

An Overview of Lithium-Ion Battery Safety: Existing Problems and Potential Solutions

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Abstract. Lithium-ion batteries (LiBs) are extensively utilised in the energy sector owing to their superior performance. In this paper, thermal runaway (TR) is introduced as one of the safety dangers, analysed the mechanism and characteristics of it. This paper focuses on the optimization of Lib, which can reduce the TR caused by mechanical, electrical and TR. The study suggests improvements in three crucial areas: electrode materials, electrolytes, and separators, aiming to reduce the dangers of TR in LiBs. Through doping, coating, nanoparticle design, and metal atom replacement, electrode materials can be improved to increase cathode safety, LiF coatings on NCM811 cathodes are one prominent example. By adding chemicals like flame retardants and creating solid-state electrolytes, electrolyte optimization greatly increases battery safety. Furthermore, improving separator stability by applying ceramic coatings, high-temperature-resistant polymers, and surface modifications fortifies mechanical and thermal endurance, lowering the risk of TR and short circuits. When combined, these methods make the LiB system safer and more dependable.

1 Introduction

The worldwide transition to sustainable energy has expedited the uptake of electric vehicles (EVs), with lithium-ion batteries (LiBs) becoming the favored energy storage choice owing to their high energy density and comparatively minimal environmental impact.

[1]. However, as battery technology advances—particularly with the shift from NMC111 to NCM811 ternary electrode materials—new safety concerns have arisen [2].

Increasing nickel content while reducing cobalt levels in these batteries can lead to significant safety risks, including susceptibility to short circuits, thermal runaway, and potential fires or explosions [2]. Resolving these difficulties is essential for guaranteeing the safe functioning of LiBs in EVs.

This report offers an in-depth review of safety concerns associated with LiBs. It highlights the primary danger that might threaten the function and security of batteries. In order to

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address these safety concerns, the study also looks into a number of potential solutions. The research seeks to increase the general safety of lithium-ion devices by suggesting enhancements. By lowering the chance of breaks down, these improvements aim to increase battery reliability for general utilization.

2 Lithium-ion battery working principle

A lithium-ion battery (LiB) is a rechargeable energy storage device that functions by moving lithium ions between the cathode and anode during charging and discharging processes. [1]. It consists of four main components: the cathode, anode, electrolyte, and separator. The cathode is typically made of oxides like LiFePO₄ and NMC, used in electric vehicles, while the anode is primarily composed of carbon or silicon materials such as graphite and SiOX [3]. The electrolyte includes organic solvents or inorganic lithium salts, and the separator is a microporous insulating material designed to prevent short circuits between the electrodes [1].

3 Thermal runaway mechanism

Thermal runaway (TR) in LiBs occurs when an unexpected rise in internal temperature triggers a series of chain reactions that can pose serious safety risks. TR is often caused by mechanical, electrical, or thermal abuse [4]. This process can lead to significant energy release, sometimes resulting in smoke, fire, or explosions. Ouyang employed Accelerating Rate Calorimetry (ARC) to investigate temperature variations during TR, identifying three critical temperatures: T1, T2, and T3 [5]. T1 signifies the initiation of self-heating, generally linked to the degradation of the solid electrolyte interface (SEI) layer; T2 indicates the commencement of TR; and T3 represents the maximum temperature attained during TR, reflecting the peak energy release. [5]. Consequently, improving battery safety necessitates the elevation of T1 and T2 while diminishing T3 [6].

3.1 Mechanical abuse

Mechanical abuse, including damage from impacts, is a significant contributor to TR in LiBs, particularly in electric vehicles. This abuse can distort the battery, impairing the separator and resulting in a short circuit between the electrodes.[3]. This leads to a rapid temperature rise to T1, breaking down the SEI film and triggering TR [6].

3.2 Electrical abuse

Electrical abuse is a common trigger for TR in LiBs. This abuse includes overcharging, over-discharging, and external short circuits [4]. External short circuits may occur due to events such as vehicle collisions, water submersion, or contamination with conductive substances. This type of short circuit leads to a rapid discharge, causing a significant temperature increase, gas production, and eventual battery expansion.

Overcharging occurs when the battery voltage exceeds its maximum limit, often due to a malfunction in the battery management system (BMS). This condition generates substantial heat, promotes lithium dendrite growth at the anode, and can damage the cathode. Conversely, over-discharging occurs when the battery voltage decreases excessively, resulting in significant heat production, probable copper dissolution in the current collector, interior short circuits, and the initiation of thermal runaway.

3.3 Thermal abuse

Thermal abuse denotes a condition in which a LiB is exposed to excessive temperatures in a high-heat environment. Such conditions can provoke chemical reactions within the battery, resulting in an immediate rise in internal temperature and pressure. This immediately induces TR, and if a single cell undergoes TR, it can initiate a chain of events that threatens the security of the whole battery group.

4 Thermal runaway characteristics

TR in LiBs generally progresses through four stages: Usually, the process starts with gas emission and venting, then TR, which is frequently accompanied by flames. An explosion could result from this intensifying into a TR. The TR event comes to an end when the flames are extinguished, completing the process. [6]. This section focuses on lithium iron phosphate (LFP) and ternary lithium batteries, the predominant types used in electric vehicles (EVs) today.

Table 1 compares the TR parameters for both battery types. LFP batteries are known for their superior heat stability due to the robust covalent P=O bond within the molecule and the octahedral structure of (PO₄)₃- [6]. As a result, LFP batteries have a longer ignition time compared to ternary lithium batteries and demonstrate enhanced safety and thermal stability.

Table 1. The comparison of the TR parameters [7-9].

	Lithium Iron Phosphate Battery	Ternary Lithium Battery		
	Electrical abuse	Thermal abuse	Electrical abuse	Thermal abuse
Ignition time/s	3040	916	810	431
Thermal runaway duration/s	186	181	670	400
Maximum temperature/°C	423	372.1	736.8	1180
Temperature rate/(°C/s)	0.12	0.32	2.33	29.50

5 Optimization of thermal runaway

This study aims to enhance safety in lithium batteries by optimising electrode materials, electrolytes, and separators to decrease the danger of thermal runaway induced by mechanical, thermal, and electrical abuse.

5.1 Optimization of electrode materials

Contemporary suggestions for enhancing the safety of cathode materials include doping, coating, micro-particle design, and metal atom substitution [10]. Doping and coating with chemically inert materials can reduce reactions between anode and electrolyte, lowering TR risks. For example, applying thermal-responsive polymers to electrodes and separators can effectively prevent short circuits and control temperature increases [11]. Coating cathode materials, such as LiNi_{0.8}Co_{0.1}Mn_{0.1}O₂ (NCM811), with LiF, enhances thermal and structural stability, minimizes interface side reactions, and reduces oxygen release during charging, thereby improving battery safety [12]. Moreover, silicon/carbon nanotube composites provide enhanced lithium storage capacity and increased electrode stability. [13].

Xu et al. have proposed a technique employing a conductive polymer (Poly(3,4-ethylenedioxythiophene)) at the microscopic level, which improves electrochemical and thermal stability while mitigating internal reactions, hence decreasing temperature elevation. [14].

These techniques, including LiF coatings, thermal-responsive polymers, and silicon/carbon nanotube composites, effectively optimize LiB electrode materials, significantly mitigating the risk of TR.

5.2 Optimization of electrolytes

The performance of the electrolyte is crucial for the safety of lithium-ion batteries, mainly improved by electrolyte additives and the advancement of novel solid-state electrolytes.

5.2.1 *Electrolyte additives*

Electrolyte additives, including film-forming agents, overcharge protection substances, and flame retardants, improve the thermal stability of LiBs. Film-forming additives facilitate the development of an SEI on the anode's surface during initial charge-discharge cycles. This passivation layer facilitates lithium ion intercalation while preventing adverse reactions between the electrolyte and electrode materials, thereby reducing electrolyte decomposition, minimizing irreversible capacity loss, and decreasing the risk of TR. Notable examples include fluoroethylene carbonate (FEC) and vinylene carbonate (VC) [15,16].

Overcharge protection additives, which encompass redox and polymeric monomer additives, remain inert under normal conditions but engage in redox reactions or electro polymerization during overcharging to prevent irreversible damage [17]. Commonly used compounds include 1,3,5-trihydroxybenzene, 2,5-difluoro-1,4-dimethoxybenzene, cyclohexylbenzene, alkyl 3,3,3-trifluoropropionate, and 4-bromoanisole [18,19].

Flame retardant additives function through mechanisms such as chemical interference (capturing free radicals), physical barriers (isolating oxygen and heat), and heat absorption, effectively reducing the risk of TR. These additives are typically phosphate esters or fluorinated organic solvents [17]. However, their interaction with other electrolyte components can negatively impact battery performance. K. Liu et al. proposed encapsulating triphenyl phosphate flame retardants in micro-sized shells via electrospinning, allowing the retardant to be released only at elevated temperatures, thus mitigating potential adverse effects [20].

5.2.2 *Solid-state electrolytes*

Advancements in solid-state electrolytes for LiBs are critical, as they offer a fundamental solution to fire risks. These electrolytes are categorized into three types: polymer, oxide, and sulfide. Polymer solid-state electrolytes provide moderate lithium-ion conductivity, stability, and ease of manufacturing. Oxide solid-state electrolytes excel in conductivity but are costlier to produce. Sulfide electrolytes offer high ionic conductivity but are sensitive to oxygen, necessitating strict environmental controls. To address the limitations of individual electrolytes, inorganic fillers can be integrated into polymer matrices, combining the benefits of both inorganic and organic materials to enhance ionic conductivity and electrochemical stability [21].

In summary, optimizing LiB electrolytes involves the use of film-forming additives, overcharge protection additives, flame retardants, and the development of solid-state electrolytes. These strategies significantly improve battery safety, with solid-state electrolytes representing a promising direction for mitigating TR.

5.3 Optimization of separator materials

The separator in LiBs functions as an ion transport channel while preventing short circuits between the anode and cathode. Traditional polyolefin separators can shrink under high temperatures, raising the risk of TR. Effective separators must also possess mechanical strength to withstand impacts and punctures, as well as chemical stability to resist electrolyte corrosion. Notably, lithium dendrites can grow through separators, potentially causing short circuits. Therefore, developing separators that inhibit dendrite growth is crucial.

Ceramic-coated separators address these challenges by maintaining structural stability at elevated temperatures and reducing pore size, thus minimizing dendrite penetration [22-27]. High-temperature-resistant polymer separators, such as polyimide (PI) and polybenzimidazole (PBI), offer excellent thermal and chemical stability, preserving integrity under heat and preventing TR. Additionally, surface modifications of polyolefin separators—through plasma treatment, UV irradiation, or chemical grafting—can enhance wettability, ionic transport, and overall mechanical strength [28]. Collectively, these strategies improve separator stability and mitigate TR risks in LiBs.

6 Conclusion

This article examines the causes of TR in LiBs and outlines strategies for prevention. Key triggers include mechanical, thermal, and electrical abuse, with different battery types exhibiting varying behaviours during TRs.

To mitigate these risks, this study propose optimizations across three main areas: electrode materials, electrolytes, and separator materials. Enhancements in cathode safety can be achieved through doping, coating, micro-particle design, and metal atom substitution. Electrolyte optimization involves using additives and developing solid-state alternatives. Additionally, employing high-temperature-resistant polymer separators, ceramic-coated separators, and surface modifications can significantly bolster separator stability, reducing TR risks.

Notably, solid-state electrolytes offer a promising solution to the safety challenges of LiBs and represent a critical area for future research.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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