

Article

Numerical Study on Effect of Ventilation on Fire Characteristics of Lithium-Ion Battery in Energy Storage Cabin

Wei Lin ¹, Lingcheng Zeng ¹, Junyu Liu ¹ and Zhiying Ding ^{2,*}

¹ China Southern Power Grid Zhongshan Power Supply Bureau, Zhongshan 528400, China; lw01@kdxinneng.cn (W.L.)

² Technical Department Guangdong National Energy Storage Technology Innovation Research Institute Co., Ltd., Guangzhou 510000, China

* Correspondence: dzy03@kdxinneng.cn

Abstract

In this work, a fire dynamics simulator numerical model of an industrial and commercial energy storage cabinet equipped with 280 Ah lithium iron phosphate cells is established; full-process quantitative analysis of heat dissipation and the total released mass of CO and H₂ is realized; and the spatial-temporal evolution of the cabin temperature field, CO/H₂ concentration field and flame spread is systematically captured. The results show that under fully closed conditions, the local peak temperature exceeds 700 °C; additionally, CO and H₂ continuously accumulate inside the cabin, with their concentrations rising to a magnitude of 1000 ppm within 60 s after thermal runaway initiation. In contrast, the open-top structure forms an unobstructed buoyancy-driven venting channel, which guides high-temperature flue gas, CO and H₂ to efficiently discharge outward. The results indicate that the peak temperature and peak concentrations of CO and H₂ in the opened condition drop by more than 80% compared with the closed case. The designated top vent channel effectively cuts down the total residual mass of toxic and combustible gases inside the cabin and suppresses continuous heat accumulation, remarkably mitigating explosion and poisoning risks triggered by trapped heat and hazardous gas mixtures.

Keywords: FDS; lithium-ion battery; energy storage system; thermal runaway

1. Introduction

Industrial and commercial energy storage cabinets represent a core form of energy storage integrated with distributed photovoltaics, industrial parks, and commercial buildings [1,2]. Owing to their advantages such as flexible deployment, a small footprint, and high power density, these cabinets are widely applied in peak–valley arbitrage, demand management, and backup power scenarios. Currently, mainstream industrial and commercial energy storage cabinets predominantly utilize 280–314 Ah LFP batteries, with the single-cabinet capacity typically ranging from 100 to 215 kWh. Within such cabinets, battery packs are arranged in densely packed multi-layer configurations, featuring narrow heat dissipation channels and a semi-enclosed spatial environment. This compact structural characteristic significantly alters the heat accumulation and gas migration law during battery failure, making the fire and explosion safety of LFP energy storage cabinets a key concern in industrial safety research [3,4]. Extensive studies have been conducted on the fire safety characteristics of LFP energy storage cabins from multiple perspectives. Existing research has explored the influence of external environmental conditions such as ambient



Academic Editor: Pascal Venet

Received: 1 June 2026

Revised: 30 June 2026

Accepted: 4 July 2026

Published: 12 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

temperature and ventilation volume on the fire spread characteristics of energy storage cabinets [5,6]. Meanwhile, numerical simulation methods have been adopted to optimize the cabinet internal detector layout and fire suppression system design, providing basic technical support for early fire warning and disaster control [7]. However, most traditional studies focus on macroscopic fire phenomena and passive fire suppression strategies, while in-depth mechanism research on the thermochemical behavior of LFP battery thermal runaway products in confined cabinet spaces remains insufficient [8,9].

Some research on LFP battery failure characteristics has clarified that the generation, diffusion, and combustion evolution of flammable vent gases are the core inducements of severe fire and even explosion accidents in confined energy storage spaces [10]. During thermal runaway, LFP cells undergo violent internal side reactions, producing mixed flammable gases dominated by hydrogen, methane, and ethylene, accompanied by electrolyte vapor and aerosol droplets [11,12]. Furthermore, results reveal that due to the hydrogen-driven chain branching in LFP cells, the released gases can be ignited by the hot surface and electric spark mode [13]. Different from nickel-based lithium-ion batteries, LFP batteries feature a lower thermal runaway temperature and unique vent gas composition characteristics, leading to distinct ignition and deflagration laws [14]. A key conclusion from the latest experimental and statistical studies is that immediate spontaneous ignition of vent gases from failing LFP cells is a rare occurrence; most LFP vent gas mixtures require appropriate concentration distributions, ambient temperature conditions, and external ignition sources to trigger combustion and deflagration [15,16]. However, the accumulation of released combustible gases within a confined space significantly increases the risk of explosion, and the explosion concentration limit varies within the range of 4–15% depending on the state of charge. Moreover, results indicate that hydrogen and carbon monoxide are the primary factors contributing to the risk of combustion and explosion in batteries. Therefore, the concentrations of these two gases are also the factors we focus on in this work.

Further studies have verified that LFP vent gases can even be ignited at concentrations below the theoretical lower explosive limit under uniform mixing conditions, revealing the complex flammability threshold characteristics of LFP thermal runaway gas mixtures in confined spaces [17–19]. In addition, cabinet structural congestion, the internal obstacle distribution, and venting pressure conditions change gas turbulence and flame acceleration effects, further affecting fire dynamics and explosion overpressure severity [20]. Although several studies have investigated the independent influence of ventilation conditions on battery combustion characteristics [21,22], few systematic full-scale studies have comprehensively coupled the whole process of LFP battery thermal runaway initiation, vent gas release, multi-factor constrained diffusion, and dynamic combustion evolution in standard energy storage cabinets. The lack of high-precision full-scale simulation research restricts the refinement of safety design specifications and accident risk prediction for megawatt-hour-level LFP energy storage systems.

Based on the above, this study develops a combustion simulation model for a representative 100 kWh industrial and commercial energy storage cabinet using FDS. The model fully reproduces the entire process from TR initiation, combustion, and propagation to stabilization. The spatiotemporal evolution of the temperature, smoke, and characteristic gas concentrations is quantitatively analyzed. The findings are expected to provide theoretical support for the safety design and accident prevention of industrial and commercial energy storage cabinets. This study aims to offer a low-cost, reproducible, and high-precision simulation tool for fire safety assessment of energy storage systems, thereby filling the technical gap in full-scale simulations of megawatt-hour-level energy storage systems and contributing to the safe, healthy, and large-scale development of the energy storage industry.

2. Model Description

2.1. Physical Model and Locations of Detectors

Based on actual engineering data, the industrial and commercial energy storage cabinet used in this study had dimensions of 1450.7 mm (length) $\times$ 1100 mm (width) $\times$ 1923 mm (height). Five battery packs were arranged vertically to form the entire battery cabinet, with the second module from the bottom set as the triggered module as shown in Figure 1a.

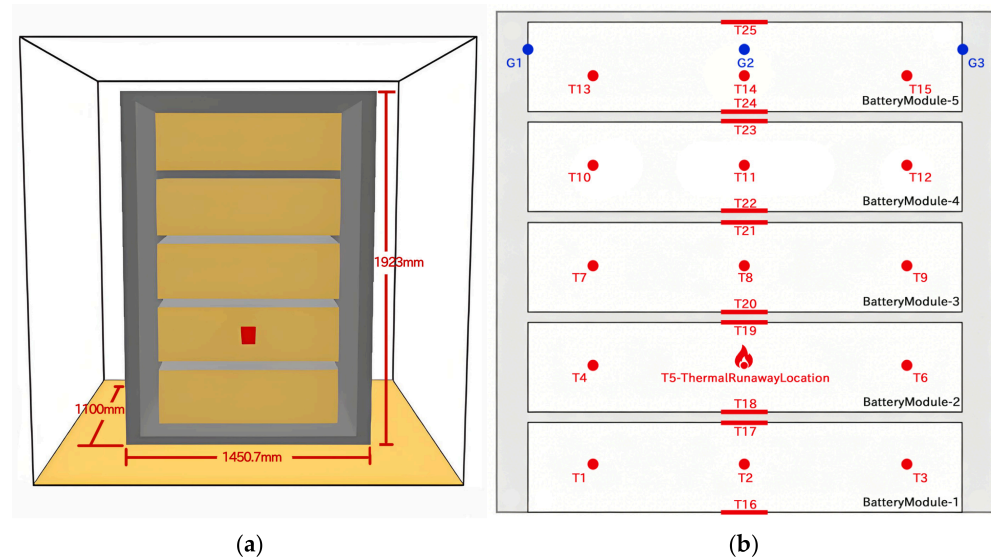


Figure 1. Geometry and schematic of the lithium-ion battery energy storage cabin: (a) geometry of the energy storage cabin; (b) locations of thermocouples and gas detectors.

As shown in Figure 1b, three measurement points (left, center, and right) were arranged on each battery module to capture the transverse temperature gradient. Additional temperature sensors were installed in the gaps between modules, as well as at the cabin ceiling and floor, forming a three-dimensional monitoring network. Among these, point T5, located at the center of Module 2, was designated as the key monitoring location for preset thermal runaway, enabling effective capture of temperature variations and vertical heat propagation signals during the thermal runaway process. For gas concentration monitoring, three measurement points (G1, G2, and G3) were arranged at the left, center, and right positions of the cabin ceiling. Each monitoring point was equipped with sensors for both CO and H₂.

2.2. Governing Equations

In this study, the Fire Dynamics Simulator (FDS) software was employed to simulate the combustion behavior of battery modules within the industrial and commercial energy storage cabinet. The fundamental governing equations solved by FDS primarily include the following [23,24]:

The momentum conservation equation:

$$\rho \left(\frac{\partial \vec{u}}{\partial t} + \frac{1}{2} \nabla \cdot |\vec{u}|^2 - \vec{u} \times \omega \right) + \nabla p - \rho \vec{g} = \vec{f} + \nabla \cdot \tau \quad (1)$$

where $\vec{f}$ is the vector of external forces acting on the fluid, p is the pressure, τ is the viscous stress tensor, ω is the vorticity, and $\vec{g}$ is the gravitational acceleration vector.

The component conservation equation:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho Y_i \vec{u}) = (\rho D_i \nabla Y_i) + \dot{m}_i^* \quad (2)$$

where i represents the i -th species, Y_i is the concentration of the i -th species, D_i is the diffusion coefficient of the i -th species, and $\dot{m}_i^*$ is the mass production rate of the i -th species.

The energy conservation equation:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h \vec{u}) = \frac{\partial p}{\partial t} + \vec{u} \cdot \nabla p - \nabla \cdot \vec{q}_r + \nabla \cdot (k \nabla T) + \sum_i \nabla \cdot (h_i \rho D_i \nabla Y_i) \quad (3)$$

where h is the specific enthalpy, $\vec{q}_r$ is the radiative heat flux, T is the temperature, and k is the thermal conductivity.

The state equation:

$$p_0 = \rho R \sum_i (Y_i / M_i) = \rho R / M \quad (4)$$

where R is the gas constant, and M is the molecular weight of the gas mixture.

2.3. Boundary Conditions

Regarding boundary conditions, the cabinet walls were made of sheet metal with an external spray coating and were set as adiabatic boundaries. The internal battery modules and the cabinet were coupled through conductive and convective heat transfer. The cabinet door and ventilation openings were respectively set as vent boundaries or hole boundaries (to simulate ventilation ducts), depending on the operating condition. The top and side surfaces of the computational domain were set as pressure outlets, while the bottom surface was set as an adiabatic wall. The cabinet door, pressure relief vents, and ventilation openings were placed according to actual installation positions, with their open/closed states treated as variable parameters for comparative studies under different operating conditions.

As shown in Figure 2, the initial input conditions were obtained by previous tests that were conducted in the full-scale fire test platform [25].



Figure 2. Full-scale fire test platform for lithium-ion battery energy storage system.

Moreover, the ambient temperature within the battery pack was set to 300 K. The mean heat release rate (HRR) during battery combustion, along with the types and volumetric ratios of gases generated during thermal runaway, were determined using boundary input conditions sourced from actual thermal runaway experimental data from previous studies as shown in Figure 3 [24–26]. The initial time of thermal runaway was uniformly defined as $t = 0$ s. When the cell temperature reached the critical thermal runaway temperature of

180 °C, heat release, high-temperature gas ejection and gas-phase combustion reactions were activated simultaneously.

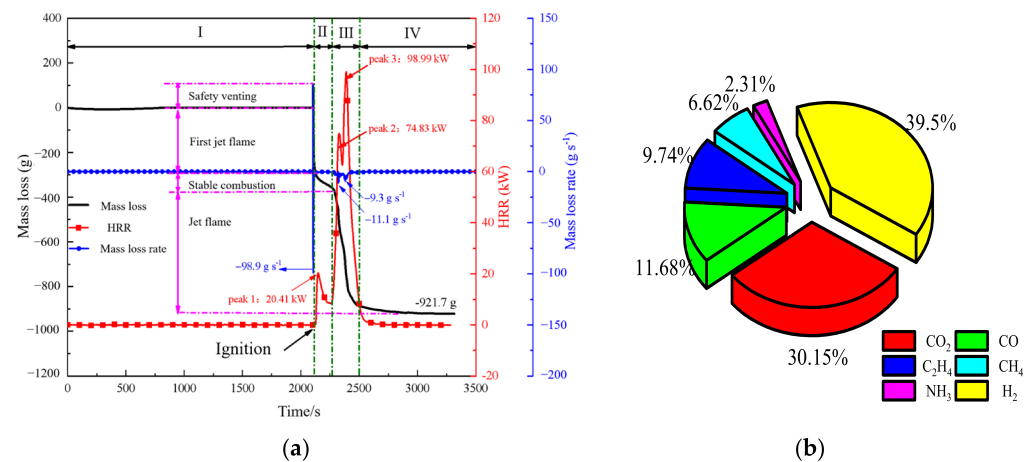


Figure 3. Experimental boundary conditions: (a) mass loss and heat release rate of lithium-ion phosphate battery with 100% SOC in thermal runaway; (b) gas type volume ratio.

It is important to note that the battery pack was modeled as a homogeneous solid block to preserve its intact physical volume and blocking effect in this study. Given the emphasis on system-level research, the intricate details of the internal battery cells were homogenized. However, the thermal runaway propagation behavior among the battery cells also significantly influenced their intense combustion behavior. Therefore, to gain a comprehensive understanding of battery combustion and thermal diffusion issues across different systems, it remains imperative to acquire specific experimental data, which can also serve to better validate the accuracy of the model.

2.4. Grid Analysis

Mesh size plays a decisive role in the simulation accuracy of FDS. According to the mesh selection criteria for FDS, the characteristic grid size δ_x should satisfy the range of $\delta_x = D^* / 10$ to $D^* / 5$; representing the characteristic diameter of the fire source, D^* is defined as

$$D^* = \left(\frac{Q}{\rho_{\infty} c_p T_{\infty} g^{\frac{1}{2}}} \right)^{\frac{2}{5}} \quad (5)$$

where $\dot{Q}$ is the heat release rate of the fire source. For the fire scenarios in this study, where the predicted peak heat release rate (PHRR) is in the range of 500–2000 kW, the characteristic fire diameter D^* is approximately in the range of 50–100 mm. Therefore, a grid size in the range of 50–100 mm is considered appropriate. To ensure the accuracy and reliability of the numerical simulation results, a grid independence study was conducted in this work. Three grid schemes (coarse grid: 100 mm, medium grid: 50 mm, and fine grid: 25 mm) were designed for convergence analysis, with the peak temperature and heat release rate curves selected as evaluation criteria to determine the final grid scheme. Under the condition of keeping the geometric model, material parameters, and boundary conditions completely consistent, three structured grid systems (coarse, medium, and fine) were constructed. The maximum temperature within the cabin, peak pressure, and peak hydrogen concentration were selected as key evaluation indicators. The results showed that the calculation results for the medium grid and the fine grid were in good agreement, and both could meet the simulation accuracy requirements. Considering both computational accuracy and

efficiency, the medium grid was selected for subsequent simulations, effectively reducing the computation time while ensuring reliable and accurate results.

3. Results and Analysis

3.1. Fire Spread Behavior in Closed Cabin

3.1.1. Fire Propagation Characteristics

Figure 4 presents the two-dimensional temperature slice nephogram captured inside the fully closed energy storage cabin at successive time instants after thermal runaway initiation. The preset thermal runaway cell acts as the core heat source, generating a high-temperature buoyant plume that vertically ascends toward the cabin ceiling. Restricted by airtight metal cabinet walls, the upward hot airflow cannot escape outward and recirculates within the confined cavity, forming a persistent high-temperature core region centered on the faulty battery module. The peak value of the temperature can reach over 740 °C. As simulation time elapses, the high-temperature color gradient region continuously expands to adjacent battery modules and inter-module gaps; low-temperature zones only exist in the marginal bottom area of the cabin and gradually shrink under long-term heat convection and radiation. The enclosed boundary blocks all heat dissipation pathways, so waste heat cannot be released to the external ambient environment, laying a fundamental condition for cascading thermal runaway of surrounding battery packs.

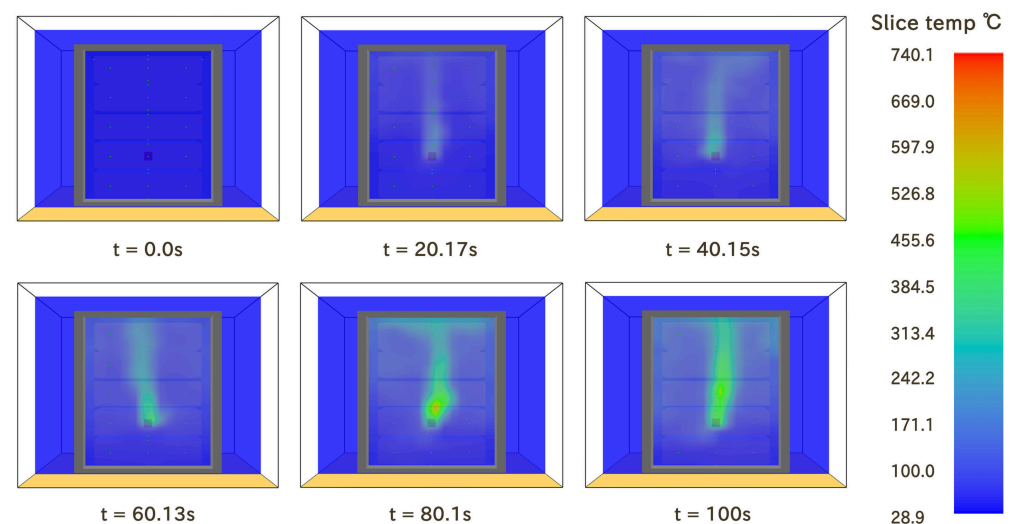


Figure 4. Schematic diagram of temperature distribution in closed cabin.

Figure 5 illustrates the temperature time-history curves of multiple thermocouple measuring points distributed vertically and horizontally inside the closed cabin, including the core thermal runaway point T05, adjacent module sensors T04 and T06, and remote lower-layer module measuring points T17, T18, T19 and T20. After thermal runaway is triggered at $t = 0$ s, the temperature of T05 surges sharply within a short time window; the local peak temperature exceeds 700 °C, which is the maximum temperature value recorded across all monitoring positions. Measuring points directly exposed to jet flame and high-temperature radiation (T04, T06) exhibit synchronized rapid temperature rises without obvious delay periods. In contrast, thermocouples installed on distant bottom battery modules display evident hysteresis in their temperature response; although their temperature growth rates are relatively mild, the temperature values maintain a monotonically increasing trend without any descending inflection points throughout the whole 0–100 s simulation period. The long-duration high-temperature background field inside

the airtight cabin continuously heats adjacent LFP cells, significantly elevating the risk of successive thermal runaway propagation and a large-scale cabinet fire accident.

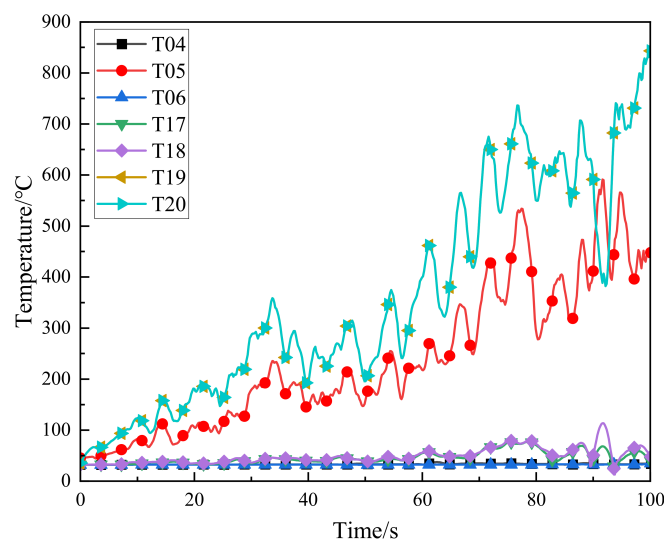


Figure 5. Schematic diagram of temperature curves in closed cabin.

The thermal stratification and local peak temperature inside the sealed cabin are highly consistent with the results of full-scale sealed container experiments [27]; the test also showed stable hot smoke stratification near the ceiling under airtight conditions. Twenty-five thermocouples were deployed in this work to precisely resolve horizontal and vertical thermal gradients, making up for the insufficient monitoring resolution of previous simplified models.

3.1.2. Gas Dispersion Analysis

Figure 6 displays sequential CO concentration slice nephograms of the closed cabin at $t = 0$ –100 s. Once thermal runaway is activated, a massive amount of CO is ejected from the cell safety vent alongside high-temperature electrolyte vapor. Subject to the closed structural constraint, CO diffuses upward slowly, relying on natural convection, and gradually accumulates on the upper ceiling of the energy storage cabin. As the simulation time proceeds, the high-concentration CO coverage area expands continuously from the local region above the faulty cell to the entire cabin top space. At $t = 60$ s, the whole upper cavity is filled with ultra-high-concentration CO, and no effective dilution or exhaust phenomenon can be observed in any cabin zone; this creates severe acute poisoning risks for on-site maintenance personnel.

Figure 7 records the real-time CO concentration variation curves for the three ceiling gas sensors G1, G2 and G3 arranged at left, central and right positions. The concentration curves for all three measuring points rise monotonically without decline stages; within 60 s after thermal runaway onset, the CO concentration reaches the order of magnitude of 104 ppm. The nearly overlapping trend of the three curves indicates that CO achieves full uniform mixing in the closed cabin's upper space, and no local low-concentration dilution area exists. CO at such an ultra-high concentration not only poses fatal inhalation hazards but also participates in homogeneous gas-phase combustion reactions, further intensifying the flame intensity and fire damage degree within the confined cabin.

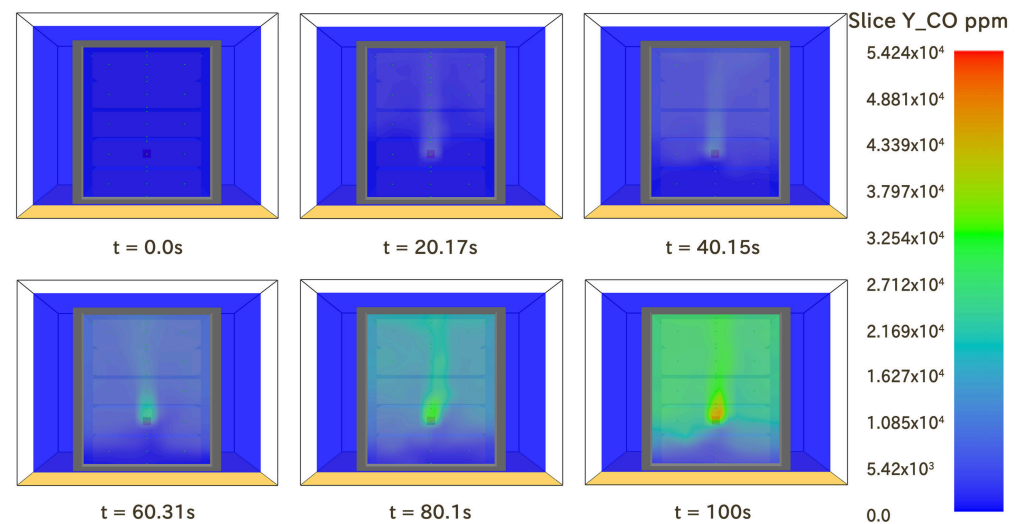


Figure 6. Schematic diagram of CO concentration distribution in closed cabin.

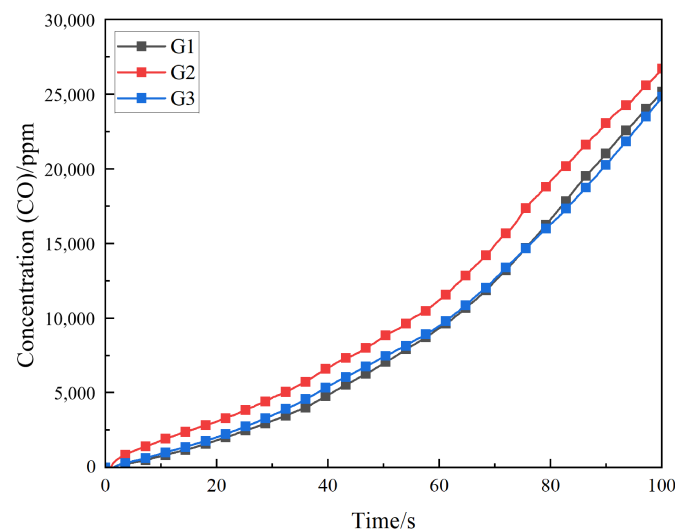


Figure 7. Concentration–time curves of CO in the closed cabin.

Figure 8 visualizes the H_2 concentration distribution nephograms inside the fully closed cabin at different moments. H_2 produced by LFP cell thermal runaway possesses much lower density than air, so the gaseous product rapidly floats upward and gathers on the cabin ceiling. Without top ventilation openings, the accumulated H_2 cannot discharge outwards, and the coverage range of high- H_2 -concentration zones expands synchronously with the simulation duration. A large-scale flammable gas cloud layer forms at the top of the cabinet and continuously approaches the explosion concentration limit of mixed vent gas, resulting in continuously escalating deflagration and explosion risks as time proceeds.

Figure 9 presents the time-history curves of hydrogen concentrations recorded by the three ceiling monitoring points G1, G2 and G3 throughout the 0–100 s simulation period. Distinct from the near-zero concentration variation of G1 and G3, the hydrogen concentration detected at G2 exhibits a consistent, continuous upward trend without any obvious descending segment. The concentration values for G1 and G3 remain nearly unchanged and stay close to zero over the whole simulation process, while G2 accumulates hydrogen significantly and reaches a peak value close to 150 ppm at 100 s. Such a prominent concentration discrepancy indicates that hydrogen generated by thermal runaway mainly accumulates at the G2 ceiling position within the fully enclosed cabin, rather than being evenly distributed in the entire upper confined space.

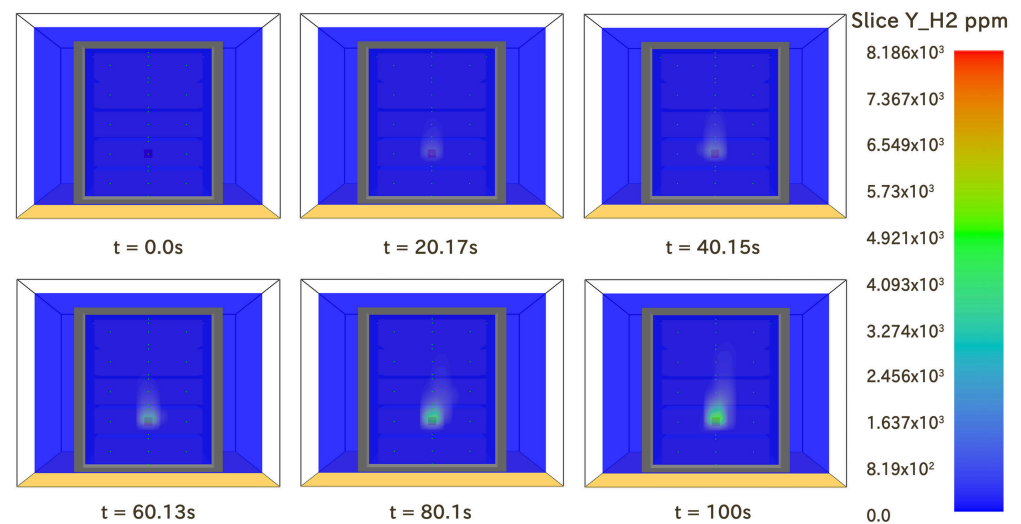


Figure 8. Schematic diagram of H_2 concentration distribution in closed cabin.

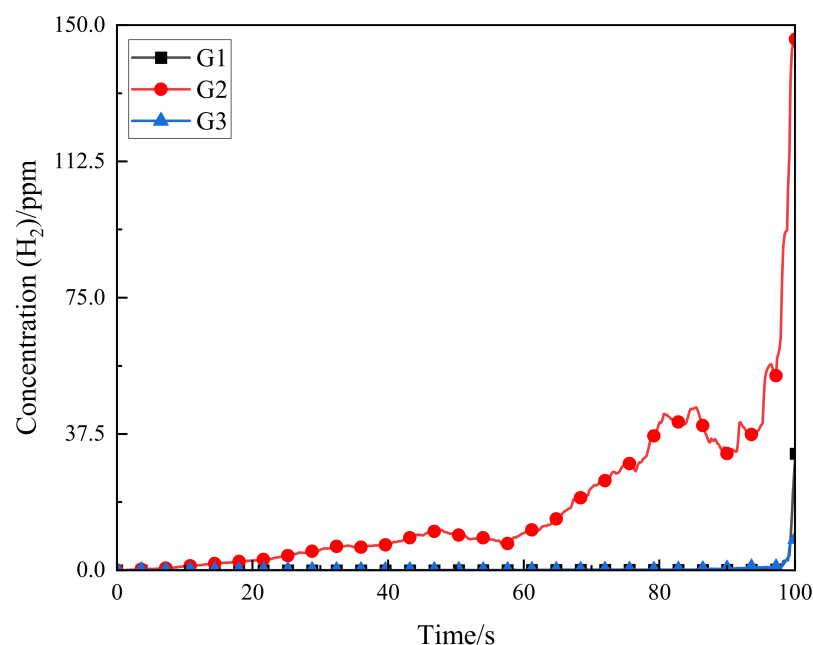


Figure 9. Concentration–time curves of H_2 in the closed cabin.

Prior experiments investigated the pre-deflagration behaviors of prefabricated storage cabins and proved that continuous H_2 accumulation in sealed spaces easily triggers deflagration [21]; the continuous rising hydrogen concentration obtained in this paper quantitatively verifies such pre-disaster risks. Previous module-scale simulations only captured local hydrogen data, while the full-scale 3D monitoring system in this paper reproduces the whole slow diffusion process of hydrogen from cells to ceiling, consistent with real commercial cabinet layouts.

3.2. Fire Spread Behavior in Cabin Without Top Cover

3.2.1. Fire Propagation Characteristics

Figure 10 presents the temperature slice nephogram of the open-top energy storage cabin at representative time nodes after thermal runaway initiation. The high-temperature buoyant plume generated by the faulty cell rises vertically and directly overflows the cabin through the uncovered top channel, rather than recirculating inside the confined cavity. Different from the full-cabin high-temperature coverage phenomenon in the closed

condition, high-temperature zones are only confined to the narrow local area surrounding the thermal runaway cell. The color gradient of the temperature illustrates that most regions of the cabin, including inter-module gaps, bottom battery packs and side wall areas, maintain relatively low temperature levels without large-area heat accumulation. The directional top exhaust channel fundamentally breaks the vicious cycle of waste heat retention and progressive temperature rise inside the enclosed space and greatly weakens radiative and convective heat transfer to adjacent intact battery modules. Some tests were previously conducted to compare multiple ventilation layouts and confirmed that top exhaust achieves optimal heat dissipation, capable of reducing the maximum cabin temperature by over 150 °C [21,28]. The full open-top design in this paper performs better than partial top air outlets while maintaining consistent core conclusions. The surrounding temperature of the battery module can reach around 400 °C while the temperature of the triggered module is around 760 °C. These valuable data also offer robust verification support for the accuracy of this model.

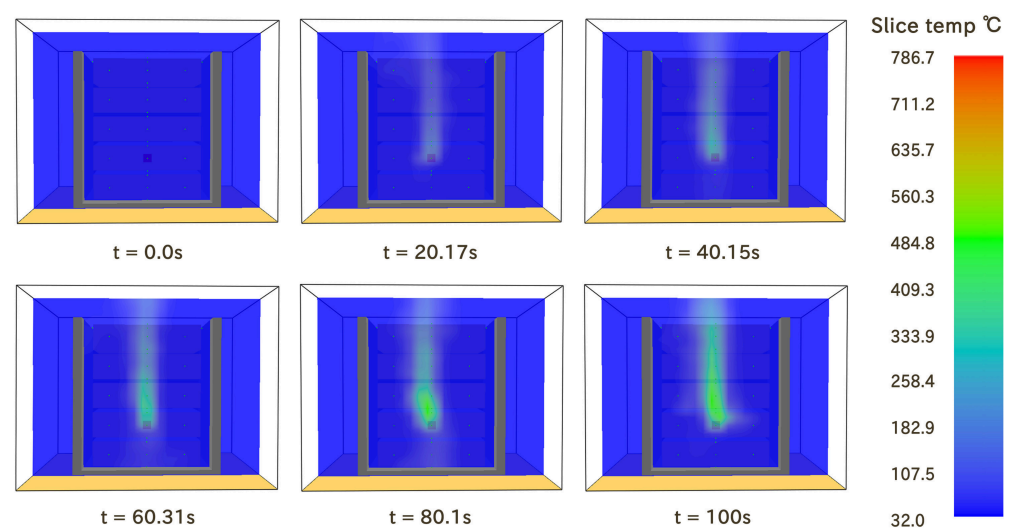


Figure 10. Schematic diagram of temperature distribution in cabin without top cover.

Figure 11 compares the temperature time-history curves of thermocouple measuring points under the open-top ventilation condition. Although the core thermal runaway sensor T05 still captures a transient high-temperature peak, the duration of ultra-high temperature above 800 °C is drastically shortened compared with the fully closed scenario. The peak temperature values of adjacent measuring points T04 and T06 decrease significantly, while remote lower-layer module sensors T17–T20 only experience mild, short-time temperature fluctuations without sustained heating. Quantitative statistical calculations indicate that the peak temperature recorded by each monitoring position drops by more than 80% relative to the closed cabin benchmark. The limited high-temperature range and shortened heat exposure duration effectively suppress the heat conduction and radiation-induced cascading thermal runaway of surrounding LFP cells, substantially reducing the overall fire spread risk of the energy storage cabinet.

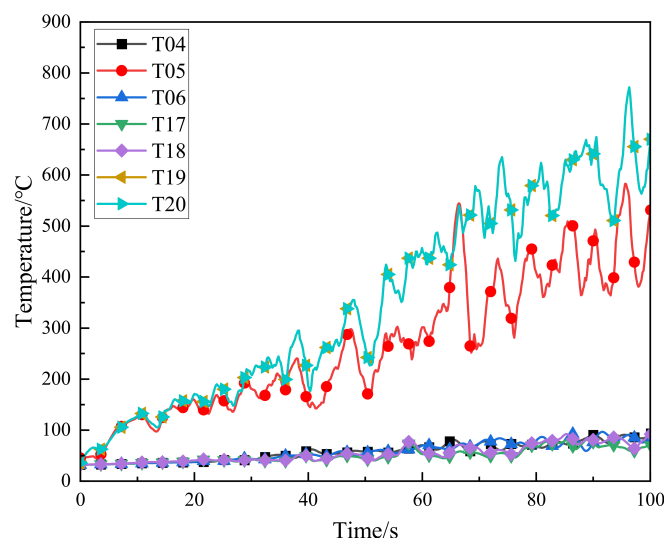


Figure 11. Schematic diagram of temperature curves in cabin without top cover.

3.2.2. Gas Dispersion Analysis

Figure 12 shows sequential CO concentration slice nephograms of the open-top cabin. CO mixed with high-temperature flue gas flows upward along the buoyancy exhaust channel and is rapidly discharged out of the cabinet. Thin, high-concentration CO layers merely exist in the tiny local zone right above the faulty battery vent, and the ceiling and remote module areas maintain extremely low CO concentration values without full-cabin toxic gas enrichment. As the simulation time advances, the local high-CO-concentration region continuously escapes through the top opening, and no expanding toxic gas cloud forms inside the cabin cavity.

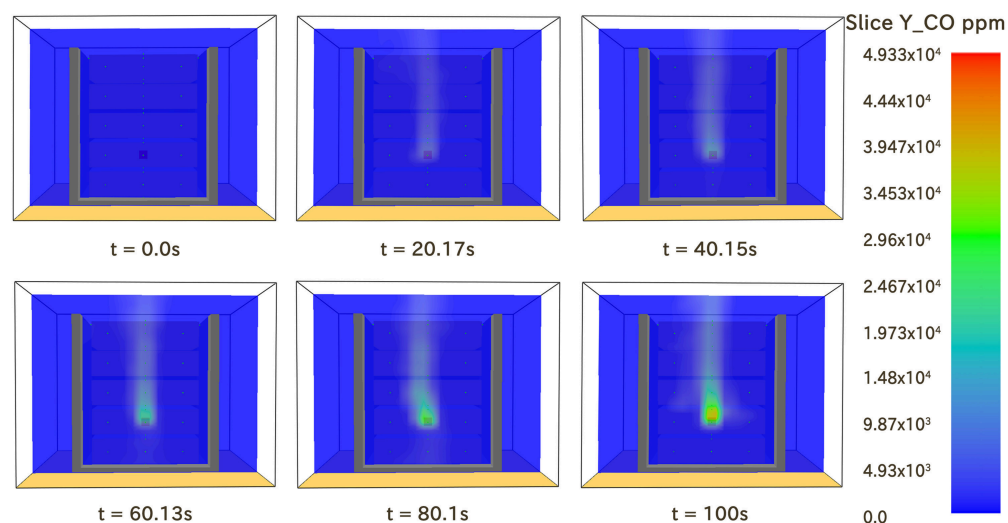


Figure 12. Schematic diagram of CO concentration distribution in cabin without top cover.

Figure 13 shows time-history curves of CO concentrations measured by the ceiling sensors G1, G2 and G3 under closed cabin conditions. The main curve A corresponds to sensor G1, while subgraphs B and C separately show the concentration variations at G2 and G3 within the same time range. As illustrated, the CO concentration at monitoring point G1 presents a continuous sharp upward trend throughout the whole test. After thermal runaway gas release, the value keeps climbing and reaches a high peak close to 80,000 ppm at the end of the experiment, accompanied by obvious fluctuating peaks and valleys during

the rising process. In contrast, the CO concentrations at G2 and G3 maintain an extremely low stable level with a tiny mild rise, and their maximum values are far below that of G1.

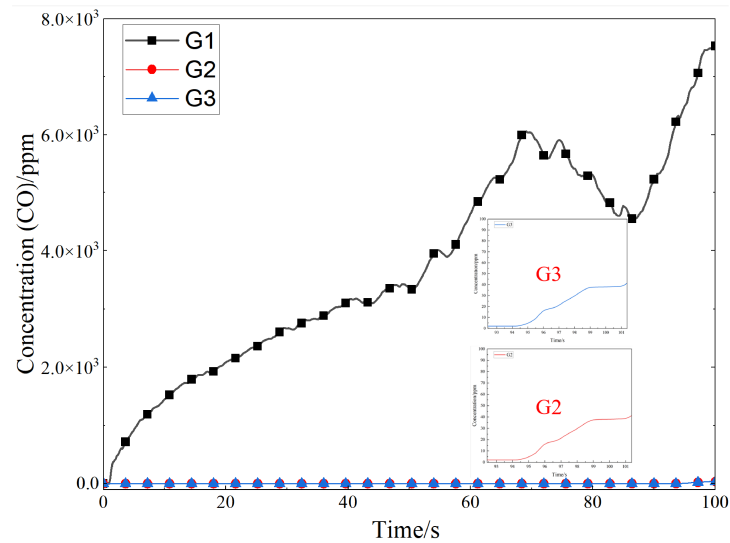


Figure 13. Concentration–time curves of CO in cabin without top cover.

Figure 14 provides the H_2 concentration slice nephogram of the open-top energy storage cabin at successive simulation instants. Lightweight H_2 floats upward immediately after ejection and is directly vented outwards via the uncovered top passage. Transient high- H_2 -concentration regions are limited to the narrow vertical space above the faulty cell, and the rest of the cabin interior maintains a negligible hydrogen concentration without large-scale flammable premixed gas cloud formation. The open-top structure avoids uniform gas mixing across the entire upper cavity, which is the core prerequisite for severe internal deflagration accidents in closed cabins.

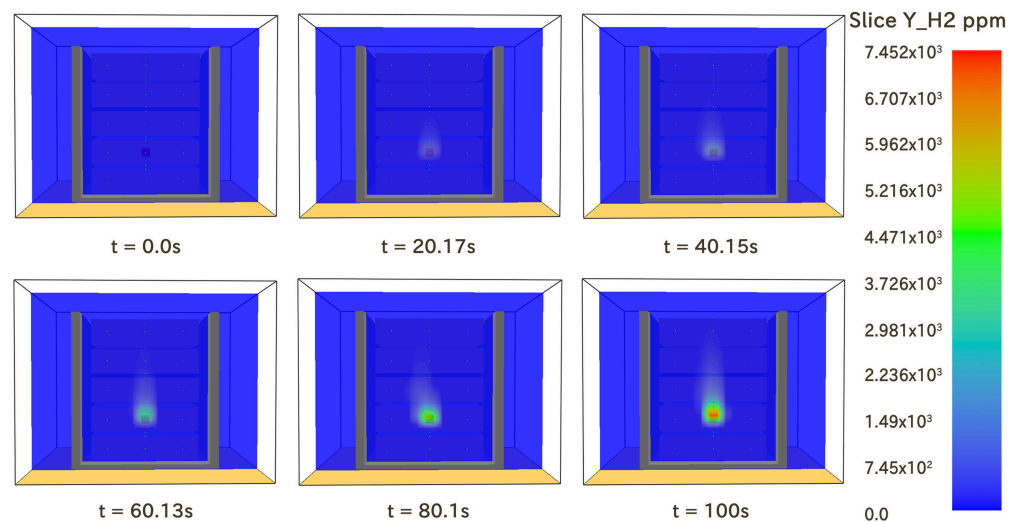


Figure 14. Schematic diagram of H_2 concentration distribution in cabin without top cover.

Figure 15 records the real-time H_2 concentration variation at the ceiling measuring points G1, G2 and G3 for the open-top case. Consistently with the CO variation rules, the peak H_2 concentration declines by over 80% compared with the fully enclosed working condition; the hydrogen concentration only rises slightly for a short instant and then decays rapidly to a low baseline level. Obvious concentration discrepancies exist among the three ceiling sensors: G1, which is closest to the thermal runaway cell, records relatively higher

transient hydrogen concentrations, whereas G2 and G3 at bilateral positions maintain extremely low readings throughout the simulation. This distinct concentration differentiation proves that H_2 escapes rapidly through the top vent without horizontal uniform accumulation on the cabin ceiling, which fundamentally eliminates the precondition for hydrogen-driven gas explosion inside the energy storage cabin. Some mechanical exhaust research [21,27,28] proved that ventilation restrains hydrogen accumulation, with peak concentrations of combustible gases falling approximately within the range of 100 to 1000 ppm; these findings have been duly validated in this study. The dilution effect of full open-top natural ventilation is more prominent in this work.

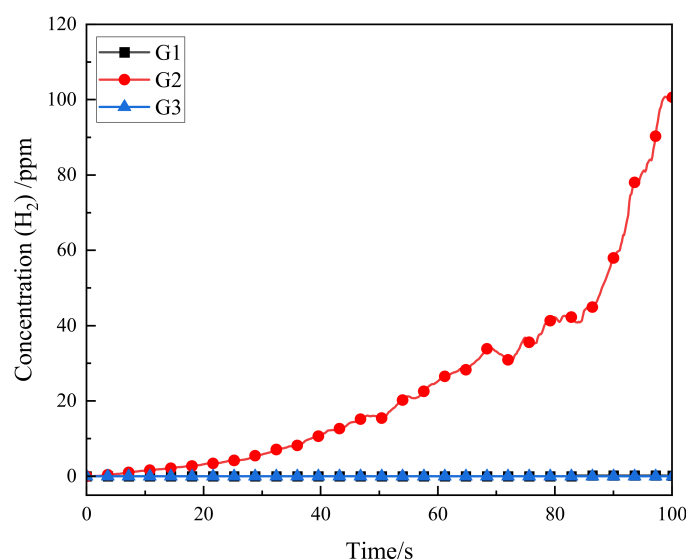


Figure 15. Concentration–time curves of H_2 in cabin without top cover.

4. Conclusions

In this study, a three-dimensional transient numerical simulation model was established to investigate single-cell thermal runaway in an energy storage cabin. The evolution of the temperature field and the concentration fields of CO and H_2 gases within the cabin were systematically analyzed for a closed cabin and for opened conditions without a top cover. The results are as follows:

- (1) After thermal runaway initiates in the closed cabin, the adjacent flame-impacted sensor rapidly reaches a local peak temperature exceeding $700\text{ }^{\circ}\text{C}$, forming a concentrated high-temperature plume centered on the faulty cell. The enclosed structure blocks external heat dissipation; while distant monitoring points show delayed mild temperature rises, the whole cabin maintains a long-term high-temperature background without effective heat dissipation.
- (2) The CO and H_2 released by cell thermal runaway cannot be evacuated in a timely manner and accumulate continuously throughout the 100 s simulation window. Both gas concentrations rise monotonically without descending inflection points, CO eventually reaching a magnitude of 10^4 ppm and H_2 reaching a magnitude of 10^3 ppm.
- (3) Ventilation can achieve remarkable reduction of hazardous gas concentrations: The peak CO and H_2 readings at side monitoring points drop by over 80% relative to the sealed working condition. High-concentration gas zones only exist locally around the thermal runaway source, and no uniform full-cabin gas accumulation occurs. The directional exhaust path breaks the vicious cycle of heat retention and hazardous gas enrichment in confined spaces, significantly lowering the dual threats of flammable gas explosion and toxic gas inhalation.

This full-scale coupled thermal–gas simulation method can be applied to the safety performance evaluation of megawatt-hour-level LFP energy storage systems, providing quantitative data support for standardized vent structure optimization, thermal runaway early warning layout and accident risk control of industrial and commercial energy storage equipment.

Author Contributions: Software, W.L.; validation, L.Z.; formal analysis, J.L. and L.Z.; writing—original draft preparation, Z.D., L.Z. and J.L.; writing—review and editing, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was sponsored by Science and Technology Project of China Southern Power Grid Company Limited (032000KC24080053 (GDKJXM20240714)).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Wei Lin, Lingcheng Zeng and Junyu Liu work for China Southern Power Grid Zhongshan Power Supply Bureau. Zhiying Ding works for the Technical Department of Guangdong National Energy Storage Technology Innovation Research Institute Co., Ltd. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Sayed, E.T.; Olabi, A.G.; Alami, A.H.; Radwan, A.; Mdallal, A.; Rezk, A.; Abdelkareem, M.A. Renewable energy and energy storage systems. *Energies* **2023**, *16*, 1415. [\[CrossRef\]](#)
2. Mitali, J.; Dhinakaran, S.; Mohamad, A. Energy storage systems: A review. *Energy Storage Sav.* **2022**, *1*, 166–216. [\[CrossRef\]](#)
3. Jia, Z.; Jin, K.; Mei, W.; Qin, P.; Jinhua, S.; Wang, Q. Advances and perspectives in fire safety of lithium-ion battery energy storage systems. *eTransportation* **2025**, *24*, 100390. [\[CrossRef\]](#)
4. Goldsmith, V. Introduction to grid-scale battery energy storage system concepts and fire hazards. *Process Saf. Prog.* **2024**, *43*, 357–363.
5. Wang, Z.; Song, Y.; Yin, B.; Shi, B.; Li, Z.; Yu, J. Effect of ambient pressure on the fire characteristics of lithium-ion battery energy storage container. *J. Loss Prev. Process Ind.* **2024**, *92*, 105459. [\[CrossRef\]](#)
6. Lou, Z.; Huang, J.; Su, Z.; Zhang, D.; Wei, X.; Yao, H. Effects of ventilation conditions on thermal runaway of lithium-ion batteries packs in an energy-storage cabin. *Process Saf. Environ. Prot.* **2025**, *196*, 106899. [\[CrossRef\]](#)
7. Li, Y.; Lan, L.; Zhang, T.; Jia, Y.; Zhang, Y.; Shan, Y.; Zhang, K.; Xie, J. Optimized smoke detector layout design approach for battery energy storage system containers based on black-winged kite algorithm. *J. Loss Prev. Process Ind.* **2025**, *100*, 105879. [\[CrossRef\]](#)
8. Lou, Z.; Huang, J.; Sun, G.; Qin, H.; Song, H.; Zhang, Z.; Yao, H. Influence of fine water mist on gas generation of lithium-ion batteries packs fire in an energy-storage cabin. *Process Saf. Environ. Prot.* **2025**, *195*, 106765. [\[CrossRef\]](#)
9. Miao, X.; Yu, J. Numerical Simulation of Fire Evolution and Fine Water Mist Suppression in Energy Storage Prefabricated Compartments. In *2025 4th International Conference on Renewable Energy and Electrical Technology (ICREET)*; IEEE: New York, NY, USA, 2025; pp. 29–32.
10. Shi, S.; Lyu, N.; Jiang, X.; Song, Y.; Lu, H.; Jin, Y. Hydrogen gas diffusion behavior and detector installation optimization of lithium ion battery energy-storage cabin. *J. Energy Storage* **2023**, *67*, 107510. [\[CrossRef\]](#)
11. Wang, H.; Xu, H.; Zhang, Z.; Wang, Q.; Jin, C.; Wu, C.; Xu, C.; Hao, J.; Sun, L.; Du, Z. Fire and explosion characteristics of vent gas from lithium-ion batteries after thermal runaway: A comparative study. *eTransportation* **2022**, *13*, 100190. [\[CrossRef\]](#)
12. Xie, W.; Zhang, L. Experimental study on thermal runaway and venting gas explosion hazards in prismatic lithium-ion batteries at different states of charge. *Process Saf. Environ. Prot.* **2025**, *198*, 107118. [\[CrossRef\]](#)
13. Wang, Y.; Zhang, W.; Yang, M.; Zhuo, P. Study on the ignition characteristics and mechanisms of battery thermal runaway gases under hot surface and electric spark conditions. *Process Saf. Environ. Prot.* **2026**, *214*, 109128. [\[CrossRef\]](#)
14. Jeong, I.; An, S.; Kang, C. Thermal runaway behaviors in 18, 650 LiFePO₄ batteries under high C-rate charge/discharge operations. *Appl. Therm. Eng.* **2026**, *289*, 129760. [\[CrossRef\]](#)
15. Wang, Q.; Wang, H.; Xu, C.; Jin, C.; Wang, S.; Xu, L.; Ouyang, J.; Feng, X. Multidimensional fire propagation of lithium-ion phosphate batteries for energy storage. *eTransportation* **2024**, *20*, 100328. [\[CrossRef\]](#)
16. Meng, X.; Yang, K.; Zhang, M.; Gao, F.; Liu, Y.; Duan, Q.; Wang, Q. Experimental study on combustion behavior and fire extinguishing of lithium iron phosphate battery. *J. Energy Storage* **2020**, *30*, 101532. [\[CrossRef\]](#)

17. Wang, Z.; Yu, X.; Ren, F.; Chen, J.; Li, J.; Yin, B.; Shi, B. Characteristics of gas emission and explosion risk for lithium iron phosphate batteries in a proof-confined chamber: Impact of methane concentration and state of charge. *Fuel* **2026**, *408*, 137703. [[CrossRef](#)]
18. Xu, Y.; Lu, J.; Zhang, P.; Gao, K.; Huang, Y. Thermal runaway and flame propagation of lithium-ion battery in confined spaces: Experiments and simulations. *J. Energy Storage* **2025**, *117*, 116154. [[CrossRef](#)]
19. Yan, L.; Huang, X.; Fu, Y.; Yang, M.; Lu, H.; Cheng, X.; Pan, Y.; Zhao, J. Experimental evaluation on cooling and suppressing thermal runaway of lithium-ion batteries in confined space by compressed air foam. *J. Energy Storage* **2025**, *133*, 118045. [[CrossRef](#)]
20. Wang, Y.; Wang, Y.; Xu, C.; Dai, F.; Zhang, X.; Wang, H.; Feng, X. Modeling study on fire propagation behavior and analysis of energy flow paths in double-layer LFP battery module. *eTransportation* **2025**, *26*, 100508. [[CrossRef](#)]
21. Zhang, C.; Li, W.; Liu, L.; Liu, X.; Li, B.; Wu, Z.; Hui, Z. Impact of venting strategies on post-deflagration fire behavior in lithium-ion battery prefabricated energy storage containers. *Process Saf. Environ. Prot.* **2026**, *210*, 108711. [[CrossRef](#)]
22. Meehan, M.A.; Kurzawski, A.; Hewson, J.C. Examination of entrainment, combustibility, and heat transfer due to cell venting inside simplified battery energy storage enclosures. *Fire Saf. J.* **2026**, *162*, 104725. [[CrossRef](#)]
23. Yu, J.; Gong, H.; Guo, C.; Jiang, X.; Wang, R.; Luo, Z.; Zou, P. Fire accident simulation and fire emergency technology simulation research of lithium iron phosphate battery in prefabricated compartment for energy storage power station. In *2022 7th International Conference on Power and Renewable Energy (ICPRE)*; IEEE: New York, NY, USA, 2022; pp. 1021–1027.
24. Wang, J.; Jia, Z.; Qin, P.; Huang, Z.; Wu, J.; Qi, W.; Wang, Q. Simulation of thermal runaway gas diffusion in LiFePO₄ battery module. *Energy Storage Sci. Technol.* **2022**, *11*, 185.
25. Li, K.; Mu, J.; Jin, Y.; Xu, J.; Liu, P.; Wang, Q.; Li, H. Fire risk of lithium iron phosphate battery. *Energy Storage Sci. Technol.* **2021**, *10*, 1177–1186.
26. Yu, D.; Li, H.; Huo, M.; Li, Z.; Li, Q. Simulation study on fire suppression in lithium-ion battery energy storage systems. *Energy Storage Sci. Technol.* **2024**, *13*, 3898.
27. Tian, J.; Liu, M.; Chen, B.; Wu, C.; Zhou, T. Full-scale energy storage container: Characterization and numerical modeling of LiFePO₄ battery thermal runaway gas diffusion behavior. *Process Saf. Environ. Prot.* **2026**, *212*, 108920. [[CrossRef](#)]
28. Wang, J.; Yang, M.; Lu, K. Ventilation condition effects on heat dissipation of the lithium-ion battery energy storage cabin fire. *Case Stud. Therm. Eng.* **2024**, *63*, 105373. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.