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Editorial

Thermal Safety of Lithium-Ion Batteries: Current Status and Future Trends

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Research on the thermal safety of lithium-ion batteries (LIBs) is crucial for supporting their large-scale application [1]. With the rapid development of high-energy-density battery systems, the issue of insufficient intrinsic thermal stability of materials has become increasingly prominent. This safety hazard is particularly severe in scenarios involving electric vehicles and energy storage stations, where the thermal runaway (TR) of individual cells within a battery pack may trigger cascading failures through thermal runaway propagation (TRP), leading to significant property damage or even personal injury [2,3].

In this context, an effective battery thermal management system (BTMS) can dissipate heat in time, keeping the LIB within an optimal temperature range, ensuring good temperature consistency, reducing the risk of TR, and improving the safety and stability of battery applications. Existing thermal management methods mainly include air cooling, liquid cooling, phase change material cooling, heat pipe cooling, and their combinations [4,5]. Efficient battery thermal management is an effective means of ensuring the safety of electrochemical energy storage systems, enabling the battery to operate within an acceptable temperature range, with a suitable temperature difference, which plays a key role in preventing TR [6]. To efficiently manage battery heat, a deep understanding of the processes of heat generation, transfer, and dissipation is crucial. Developing thermal models for batteries through theoretical derivation and experimentation is an effective approach, and thermal models also serve as the foundation for the TRP models of battery modules [7].

Excessive temperature can cause TR in batteries, which is the leading cause of battery fires and explosions. Once TR reaches a certain level, the gases and flammable materials produced inside the battery are expelled simultaneously, forming a strong smoke flow, which eventually leads to a fire. The triggering conditions and mechanisms of TR have been comprehensively explored to improve the safety of LIB systems. Researchers have also conducted experimental and numerical simulation studies on the TRP in LIB modules. The propagation mechanism of TR in large-capacity LIB modules has been analyzed, the TRP model has been established, and the temperature distribution and evolution during the TRP of battery modules through experiments and computational fluid dynamics simulations have been demonstrated. On the other hand, after TR and fire occurrence, effective safety measures are also required to block the heat transfer path between batteries or to dissipate heat from runaway batteries in a timely manner, thereby delaying or blocking the TRP. TRP suppression based on existing battery module thermal management has been proposed, achieving good results in phase change material thermal management systems [8,9]. Monitoring and early warning refer to the technology of predicting potential TR disasters in LIB systems by monitoring voltage, temperature, and other signal states during the operation of the LIB system, even in the absence of open flames or smoke. For example, an intelligent early warning system based on gas composition monitoring (such as CO/H_2) can identify the early signs of TR and shorten the accident response time [10].

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Currently, research on LIB fire extinguishing technology mainly focuses on fire suppression, thermal management, and optimization of fire extinguishing agents. Researchers are improving water-based, foam, and solid fire extinguishing agents to enhance the extinguishing effect and reduce secondary damage from battery fires [11]. Additionally, various new fire suppression materials have been developed for the special properties of LIBs, such as materials with high thermal conductivity or phase change properties, to enhance thermal management capabilities and prevent overheating or TR. Some studies have also explored fire suppression systems based on automation technologies, using sensors and intelligent control for early fire detection and immediate extinguishing. Despite this progress, the complexity of lithium-ion battery fires still presents a challenge for existing technologies, and research continues to explore more efficient and safer fire suppression solutions [12].

Artificial intelligence (AI) also plays a crucial role in enhancing battery thermal safety [13]. AI is applied in various ways, including modeling and forecasting, where machine learning and deep learning algorithms predict battery behavior and potential risks, such as TR, by analyzing factors like temperature, pressure, and voltage. AI also supports failure mode and effects analysis by identifying potential failure modes through data analysis, helping detect patterns or anomalies in battery behavior. Furthermore, AI-driven, data-centered digital solutions allow for real-time monitoring and adaptive safety strategies by processing large datasets from battery systems. AI is also involved in the optimization of battery cell and pack design, improving heat dissipation and enhancing thermal management to prevent TR. Overall, AI contributes to more accurate predictions, better risk management, and the development of safer, more efficient battery systems [14].

This Special Issue of the journal *Batteries*, "Thermal Safety of Lithium-ion Batteries", brings together 15 research papers on the thermal safety of LIBs, covering a wide range of fields from basic research to applied technology. These studies provide valuable references for improving battery safety and performance. In terms of the TR mechanism and characteristics, Matthew Claassen et al. characterized the particle size distributions and chemical compositions of fine particles (PM2.5) and acidic gases released during TR. The study provided key insights into the emission profiles and potential health hazards, contributing to a better understanding of the risks associated with battery TR [15,16]. Kuntz et al. investigated the impact of LIB aging on safety behavior, comparing the safety performance of fresh and aged cells under various thermal and standardized safety tests [17]. Zhang et al. investigated the TR behavior of a large-capacity ternary lithium battery, providing valuable insights into the temperature profiles, gas emissions, and ejection dynamics and contributing to improved safety design and the suppression of TRP [18]. Wang et al. highlighted the influence of chamber pressure on battery temperature, internal pressure, venting dynamics, and gas composition, contributing insights on the safety assessment and early warning systems for energy storage batteries in high-altitude areas [19]. In terms of TR monitoring and warning, Hebenbrock et al. introduced a novel monitoring method for prismatic lithium-ion cells using a fiber Bragg grating sensor applied to a rupture disk to detect pressure increases [20]. Kisseler et al. developed a method for real-time monitoring of internal and surface temperatures in prismatic lithium-ion cells during TR induced by overcharging [21]. In the field of fire extinguishing technology, Miao et al. demonstrated that water mist effectively extinguished flames and provided significant cooling, offering valuable insights for improving TR suppression in LIBs [22]. Bordes et al. found that run-off waters could pose significant environmental hazards, emphasizing the need for careful assessment of their impact in large-scale battery incidents [23].

In the domain of battery thermal management systems (BTMSs), Liu et al. reviewed recent research on liquid cooling BTMSs, comparing different coolants, liquid channel designs, and system structures for both indirect and direct cooling methods. It also examined the integration of liquid cooling with other techniques, such as air cooling and phase change materials, and highlighted the safety benefits of liquid cooling in managing thermal runaway [24]. Rahmani et al. reviewed the latest developments in BTMSs from 2023 and 2024, highlighting new cooling methods and hybrid designs aimed at improving thermal management efficiency [25]. Yu et al. introduced a novel flame-retardant composite phase change material (CPCM) to enhance thermal management and safety in LIB systems, which effectively controlled battery temperatures and reduced thermal gradients [26]. Murphy et al. provided insights into the optimization of cooling systems, demonstrating that the optimal design achieved superior temperature regulation and uniformity compared to other designs [27]. Graichen et al. introduced a novel thermal management and safety system using polymer-based mini-channel cold plates to delay TR and prevent TRP [28]. Mei et al. proposed a CPCM, specifically with sodium acetate trihydrate, which effectively slowed temperature rise and reduced combustion duration, offering valuable insights for safer thermal management system design [29].

In summary, this Special Issue showcases the latest research results in the field of thermal safety of LIBs, covering a wide range of topics from basic research to applied technology, and provides valuable references for improving battery safety and performance. Looking ahead, with the continuous improvement of battery energy density and the diversification of application scenarios, the thermal safety research of LIBs is expected to encounter greater challenges. Future research should further explore the TR mechanism, develop new thermal management materials and technologies, and improve the monitoring and early warning system to ensure the safety and reliability of batteries under high energy density and complex working conditions. Additionally, AI's integration with advanced sensor networks and real-time data analytics will further enable the development of autonomous, self-learning systems capable of continuously optimizing battery performance and safety under dynamic operating conditions.

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References

1. Lyu, P.; Liu, X.; Qu, J.; Zhao, J.; Huo, Y.; Qu, Z.; Rao, Z. Recent advances of thermal safety of lithium ion battery for energy storage. *Energy Storage Mater.* **2020**, *31*, 195–220. [CrossRef]
2. Peng, R.; Kong, D.; Ping, P.; Gao, W.; Wang, G.; Gong, S.; Yang, C.; Gao, X.; He, X. Experimental investigation of the influence of venting gases on thermal runaway propagation in lithium-ion batteries with enclosed packaging. *eTransportation* **2025**, *23*, 100388. [CrossRef]
3. Li, H.; Duan, Q.; Zhao, C.; Huang, Z.; Wang, Q. Experimental investigation on the thermal runaway and its propagation in the large format battery module with $Li(Ni_1/Co_{1/3}/Mn_1/_3)O_2$ as cathode. *J. Hazard. Mater.* **2019**, *375*, 241–254. [CrossRef] [PubMed]
4. Chavan, S.; Venkateswarlu, B.; Salman, M.; Liu, J.; Pawar, P.; Joo, S.W.; Choi, G.S.; Kim, S.C. Thermal management strategies for lithium-ion batteries in electric vehicles: Fundamentals, recent advances, thermal models, and cooling techniques. *Int. J. Heat Mass Transf.* **2024**, *232*, 125918. [CrossRef]
5. Zhao, L.; Li, W.; Wang, G.; Cheng, W.; Chen, M. A novel thermal management system for lithium-ion battery modules combining direct liquid-cooling with forced air-cooling. *Appl. Therm. Eng.* **2023**, *232*, 120992. [CrossRef]
6. Nasiri, M.; Hadim, H. Advances in battery thermal management: Current landscape and future directions. *Renew. Sustain. Energy Rev.* **2024**, *200*, 114611. [CrossRef]
7. Fu, H.; Wang, J.; Li, L.; Gong, J.; Wang, X. Numerical study of mini-channel liquid cooling for suppressing thermal runaway propagation in a lithium-ion battery pack. *Appl. Therm. Eng.* **2023**, *234*, 121349. [CrossRef]
8. Chen, M.; Yu, Y.; Ouyang, D.; Weng, J.; Zhao, L.; Wang, J.; Chen, Y. Research progress of enhancing battery safety with phase change materials. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113921. [CrossRef]
9. Chen, M.; Zhu, M.; Zhao, L.; Chen, Y. Study on thermal runaway propagation inhibition of battery module by flame-retardant phase change material combined with aerogel felt. *Appl. Energy* **2024**, *367*, 123394. [CrossRef]

10. Kong, D.; Lv, H.; Ping, P.; Wang, G. A review of early warning methods of thermal runaway of lithium ion batteries. *J. Energy Storage* **2023**, *64*, 107073. [CrossRef]
11. Zhang, L.; Jin, K.; Sun, J.; Wang, Q. A review of fire-extinguishing agents and fire suppression strategies for lithium-ion batteries fire. *Fire Technol.* **2024**, *60*, 817–858. [CrossRef]
12. Ghiji, M.; Novozhilov, V.; Moinuddin, K.; Joseph, P.; Burch, I.; Suendermann, B.; Gamble, G. A review of lithium-ion battery fire suppression. *Energies* **2020**, *13*, 5117. [CrossRef]
13. Zhao, J.; Lv, Z.; Li, D.; Feng, X.; Wang, Z.; Wu, Y.; Shi, D.; Fowler, M.; Burke, A.F. Battery engineering safety technologies (BEST): M5 framework of mechanisms, modes, metrics, modeling, and mitigation. *eTransportation* **2024**, *22*, 100364. [CrossRef]
14. Wang, S.; Zhou, R.; Ren, Y.; Jiao, M.; Liu, H.; Lian, C. Advanced data-driven techniques in AI for predicting lithium-ion battery remaining useful life: A comprehensive review. *Green Chem. Eng.* **2024**, *6*, 139–153. [CrossRef]
15. Claassen, M.; Bingham, B.; Chow, J.C.; Watson, J.G.; Wang, Y.; Wang, X. Characterization of Lithium-Ion Battery Fire Emissions—Part 1: Chemical Composition of Fine Particles (PM2.5). *Batteries* **2024**, *10*, 301. [CrossRef]
16. Claassen, M.; Bingham, B.; Chow, J.C.; Watson, J.G.; Chu, P.; Wang, Y.; Wang, X. Characterization of Lithium-ion Battery Fire Emissions—Part 2: Particle Size Distributions and Emission Factors. *Batteries* **2024**, *10*, 366. [CrossRef]
17. Kuntz, P.; Lonardoni, L.; Genies, S.; Raccurt, O.; Azaïs, P. Evolution of safety behavior of high-power and high-energy commercial Li-Ion cells after electric vehicle aging. *Batteries* **2023**, *9*, 427. [CrossRef]
18. Zhang, H. Study on Thermal Runaway Behavior and Jet Characteristics of a 156 Ah Prismatic Ternary Lithium Battery. *Batteries* **2024**, *10*, 282. [CrossRef]
19. Wang, Y.; Wang, Y.; Zhao, J.; Li, H.; Xu, C.; Li, Y.; Wang, H.; Lu, L.; Dai, F.; Yu, R. Experimental Research on Thermal-Venting Characteristics of the Failure 280 Ah LiFePO4 Battery: Atmospheric Pressure Impacts and Safety Assessment. *Batteries* **2024**, *10*, 270. [CrossRef]
20. Hebenbrock, A.; Orazov, N.; Benger, R.; Schade, W.; Hauer, I.; Turek, T. Innovative early detection of high-temperature abuse of prismatic cells and post-abuse degradation analysis using pressure and external fiber bragg grating sensors. *Batteries* **2024**, *10*, 92. [CrossRef]
21. Kisseler, N.; Hoheisel, F.; Offermanns, C.; Frieges, M.; Heimes, H.; Kampker, A. Monitoring of Thermal Runaway in Commercial Prismatic High-Energy Lithium-Ion Battery Cells via Internal Temperature Sensing. *Batteries* **2024**, *10*, 41. [CrossRef]
22. Miao, B.; Lv, J.; Wang, Q.; Zhu, G.; Guo, C.; An, G.; Ou, J. The suppression effect of water mist released at different stages on lithium-ion battery flame temperature, heat release, and heat radiation. *Batteries* **2024**, *10*, 232. [CrossRef]
23. Bordes, A.; Papin, A.; Marlair, G.; Claude, T.; El-Masri, A.; Durussel, T.; Bertrand, J.-P.; Truchot, B.; Lecocq, A. Assessment of Run-Off Waters Resulting from Lithium-Ion Battery Fire-Fighting Operations. *Batteries* **2024**, *10*, 118. [CrossRef]
24. Liu, J.; Chen, H.; Huang, S.; Jiao, Y.; Chen, M. Recent progress and prospects in liquid cooling thermal management system for lithium-ion batteries. *Batteries* **2023**, *9*, 400. [CrossRef]
25. Rahmani, A.; Dibaj, M.; Akrami, M. Recent advancements in battery thermal management systems for enhanced performance of Li-ion batteries: A comprehensive review. *Batteries* **2024**, *10*, 265. [CrossRef]
26. Yu, Y.; Zhang, J.; Zhu, M.; Zhao, L.; Chen, Y.; Chen, M. Experimental investigation on the thermal management for lithium-ion batteries based on the novel flame retardant composite phase change materials. *Batteries* **2023**, *9*, 378. [CrossRef]
27. Murphy, M.; Akrami, M. Advanced Thermal Management of Cylindrical Lithium-Ion Battery Packs in Electric Vehicles: A Comparative CFD Study of Vertical, Horizontal, and Optimised Liquid Cooling Designs. *Batteries* **2024**, *10*, 264. [CrossRef]
28. Graichen, H.-C.; Boye, G.; Sauerhering, J.; Köhler, F.; Beyrau, F. The impact of a combined battery thermal management and safety system utilizing polymer mini-channel cold plates on the thermal runaway and its propagation. *Batteries* **2023**, *10*, 1. [CrossRef]
29. Mei, J.; Shi, G.; Liu, H.; Wang, Z. Organic and Inorganic Hybrid Composite Phase Change Material for Inhibiting the Thermal Runaway of Lithium-Ion Batteries. *Batteries* **2023**, *9*, 513. [CrossRef]