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Battery management systems and material optimization for improved electric vehicle safety

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Abstract. Electric vehicles (EVs) are considered a key solution to reducing global carbon emissions and moving towards a more sustainable transportation future. Driven by government environmental policies and consumer acceptance, the EV market is rapidly expanding, and the safety of lithium-ion batteries has become a critical technical and public issue. Accidents related to thermal runaway, fire hazards, and potential explosions highlight the urgent need to strengthen battery safety mechanisms. These challenges stem from inherent material instabilities, operational stresses, and the limitations of existing monitoring and protection systems. Therefore, various innovative strategies are being developed to mitigate these risks. This article explores the root causes of battery failures, highlighting current challenges in battery reliability and safety margins and battery management systems (BMS). Furthermore, this article summarizes the current research status in ceramic separator design, electrolyte additives, and electrode material modifications to improve battery safety. These studies will help accelerate interdisciplinary research collaboration to improve the performance and safety of electric vehicles.

Keywords: Lithium-ion battery; battery safety; thermal runaway.

1. Introduction

With the rapid growth of electric vehicles (EVs), people choose to use lithium-ion batteries (LIBs) to replace fossil fuels, which currently power most EVs. China leads the global EV market with 60% of sales in 2022 [1]. Although these batteries provide high energy density, a lengthy cycle life, and affordability, their safety has become a major concern [2]. In particular, occurrences of battery fires and explosions have raised alarms among both industry professionals and consumers. They seek to gain a thorough understanding of the underlying causes and potential solutions. These fire and explosion incidents are often initiated when batteries surpass their ignition or explosion thresholds, typically due to overheating within the battery cell, internal short circuits, or manufacturing flaws [3]. Once these thresholds are crossed, the system rapidly causes thermal runaway (TR), resulting in fires or even explosions.

A key idea to mitigate these dangers is the safety boundary, which is the region where the battery can be made to operate safely, without danger. The danger only exists as long as the boundary is not crossed. Currently, the dominant strategy to enforce safety boundaries relies on Battery Management Systems (BMS). BMS are designed to continuously monitor and control parameters, such as voltage, temperature, and current in real time to prevent dangerous conditions like overcharging, TR, and physical damage [4]. When abnormal behavior is detected by the system, power is disconnected. While this approach provides the defense line, it also highlights a limitation that cannot be ignored: BMS can only affect after anomalies occur rather than eliminating the root causes of the risk within the battery itself.

This paper, therefore, outlines that EV battery safety must be reinforced by both strengthening monitoring and control mechanisms while simultaneously enhancing the safety of battery materials. A review of (1) the battery management systems, (2) the integration of flame-retardant materials such as ceramic separators to suppress the spread of fire, and (3) material-level innovations, including electrolyte additives and electrode aspects to increase battery resilience. By combining system management level with materials innovation, the safety boundary can be extended to reduce the likelihood of battery risks. The purpose of this research is to build a broader understanding of addressing the growing challenge of EV battery safety to ensure consumer trust and protection.

2. Battery Safety Overview

2.1. Fundamental Causes of EV Battery Hazards

The safety issues in EVs associated with lithium-ion batteries were caused by interactions between the thermal and electrochemical factors. Thermal runaway (TR) is the most significant failure. TR happens when a single battery cell overheats due to short circuits, overcharging, or physical damage, and the heat spreads to neighboring cells. This chain reaction leads to a domino effect that can result in fire or even an explosion [3].

A central element in TR is the electrolyte. Conventionally, in lithium-ion batteries, electrolytes were composed of organic carbonate solvents like ethylene carbonate and dimethyl carbonate that dissolve lithium salts [5]. However, these electrolytes are highly flammable. At elevated temperatures, electrolytes break down into hydrocarbon gases, including hydrogen, methane, and ethane, which will be ignited at high temperatures [6]. The flammability of conventional electrolytes represents a fundamental weakness in current lithium-ion battery designs.

Another important contributor to battery fires is internal short-circuiting (ISC), which occurs when the separator fails to isolate the cathode and anode. Short-circuits can be caused by physical damage that compromises battery structures, separator shrinkage at high temperatures, or manufacturing defects like uneven material distribution inside the separator. Even a localized internal short circuit can generate extremely high current density, cause rapid battery heating and localize thermal runaway within milliseconds. Although the probability of these events is statistically rare, around 1 in five to ten million [7], the consequence of the cell failure will become catastrophic. Therefore, internal short circuits are considered one of the most critical and difficult to predict hazards in lithium-ion battery safety.

2.2. Battery Management Systems and Their Limitations

The degradation of the battery directly affects the performance and safety of the EV; a monitor system is crucial [4]. A battery management system (BMS) is used to maintain the safety boundary of EVs. BMS is an electronic system that continuously monitors parameters such as voltage, current, and temperature to ensure safety and performance [8]. When abnormal conditions are detected, the system can shut off the battery, regulate battery temperature, and prevent short circuits.

However, relying solely on the BMS for electric vehicle battery safety also reveals some limitations. Fundamentally, the BMS is a response to emergencies rather than a solution to the root causes of these failures. Moreover, it responds only after the abnormality is detected, but if faced with some rapidly developing faults, it will be too late for the BMS to solve the problem. Furthermore, the effectiveness of the BMS is limited to the accuracy and location of its sensors. For example, if an abnormal hotspot occurs outside the sensor's measurement area, the sensor will not be able to detect it.

Furthermore, BMS cannot address the intrinsic material properties of the battery, such as the electrolyte, electrodes, and separators, which are the root causes of many battery failures. Thus, to fundamentally solve the problem of EV battery fires, more improvements should be focused on raising the threshold of stability at the material level.

3. Solutions to Prevent and Mitigate Battery Fires

3.1. Flame-Retardant Materials: Ceramic Separators

In terms of EV battery safety, flame-retardant materials are critical for preventing the spread of fires or explosions caused by failure, such as thermal runaway or internal short circuits. Although lithium-ion batteries have high energy density and are widely used, they are prone to risks like overheating, overcharging, and physical damage. These hazards are often related to the highly flammable battery components and result in a chain reaction of fires or explosions. Therefore, the introduction of flame-retardant materials is essential in improving battery safety.

In the structure of the separator, there is a thin layer that keeps the positive and negative electrodes apart while still allowing lithium ions to move between them. Ceramic separators are the most promising flame-retardant materials for LIBs. Traditional separators are usually made from polyolefin materials such as polyethylene (PE) or Polypropylene (PP) [9]. While these are great commercial successes, they are instability at around 130 °C. Above this temperature, the polyolefin separators start to shrink or melt. When this happens, the electrodes may touch each other and cause a short circuit (ISC). To solve this issue, researchers turned to a ceramic separator as a way to make the separators safer. Ceramic materials such as alumina (Al_2O_3) and Tin (IV) oxide (SnO_2) are known for their high melting points and non-flammable properties. Unlike the polyolefin separators that can melt or shrink under heat, ceramic separators remain stable and intact even under extreme temperatures, preventing the battery from the TR conditions.

The key benefit of ceramic separators is their ability to act as a barrier. When a cell reaches a dangerous temperature, ceramic separators form a protective shield over the cells, reducing the risks of fire. They prevent the contact between the anode and cathode, effectively stopping the spread of thermal runaway from one cell to another.

Moreover, these ceramic separators can stay stable up to 200 °C, showing no deformation at high temperatures [10]. They also improve mechanical strength and absorb electrolytes more efficiently. Companies such as Samsung SDI and Entek have already started using them in their commercial EV battery packs, and reports suggest that fire-related incidents have decreased since then. Ceramic-coated separators (CCS) were implemented in Samsung SDI manufacturing. This design improves thermal stability and prevents shrinkage, allowing LIBs to operate more safely. According to their official reports, CCS technology has already contributed to a reduction in battery fire incidents.

Despite their advantages, ceramic separators face certain challenges. The cost is an issue. It is more expensive to manufacture ceramic separators when compared to conventional polymer separators. The production of ceramic materials requires specialized manufacturing processes that add to the overall cost. Furthermore, coating the ceramic particles onto polymer separators requires complex processes, making large-scale production more challenging. Another aspect that needs to be considered is the size of the ceramic particles. As the size range is larger than 100 nm, there will be a random distribution and severe blockage of the pores of the separator, which will significantly slow down the ion transport and greatly decrease the performance of the separator itself. It will also decrease the efficiency of the battery because of less ion flow inside the battery during charge or discharge. In contrast, particles smaller than 100 nm can improve the uniformity of the separator structure and enhance ion conductivity, thus improving the overall performance of the battery [11].

As electric vehicles become increasingly popular, enhancing battery safety is crucial for building consumer confidence. Ceramic separators are among the most effective solutions for this purpose. Currently, ceramic-coated separators (CCS) are anticipated to gain wider adoption. As manufacturing processes become more efficient and material expenses decrease, CCS might emerge as a standard in the EV battery sector. This shift would ensure that the majority of EV batteries available in the market gain improved thermal stability and a lower risk of fire.

3.2. Electrolyte and Electrode Materials Optimization

The safety of lithium-ion batteries (LIBs) is not only influenced by external safety strategies such as battery management systems (BMS) and flame-retardant materials, but more importantly, the intrinsic electrochemical and thermal stability properties of their internal constituent materials—the electrodes and electrolytes. These materials directly determine the battery's reactivity under abusive conditions (such as overheating, overcharging, and short-circuiting), making their optimization a key path to improving battery safety. This section will focus on innovative design and modification of electrolyte and electrode materials to mitigate the risk of thermal runaway and fire at the source while maintaining long-term electrochemical performance.

Conventional liquid electrolytes, which mostly use organic carbonate solvents, are volatile and have low flash points. They are prone to decomposition and release flammable gases under high temperatures or short-circuit conditions, significantly increasing the risk of thermal runaway. To overcome this limitation, researchers have developed a series of highly effective flame-retardant additives that, when incorporated into the electrolyte system, significantly improve its flame resistance. Such additives are usually compounds containing phosphorus, fluorine or chlorine, such as triphenyl phosphate (TPP) and tributyl phosphate (TBP), which can inhibit free radical chain reactions in the gas phase or condensed phase, thereby delaying or even preventing the combustion process. In addition, these flame retardants can also participate in the formation of a more stable interfacial protective layer (SEI) on the electrode surface, weakening the exothermic reaction between the fully charged negative electrode and the electrolyte, thereby effectively delaying the occurrence of thermal runaway [12]. It is worth noting that the selection of additives needs to comprehensively consider their effects on ionic conductivity, cycle life and rate performance to achieve synergistic optimization of safety and performance.

Another promising development direction is the development and application of solid electrolytes (SSE). Unlike conventional liquid electrolytes, solid electrolytes usually have the advantages of being non-flammable, leak-free and highly thermally stable. Their decomposition temperature is much higher than that of organic liquid electrolytes, which essentially improves the thermal safety margin of the battery [13]. In addition, many solid-state electrolyte systems (such as sulfides, oxides, and polymer-based electrolytes) have improved compatibility with lithium metal anodes, making it possible to use high-capacity lithium metal anodes, thereby significantly improving the energy density of the battery. This not only helps to improve the range of electric vehicles, but also further promotes the practical application of high-safety, high-energy-density solid-state battery systems. Despite this, solid-state batteries still face challenges such as large interfacial impedance, high material costs, and immature large-scale preparation processes. Current research is committed to achieving their commercial application by breaking through these bottlenecks.

On the other hand, developments in the stability of positive and negative electrodes are required to avoid short-circuits within the cell. Graphite is the most common anode material because of its stability and conductivity. However, graphite can be thermally unstable and thus damaged after repeated charging. One new technology is the development of silicon-based anodes. Silicon anodes offer a significant performance advantage over traditional graphite anodes due to their high theoretical capacity of 4200 mAh/g, much higher than graphite's 372 mAh/g [14]. Silicon has a low delithiation potential, which can prevent the formation of dendrites [15]. Dendrites are metallic needles that grow from the negative electrode during charging and may penetrate the separator to cause ISC and trigger thermal runaway. The innovation of the silicon anode greatly reduces the risk of dendrite cracks.

For the cathode, researchers also invented single-crystal nickel-rich cathode materials (SC-NCM). SC-NCM has better mechanical strength, cycle stability, and safer overall performance compared to conventional polycrystalline cathode. The grain boundary is eliminated, and the surface area of each single crystal is limited, so the crack will not be formed during cycling [16]. The absence of grain boundaries helps to reduce the risk of side reactions and oxygen release. At high temperature and high voltage, this issue will be more sensitive. As a result, SC-NCM shows better crack resistance and cycling stability, resulting in better battery safety and longer lifespan under harsh conditions. Also, the single crystal structure can provide an easy insertion for lithium ions, which will improve the rate capability and other performances of the battery. SC-NCM also has better thermal stability. Under high voltage and high temperature conditions, this single crystal nickel-rich cathode material can prevent the thermal runaway, and improve the battery safety.

4. Conclusion

The safety and performance of lithium-ion batteries are critical for the widespread adoption of electric vehicles. In this paper, battery safety improvement was reviewed through battery management systems, flame-retardant materials, and electrolytes and electrodes advancement. All these steps minimize risks such as thermal runaway, internal short circuits, and other failures. Solid-state electrolytes (SSEs) and ceramic separators have shown significant importance in improving battery safety. SSEs offer non-flammability and good thermal stability compared to conventional liquid electrolytes. Ceramic separators avoid internal short circuits and can hinder fire spread, further improving the safety of the battery under extreme conditions. Furthermore, single-crystal nickel-rich cathodes improve lithium-ion battery energy density and cycle stability. Silicon-based anodes offer significant improvements in energy density and inhibit dendrite formation. Continuous innovations in material and battery design will be essential to solve battery fires and explosion issues. Overall, by concentrating on both material enhancements and safety features, the next generation of batteries can reach improved performance and reliability, reducing the risks of fires and explosions.

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