Review of Thermal Runaway Protection for Lithium-Ion Batteries

Xingyu Qi
Central South University, Changsha, Hunan, China

Abstract: Lithium-ion batteries are now widely used in various fields of social production and life. However, the safety hazards of Li-ion batteries are still the main problem limiting their development and application. Among them, the thermal runaway of Li-ion batteries is one of the most common safety hazards. This review summarizes the current research status of thermal runaway protection of Li-ion batteries at home and abroad, compares different protection technologies for thermal runaway of Li-ion batteries in different directions, and systematically describes the research progress, key issues, and future development trends in this field.

Keyword: Lithium-ion Batteries, Thermal Runaway, Thermal Runaway Protection.

1. Introduction

Lithium-ion batteries have successfully expanded from consumer electronics to megawatt-scale application scenarios such as EVs and smart grids by their high energy density, long cycle life, and modular scalability, and they have developed into the core carrier of modern electrochemical energy storage technology [1]. However, the instability of thermal runaway is an important factor threatening the safety of lithium batteries. Therefore, how to effectively inhibit the thermal runaway of lithium batteries has become an important issue in improving the safety of lithium batteries. Usually, a lithium-ion battery runaway is caused by the exothermic reaction between the electrolyte, anode, and cathode, and the battery will eventually rupture as the temperature and pressure inside the battery increase. The major factors leading to TR in Li-ion batteries are short circuit, overcharging, mechanical compression, heat build-up, and manufacturing defects [2~4].

The protection of lithium battery thermal runaway is mainly divided into two ways, starting from the outside and starting from the source. Starting from the outside, i.e., selecting a safe and efficient thermal management system. From the source, i.e., to improve the material research. The purpose of this review is to summarize the current research progress on thermal runaway protection measures for Li-ion batteries at home and abroad, compare different protection methods horizontally and vertically, summarize their respective advantages and disadvantages, and put forward the most suitable protection method for the actual situation.

2. State of the Literature Review

2.1 Battery Management System (BMS)

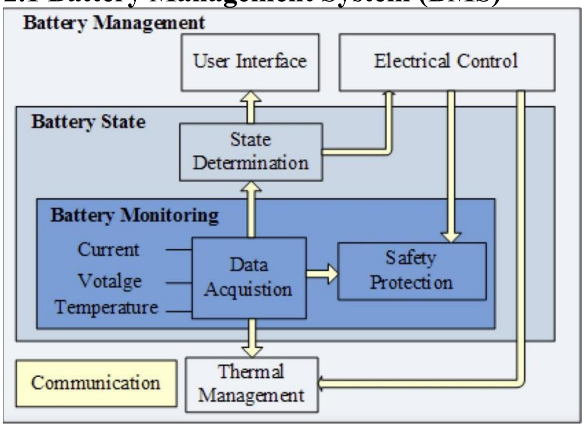

Figure 1. Illustration of a Battery Management System [5].

The purpose of a BMS is to ensure the safe and reliable operation of the battery. To maintain the safety and reliability of the battery, condition monitoring and assessment, charge control, and battery balancing are the functions implemented in the BMS. Gold [5] proposed a systematic classification approach in the study of functional architectures for battery management systems (BMS) and constructed a generalised BMS architecture model. As shown in Fig. 1, this architecture achieves simultaneous acquisition of multiple parameters at the monitoring level by configuring multiple sensor arrays in the battery pack. The real-time dynamic data acquired based on this architecture has a dual functional value: on the one hand, it safeguards the operation safety of the battery system through online diagnosis, and on the other hand, it provides data support for the accurate estimation of battery state parameters.

When the BMS detects thermal runaway precursors such as overcharging/ over discharging, temperature abnormality, or internal short-circuit, the system can take active protective measures such as relay cut-off, charging current limitation, and forced cooling, and it can also activate the heating system to maintain the battery performance in a low-temperature environment [6] . However, the traditional BMS relies on external parameter threshold judgement, which can only respond to obvious faults with a lag and cannot identify the internal state of the battery and potential faults at an early stage [7~8]

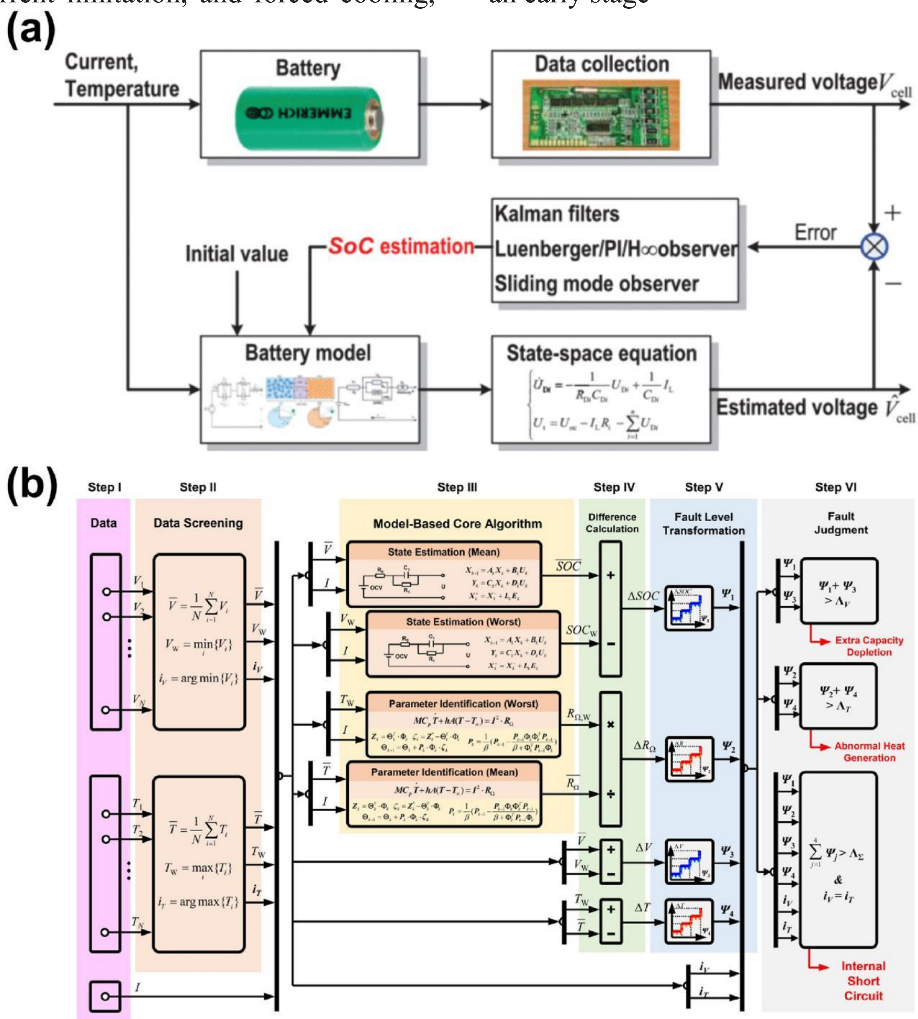

Figure 2. Model-driven BMS Diagnostic Approach

(a) Flowchart of the model-based battery state estimation method [11]. (b) Scheme of the proposed model-based troubleshooting algorithm for ISC detection [10].

Integrating intelligent algorithms with BMS significantly improves the level of fault prediction, and the main technological paths can be classified into model-based physical simulation methods and AI-based data-driven methods (Fig. 2a) [9-11]. Taking the model-driven strategy developed by Feng's team as an example (Fig. 2b), an internal short circuit (ISC) feature extraction algorithm was constructed by mapping the measured voltage/temperature data into electrochemical state parameters [13,14]

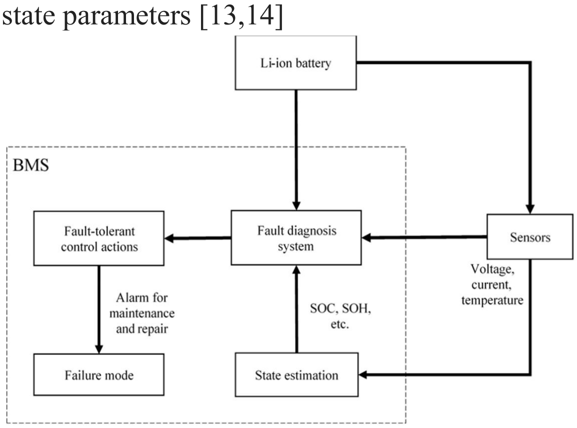

Figure 3. Battery management system (BMS) troubleshooting schematic [12].

In addition to this, in 2023 Manas et al [12] developed a centralised battery management system (BMS) designed to support a dynamically evolving EV transport system. Through system simulation and experimental validation, this research team confirmed the effectiveness of the proposed BMS architecture in terms of cooperative multi-sensor monitoring of voltage, current, and temperature.

But model training and validation are the difficulties of model-based BMS. A model algorithm often requires a large amount of data for training and validation, and fault data is difficult, costly, and even dangerous to obtain.

The combination of Artificial Intelligence (AI) technology with a Battery Management System significantly improves the management performance of lithium batteries.2024 Badran and Toha [13] stated that AI technology is widely used in functions such as monitoring, battery state estimation (e.g., SOC, SOH, and SOP), fault diagnosis, and cell unit balancing of the BMS.

2.2 Material

2.2.1 Use of composite materials

Wilke et al.[14] verified for the first time the blocking effect of phase change composites (PCC) on the thermal runaway propagation of battery packs. The pinning experiments showed that PCC could completely inhibit the thermal runaway spread by its high thermal conductivity (20 W/m-K) and the wax-based phase change thermal storage mechanism, whereas full-scale thermal spreading occurred in the conventional air-cooled group. Its core advantage lies in its ability to quickly absorb short-circuit-parallel-connection-induced heat spikes and keep the battery temperature within a safe threshold through phase-change energy storage.

In contrast, the sandwich-type PEE@EBF composite (paraffin/expanded graphite/EVA core + epoxy resin/boron nitride/flame retardant shell) developed by Shen et al [15] demonstrated a more comprehensive thermal safety performance: latent heat up to 166.6 J/g, thermal conductivity of 0.8 W/(m-K), flame retardancy of UL94 V-0 class, and reduction of the heat release and smoke production rates by 67.8% and81.8% respectively. The material provides an integrated thermal management and fire protection solution for high-rate battery systems through the synergistic mechanism of phase change temperature control and fire protection.

2.2.2 Electrolytes

1) Flame Retardant

By introducing flame retardants such as phosphorus (trivalent/pentavalent phosphite), nitrides (C═C double bond-containing compounds), and halogens (e.g., MFA), the free radicals in the combustion chain reaction can be effectively captured while enhancing the thermal stability of the electrolyte and electrode compatibility [16]. DTYP developed by Zhu et al.[17] and TAC/TAIC heterostructures designed by Cho et al.[18] have both flame-retardant and cathodic protection.

2) Overcharge Protectants

Redox shuttlers (e.g., DBBD2, DDB, MPT, TEMPO) and electrochemical polymerizers (biphenyl, CHB) are the two dominant types of overcharge protection additives [16]. Weng et al.[19] found that the performance of DBBD2 was stable over 20 overcharge cycles, whereas Moshurchak et al.[20] demonstrated that additives such as DDB could make the $LiFePO_4$ cells withstand 100 cycles of 0.1 C overcharge.

3) Aqueous Electrolyte

Although aqueous batteries offer high safety advantages, their development is limited by a narrow voltage window (<2V) and low energy density. Hybrid aqueous/non-aqueous electrolyte (HANE) strategies break through the limitations through synergistic effects: the PC-water system developed by Zhang et al.[21]achieves a 2.8 V window and an ionic conductivity of 20 mS cm^{-1}.

4) Solid State Electrolyte

Solid-state electrolytes radically improve battery safety by eliminating the risk of liquid electrolyte leakage and lithium dendrites, and their ionic conductivity ($>10^{-4}$ S/cm) and electrochemical window (>4.5 V) are close to practical standards [16]. Current research focuses on (i) inorganic/polymer/gel electrolyte interface optimisation, such as in-situ polymerisation to reduce interfacial impedance; (ii) novel material development (composite electrolyte, high-entropy ceramics); and (iii) high-energy electrode matching and full battery integration process.

2.3 Thermal Management Technology

2.3.1 Adoption of Phase Change Material Cooling System

TR inhibition using phase change materials (PCMs) has been a popular research topic in recent years. Scholars have significantly improved the TR suppression performance of PCMs through strategies such as material modification, structure optimization, and multi-method synergy.

Composite development: Wilke et al.[14] developed phase change composites (PCCs) that can significantly block TR propagation by lowering the peak temperature of adjacent cells by 60°C; and Weng et al.[22] combined aerogels to achieve the dual functions of TR inhibition and heat dissipation.

Structural optimisation: Verma et al.[23] demonstrated that thin-layered decanoic acid has more TR inhibition advantages than paraffin;

Synergistic strategy: Kshetrimayum et al.[24] integrated a microchannel cooling plate and PCM to achieve temperature stabilisation under TR conditions in multiple cells; Zhang et al.[25] designed a liquid cooling-PCM composite system combining latent heat buffer and active heat dissipation to enhance heat transfer;

Parametric research: Ni et al.[26] revealed the regulation mechanism of PCM thermal conductivity, latent heat, and melting temperature on TR through the numerical model, which filled the theoretical gap of the quantitative design of material parameters and promoted the engineering application.

2.3.2 Liquid Cooling System

Liquid-cooling technology enhances heat dissipation efficiency through enhanced convection and phase change synergy:

Direct liquid cooling: Patil et al.[27] designed a dielectric fluid immersion system to effectively manage TR, but it relies on high-precision sealing techniques;

Composite liquid cooling: Wang et al [28] combined heat pipes with water rings to achieve efficient heat transfer using evaporation-condensation phase change cycle; Choudhari et al [29] integrated fins and PCM at the periphery of cylindrical batteries to maintain low-temperature uniformity even with 4C charging.

3. Challenges and Open Issues

Categorization	Methodology/technology	Vantage	Drawbacks
Battery Management System	Traditional BMS	-Real-time monitoring of temperature, voltage, current, and other parameters -Active protection measures can be taken (disconnection of electrical circuits, forced cooling, etc.)	-Dependent on external threshold judgement, lagged response -Lack of early identification of internal conditions and potential faults
	Intelligent Algorithm Fusion BMS	- Combined with AI or model-driven to improve fault prediction capabilities - Achieving early warning	- Relies on large amounts of data for training - High cost of model validation and difficulty in obtaining failure data
Material Improvement	Phase Change Composites	-High thermal conductivity, fast heat absorption -Suppression of thermal runaway propagation	-Long-term cycling stability needs to be verified
	Sandwich-type PEE@EBF composites	-Thermal management - fire protection integration -Reduced heat release rate and smoke production rate	-Complex preparation process -Latent heat and thermal conductivity still have room for optimisation
Electrolyte Improvement	Flame retardants (phosphorus, nitride)	-Improved electrolyte thermal stability -Compatible electrode materials	-May reduce electrochemical performance
	Overcharge Protection Additive	-Resistant to multiple overcharge cycles -Trigger the fusion mechanism to ensure safety	-Additive stability needs to be verified over time -May increase internal resistance
	Aqueous/non-aqueous hybrid electrolytes	-Wide voltage window -Improved safety and energy density	-Low ionic conductivity -Interfacial compatibility to be optimised

	Solid State Electrolyte	-Eliminate leakage and lithium dendrite risk -High electrochemical window	-Higher interfacial impedance -High cost of production at scale
Thermal Management Technology	Phase Change Material Cooling Systems	-Latent heat buffer reduces peak temperature -Passive heat dissipation combined with active control	-PCM flammability problem to be solved by modification -melting temperature range to be precisely designed
	Liquid Cooling System	-Highly efficient heat dissipation -Adaptable to high rate charging and discharging	-Dependence on precision sealing technology -high system complexity and maintenance costs

Table 1. Challenges and Open Issues

4. Future Directions

The thermal safety protection system of lithium-ion batteries is evolving towards a collaborative architecture of "intelligent perception-dynamic regulation-intrinsic defense". This development trend is based on the integration of three dimensions of technology: the multimodal signal decoupling capability of the algorithm layer, the adaptive protection characteristics of the material layer, and the multi-physical field coupling regulation mechanism of the system layer.

In the dimension of algorithm innovation, breaking through the limitations of traditional threshold monitoring has become an inevitable direction. Digital twin technology characterized by information-physical integration has brought new opportunities for the development of battery management systems. By establishing a digital twin that maps to the physical entity of the battery, virtual-real interactive feedback, mechanism and data fusion, the development of intelligent battery management systems can be realized [30] . It is worth noting that the fusion algorithm of transfer learning and physical information neural network can effectively remove the interference of sensor noise on warning signals, which provides a new paradigm for establishing a digital twin model of the health status of the battery throughout its life cycle.

The dimension of material innovation presents the dual characteristics of functional integration and intelligent response. Composite electrolyte materials with gradient phase change characteristics can autonomously adjust the lithium ion transmission path through lattice reconstruction and form a dynamic barrier for ion conduction in the heat accumulation stage.

In terms of system integration, thermal management technology is upgrading from passive defense to a dynamic control system. The composite heat dissipation system based on variable topology liquid cooling channels and phase change materials (PCM) can match the heat dissipation requirements of different thermal runaway stages by adjusting the flow entropy value of the cooling medium in real time.

The bottlenecks that need to be broken through are concentrated in three aspects:

(1) To improve the confidence of multi-source information fusion, it is necessary to develop a hybrid algorithm that combines electrochemical mechanism constraints and data-driven characteristics;

(2) Large-scale preparation process of intelligent materials, focusing on breaking through the balance between structural stability and interface compatibility of high-entropy materials;

(3) The spatiotemporal consistency of subsystem collaborative control requires the establishment of a cross-scale control model covering second-level thermal response and quarter-level aging evolution.

The solution to these challenges will promote the thermal runaway protection system to form a full-chain defense capability of "molecular scale failure blocking → monomer-level energy management → system-level path reconstruction", and ultimately achieve a leapfrog development of power battery systems from "risk avoidance" to "intrinsic safety".

5. Conclusion

The thermal runaway protection technology of lithium-ion batteries has formed a multi-dimensional and interdisciplinary research system, which has significantly improved the safety threshold of lithium batteries through the deep integration of intelligent, algorithm-driven, intrinsically safe material innovation and system-level cooperative control. However, current research still faces challenges such as the data dependence of intelligent algorithms (e.g., scarcity of failure samples), the scaling bottleneck of high-cost materials (e.g., interfacial impedance of solid-state electrolytes), and the synergistic complexity of multi-physics field systems. In the future, it is necessary to further explore self-repairing materials, digital twin technology, and cross-scale failure mechanism modelling to build a full chain of solutions from micro-material failure to macro-system protection and to provide theoretical support and technological guarantee for high-security scenarios such as electric vehicles and energy storage power stations.

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