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Study on the Performance Degradation Mechanisms and Structural Optimization Strategy of Lithium-ion Batteries in High-altitude and Low-pressure Environments

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Abstract

High-altitude and low-pressure environments pose severe challenges to the electrochemical performance, structural stability and thermal safety of lithium-ion batteries. This paper systematically reviews the degradation mechanisms of battery performance in this environment, including increases in electrochemical impedance and mechanical stress-induced structural damage, with a focus on the core causes of the increased risk of thermal runaway. On this basis, this paper reviews the research progress on coping strategies, focusing on two directions: First, optimize electrode materials and structures through the construction of nanostructures and functional material coatings. Second, optimize thermal management systems through composite phase change materials and intelligent algorithms. Future research should emphasize an in-depth understanding of the multiphysics coupling mechanism and the development of a collaborative optimization design that integrates material – structure – thermal management to improve the comprehensive performance and safety of batteries in high-altitude environments.

Keywords

lithium-ion battery, high-altitude environment, low pressure, electrochemical properties, structural optimization

1. Introduction

Against the background of the accelerated green transformation of the global energy structure and the vigorous development of electrification technology, the demand for energy systems adaptable to extreme environments has become increasingly urgent in frontier areas such as aerospace, low-altitude economy, and plateau communication. Relying on their core performance advantages, such as high energy density, excellent power characteristics, excellent cycle stability and low self-discharge rate, lithium-ion batteries have achieved large-scale application in the above fields and have gradually become the core power source of the new generation of aircraft energy systems.

However, the dynamic changes in the operating environment of a spacecraft, especially in high-altitude and low-pressure environments (typical pressure <30 kPa), have posed severe technical challenges to Li-ion battery systems. The environmental characteristics in the aerospace context place strict requirements on the performance of lithium-ion batteries. According to the “Cabin Altitude and Pressurizatin” specification of the Federal Aviation Administration, commercial aircraft cabin pressure is typically maintained at an equivalent altitude of 2,400 meters (70-80 kPa), while drones, high-altitude communication base stations, and other scenarios may face lower pressure environments (such as only 26 kPa at an altitude of 10,000 meters). Under these extreme conditions, battery systems face multiple compound challenges.

Studies have shown that when the ambient pressure suddenly decreases from normal pressure (101.3 kPa) to 20 kPa, the battery system will encounter three compound degradation mechanisms. First, the electrolyte volatilization rate significantly increases, which reduces the effective ion concentration and in turn triggers electrode/electrolyte degradation mechanisms. The interfacial kinetic impedance increases significantly (Hoenicke et al., 2023). Furthermore, the pressure change triggers swelling of the battery structure, resulting in pulverization of the electrode material and separation from the current collector (Wan et al., 2025). Finally, in a low-pressure environment, the thermal runaway onset temperature is significantly reduced, the thermal runaway response time is extended to 133 s, and the amount of toxic gas release is significantly increased (Meng et al., 2024). These effects dramatically increase the risk of electrochemical–mechanical–thermal coupling failure of traditional liquid electrolyte systems in high-altitude environments.

This review focuses on the multiphysics failure mechanism of lithium-ion batteries under typical aircraft working conditions (-50 °C~70 °C, 20~90 kPa) and systematically reviews breakthrough research progress in key areas such as the degradation mechanisms of battery electrochemical performance under low-pressure environments, the kinetic laws of thermal runaway evolution, and structural integrity assessment methods. The purpose of this study is to provide a solid theoretical basis and feasible technology path for the safety design and performance improvement of high-altitude electric aircraft battery systems.

2. Effect of High-Altitude and Low-Pressure Environments on the Performance of Lithium-Ion Batteries

2.1 Experimental Analysis of Electrochemical Performance Degradation

The electrochemical performance of batteries includes the performance degradation under actual application and the degradation of core parameters exhibited in the experiments. The degradation of batteries under high-altitude and low-voltage environments is analyzed from the two aspects of practical application and the core mechanism, respectively.

2.2 Decrease in Electrochemical Performance

High-altitude and low-pressure environments significantly accelerate the degradation of the electrochemical performance of Li-ion batteries. Studies have shown that both the capacity retention rate and the state of health (SOH) of batteries deteriorate. For example, an experiment on an NCM523 pouch battery revealed that after 90 cycles under a low-pressure environment of 60 kPa, its SOH decreased significantly from 99.75% at atmospheric pressure to 96.67%, and the capacity fade rate was much greater than that under atmospheric pressure conditions (Xie et al., 2022).

The core mechanism of performance degradation is the sharp increase in the internal impedance of the battery. Compared with the normal pressure environment (96 kPa), under a low pressure of 60 kPa, the DC discharge internal resistance, ohmic impedance and charge transfer impedance of the battery increase by 31.61%, 6.22% and 45.76%, respectively (Xie et al., 2022). A substantial increase in the charge-transfer impedance is particularly critical. This finding directly reflects that the low-pressure environment limits the deintercalation kinetics of lithium ions at the electrode/electrolyte interface, resulting in reduced ion transfer efficiency and ultimately exacerbating the overall performance degradation and shortened lifetime of the battery.

2.3 Mechanical Stress Leads to Structural Changes in the Battery

Internal and external pressure differences caused by high-altitude and low-pressure environments induce significant mechanical stress. This stress may lead to plastic deformation, pulverization, and even separation of the electrode material from the current collector and may also cause damage to the separator (Wan et al., 2025, Duan et al., 2022). Through multiphysics coupling modeling and experimental validation, Duan Xudong et al. systematically revealed the failure mechanism of lithium-ion batteries under mechanical stress. Studies have shown that mechanical stress induces multiscale structural responses inside the battery, including plastic deformation of positive and negative electrode materials, mechanical rupture of the separator, and nonuniform distribution and migration of the electrolyte solution, which eventually leads to abnormal contact between the positive and negative electrodes and triggers battery failure. Internal short-circuit behavior (Duan et al., 2022). This structural microscopic damage is an important cause of internal short circuits in batteries and forms a vicious cycle with the electrochemical degradation process to accelerate battery failure.

2.4 Thermal Runaway and Its Subsidiary Hazards

Thermal runaway (TR) of lithium-ion batteries has always been the core safety bottleneck restricting their large-scale application. When the operating temperature of the battery exceeds the critical threshold, a self-accelerating exothermic reaction chain is triggered internally, with the chain effects of the release of toxic and combustible gases and the propagation of thermal runaway posing a serious threat to personal safety and property safety. In a high-altitude and low-pressure environment (typical air pressure <30 kPa), the battery system faces multidimensional risk superposition. First, the environmental pressure gradient causes the battery to bear significant mechanical load, which triggers plastic deformation of the electrode material, rupture of the separator and peeling off of the current collector, resulting in the formation of microshort-circuit channels. The trigger energy barrier of thermal runaway should be reduced (Duan et al., 2022). Furthermore, the convective heat transfer coefficient of air decreases in a low-pressure environment, which destroys the dynamic balance between battery heat generation and heat dissipation and reduces the thermal runaway initiation temperature by 10–20 °C on average (Sun et al., 2024). Finally, the explosion limits of gases are broadened. As shown in Table 2, when the ambient pressure decreases from 101 kPa to 70 kPa and 30 kPa, the lower explosion limit (LEL) of flammable gases (such as $C2H_4$ and H2) gradually decreases, and the upper limit (UEL) gradually increases. According to the Formula H_f = (UEL-LEL)/LEL, the risk of explosion significantly increases. Moreover, with decreasing CO_2 concentration, the concentrations of CO and C_xH_y significantly increase, the emission of toxic and flammable gas increases, and the aggravation of the cabin air is severe. Equipment and personnel safety risks (Sun et al., 2024, Zhang et al., 2023).

Table 2: Comparison of Data Related to the Thermal Runaway Under Environmental Pressures of 101–70–30 kPa (Zhang et al., 2023)

	101 kPa	70 kPa	30 kPa
UEL	30.2%	34.5%	37.5%
LEEL	8.8%	8.3%	7.9%
H_f	2.43	3.16	3.75

At the same time, experiments by Sun's team at the equivalent civil aviation flight altitude (air pressure of 15–80 kPa) revealed that the opening time of the safety valve of the pouch battery decreased by 58%-72% with decreasing air pressure and that the thermal runaway time of the cylindrical battery decreased by 41%-55%. , and the total amount of gas production increases by 35%-48% (Sun et al., 2024).

In summary, in high-altitude and low-pressure environments, the coupling effect of mechanical-thermal-chemical multifields significantly exacerbates the probability of thermal runaway and the secondary harm of lithium-ion batteries, revealing a strong correlation between gas release dynamics and thermal runaway evolution in this scenario and providing guidance for aeronautical researchers. The intrinsically safe design of battery systems in the aerospace field provides a key scientific basis.

3. Structural Optimization Strategy for Li-Ion Batteries under Extreme Environments

High-altitude and low-pressure environments are characterized by low air pressure, large temperature fluctuations, and significant mechanical stress, which poses problems for Li-ion batteries, such as structural deformation, an increased risk of thermal runaway, and a shortened cycle life. To address these challenges, battery performance needs to be improved in terms of two aspects: the **material structure** and the **thermal**

management system.

3.1 Structural Optimization of Battery Materials

During multiple charge–discharge cycles, the electrode materials of lithium-ion batteries often swell, which causes different degrees of stress, subsequently generating cracks and aggravating the deformation of the battery structure to a certain extent, leading to mechanical failure and operational instability (Ai et al., 2022). Studies have shown that the use of nanoparticle materials can effectively relieve irreversible damage to batteries caused by stress concentration. Through experiments and scanning electron microscopy (SEM), Muller et al. found that lithium-ion batteries using nanostructures and open-pore particle morphologies maintain better structural stability after multiple charge-discharge cycles compared to dense active materials, while also exhibiting higher discharge capacity and capacity retention rates (Müller et al., 2021). Moreover, during the research process, Dongsheng Yang's team reported that compared with the traditional porous Si–C electrode structure of lithium-ion batteries, the coating of a small amount of a cross-linked conductive polyaniline layer as the Si–C sealing layer can effectively light the battery. Click swelling phenomenon occurs during the charge–discharge cycle, resulting in better cycle life (Yang et al., 2024).

3.2 Thermal Management Optimization

Among the existing temperature monitoring methods, thermocouples and thermal imaging are the most common methods. These monitoring methods are relatively simple, easy to operate, and involve relatively mature technologies. However, these methods face many challenges, such as space position limitations, response lag, and thermal inertia, when they are applied to monitor the internal temperature of Li-ion batteries. In this context, researchers developed a standard 2D multiphysics coupling model based on thermal runaway, which can very well monitor the safety issue of battery thermal runaway (Duan et al., 2022). In terms of thermal management, while monitoring the battery temperature, it is also very important to cool the battery. Studies have shown that the combination of composite phase change material and plate heat pipes, with the addition of liquid cooling to further assist heat dissipation, can significantly reduce the maximum temperature of the battery pack module (Xin et al., 2023). Moreover, the combination of AI technology for academic research can increase the convenience and reliability of research. Using a 3D electrothermal model coupled with fluid mechanics, the researchers used training and numerical output methods in the ANN model to optimize and adjust the battery temperature management system, which eventually reduced the maximum battery temperature by 1.9%. decreased by 4.5% (Li et al., 2022)

In summary, optimizing the material structure and thermal management system of lithium-ion batteries can effectively improve their operating efficiency, service life and safety factor in high-altitude and low-pressure environments.

4. Conclusion

This paper systematically reviews the compound challenges posed by high-altitude and low-pressure environments on the performance of lithium-ion batteries. Studies have shown that low voltage not only accelerates electrochemical performance degradation by increasing internal impedance but also destroys the structural integrity of the electrode/separator by inducing mechanical stress and significantly aggravates the risk of thermal runaway by weakening heat dissipation. To address these problems, this paper analyzes the optimization strategy from the two dimensions of material and thermal management. The results indicate that enhancing structural stability through the nanolization of electrode materials and the design of functional coatings, as well as improving thermal management systems by combining advanced composite materials and intelligent algorithms, are the core technology paths for improving the performance and safety of batteries in high-altitude environments. Future research should focus on multifield coupling failure mechanisms and material–structure–thermal management synergistic optimization.

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Conflicts of Interest

The authors declare no conflict of interest.

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