcharging, external short circuits, or forced discharging. These can lead to high current, overheating, or lithium plating. Mechanical tests such as crush, penetration, or damage during transport or accidents [13].

In one study, researchers tested several pouch cells with different materials under both thermal and overcharge conditions. They found that battery type and trigger method will influence the risk level and gas release [8].

5.2 Quantitative Risk Models

Traditional tests only give two kinds of results which is fall and pass, but newer approaches use quantitative models to calculate safety levels. One example is the Fuzzy Analytic Hierarchy Process model. This model is relatively complete, it combines many factors such as internal resistance, temperature rise, gas volume, and short-circuit current. After calculation, it will give a safety score. The FAHP model has two versions. The first one is a Simplified Engineering Model uses basic data from common tests. The second one is a General System Model, which adds more detailed information such as battery aging and intrinsic safety parameters [11].

In a recent study, researchers test new and aged batteries with new models. They found that older batteries released more gas but they were less likely to have thermal and electrical abuse. The models helped divide the batteries into different group with different safety levels and suggested customers when they should be replaced [11].

5.3 Hazard Classification Systems

To compare battery risks, some researchers use hazard ranking systems, like EUCAR levels. These systems classify battery from safe to dangerous with different numbers. Level 0 represents that the battery is safe, while Level 7 means the battery is highly likely to fire or explosion [8].

One paper tested over 70 batteries and used temperature, pressure, and gas data to assign each one a hazard level. This approach helps manufacturers and safety labs judge the different safety of different battery designs [8].

6. Conclusion

Lithium-ion battery safety has become a major challenge because of the increase of the demand for high-performance energy storage. Recent studies have shown that battery failure is not caused by a single factor but a combination of internal defects, thermal runaway triggers, gas release, and multi-abuse conditions. Real-world failure analysis has revealed that even small structural defects can lead to serious consequences, while aging is also one of the most important influence factors to battery behaviours under stress.

To improve safety, both internal design and system-level strategies are needed. Material innovations such as safer cathodes and solid-state electrolytes can reduce the chance of fire. At the same time, external protections like BMS monitoring, thermal management, and gas detection can provide real-time prevention. Quantitative risk models provide a new way to assess battery safety based on measurable indicators, making it possible to compare the battery systems more effectively.

Looking ahead, future work should focus on summarizing and combining these solutions. Battery packs should be designed with better thermal isolation and warning sensors. In addition, aging effects and gas release should be key factors while testing the battery safety. Only by combining material science, engineering design, and smart system control, we can finally find a better way to increase the safety of lithium-ion batteries in the real word.

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