Research and Reflections on the Safety of Automotive Lithium-ion Batteries

Tongshu Zheng*

School of Royal High School, Bath, England, UK

*Corresponding author: zhent1.student@rhsb.gdst.net

Abstract. This article provides a comprehensive analysis of safety challenges in lithium-ion batteries for electric vehicles (EVs) and proposes mitigation strategies to address these risks. Li-ion batteries, while pivotal for EVs adoption due to their high energy density and efficiency, face critical safety concerns such as thermal runaway, mechanical deformation, and electrochemical instability. Thermal runaway—triggered by mechanical collisions, electrical abuse (overcharging, over-discharging), or internal short circuits—remains the most severe hazard, often leading to fires or explosions through exothermic reactions, electrolyte decomposition, and gas release. Mechanical failures, including structural damage from crashes or vibration, exacerbate risks by inducing internal short circuits and heat accumulation. Current safety measures emphasize advanced battery management systems (BMS) for real-time voltage, current, and thermal monitoring, alongside thermal management systems (TMS) utilizing liquid cooling, phase-change materials, and micro heat pipe arrays to enhance heat dissipation. Material innovations, such as flame-retardant additives, solid-state electrolytes, and silicon anodes, aim to reduce flammability and dendrite formation. Structural protections, including reinforced housings and optimized cell-to-pack designs, further improve crash resilience. Future directions highlight AI-driven fault prediction, in-situ diagnostics, solid-state battery development, and sustainable recycling methods. This study underscores the necessity of multidisciplinary approaches integrating electrochemistry, mechanical engineering, and data analytics to advance battery safety, ensuring EVs meet rigorous reliability standards and foster public confidence in sustainable transportation.

Keywords: battery safety, lithium battery, electric vehicles.

1. Introduction

The rapid adoption of electric vehicles (EVs) has brought lithium-ion batteries to the forefront of automotive energy storage solutions. While Li-ion batteries offer high energy density, long cycle life, and fast charging capabilities, their safety remains a critical concern [1].

Battery safety is influenced by multiple factors, including thermal, mechanical, and electrochemical stability. Failures can result from manufacturing defects, external abuse like crashes, or internal short circuits. Addressing these risks requires a multidisciplinary approach involving material science, engineering, and regulatory oversight. The safety of EVs batteries is paramount due to their critical role in ensuring operational reliability and minimizing risks such as thermal runaway, fire, or explosion. Lithium-ion batteries, widely used in EVs, are susceptible to thermal instability if improperly managed, posing severe safety hazards. Robust battery management systems (BMS), advanced thermal regulation, and rigorous manufacturing standards are essential to mitigate these risks. Furthermore, battery safety directly impacts consumer confidence, regulatory compliance, and sustainable transportation adoption. Research into solid-state electrolytes and enhanced failure-detection algorithms continues to address these challenges. Prioritizing battery safety safeguards users [2].

This paper explores the root causes of Li-ion battery failures, analyzes existing safety measures, and proposes future improvements to ensure safer EVs deployment. And the safety challenges associated with automotive Li-ion batteries, including thermal runaway, mechanical damage, and electrochemical instability. Furthermore, it explores mitigation strategies such as advanced BMS. By addressing these challenges, the automotive. The transition from internal combustion engines (ICEs) to EVs is accelerating due to environmental concerns and technological advancements. Lithium-ion batteries are the dominant energy storage technology in EVs due to their superior energy density, efficiency, and decreasing costs.

2. Safety Challenges in Automotive Li-ion Batteries

Thermal runaway is the most critical safety issue in Li-ion batteries. It occurs when an exothermic reaction within the battery leads to uncontrolled temperature increases, potentially causing fire or explosion. The common thermal runaway has two different types. The first type is mechanical collision, and the second type internal chemical reaction. Automotive batteries are susceptible to mechanical damage from collisions or impacts. A crushed battery cell can lead to mechanical failure or electrical faults.

Among them, impacts and compression suffered by the vehicle during operation are the main sources of mechanical failure in the battery system. When a mechanical failure occurs in the battery system, deformation of the battery leads to the leakage of internal gases and electrolytes, resulting in bulging of the battery. The internal resistance of the battery increases, generating more heat. If this heat is not effectively dissipated, it can ultimately lead to fire and explosion incidents. Similarly, when the battery system experiences overcharging, over-discharging, internal short-circuits, or external short-circuits that trigger electrical faults, it causes the battery temperature to rise, which can in turn trigger internal membrane melting, electrolyte decomposition, and positive electrode material decomposition, leading to severe incidents such as battery leakage, fire, and explosion. During the operation of electric vehicles, due to bumps and connectors due to impacts corrosion and other conditions may cause loosening of the internal battery system connection components obstacles, which cause mechanical abuse of the battery system and trigger an internal short circuit, such as this faults are usually manifested as an increase in the internal resistance of the battery in contact, identifying this fault class the type is mainly used to detect the pressure between the cells in the operation of the battery system difference case, and the change in voltage recovery differential voltage in the case of holding. If the fault is not monitored and eliminated in time, the resistance that is too high will cause local high temperature, after the temperature accumulates and overheats, it will cause the nearby monolithic body. A side reaction occurs that causes the irreversible occurrence of active substances inside the battery reaction, also when the temperature cannot diffuse effectively, causing the diaphragm to melt, After the electrolyte decomposes, it will cause a battery thermal runaway accident. The primary causes of thermal runaway in lithium-ion batteries during operation are mechanical and electrical abuse. Mechanical abuse can occur due to impacts or compression of the cell itself. When the battery sustains minor damage, this injury can amplify with subsequent cycles of use, leading to failure. In severe cases, this may result in casing cracks, electrolyte leakage, or even internal short circuits, potentially leading to fire or explosion. Electrical abuse primarily includes overcharging, over-discharging, and external short circuits, with overcharging being the most likely to trigger thermal runaway. During the overcharging process, a steady increase in voltage, destruction of positive electrode materials, capacity loss, and rapid temperature rise will occur. In severe instances, this can generate large amounts of gas inside the battery, causing swelling, rupture, and potentially fire or explosion [1].

When the charge and discharge monitoring technology of the battery system cannot achieve accuracy regulation, resulting in the occurrence of a single or partial single cell in the battery system charging and over discharging phenomenon. Usually when the battery is overcharged, the negative electrode surface will open, and the long-term precipitation of lithium ions may induce the appearance of lithium dendrites, which will continue to grow.

To a certain extent, it will puncture the separator, which will cause micro-micro-scabies to appear inside the battery. Short circuit, a short circuit in the battery causes the temperature to rise, so it mainly passes the inspection measure the rapid rise in temperature to identify internal short circuit faults that have occurred in the battery when discharged, the negative electrode SEI film and the surface lithium ions will be completely embedded leads to irreversible loss of the structure of the negative electrode and its active substance, which is electrical the characteristics of pool failure are rapid attenuation of capacity and rapid increase of internal resistance. If there is a serious over discharge phenomenon, the copper deposited on the surface of the negative electrode of the battery is the same. The phenomenon of puncturing the diaphragm may occur serious accidents, which occurs with a severity similar to that of overcharge [2].

Crash safety standards mandate rigorous testing, but real-world scenarios remain unpredictable. The accidents always happen tough there are safety test. Also because of the technology growing, there are many new ways to test safety. The first way is model comparison. We compare the malfunctional model with normal model to find which place is different, that make the car appear safety problem. The second way is model-free, data-driven fault diagnosis the off-end method relies on sample data and does not require modeling from the battery. It avoids the online parameter update of the battery model, and this kind of fault diagnosis methods include fault diagnosis based on statistical analysis of information entropy [3, 4], based on data-driven modeling (artificial neural networks [4, 5], radial basis neural networks, multi-model fusion strategy, etc.). Combine the advantages of fuzzy logic and neural networks to make use of neural network pairs the battery failure data is learned, and then the fault is detected by fuzzy logic symptoms are identified to achieve accurate diagnosis of battery failure. The correlation coefficient analysis method is used to calculate the terminal voltage of the battery system correlation, and evaluate battery system anomalies through the results of correlation coefficients to realize battery system fault diagnosis.

Over discharging, that the excessive voltage can lead to lithium plating and electrolyte decomposition. Dendrite growth or separator failure can create short circuits, generating heat. Exposure to high ambient temperatures or fire can initiate thermal runaway. During the charge and discharge of lithium-ion batteries, the intercalation and deintercalation of lithium can cause material deformation, while the internal resistance produces Joule heat, leading to mechanical and thermal stress within the battery. This is a critical factor contributing to internal short circuits and the decline of electrochemical performance. Key components such as the electrolyte, separator, and anode are flammable, and the operation of numerous individual cells in compact series and parallel configurations within a confined space further elevates safety risks. The characteristics of high energy density, intercalation reactions at the anode and cathode, flammable materials, and a compact sealed working environment contribute to the inherent risk of thermal runaway in lithium-ion batteries [6]. Once initiated, thermal runaway propagates rapidly, releasing flammable gases such as hydrogen and toxic fumes like hydrofluoric acid. These flammable gases will let people beside them be hurt badly.

3. Current Safety Mitigation Strategies

3.1. Battery Management Systems (BMS)

A BMS monitors and controls battery operation to prevent unsafe conditions like, Voltage and Current Regulation: Prevents overcharging and over discharging. State-of-Charge (SOC) Estimation: Ensures optimal operating range. Thermal Monitoring which Detects abnormal temperature rises. Advanced BMS incorporates AI for predictive failure detection.

3.2. Thermal Management Systems (TMS)

Effective cooling is essential for preventing thermal runaway. Experimental research has proven that micro heat pipe arrays possess good temperature uniformity and a fast-thermal response speed [7]. **Figure 1** shows a schematic diagram of the internal structure of the micro heat pipe array, which contains a certain number of identically sized and parallel-arranged independent micro heat pipes. Even if one of the micro heat pipes is damaged, the other independent micro heat pipes can still function normally [8].

Fig. 1 Photograph of MHPAs

Liquid Cooling: Most EVs use liquid-cooled systems for efficient heat dissipation. Phase Change Materials (PCMs) which Absorb excess heat during thermal events. The charging and discharging device of the battery utilizes the Newell EVT500 V~300 A. The Agilent 34970A data acquisition system is employed to collect temperature variations, which are transmitted in real time to the computer. The BMS is connected to each individual battery, using the battery system integration testing platform to monitor parameters such as voltage and capacitance of each battery, preventing overcharging and over-discharging [8]. Air cooling also a normal way to use. It is ess effective but used in some low-cost EVs.

3.3. Material Innovations

The research focuses on safer battery chemistries, such as using solid-state batteries that replace liquid electrolytes with non-combustible solids. Compared to graphite, silicon anodes reduce the formation of dendrites. Multifunctional liquid electrolytes and separators play a critical role in physically separating high-energy cathodes and anodes. Therefore, well-designed multifunctional electrolytes and separators can significantly protect batteries in the early stages of thermal runaway. To protect the batteries from mechanical crushing, a shear-thickening liquid electrolyte was obtained by simply adding smoke-silicon dioxide to a carbonate electrolyte (1 M $LiPF_6$ in EC/DMC). Under mechanical pressure or impact, this liquid exhibit shear-thickening effects, increasing viscosity, which disperses impact energy and demonstrates resistance to crushing. The isolation membrane can provide electronic insulation for the cathode and anode, playing a crucial role in in-situ monitoring of the battery's health to prevent further deterioration beyond the first stage [9]. For instance, a 'multifunctional isolation membrane' with a polymer-metal-polymer Tri layer configuration can introduce a new voltage sensing capability. When dendrites grow and reach the intermediate layer, they connect the metal layer and the anode, allowing for immediate detection of the voltage drop between them as an output. Besides detection, the Tri layer isolation membrane design also aims to consume harmful lithium dendrites and slow their growth after they penetrate the isolation membrane. A layer of silica nanoparticles placed between two layers of commercial polyolefin isolation membranes can effectively consume any harmful lithium dendrites that penetrate, thereby significantly enhancing the safety of the battery. The life of the protected battery was significantly extended by approximately five times compared with that having conventional separators.

4. Future Research Directions

Based on the understanding of battery thermal runaway, many approaches are being studied, with the aim of reducing safety hazards through the rational design of battery components. In the succeeding sections, we summarize different materials approaches to improving battery safety, solving problems corresponding to different thermal runaway stage.

4.1. A High-Confidence Battery Failure Model is an Indispensable path

The characteristics of batteries under failure conditions are extremely complex. Developing a model to characterize the failure characteristics of batteries is an effective measure for diagnosing failures and analyzing failure characteristics. However, most existing battery safety research is based on traditional electrochemical models or slightly modified equivalent circuit models, which have questionable credibility and applicability under failure states. The internal electrochemical characteristics of a battery during a failure significantly differ from those during normal operation. Some "side reactions" that occur under normal conditions may, in fact, become the dominant "main reactions" during failure, leading to substantial changes in the corresponding equivalent circuit characteristics. Therefore, traditional battery models cannot accurately depict the mechanisms of batteries under failure states. Analyzing and establishing high-precision, high-confidence battery models corresponding to various failure modes of batteries is crucial for uncovering the essence of battery safety issues and for establishing effective diagnostic mechanisms and safety management methods [10].

4.2. The study of characteristics of multi-fault complex states is a trend.

Existing research on fault diagnosis mostly focuses on diagnosing a single fault with a "0/1" approach. However, in practical situations, the types of battery faults are unknown and uncertain, and multiple faults may occur concurrently, with their characteristics being mutually coupled. The applicability of current fault diagnosis strategies is difficult to ensure. Moreover, thermal runaway is the main cause of fire in power batteries, but not all battery fires are necessarily caused by thermal runaway. In the event of a collision, a severe impact may directly lead to significant damage to the battery, massive leakage of electrolyte, and the release of flammable gases, which can ignite immediately upon exposure to an open flame, potentially causing a fire or explosion. Therefore, approaching the battery's safety issues from a single perspective such as "thermal" or "electrical" is insufficient for accurately depicting the problem. Future research must integrate multiple disciplines including "thermal, electrical, fluid, chemical, and mechanical" to explore the coupling mechanisms of multi-domain characteristics of batteries under extreme faults and concurrent complex situations, and establish a comprehensive and effective battery safety management system that is oriented towards practical applications [11].

5. Conclusion

The safety of automotive Li-ion batteries is paramount for widespread EVs adoption. While significant progress has been made in BMS, thermal management, and material science, challenges remain. Future advancements in solid-state batteries, AI-driven diagnostics, and stricter regulations will further mitigate risks. By prioritizing safety, the automotive industry can ensure that EVs remain a sustainable and secure transportation solution. The safety of lithium-ion batteries in EVs is a cornerstone for achieving sustainable transportation and ensuring public trust in electrification. While Li-ion batteries have revolutionized the automotive industry with their high energy density and efficiency, their inherent risks—thermal runaway, mechanical failure, and electrochemical instability—demand continuous innovation and multidisciplinary collaboration. Existing mitigation strategies, such as advanced BMS and TMS, have significantly improved safety by enabling real-time monitoring of voltage, temperature, and SOC. For instance, liquid cooling systems and PCMs effectively dissipate heat, while micro heat pipe arrays enhance thermal uniformity and response speed, as demonstrated in experimental studies. Material advancements, including flame-retardant electrolytes, silicon anodes, and solid-state battery prototypes, further address flammability and dendrite growth risks. Structural reinforcements like crash-resistant housings and cell-to-pack designs also mitigate mechanical abuse.

However, challenges persist. Thermal runaway remains the most critical threat, often triggered by mechanical collisions, overcharging, or internal short circuits. The propagation of exothermic reactions releases flammable gases (e.g., hydrogen) and toxic compounds (e.g., hydrofluoric acid), posing severe hazards. Current diagnostic methods, such as model-based comparisons and data-driven fault detection, still lack robustness in predicting multi-fault scenarios. For example, concurrent mechanical deformation and electrical abuse can lead to complex failure modes that traditional single-fault models fail to capture. Future research must prioritize the development of high-confidence failure models that integrate electrochemical, thermal, and mechanical dynamics under extreme conditions. AI and machine learning offer transformative potential here, enabling predictive analytics for early fault detection and adaptive BMS algorithms.

The transition to solid-state batteries represents a paradigm shift, eliminating flammable liquid electrolytes and enhancing thermal stability. Innovations in sodium-ion chemistries, though less energy-dense, provide safer alternatives for specific applications. Recycling and second-life applications also play a pivotal role in sustainability, reducing hazardous waste and extending battery utility in grid storage. Regulatory frameworks must evolve to standardize safety protocols, incentivize recycling, and mandate rigorous testing for emerging technologies.

Ultimately, ensuring battery safety requires a holistic approach. Collaboration across material science, mechanical engineering, data analytics, and policy-making is essential to address multi-domain challenges. By advancing diagnostics, materials, and system designs, the automotive industry can mitigate risks, enhance consumer confidence, and accelerate the global shift toward zero-emission mobility.

References

[1] HAO Xin, DU Jianhua, LIANG Haobin, et al. A review of the safety characteristics of lithium-ion batteries after impact extrusion, Journal of energy chemistry, 2021, 59: 83-99.

[2] WANG Zhenpo1, LI Xiaoyu1, 2 YUAN Changgui1, LI Xiaohui, ea al. Challenge and Prospects for Fault Diagnosis of Power Battery System for Electrical Vehicles Based on Big-data. JOURNAL OF MECHANICAL ENGINEERING, 2021, 57: 52-63.

[3] SUN Z, LIU P, WANG Z, et al. Real-time fault diagnosis method of battery system based on Shannon entropy. Energy Procedia, 2017, 105： 2354-2359.

[4] YAO L, WANG Z, MA J, et al. Fault detection of the connection of lithium-ion power batteries based on entropy for electric vehicles. Journal of Power Sources, 2015, 293 : 548-561.

[5] HONG J, WANG Z, YAO Y,et al. Fault prognosis of battery system based on accurate voltage abnormity prognosis using long short-term memory neural networks. Applied Energy, 2019, 251 : 113381.

[6] Shu Qiang, Wang Yifan & Liang Yuan, et al. Research Institute for Road Safety of the Ministry of Public Security. Fire Science and Technology, 2021, 40(7): 963-967.

[7] DENG Y C, ZHAO Y H, WANG W, et al. Experimental investigation of performance for the novel flat plate solar collector with micro channel heat pipe array, applied thermal engineering, 2013, 54: 440-490.

[8] YE Xin, ZHAO Yaohua, QUAN Zhenhua, el at.Thermal management system of lithium-ion battery module based on micro heat pipe array, 2017, 126068, 269.

[9] H. Wu, D. Zhuo, D. Kong, Y. Cui, et al.Improving battery safety by early detection of internal shorting with a bifunctional separator. Nat. Commun. 5, 5193 (2014).

[10] WU C, ZHU C, GE Y,et al. A new fault diagnosis and prognosis technology for high-power lithium-ion battery. IEEE Transactions on Plasma Science, 2017, 45(7) : 1533-1538.

[11] CHEN Zeyu1, 2 XIONG Rui2, et al.SUN Fengchun2. Applied Thermal Engineering, 2013, 54(2): 440-449.