

Article

Thermal Runaway Simulation and Fire Risk Assessment of Electric Vehicle Power Battery Packs

Junwei Shi *, Ziyang Zhang and Mengyao Zhang

College of Management Science and Engineering, Shandong Technology and Business University, Yantai 264005, China; 2024410081@sdtbu.edu.cn (Z.Z.); 2022210016@sdtbu.edu.cn (M.Z.)

* Correspondence: 201513457@sdtbu.edu.cn

Abstract

Thermal runaway in electric vehicle power battery packs is a key risk in fire prevention and control for electric transportation. Its triggering, propagation, and failure modes are jointly affected by external thermal abuse, material insulation performance, and side reactions inside cells. To identify the temperature response and fire risk of power battery packs under different thermal abuse intensities, this study established a three-dimensional multiphysics thermal runaway simulation model in COMSOL Multiphysics 6.1, coupling solid heat transfer, electrochemical heat generation, and side-reaction heat release. A semi-quantitative risk ranking was then performed using failure mode, effects, and criticality analysis (FMECA). The model considered the low-temperature safe conditions, 120 °C, 140 °C, and 170 °C, as the main ambient temperature conditions, while also analyzing the effects of the heat transfer coefficient on trigger time and peak temperature. The results show that, under the low-temperature safe condition and the 120 °C condition, the battery module mainly exhibits slow heating and does not undergo thermal runaway. Based on the side-reaction characteristics, the temperature near 125 °C can be used as a risk warning threshold for thermal runaway. At 140 °C, the side-reaction heat source increases markedly, and the system enters the thermal runaway risk region. Because the trigger time is strongly affected by the heat transfer coefficient and monitoring position, this condition is interpreted only as a risk-acceleration stage under critical thermal abuse. Approximately 167 °C can be regarded as the critical threshold for irreversible thermal runaway. Under severe thermal abuse at 170 °C, rapid intensification of internal side reactions increases the peak module temperature to 375–385 °C. Temperature field evolution shows that heat is transferred mainly from the exterior to the interior before thermal runaway, forming an outside-high- and inside-low-temperature distribution. After the runaway stage begins, heat release from internal cell side reactions becomes dominant, and the high-temperature region concentrates inside the module, producing a gradient reversal with a higher internal temperature. The FMECA results show that the positive electrode–electrolyte reaction has the highest RPN, with a value of 405. Accelerated SEI decomposition and the negative electrode–electrolyte reaction also form key risk links in the chain heat-release pathway. This study provides a reference for thermal management, fire barrier design, and fire risk classification of power battery packs.

Keywords: power battery pack; thermal runaway; fire evolution pathway; FMECA; fire risk assessment



Academic Editors: Longfei Han,
Yan Wang and Junling Wang

Received: 15 June 2026

Revised: 13 July 2026

Accepted: 20 July 2026

Published: 22 July 2026

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1. Introduction

The rapid growth in electric vehicle ownership has made power battery fire risk an important issue for vehicle safety and fire prevention and control. Under abuse conditions such as overheating, overcharging, mechanical damage, or internal short circuit, power battery packs may undergo thermal runaway and rapidly trigger combustion, explosion, or thermal propagation. The existing accident statistics and the literature indicate that thermal-runaway-related fires in power batteries are not only related to the cell material system but are also jointly affected by the vehicle operating environment, state of charge, thermal management system, and battery pack structural design [1–4].

Thermal runaway in lithium-ion batteries is essentially a temperature-driven, chain exothermic process. As the cell temperature increases, the solid electrolyte interphase (SEI) film decomposes first, exposing the active negative electrode material and further triggering the negative electrode–electrolyte reaction. When the temperature rises to higher thresholds, the positive electrode–electrolyte reaction and electrolyte decomposition are successively intensified. Heat released by side reactions may then exceed the heat dissipation capacity, driving the battery from local heating into irreversible thermal runaway. Therefore, identifying key temperature thresholds, heat source evolution, and the spatial distribution of the temperature field is the basis for fire risk assessment of battery packs [5–9].

Previous studies have examined thermal runaway experiments, numerical simulations, thermal management design, and risk assessment. Experimental studies have revealed thermal runaway characteristics under different material systems, SOC levels, and abuse conditions. Numerical simulation methods such as COMSOL can describe the battery pack temperature field, heat transfer paths, and variations in side-reaction heat sources [10–15]. Thermal management studies have focused on the suppression of temperature rise by liquid cooling, phase change materials, and thermal insulation materials [16]. Reliability methods such as failure mode, effects, and criticality analysis (FMECA) can link failure modes with risk levels [17–19]. These studies provide a methodological basis for thermal safety analysis of battery packs.

However, three limitations remain in existing studies. First, some studies focus mainly on single cells or a single thermal abuse condition, with insufficient consideration of the coupling among battery pack structure, thermal insulation materials, phase change materials, and external heat input. Second, simulation results usually focus on temperature or voltage responses, and their connection to fire risk ranking is often insufficient. Third, the correspondence among temperature thresholds, side-reaction heat source evolution, and FMECA failure modes requires further clarification, especially because trigger time, peak temperature, and risk level must be interpreted consistently across the critical temperature region and severe thermal abuse conditions.

To address these issues, this study established a three-dimensional multiphysics thermal runaway simulation model for a power battery pack. The effects of the low-temperature safe condition, ambient temperatures of 120 °C, 140 °C, and 170 °C, and different heat transfer coefficients on thermal runaway trigger time, peak temperature, and temperature field evolution were analyzed. FMECA was then used to identify weak links in fire risk. The objective was to establish an analytical chain linking simulation results, failure modes, and risk ranking, thereby providing a methodological reference for battery fire risk assessment, thermal management optimization, and fire barrier design.

2. Materials and Methods

This section first defines the research object and modeling parameters, then presents the governing equations and side-reaction kinetic model and finally verifies model validity

through mesh-independence analysis and comparison with reference values. On this basis, the thermal runaway evolution process was simulated under the low-temperature safe condition and ambient temperatures of 120 °C, 140 °C, and 170 °C. Temperature contour results under different ambient temperature states were analyzed, and the effect of the heat transfer coefficient on thermal runaway trigger time was evaluated.

2.1. Research Object and Battery Pack Structure

This study used a representative module unit in an EV power battery pack as the research object and described its corresponding full-pack system in the engineering context. To reduce computational complexity, the actual battery pack was simplified into a representative three-dimensional unit containing several cells, thermal insulation layers, and a paraffin-based phase change material layer. This unit was used to analyze temperature response, thermal runaway triggering, and risk evolution under external thermal abuse. Such batteries have high energy density and are widely used in the market, but their thermal stability is relatively poor and the thermal runaway risk is prominent. They are therefore important objects of industry safety research [6,10,14,15]. The selected indicators are key parameters for battery thermal runaway simulation and safety assessment. Basic indicators such as rated capacity, number of cells, charge–discharge rate, and SOC determine the battery operating state and heat generation intensity. Parameters such as thermal conductivity, density, heat capacity, and convective heat transfer coefficient are core indicators in COMSOL multiphysics modeling. Thermal runaway trigger temperature, side-reaction heat generation rate, and reaction rate quantify the self-accelerating and propagation mechanisms of thermal runaway. Electrical performance indicators such as voltage, potential, and internal resistance can provide early evaluation features, while modal, vibration, and impact indicators represent complex vehicle operating conditions. In FMECA, occurrence, severity, detection, and RPN values are used for graded and quantitative fire risk assessment [17–19]. These indicators are interconnected. They provide data support for the multiphysics coupling model, help explain the evolution of thermal runaway, support improvements in thermal management systems and fire risk assessment models, and provide a theoretical basis for reliability design and safety risk prevention in power battery packs.

An actual power battery pack consists of tens to hundreds of cells. Under high-energy-density conditions, cells are arranged closely, and local thermal runaway can induce thermal propagation to adjacent cells through heat conduction and radiation, potentially leading to battery pack fire or explosion [14,15]. In engineering design, thermal insulation layers are usually arranged between cells, and a phase change material layer is placed outside the module to reduce heat transfer intensity and buffer high-temperature impact [16]. Based on engineering practice, this study abstracted a large power battery pack into a representative three-dimensional unit containing cells, thermal insulation layers, and a paraffin-based phase change material layer. The simplified model retains the main heat transfer paths among the cells, insulation structure, and external thermal protection layer in a real battery pack and can be used to analyze temperature response, thermal runaway triggering, and risk evolution under external thermal abuse.

A prismatic lithium-ion battery module was selected for model construction. Thermal insulation layers were arranged between adjacent cells, while a paraffin-based phase change material layer was placed around the module to provide thermal buffering against external heat input. Cell parameters and phase change material parameters are listed in Table 1 and Table 2, respectively. The thermal insulation material is a nanofiber-type material, and its parameters are listed in Table 3. The model mesh used a mixed tetrahedral and triangular mesh, with 1061 tetrahedral elements, 3984 triangular elements, and 21,042 mesh vertices.

The relevant mesh numbers and mesh-independence verification results are presented later in the model validation section.

Table 1. Equivalent thermophysical properties of the battery.

Material	Density	Specific Heat Capacity at Constant Pressure
Equivalent battery material	2000 kg/m ³	1400 J/(kg·K)

Table 2. Equivalent thermophysical properties of the unreinforced paraffin-based phase change material.

Material	Thermal Conductivity	Density	Specific Heat Capacity at Constant Pressure
Unreinforced paraffin-based phase change material	0.20 W/(m·K)	778 kg/m ³	3200 J/(kg·K)

Table 3. General battery and model parameters.

Parameter	Physical Meaning	Unit	Value
Rated capacity (equivalent charge)	Rated capacity of a single cell	C	14,400
In-plane thermal conductivity	Thermal conductivity, in-plane	W/(m·K)	30
Cross-sectional thermal conductivity	Thermal conductivity, cross-sectional	W/(m·K)	1
Charge–discharge rate	Charge–discharge rate	-	4
Reference temperature	Reference temperature	K	293.15
Battery heat capacity	Battery heat capacity	J/(kg·K)	1400
Heat transfer coefficient	Heat transfer coefficient	W/(m ² ·K)	30
Battery density	Battery density	kg/m ³	2000
Initial/reference temperature	Initial/external temperature	K	293.15
Initial flow velocity	Initial flow velocity	m/s	0.01

The paraffin-based phase change material used in the present model did not contain aluminum foam, expanded graphite, graphene, or other thermally conductive additives. Therefore, it was treated as an unreinforced paraffin-based PCM, and its thermal conductivity was revised from 15 W/(m·K) to 0.20 W/(m·K). The PCM region was represented using constant equivalent thermophysical properties and was primarily used as a thermal-buffering layer to reduce the rate of external heat transfer into the battery module. Temperature-dependent phase-transition and latent-heat behavior were not explicitly resolved in the current model. The adopted thermophysical properties were selected with reference to previous studies on PCM-based battery thermal management [16,20,21].

2.2. Multiphysics Model of Thermal Runaway

A COMSOL-based multiphysics coupling model for thermal runaway in a power battery pack was established to describe the relationship among the internal temperature field, side-reaction heat sources, and risk assessment indicators under external high-temperature thermal abuse. The model used a prismatic ternary lithium-ion battery module as the research object and incorporated heat transfer among cells, thermal insulation material, the paraffin-based phase change material layer, and the external environment into a unified three-dimensional transient solution framework. The analysis focused on thermal runaway triggering, temperature field evolution, and variations in side-reaction heat sources [10–12,22–24].

The model consists of three core parts: solid heat transfer, electrochemical heat generation, and side-reaction heat release. Heat sources include Joule heat, electrochemical

reaction heat, and side-reaction heat. Joule heat and electrochemical reaction heat mainly describe basic heat generation during normal charge–discharge or heating processes, whereas side-reaction heat is the primary heat source during thermal runaway. The side-reaction component considers SEI decomposition, the negative electrode–electrolyte reaction, the positive electrode–electrolyte reaction, and electrolyte decomposition, and the heat generation rates of these reactions are calculated using the subsequent governing equations and side-reaction kinetic equations.

During the three-dimensional transient heat conduction solution, the model describes the coupled relationship between external high-temperature input, heat absorption by the phase change material, thermal blocking by the insulation material, and heat release from side reactions inside cells. To ensure computational feasibility, the materials in each region were treated as equivalent homogeneous media. The paraffin-based phase change material was represented using constant equivalent thermophysical properties, while the parameters of the thermal insulation material were obtained from the literature values or engineering approximations. The model does not further simulate complex gas-phase reactions, jet fire, or explosion pressure after combustion. The FMECA performs semi-quantitative risk ranking based on simulation outputs, including temperature, trigger time, peak temperature, and side-reaction heat sources.

2.3. Governing Equations and Side-Reaction Kinetics

The energy conservation equation can be expressed as: The above parameters are required for model construction. To accurately reflect the thermal runaway evolution of a power battery pack in a high-temperature environment during simulation, a system of governing equations capable of describing the coupling among heat transfer, internal heat generation, and side-reaction kinetics must be established. Based on the law of energy conservation, the electrochemical heat source model, and Arrhenius reaction kinetics, the following three types of equations are given in sequence:

The following equation is used to describe the variation in the internal temperature field of the battery module over time and space. It considers heat conduction through the insulation layer, phase change material, and cells; heat convection between the casing and the environment; and internal heat sources composed of Joule heat, electrochemical reaction heat, and side-reaction heat. This equation is the core governing equation of the COMSOL solid heat transfer module [22–24].

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \quad (1)$$

where ρ is the density; C_p is the specific heat capacity at constant pressure; T is temperature; t is time; k is the thermal conductivity; Q is the total heat generation rate per unit volume; and $\nabla \cdot (k \nabla T)$ is the heat conduction term.

The total heat generation rate per unit volume inside the battery can be decomposed as:

The total volumetric heat generation rate Q_{total} inside the battery is decomposed into three components: Joule heat (ohmic heat), reversible electrochemical reaction heat (entropic heat), and side-reaction heat. Among them, side-reaction heat is the main driving energy of thermal runaway, whereas the other two make relatively small thermal contributions during normal charge–discharge or high-temperature exposure. This decomposition provides the theoretical framework for subsequently calculating the heat contribution of each side reaction.

$$Q = Q_{\text{joule}} + Q_{\text{rev}} + Q_{\text{side}} \quad (2)$$

The side-reaction heat source can be further expressed as:

$$Q_{\text{side}} = Q_{\text{SEI}} + Q_{\text{ne}} + Q_{\text{pe}} + Q_{\text{ele}} \quad (3)$$

where Q_{joule} is Joule heat; Q_{rev} is reversible electrochemical reaction heat; Q_{side} is side-reaction heat; Q_{SEI} is heat from SEI film decomposition; Q_{ne} is heat from the negative electrode–electrolyte reaction; Q_{pe} is heat from the positive electrode–electrolyte reaction; and Q_{ele} is heat from electrolyte decomposition.

Side-Reaction Kinetic Equations

Thermal runaway is essentially a chain process in which a series of exothermic side reactions are activated stepwise according to temperature thresholds. To quantitatively describe the reaction progress and heat generation rate of each side reaction, this study introduces a general reaction rate equation based on the Arrhenius equation and establishes kinetic equations for SEI decomposition, the negative electrode–electrolyte reaction, the positive electrode–electrolyte reaction, and electrolyte decomposition. These equations determine the thermal runaway trigger time, temperature rise rate, and final peak temperature and form the bridge between the thermal field and chemical reactions.

The reaction rate of each side reaction is described using the Arrhenius form:

$$\frac{d\alpha_i}{dt} = A_i \exp\left(-\frac{E_i}{RT}\right) f(\alpha_i) \quad (4)$$

The corresponding side-reaction heat generation rate can be expressed as:

$$Q_i = H_i W_i \frac{d\alpha_i}{dt} \quad (5)$$

where α_i is the normalized reaction progress of the i th exothermic side reaction, ranging from 0 to 1; A_i is the pre-exponential factor; E_i is the activation energy; R is the universal gas constant; T is the absolute temperature; $f_i(\alpha_i)$ is the corresponding reaction progress function; H_i is the effective reaction heat per unit mass of equivalent cell material; W_i is the effective reactive-mass coefficient; and $d\alpha_i/dt$ is the reaction rate. Positive values of Q_i denote heat release from the corresponding side reaction.

The four exothermic side reactions considered in the model were SEI decomposition, the negative electrode–electrolyte reaction, the positive electrode–electrolyte reaction, and electrolyte decomposition. The pre-exponential factors, activation energies, effective reaction heats, and reaction progress functions used in the equivalent kinetic model are summarized in Table 4.

Table 4. Equivalent kinetic parameters of the four exothermic side reactions used in the thermal runaway model.

Parameter	Physical Meaning	Unit	Value
A_{SEI}	Pre-exponential factor for SEI decomposition	s^{-1}	9.480×10^{10}
E_{SEI}	Activation energy for SEI decomposition	kJ/mol	118.58
H_{SEI}	Effective reaction heat of SEI decomposition per unit equivalent cell mass	J/kg	3.3515×10^4
$f_{\text{SEI}}(\alpha_{\text{SEI}})$	Reaction progress function for SEI decomposition	–	$1 - \alpha_{\text{SEI}}$
A_{NE}	Pre-exponential factor for the negative electrode–electrolyte reaction	s^{-1}	2.550×10^7
E_{NE}	Activation energy for the negative electrode–electrolyte reaction	kJ/mol	88.04
H_{NE}	Effective reaction heat of the negative electrode–electrolyte reaction per unit equivalent cell mass	J/kg	2.0152×10^4
$f_{\text{NE}}(\alpha_{\text{NE}})$	Reaction progress function for the negative electrode–electrolyte reaction	–	$1 - \alpha_{\text{NE}}$
A_{PE}	Pre-exponential factor for the positive electrode–electrolyte reaction	s^{-1}	3.936×10^{10}
E_{PE}	Activation energy for the positive electrode–electrolyte reaction	kJ/mol	124.78
H_{PE}	Effective reaction heat of the positive electrode–electrolyte reaction per unit equivalent cell mass	J/kg	8.6303×10^4
$f_{\text{PE}}(\alpha_{\text{PE}})$	Reaction progress function for the positive electrode–electrolyte reaction	–	$\alpha_{\text{PE}}^{6.34}(1 - \alpha_{\text{PE}})^{1.94}$
A_{EL}	Pre-exponential factor for electrolyte decomposition	s^{-1}	2.831×10^{11}
E_{EL}	Activation energy for electrolyte decomposition	kJ/mol	116.29
H_{EL}	Effective reaction heat of electrolyte decomposition per unit equivalent cell mass	J/kg	1.9667×10^5
$f_{\text{EL}}(\alpha_{\text{EL}})$	Reaction progress function for electrolyte decomposition	–	$\alpha_{\text{EL}}^{4.61}(1 - \alpha_{\text{EL}})$

2.4. Boundary Conditions, Simulation Conditions, and Parameter Settings

A baseline initial battery temperature of 20 °C was used. The temperature-contour cases presented in Section 3.1 were the 90 °C low-temperature safe condition and the ambient temperature conditions of 120 °C, 140 °C, and 170 °C. The 70 °C condition was used for the full-process low-temperature comparison and the heat-transfer-coefficient sensitivity analysis, while the sensitivity cases were conducted at ambient temperatures of 70 °C, 125 °C, 140 °C, and 170 °C. The 125 °C condition was selected as a representative comparison condition near the early-warning region for initial side-reaction intensification.

In this study, thermal runaway onset was identified from the full-process maximum-temperature curve as the beginning of a sustained self-accelerating temperature rise dominated by side-reaction heat release, after the maximum module temperature approached the irreversible critical region near 167 °C. The times listed in the corresponding temperature-contour tables and figures in Section 3.1 are selected sampling times used to illustrate the spatial evolution of the temperature field. They are not, by themselves, thermal runaway trigger times. Unless otherwise stated, the trigger times reported in the text and comparison tables were determined from the corresponding full-process temperature curves using this criterion.

The heat transfer coefficient cases were set as $h = 5, 10, 15, \text{ and } 25 \text{ W}/(\text{m}^2 \cdot \text{K})$ to study the effect of external heat input intensity on thermal runaway trigger time and peak temperature. The specific material parameters, thermophysical parameters, and model validation parameters are provided in the preceding tables and the model validation section. All reported time and temperature values were extracted from the corresponding model-output curves using the criteria defined in this study [25–27].

For boundary conditions, convective heat transfer was applied between the outer surface of the battery pack and the environment. Heat conduction between cells occurred through the thermal insulation material, and the external phase change material layer provided heat absorption buffering. Where direct measurements were unavailable, the boundary parameters were assigned based on the literature values and clearly defined model assumptions to ensure continuity of the heat-transfer paths among the cells, insulation layers, phase change material, and external environment.

The simulation monitoring indicators include the maximum module temperature, minimum module temperature, thermal runaway trigger time, peak temperature, temperature rise rate, terminal voltage variation, and heat generation rates of four side reactions: SEI decomposition, the negative electrode–electrolyte reaction, the positive electrode–electrolyte reaction, and electrolyte decomposition. The FMECA section further extracts occurrence (O), severity (S), detection (D), and RPN to form the relative risk ranking of failure modes. These conditions reveal the staged evolution of the battery pack from safe heating to critical heat accumulation and finally irreversible thermal runaway under different thermal abuse intensities.

2.5. Model Evaluation and Benchmark Comparison

2.5.1. Mesh-Independence Validation

To ensure that the simulation results were mesh independent, five mesh schemes with different densities were designed, as shown in Table 5. Taking the case with an ambient temperature of 170 °C and a heat transfer coefficient of 10 as an example, the variation in the maximum battery module temperature with mesh number is shown in Table 5.

When the mesh number increased from 126,000 to 243,000, the thermal runaway trigger time changed by 0.85 s, and the peak temperature also changed slightly. After the mesh density was further increased to 368,000, these parameter variations decreased further and reached

convergence. Considering both computational accuracy and efficiency, the Grid 3 scheme with 368,000 mesh nodes was selected for subsequent simulation calculations.

Table 5. Comparison of mesh numbers.

Mesh ID	Number of Mesh Nodes/(10,000)	Maximum Simulated Temperature/°C	Relative Error of Temperature Field/%	Single-Step Computing Time/s
Grid 1	12.6	368.4	5.27	12.6
Grid 2	24.3	356.1	1.72	24.1
Grid 3	36.8	351.8	0.48	35.8
Grid 4	49.2	350.1	0.12	48.3

Mesh-independence validation ensures the accuracy and reliability of the simulation results. The calculation result with 492,000 mesh nodes was used as the benchmark, and the relative error of the maximum temperature for the Grid 3 scheme was less than 0.5%, meeting the accuracy requirement for engineering calculations.

2.5.2. Benchmark Comparison with the Literature-Reported Reference Values

The thermal runaway simulation model was evaluated under three ambient temperature conditions, namely 127 °C, 145 °C, and 170 °C, and benchmarked against the literature-reported reference values. All three cases used a heat transfer coefficient of 10 W/(m²·K) and an initial battery temperature of 20 °C. The simulation model used the same boundary conditions as the operating cases for the transient solution. Based on the chain-reaction evolution from external heat transfer to separator melting and then to positive-electrode oxygen release described in previous studies [5–8,13,28–32], an analogous calculation was performed using the thermophysical parameters of this module as a basis for trend validation of the simulation results. Figure 1 shows the simulated and reference curves of the maximum module temperature over time under the three conditions, and Table 6 summarizes and compares the simulated and reference values of the main thermal runaway indicators.

Table 6. Comparison of simulated and reference values of key thermal runaway indicators under different conditions.

Ambient Temperature/°C	Data Type	Thermal Runaway Triggered	Trigger Time/s	Peak Temperature/°C	Temperature Rise Rate/(°C min ^{−1})
127	Reference value	No	—	83	<0.1
127	Simulated value	No	—	85.7	0.08
145	Reference value	Yes	13,800	352	2.8
145	Simulated value	Yes	14,150	357.4	2.91
170	Reference value	Yes	9120	376	4.3
170	Simulated value	Yes	9350	381.2	4.52

The data in Figure 1 and Table 6 show that, under the 127 °C condition, both the simulated curve and the reference curve exhibit slow heating followed by stabilization. The maximum module temperatures are approximately 85.7 °C and 83 °C, respectively, and thermal runaway does not occur. The analysis indicates that the model can accurately distinguish between the critical safe condition and thermal runaway conditions.

Under the 145 °C and 170 °C conditions, the simulated curves both reflect the main feature of abrupt temperature change during thermal runaway. That is, when the module temperature reaches approximately 165–170 °C, the temperature rise rate increases significantly, and the temperature rises above 350 °C within a short time. The predicted thermal runaway trigger times are approximately 2.5% later than the reference values, and the deviations in peak temperature are within 1.5%. The trigger-time delay is attributed to

the equivalent thermal-buffering effect of the paraffin-based phase change material layer, which reduces the rate of external heat transfer to the cells and delays their reaching the critical side-reaction temperature.

Comparison of the maximum temperature variations of the module under different ambient temperatures

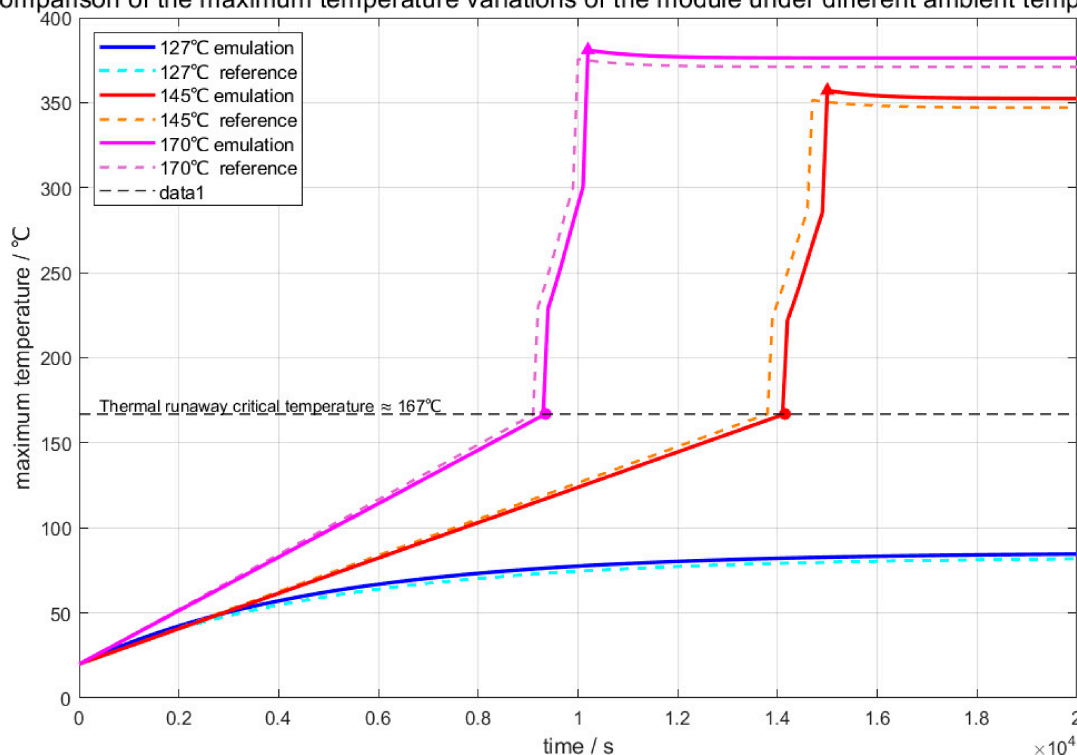


Figure 1. Comparison of simulated and reference curves for the maximum temperature of the battery module under different ambient temperatures.

The simulation results and the literature-reported reference values show good agreement in temperature-evolution trends, thermal runaway triggering judgment, and peak-temperature magnitude, indicating that the model can be used to compare thermal responses under different external thermal abuse conditions. The simulated trigger time of 14,150 s in Table 6 corresponds to the 145 °C benchmark condition, whereas the trigger time of approximately 16,200 s reported in Section 3.1 corresponds to the separate 140 °C analysis condition. The two values therefore represent different ambient temperature cases. Because an experimental dataset with fully matched battery geometry, material system, boundary conditions, and reported uncertainty intervals was unavailable, the present comparison is treated as the literature-based benchmark evaluation rather than direct experimental validation. The reported deviations represent deterministic differences between the simulated and reference values and should not be interpreted as experimental uncertainty bounds.

2.6. FMECA-Based Fire Risk Assessment Method

This study uses thermal runaway simulation of a power battery pack as the main basis for FMECA, defining the analysis scope, data sources, and validation method. A prismatic ternary battery module pack used in electric vehicles is treated as the research object, and the main data are derived from COMSOL thermal analysis simulations. Quantitative indicators that can be directly obtained, including thermal runaway trigger time, peak temperature, thermal propagation range, and detection delay time, constitute the data and provide the only verifiable data support for the entire process analysis. Meanwhile, the

FMECA used in this study is a semi-quantitative risk assessment method. The occurrence and detection scores are based on simulation cases and the literature experience, aiming to identify relative risk ranking and weak links in the system under abuse conditions rather than to predict the absolute probability of accidents [17–19].

2.6.1. Overview of the FMECA Method

FMECA is a bottom-up method for system reliability analysis. It identifies all potential failure modes of each system component, analyzes their causes and effects on the system, and ranks risk priority based on severity, occurrence, and detection. In this study, FMECA is applied to the fire risk assessment of power battery packs. Quantitative data obtained from the preceding thermal runaway simulations, including the temperature field, side-reaction heat sources, and thermal runaway trigger time, are used to classify the semi-quantitative risk level of each failure mode and obtain the relative risk ranking.

The assessment process mainly includes six steps: system definition and functional analysis, failure mode identification, failure cause and effect analysis, risk priority number RPN calculation, identification of high-risk weak links, and recommendations for improvement measures.

2.6.2. Battery Pack System Definition and Functional Hierarchical Decomposition

The thermal runaway simulation results indicate that different layers have different effects at different times and under different conditions during the chain propagation of thermal runaway, and failures can propagate across different layers. The hierarchical decomposition of the battery pack components is summarized in Table 7.

Table 7. Hierarchical decomposition of battery pack components.

Level	Component	Main Function
Cell layer	Positive electrode material, negative electrode material, electrolyte, separator, and SEI film	Electrochemical energy storage and release
Module layer	Cell group, thermal insulation material, and busbar	Cell grouping and thermal isolation
Outer package layer	Paraffin-based phase change material layer, liquid-cooling plate, and structural parts	Thermal management and mechanical protection

2.6.3. Overall Framework for FMECA Application

To organize the analysis, this study divides the work into two main directions. The first is to improve the simulation data, including establishing the COMSOL model, solving it, and extracting the main quantitative data. The second is to identify failure modes, perform quantitative scoring, and formulate improvement measures based on the simulation data, thereby completing the risk analysis. The safety risk assessment first semi-quantifies the triggering conditions for thermal runaway. The simulation results show that the safety state of the battery module is not determined by a single parameter; instead, it is jointly governed by ambient temperature, heat dissipation conditions, initial state, and the progress of internal side reactions. The technical route for safety risk classification is shown in Figure 2:

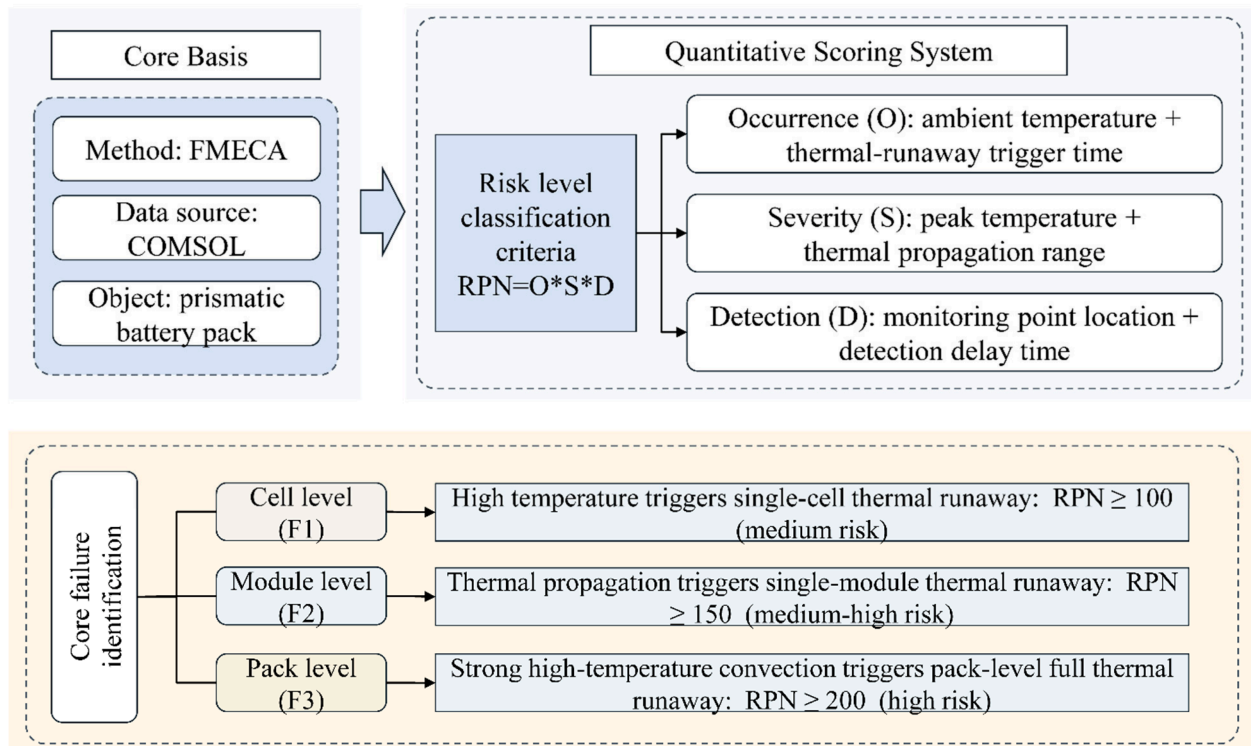


Figure 2. Technical route diagram.

2.6.4. Occurrence (O)

The risk priority number (RPN) is jointly determined by occurrence O, severity S, and detection D, and can be expressed as:

$$RPN = O \times S \times D \quad (6)$$

where O is occurrence, S is severity, and D is detection. The values of O, S, and D are determined according to Table 8, Table 9 and Table 10 respectively.

Table 8. Occurrence rating criteria.

Score (O)	Determination Criterion	Corresponding Simulation Condition
1–2	Extremely unlikely	70 °C or low-temperature safe condition, without thermal runaway
3–4	Low probability	120 °C or near 125 °C, where weak SEI decomposition may occur but chain thermal runaway is not formed
5–6	Moderate probability	140 °C critical condition, with enhanced side reactions and a long trigger time
7–8	High probability	170 °C high-temperature thermal abuse condition, with markedly advanced thermal runaway
9–10	Extremely likely	170 °C with high heat-transfer input, multiple protection failures, or PCM failure, giving the shortest trigger time

Table 9. Severity rating criteria.

Score (S)	Determination Criterion	Determination Scenario
1–2	Battery temperature < 90 °C, no side reaction triggered, normal function	70 °C ambient condition, module temperature stable at approximately 69 °C, and heat-source curves equal to zero
3–4	Temperature of 90–125 °C, with slight SEI decomposition but no chain reaction, recoverable to normal operation	120 °C ambient condition: the module temperature remains below the 125 °C warning threshold, with limited SEI-related heat release and no chain thermal runaway.

Table 9. Cont.

Score (S)	Determination Criterion	Determination Scenario
5–6	Temperature of 125–167 °C, with substantial SEI decomposition and negative-electrode reaction initiation; local cell damage occurs but propagation remains controllable	140 °C, $h = 5 \text{ W}/(\text{m}^2 \cdot \text{K})$: only local overheating of a single cell, without propagation to the module
7–8	Temperature > 167 °C, chain side reactions triggered, complete thermal runaway of a single module, and peak temperature > 350 °C	140 °C, $h = 10 \text{ W}/(\text{m}^2 \cdot \text{K})$: propagation limited to a single module
9–10	Full-pack thermal runaway, peak temperature > 370 °C, uncontrollable propagation, and fire or explosion	170 °C, $h = 25 \text{ W}/(\text{m}^2 \cdot \text{K})$ condition: triggered at approximately 4600 s, peak temperature approximately 374 °C, and full-pack propagation

Table 10. Detection rating criteria.

Detection Level	Score	Basis for Judgment
Very easy to detect	1–2	Abnormal battery surface temperature and abrupt decrease in coolant flow
Relatively easy to detect	3–4	Persistently high temperature-rise rate and gradually increasing module temperature difference
Moderately detectable	5–6	Degradation of the thermal-buffering performance of the phase change material and deterioration of the insulation performance
Difficult to detect	7–8	Slow SEI decomposition and early triggering of the negative electrode–electrolyte reaction
Extremely difficult to detect	9–10	Intense positive electrode–electrolyte reaction and extensive electrolyte decomposition

This study treats the 70 °C low-temperature safe condition, the 120 °C simulation condition, the risk warning threshold near 125 °C, the 140 °C critical triggering condition, and the 170 °C severe thermal abuse condition separately and revises the occurrence scoring direction accordingly.

2.6.5. Severity (S)

Severity characterizes the degree of harm caused by a thermal runaway failure to the power battery pack, the vehicle, and personnel. The main determination basis is the thermal runaway peak temperature and propagation range that can be extracted from COMSOL simulations. The higher the peak temperature and the larger the thermal propagation range, the higher the severity score. Severity mainly depends on the position of the failure mode in the chain reaction of thermal runaway. The later the position, the higher the temperature, the wider the propagation, and the higher the severity. All data were directly extracted from the temperature contours and thermal propagation animations obtained from the COMSOL simulation and were statistically analyzed.

2.6.6. Detection (D)

Detection describes the difficulty of identifying each failure mode under the current monitoring conditions. This study divides detection into five levels. According to the above criteria, each failure mode was scored as follows: insufficient heat dissipation of the liquid-cooling system and battery overheating can be directly observed using conventional sensors such as temperature and flow sensors and therefore have low detection difficulty. Phase change material failure and insulation material failure have more concealed signals and require indirect inference using temperature rise rate or temperature difference changes, corresponding to moderate detectability. Accelerated SEI decomposition and the negative electrode–electrolyte reaction both occur inside cells, both scoring 7, and are difficult to detect because direct measurement methods are lacking. The electrolyte decomposition

reaction scores 8, and the intense positive electrode–electrolyte reaction scores 9. Their simultaneous occurrence indicates that thermal runaway has entered an irreversible stage, making early detection very difficult.

3. Results

3.1. Thermal Runaway Triggering Behavior Under Different Ambient Temperatures

Temperature Variation in the Battery Module under the Low-Temperature Safe Condition at 90 °C: To describe the effect of ambient temperature on the thermal safety characteristics of the battery module, the temperature-contour results are organized according to the 90 °C low-temperature safe condition and the ambient temperature conditions of 120 °C, 140 °C, and 170 °C. Under the 90 °C condition, the battery module exhibits only mild heating, and chain thermal runaway is not triggered [25–27,31,32].

As shown in Figure 3, under the 90 °C low-temperature safe condition, the overall temperature rise in the battery module is mild, and the temperature field remains relatively uniform. The maximum module temperature increases from 59.85 °C at 481 s to 88.85 °C at 1961 s, but no abrupt temperature rise or evident chain side reaction occurs. The four times listed in Table 11 are selected temperature-field sampling times and do not represent thermal runaway onset [16,25,26].

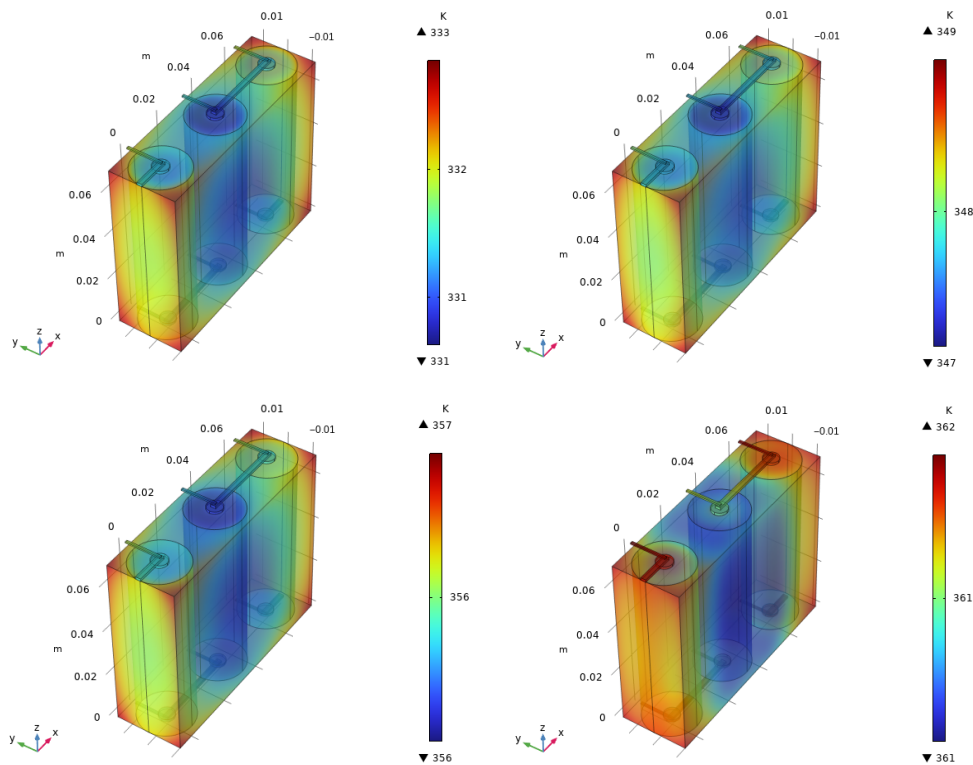


Figure 3. Temperature contour under the 90 °C low-temperature safe condition.

Table 11. Temperature distribution characteristics of the module under the 90 °C low-temperature safe condition.

No.	Time/s	Maximum Module Temperature/°C	Minimum Module Temperature/°C	Location of Maximum Temperature
a	481	59.85	57.85	Surfaces of the two outermost cells
b	1001	75.85	73.85	Surfaces of the two outermost cells
c	1481	83.85	82.85	Surfaces of the two outermost cells
d	1961	88.85	88.85	Central regions of the two outermost cells

Temperature Variation in Battery Thermal Runaway at an Ambient Temperature of 120 °C. The temperature distribution characteristics of the module under the 120 °C condition are summarized in Table 12.

Table 12. Temperature distribution characteristics of the module under the 120 °C condition.

No.	Time/s	Maximum Module Temperature/°C	Minimum Module Temperature/°C	Location of Maximum Temperature
a	800	75	72	Surfaces of the two outermost cells
b	1001	91	89	Surfaces of the two outermost cells
c	1481	96	93	Surfaces of the two outermost cells
d	1961	115	113	Central regions of the two outermost cells

As shown in Figure 4, when the ambient temperature is 120 °C, the temperature of the outer cells rises first, and heat is subsequently transferred through the insulation material to the inner cells. At the final sampling time of 1961 s, the maximum module temperature is approximately 115 °C, which remains below the warning temperature near 125 °C associated with marked intensification of initial side reactions. Therefore, the module exhibits a normal heating process without chain thermal runaway. The 120 °C value denotes the imposed ambient temperature condition, whereas 125 °C denotes an internal temperature-based risk-warning threshold; these two values represent different physical quantities.

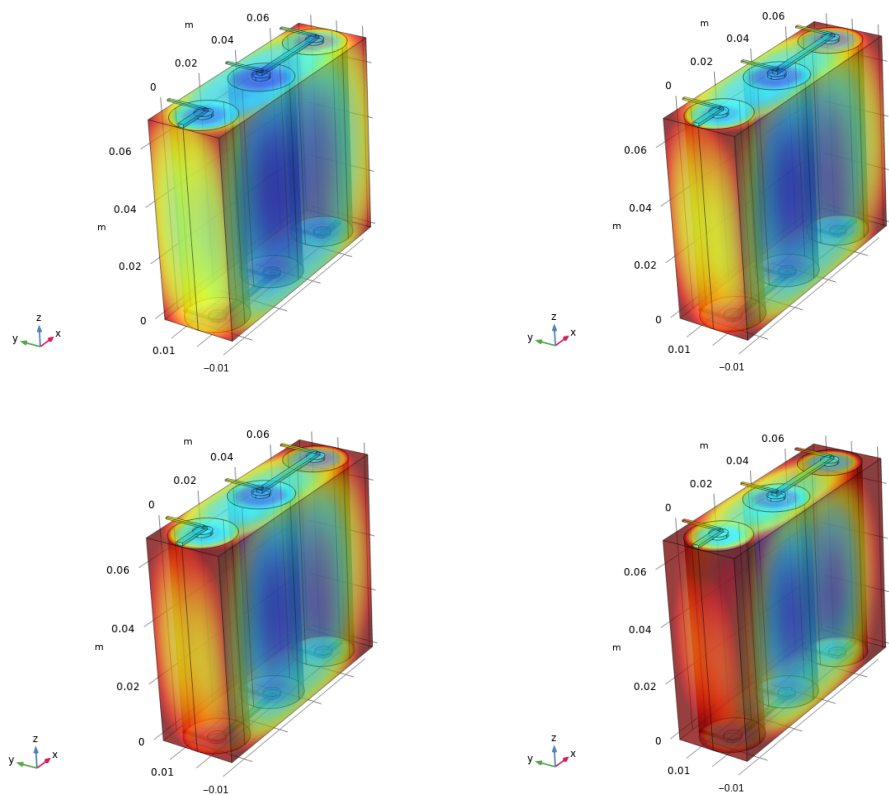


Figure 4. Temperature contour under the 120 °C condition. The color scale represents temperature, with blue indicating lower temperatures and red indicating higher temperatures.

Temperature Variation in Battery Thermal Runaway at an Ambient Temperature of 140 °C

Figure 5 and Table 13 present selected temperature-field snapshots during the early and intermediate heating stages under the 140 °C ambient condition. The maximum module temperature increases from 73 °C at 700 s to 140 °C at 1900 s, accompanied by the

gradual development of heat accumulation and initial side-reaction activity. The contour at 1900 s therefore represents an intermediate risk-acceleration state rather than the onset or peak of thermal runaway. Based on the full-process maximum-temperature curve and the unified criterion defined in Section 2.4, thermal runaway is triggered at approximately 16,200 s under the corresponding baseline 140 °C condition. Thus, 1900 s and 16,200 s describe different stages of the same heating process and are not conflicting trigger-time values.

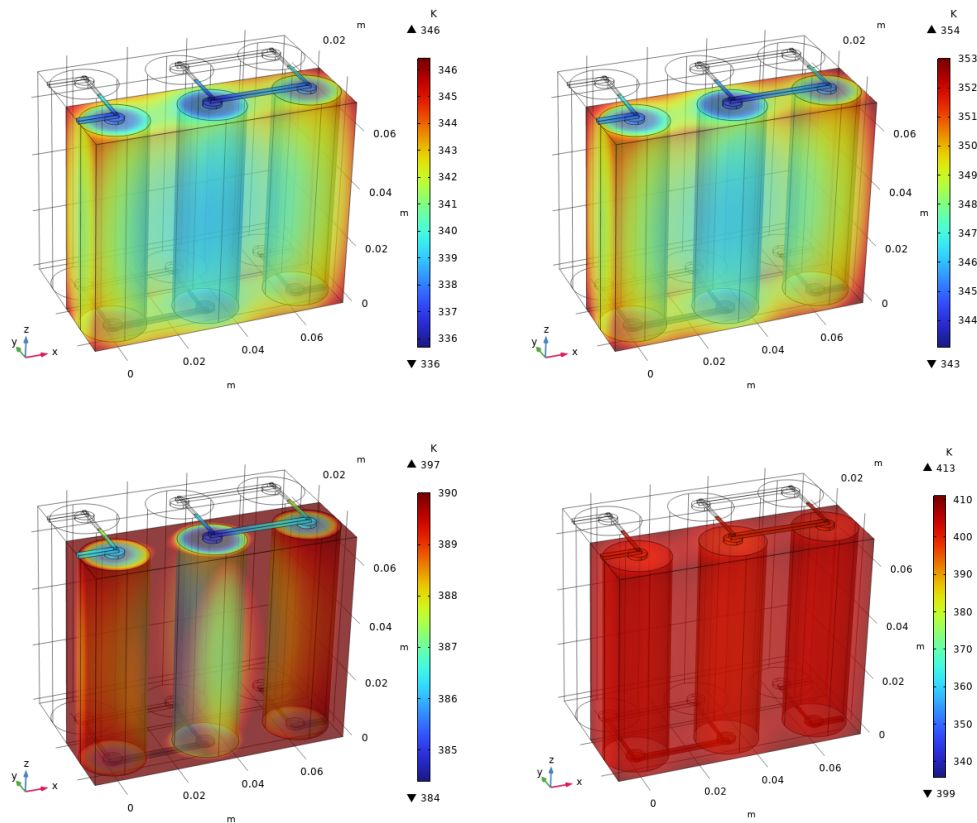


Figure 5. Temperature contour under the 140 °C condition.

Table 13. Temperature distribution characteristics of the module under the 140 °C condition.

No.	Time/s	Maximum Module Temperature/°C	Minimum Module Temperature/°C	Location of Maximum Temperature
a	700	73	63	Surfaces of the two outermost cells
b	1100	81	70	Surfaces of the two outermost cells
c	1500	124	111	Interface between the outer cell and inner cells
d	1900	140	126	Entire battery pack

The 140 °C condition represents a thermal runaway risk-acceleration region. During the contour-sampling period, SEI decomposition and the negative electrode–electrolyte reaction gradually intensify, but the module has not yet entered the sustained self-accelerating temperature-rise stage. The temperature near 125 °C is regarded as an early-warning threshold, whereas approximately 167 °C represents the critical region associated with irreversible thermal runaway. The trigger time of approximately 16,200 s was obtained from the complete temperature curve rather than from the selected contours shown in Figure 5.

Temperature Variation in Battery Thermal Runaway at an Ambient Temperature of 170 °C. The temperature distribution characteristics of the module under the 170 °C condition are summarized in Table 14.

Table 14. Temperature distribution characteristics of the module under the 170 °C condition.

No.	Time/s	Maximum Module Temperature/°C	Minimum Module Temperature/°C	Location of Maximum Temperature
a	600	72	61	Surfaces of the two outermost cells
b	950	107	95	Interface between the outer cell and inner cells
c	1520	136	123	Interface between the outer cell and inner cells
d	2000	157	143	Interface between the outer cell and inner cells

As shown in Figure 6, under the 170 °C severe thermal abuse condition, the module heats more rapidly than under the lower-temperature conditions. The selected temperature-field snapshots show that the maximum module temperature increases from 72 °C at 600 s to approximately 157 °C at 2000 s. The contour at 2000 s therefore represents a pre-critical temperature-field state close to, but still below, the irreversible critical region near 167 °C, rather than the onset or peak of thermal runaway. Based on the corresponding full-process maximum-temperature curve, thermal runaway occurs at approximately 9350 s, after which intensive side-reaction heat release drives the module temperature rapidly to approximately 375–385 °C. Thus, 2000 s and 9350 s represent a selected pre-critical sampling time and the full-process trigger time, respectively.

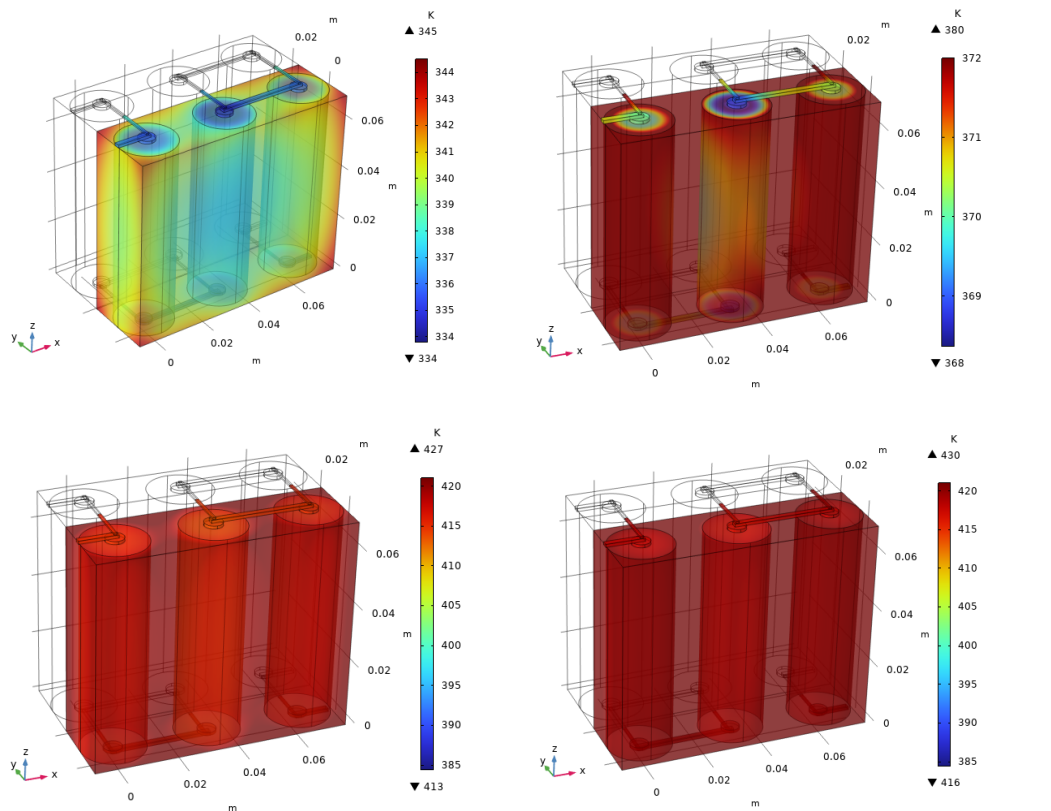


Figure 6. Temperature contour under the 170 °C condition.

Overall, under different ambient temperature conditions, temperature and temperature rise rate are more sensitive to the intensity of external thermal abuse and the critical triggering state and can serve as important response indicators for early warning of thermal runaway. By contrast, terminal voltage variation mainly reflects electrochemical performance degradation under high-temperature conditions and can be used as auxiliary judgment information, but it is not the main basis for fire risk classification in this study.

3.2. Temperature Field Evolution Under the 170 °C Condition

Analysis of Full-Process Module Temperature Evolution at 170 °C

Based on the heating behavior of the battery module at each critical temperature point, the 170 °C condition covers the full thermal runaway process of the battery module. Therefore, the battery module at 170 °C was selected for full-process temperature analysis to investigate the thermal runaway behavior of the battery pack.

At an ambient temperature of 170 °C and an initial module temperature of 20 °C, the thermal response of the battery module can be divided into an externally dominated heating stage, a pre-critical heat-accumulation stage, and a self-accelerating thermal runaway stage. During the initial period from 0 to 1000 s, heat is continuously transferred from the high-temperature environment into the module, while side-reaction heat generation remains limited. The average module temperature-rise rate during this period is approximately 0.008 °C/s. At the selected contour time of 2000 s, the maximum monitored temperature reaches approximately 157 °C, indicating that the module is approaching the irreversible critical region near 167 °C; however, this contour time is not defined as thermal runaway onset. The paraffin-based PCM layer provides an equivalent thermal-buffering effect that delays external heat transfer into the battery body. Based on the full-process maximum-temperature curve, sustained self-accelerating temperature rise begins at approximately 9350 s. After this point, the positive electrode–electrolyte reaction and electrolyte decomposition intensify markedly, driving the module temperature rapidly toward approximately 375–385 °C [5–8,16,20,21,33].

Figure 7 presents the complete maximum-temperature evolution of the battery module under the 170 °C severe thermal abuse condition. The times between approximately 1000 and 2000 s discussed together with Figures 6 and 8 correspond to selected early and pre-critical temperature-field states. In particular, the monitored maximum temperature reaches approximately 157 °C at 2000 s, indicating proximity to the irreversible critical region near 167 °C but not defining thermal runaway onset. Using the unified criterion defined in Section 2.4, the simulated thermal runaway trigger time is approximately 9350 s. After triggering SEI decomposition, the negative electrode–electrolyte reaction, the positive electrode–electrolyte reaction, and electrolyte decomposition intensify sequentially and drive the subsequent rapid temperature rise [5–8,22,33].

Analysis of Full-Process Temperature Field Evolution Contours at 170 °C.

As shown in Figure 8, before 1000 s, the temperature rise in the battery module is mainly governed by external thermal input, and the contribution of internal side reactions remains limited. At approximately 1500 s, the module enters a heat-accumulation stage in which initial side reactions gradually intensify. At 2000 s, the maximum monitored temperature approaches 157 °C, indicating a pre-critical state close to the irreversible threshold near 167 °C. These contours are selected to illustrate the spatial evolution of the temperature field before thermal runaway onset and should not be interpreted as defining the trigger time. The subsequent thermal runaway trigger time of approximately 9350 s was determined from the complete maximum-temperature curve shown in Figure 7. A systematic comparison of the module behavior under different temperature conditions is presented in Table 15.

Table 15. System comparison under different temperature conditions.

Comparison Item	Low-Temperature Safe Condition (70 °C)	120 °C	140 °C	170 °C
Ambient temperature range	Safe region	Critical Safe region	Thermal runaway Trigger region	Severe thermal abuse region
SEI film state	Almost intact	Slow decomposition	Approaching Complete decomposition	Instantaneous complete decomposition

Table 15. Cont.

Comparison Item	Low-Temperature Safe Condition (70 °C)	120 °C	140 °C	170 °C
Negative electrode–electrolyte reaction	None	None	Fully developed	Completed within a very short time
Positive electrode–electrolyte reaction	None	None	About to be triggered	Triggered with intense heat release
Electrolyte decomposition reaction	None	None	None	About to trigger or causing fire
Final peak temperature	~69 °C	~130 °C	>350 °C	375–384 °C
Thermal runaway trigger time	Not triggered	Not triggered	Approximately 16,200 s	Approximately 9350 s
Fire risk level	Thermal runaway not triggered	Thermal runaway not triggered	High thermal runaway risk	Severe thermal runaway risk

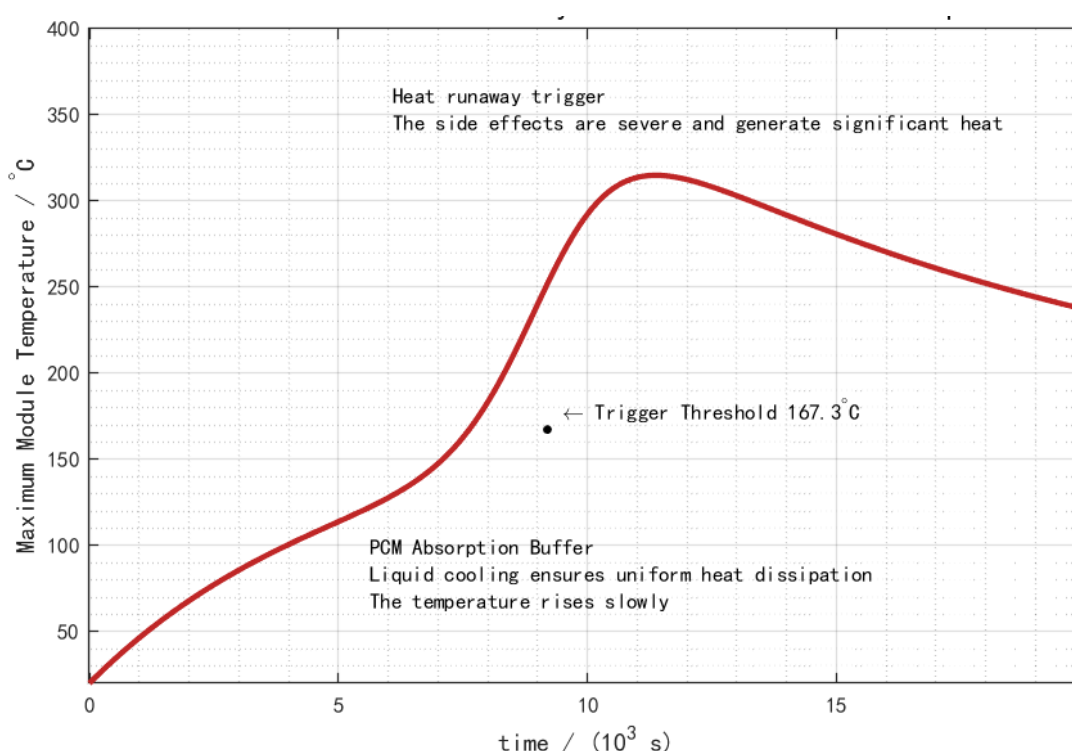


Figure 7. Full-process temperature evolution curve of the battery module at an ambient temperature of 170 °C.

3.3. Effect of the Heat Transfer Coefficient on Thermal Runaway Trigger Time

Figure 9 compares the maximum battery-module temperatures under ambient temperatures of 70 °C, 125 °C, 140 °C, and 170 °C for heat-transfer coefficients of 5, 10, 15, and 25 W/(m²·K). The 125 °C condition was selected to evaluate the influence of heat-transfer intensity near the early-warning region for initial side-reaction intensification [25–27,34,35].

The data in the figure show that the influence of the heat transfer coefficient on the temperature rise behavior of the battery module is strongly coupled with ambient temperature. When the ambient temperature remains at the relatively low value of 70 °C, the differences among the temperature curves corresponding to the four heat transfer coefficients are small. The module temperature shows a slow increasing trend and gradually reaches a stable state, while the maximum temperature remains below 80 °C and no thermal runaway occurs. Because the temperature difference between the environment and the battery is

small, increasing the heat transfer coefficient still cannot introduce enough heat into the module per unit time to trigger intense side reactions.

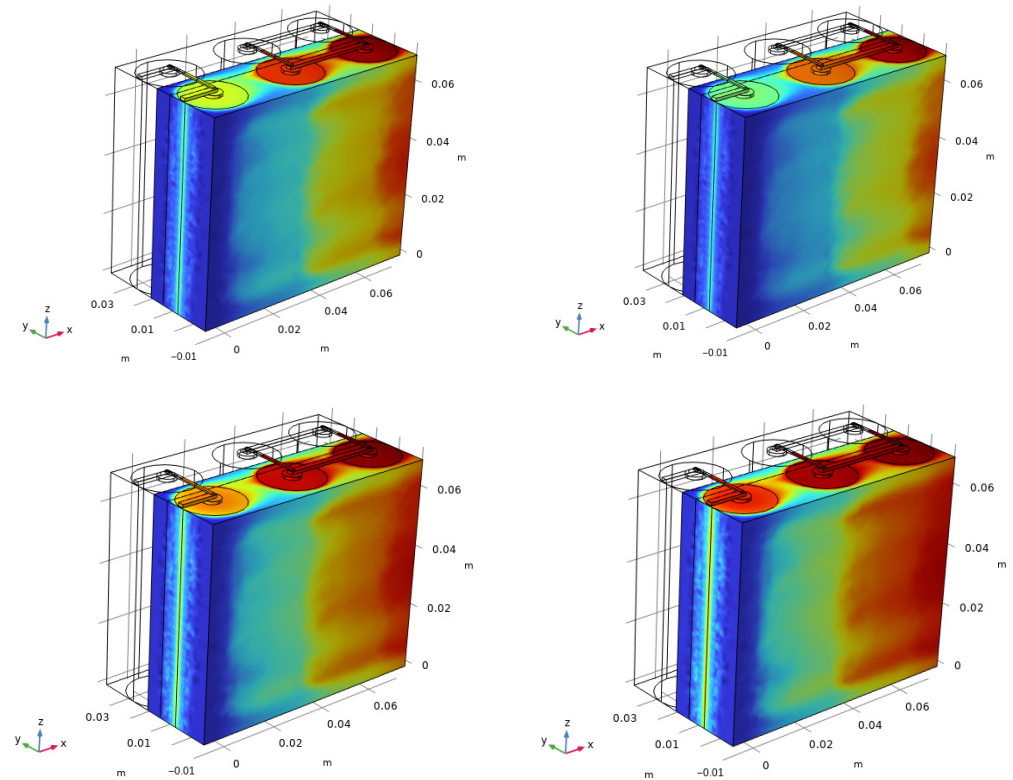


Figure 8. Temperature field evolution at an ambient temperature of 170 °C. The color scale represents temperature, with blue indicating lower temperatures and red indicating higher temperatures.

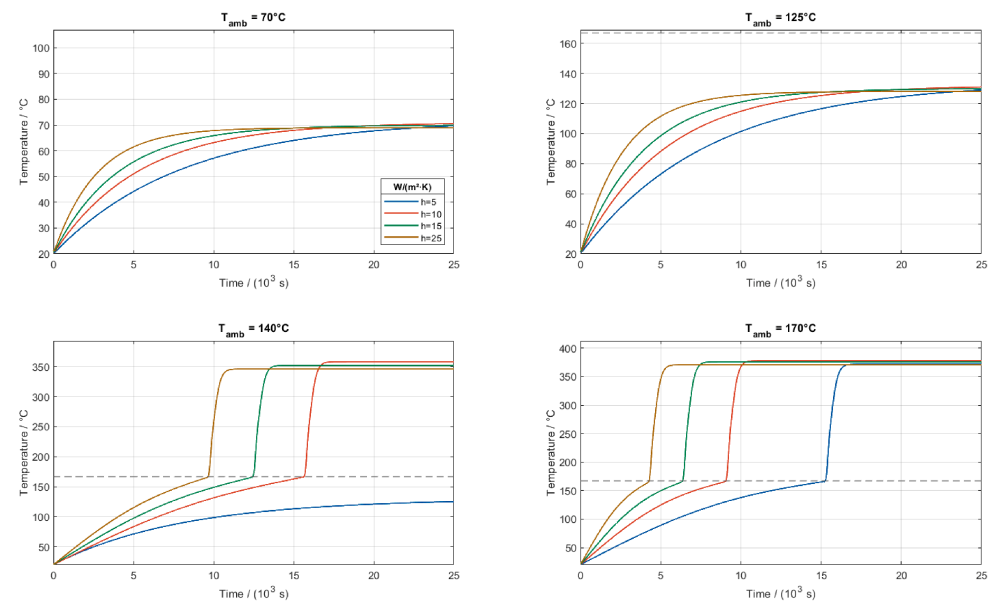


Figure 9. Temperature curves of the battery module under different heat transfer coefficients.

Under the comparison condition near the 125 °C risk warning threshold, the heat transfer coefficient shows different effects: the temperature rise rate under $h = 25 \text{ W}/(\text{m}^2 \cdot \text{K})$ is faster than that under $h = 5 \text{ W}/(\text{m}^2 \cdot \text{K})$, but all curves eventually stabilize, and the maximum temperature does not exceed 140 °C. The battery module therefore remains in a safe state. This indicates that, when the temperature is below the critical threshold,

increasing the heat transfer coefficient accelerates heating, but the heat generated by side reactions is still limited and cannot trigger chain thermal runaway.

When the ambient temperature reaches 140 °C, the influence of the heat-transfer coefficient becomes increasingly apparent. The curves corresponding to $h = 10, 15$, and $25 \text{ W}/(\text{m}^2 \cdot \text{K})$ exhibit abrupt temperature-rise inflection points at different times, demonstrating that each heat-transfer condition has its own trigger time. The value of approximately 16,200 s reported in Section 3.1 corresponds to the baseline full-process 140 °C case and should not be assigned to all heat-transfer-coefficient curves in Figure 9. Similarly, the contour time of 1900 s shown in Figure 5 is only a selected temperature-field sampling time and does not represent the trigger time of any curve in Figure 9.

When the ambient temperature reaches 170 °C, all four heat-transfer-coefficient cases eventually enter thermal runaway, but the trigger time decreases as the heat-transfer coefficient increases. The simulated trigger time of approximately 9350 s corresponds to $h = 10 \text{ W}/(\text{m}^2 \cdot \text{K})$, whereas the shorter trigger time of approximately 4600 s corresponds to $h = 25 \text{ W}/(\text{m}^2 \cdot \text{K})$. These values therefore describe different boundary conditions and are not contradictory. The heat-transfer coefficient mainly affects the time required to reach thermal runaway onset, while the final peak temperature remains primarily controlled by internal side-reaction heat release.

3.4. FMECA-Based Fire Risk Ranking Results

Based on the preceding thermal runaway simulation analysis and common battery pack failure types, this study identifies the following major fire-related failure modes. Each mode is identified based on the quantitative simulation conclusions described above: The identified failure modes, their causes, simulation bases, and effects are summarized in Table 16.

Table 16. Common failure modes and causes of battery packs.

Failure ID	Failure Mode	Failure Cause	Simulation Basis	Failure Effect
F1	Battery overheating	Excessive ambient temperature and insufficient heat dissipation	Side-reaction heat magnitude increased when the ambient temperature was $\geq 140 \text{ }^\circ\text{C}$	Triggered SEI decomposition and initiated chain thermal runaway
F2	Accelerated SEI decomposition	High-temperature environment and electrolyte side reactions	125–140 °C was the critical threshold range, and the SEI film was the starting point of thermal runaway	Negative electrode exposure and subsequent sequential reactions
F3	Intense negative electrode–electrolyte reaction	Failure of SEI decomposition protection	Triggered at 167 °C with a large increase in heat generation magnitude	Drove continued temperature rise
F4	Intense positive electrode–electrolyte reaction	Temperature reached approximately 167 °C	Largest heat generation magnitude in the heat source curves	Drove a rapid temperature rise above 350 °C
F5	Electrolyte decomposition reaction	Temperature exceeded 200 °C	Final chain reaction with the highest heat generation	Sustained temperature increase with potential fire initiation
F6	Thermal insulation material failure	High temperature exceeded the tolerance limit of the thermal insulation material	The insulation layer lost its blocking capability in thermal runaway propagation simulation	Thermal runaway propagated from a local region to the whole group
F7	Phase change material failure	Prolonged high-temperature exposure exceeded the effective thermal-buffering capacity of the PCM layer	The PCM layer no longer prevented rapid module temperature rise after the critical threshold was reached	Loss of effective thermal-buffering capacity
F8	Insufficient heat dissipation of the liquid-cooling system	Insufficient coolant flow rate and flow-channel blockage	Simulations with different heat transfer coefficients showed that $h \leq 5$ can delay triggering	Heat accumulation accelerated thermal runaway

The RPN values listed in Table 17 were calculated from the adopted occurrence, severity, and detection scores.

Table 17. Failure-level determination intervals.

Failure ID	Failure Mode	Occurrence (O)	Severity (S)	Detection (D)	RPN (O × S × D)
F1	Battery overheating	5–6 (selected as 5)	5–6 (selected as 5)	3–4 (selected as 3)	75
F2	Accelerated SEI decomposition	7–8 (selected as 7)	5–6 (selected as 5)	7–8 (selected as 7)	245
F3	Negative electrode–electrolyte reaction	5–6 (selected as 5)	7–8 (selected as 7)	7–8 (selected as 7)	245
F4	Positive electrode–electrolyte reaction	5–6 (selected as 5)	9–10 (selected as 9)	9–10 (selected as 9)	405
F5	Electrolyte decomposition reaction	3–4 (selected as 3)	9–10 (selected as 9)	9–10 (selected as 9)	243
F6	Thermal insulation material failure	5–6 (selected as 5)	7–8 (selected as 7)	5–6 (selected as 5)	175
F7	Phase change material failure	3–4 (selected as 3)	5–6 (selected as 5)	5–6 (selected as 5)	75
F8	Insufficient heat dissipation of the liquid-cooling system	5–6 (selected as 5)	5–6 (selected as 5)	3–4 (selected as 3)	75

Based on the RPN values listed in Table 17, the risk ranking of the failure modes is presented in Table 18.

Table 18. Risk ranking of failure modes.

Rank	Failure Mode	RPN	Risk Level
1	F4	405	Level I
2	F2	245	Level I
2	F3	245	Level I
4	F5	243	Level I
5	F6	175	Level II
6	F1	75	Level III
6	F7	75	Level III
6	F8	75	Level III

Among the eight battery pack thermal-runaway-related failure modes identified in this study, the intense positive electrode–electrolyte reaction (F4) has the highest RPN value (405) in the current scoring system and therefore shows a higher priority. This mode corresponds to the irreversible thermal runaway stage. The peak temperature can rise above 374 °C, and the detection difficulty score is high (D = 9), so it should be a key focus. Accelerated SEI decomposition (F2) and the intense negative electrode–electrolyte reaction (F3) both have RPN values of 245 and are tied as higher-priority modes. Although SEI decomposition itself does not generate the largest amount of heat, it is the starting point of the battery thermal runaway chain reaction and is difficult to detect. The negative-electrode reaction is the key link that drives the temperature up to the positive-electrode triggering threshold. It should be emphasized that the current FMECA results are used to identify relative risk ranking and not to predict the absolute probability of accidents. The reported RPN values represent the final results calculated using the adopted scoring criteria.

4. Discussion

4.1. Engineering Significance of Thermal Runaway Critical Thresholds

As shown in Figure 10, different ambient temperature conditions reflect the staged risk of power battery packs from safe heating to irreversible thermal runaway. Under the low-temperature safe condition and the 120 °C condition, the module temperature

is mainly controlled by external heat transfer. The overall behavior is slow heating with a relatively uniform temperature distribution, and no chain thermal runaway is formed. Based on the side-reaction heat source changes, the temperature near 125 °C can be used as a risk warning threshold to indicate that SEI decomposition and early side reactions may begin to intensify, but it should not be equated with a complete thermal runaway condition [31–33].

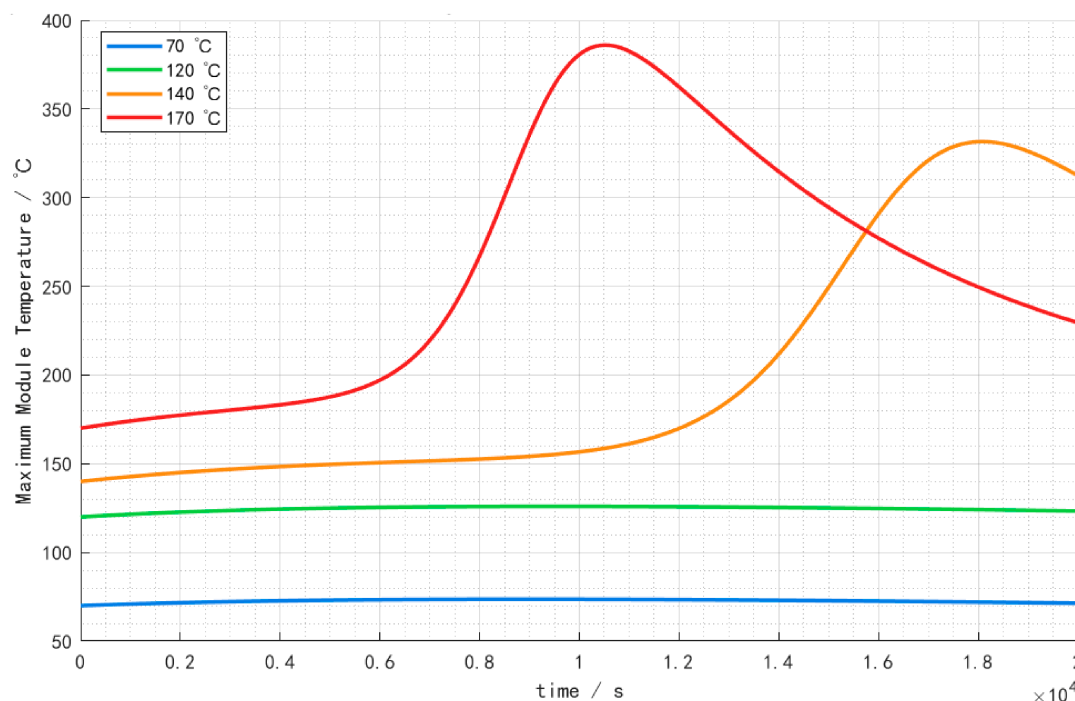


Figure 10. Temperature variation curves of the battery module under different temperature states.

The 140 °C condition represents a thermal runaway risk-acceleration region. The contour at 1900 s illustrates an intermediate heat-accumulation state rather than thermal runaway onset, whereas the trigger time of approximately 16,200 s was identified from the corresponding full-process temperature curve. At this temperature level, the contributions of SEI decomposition and the negative electrode–electrolyte reaction gradually increase, but sustained self-accelerating temperature rise occurs only after the module approaches the irreversible critical region near 167 °C. Above this critical region, the positive electrode–electrolyte reaction and electrolyte decomposition intensify significantly, and side-reaction heat release becomes the dominant factor in rapid temperature rise [5–8,22,34,35].

The 170 °C condition represents severe thermal abuse. Under this condition, the contour at 2000 s shows a pre-critical state with a maximum module temperature of approximately 157 °C, whereas thermal runaway onset occurs later, at approximately 9350 s in the corresponding full-process simulation. After triggering, rapid intensification of internal side reactions drives the peak module temperature to approximately 375–385 °C. The temperature field consequently changes from an outside-high and inside-low distribution during the early external-heating stage to an inside-high and outside-low distribution dominated by internal side-reaction heat release. This result indicates that the principal intervention window lies between the early-warning temperature near 125 °C and the irreversible critical region near 167 °C [14,15,31,32,34,35].

SEI decomposition remains the key to understanding the starting point of the chain reaction. Although it does not generate the largest amount of heat, it destroys the protective layer of the negative electrode, causing the negative electrode–electrolyte reaction, positive electrode–electrolyte reaction, and electrolyte decomposition to intensify sequen-

tially. Potential and terminal-voltage variations may provide supplementary early-warning information; future work will incorporate synchronized electrochemical measurements to further evaluate their diagnostic value [5–9].

4.2. Implications for Thermal Management and Thermal Propagation Barrier Design

Thermal management strategies need to distinguish between normal operating heat dissipation and external fire heat intrusion. Under normal operating conditions, the heat dissipation system should improve heat removal efficiency and reduce the possibility of long-term heat accumulation and local hot spot formation. Under external high-temperature thermal abuse or fire exposure scenarios, the control objective shifts to reducing external heat input into the cells and preventing the battery from rapidly reaching the side-reaction triggering threshold [16,20,21,36–42].

The heat transfer coefficient analysis shows that, under external high-temperature thermal abuse, a larger heat transfer coefficient causes faster external heat input, allowing the battery to reach the side-reaction triggering threshold earlier and shortening the thermal runaway trigger time. However, the peak temperature after complete thermal runaway is mainly determined by heat release from internal side reactions and is relatively less affected by the heat transfer coefficient. Thus, PCM and thermal insulation materials can delay triggering through heat absorption and heat-transfer blocking, but cannot prevent chain heat release after the irreversible stage above approximately 167 °C. In engineering design, the thermal input under external fire heat intrusion should be reduced through insulation layers, fire barriers, and thermal blocking structures while maintaining normal operating heat dissipation capacity, rather than simply reducing the heat transfer capacity of the cooling system [25–27,34–37].

Although the absolute trigger time varies with the heat-transfer coefficient, the overall trend remains unchanged: stronger external heat transfer advances thermal runaway onset and narrows the available protection window. The values of approximately 16,200 s at 140 °C and 9350 s at 170 °C refer to the respective full-process cases discussed in Sections 3.1 and 3.2, whereas shorter trigger times reported in the sensitivity analysis correspond to higher heat-transfer-coefficient conditions.

4.3. Implications of FMECA Results for Fire Prevention and Control

The significance of the FMECA results lies in identifying relatively high-risk failure modes rather than predicting the absolute probability of accidents. By linking simulated temperature thresholds, heat-source evolution, and trigger time with failure modes, the thermal runaway process can be transformed into rankable fire prevention and control targets. The current scoring results show that the intense positive electrode–electrolyte reaction has the highest RPN, at 405, mainly because this reaction occurs in the irreversible thermal runaway stage, has high severity, and is difficult to detect [17–19].

Although accelerated SEI decomposition and the negative electrode–electrolyte reaction are not the links with the highest heat generation, they occur early in the chain reaction and trigger subsequent positive-electrode reaction and electrolyte decomposition. They should therefore be key targets for early warning and BMS strategy optimization. By contrast, failures such as battery overheating, PCM failure, and insufficient heat dissipation of the liquid-cooling system can be addressed through routine maintenance and risk reduction based on monitoring of temperature, temperature difference, cooling state, and material aging. The closed loop formed by simulation results, failure modes, and risk ranking can provide a basis for battery pack thermal management, fire barriers, and graded early warning. The RPN values in Table 17 were calculated using the finalized scoring criteria and are used to identify the relative priority of the failure modes [5–9,17–19,38]. The

chain-failure mechanism of thermal runaway in EV power battery packs is summarized in Figure 11.

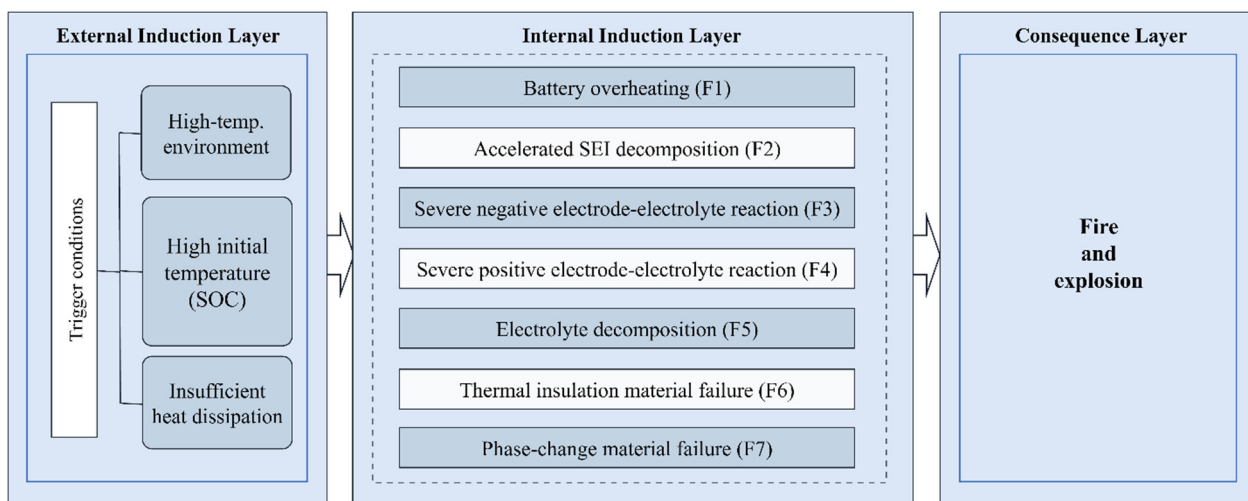


Figure 11. Chain-failure mechanism of thermal runaway in EV power battery packs.

4.4. Limitations

This study establishes a thermal runaway model of a power battery pack based on COMSOL numerical simulation and the literature-derived parameters. Empirical thermal runaway data obtained from repeated experiments with the same battery geometry, material system, boundary conditions, and thermal abuse conditions were unavailable. Therefore, the present model evaluation is limited to mesh-independence analysis and the literature-based benchmark comparison, and no statistical uncertainty intervals are reported. The comparison supports the reasonableness of the temperature-evolution trends, trigger judgment, and magnitude of the principal indicators, but cannot replace direct experimental validation using the same battery module [10–15,34,35].

The cells, thermal insulation material, and phase change material were treated as equivalent homogeneous media, which reduced computational complexity and supported comparisons among operating conditions. In particular, the paraffin-based phase change material was represented using constant equivalent thermophysical properties, and its temperature-dependent latent-heat behavior was not explicitly resolved. Therefore, the model does not fully reflect the internal structure of a real battery pack, local material differences, contact thermal resistance, or manufacturing and assembly deviations. The model focuses on solid-phase heat transfer and side-reaction heat release and does not deeply simulate gas release, jet fire, combustion flame, explosion pressure, or their coupled propagation with the compartment space after thermal runaway [10,12,39–42].

FMECA is a semi-quantitative risk assessment method. The O, S, and D scores are affected by simulation conditions, the literature experience, and expert judgment, and the RPN results are mainly used to identify relative risk ranking rather than to predict the absolute probability of accidents.

The qualitative mechanisms identified in this study, including externally dominated heating before thermal runaway onset, sequential intensification of exothermic side reactions, and the influence of external heat-transfer intensity on trigger time, may provide a reference for other lithium-ion battery systems. However, the quantitative warning temperatures, trigger times, peak temperatures, and FMECA rankings reported here are specific to the prismatic ternary lithium-ion battery module, thermophysical properties, state of charge, boundary conditions, and PCM–insulation configuration adopted in the present model. Application to cylindrical or pouch cells, lithium iron phosphate or other battery chemistries,

and different module or pack geometries requires recalibration of the thermophysical and kinetic parameters and renewed evaluation under matched operating conditions.

Future work may supplement the current model with thermal runaway experimental validation, gas release models, flame propagation models, and multi-module thermal propagation experiments, and may further verify the effects of phase change material, thermal insulation material, heat transfer coefficient, and initial temperature on trigger time and risk ranking results [34,35,38–42].

5. Conclusions

- (1) A three-dimensional multiphysics thermal runaway simulation model for a power battery pack was established, coupling solid heat transfer, electrochemical heat generation, and side-reaction heat release. The model was evaluated through mesh-independence analysis and benchmark comparison with the literature-reported reference conditions. It can be used to analyze battery pack temperature field evolution, trigger time, and side-reaction heat source changes under external thermal abuse.
- (2) The staged thermal runaway characteristics under different ambient temperatures were clarified. Under the low-temperature safe condition and the 120 °C condition, the module exhibited gradual heating without chain thermal runaway, while approximately 125 °C was identified as an early-warning temperature for initial side-reaction intensification. Under the 140 °C condition, the contour at 1900 s represents an intermediate risk-acceleration state, whereas thermal runaway onset occurs at approximately 16,200 s in the corresponding full-process case. Under the 170 °C severe thermal abuse condition, the contour at 2000 s represents a pre-critical state with a maximum temperature of approximately 157 °C, and the simulated full-process trigger time is approximately 9350 s. After triggering, the peak module temperature reaches approximately 375–385 °C.
- (3) Temperature field evolution shows that, before thermal runaway, heat is mainly transferred from the exterior to the interior, producing an outside-high and inside-low distribution. During the thermal runaway stage, heat release from side reactions inside cells dominates, and the high-temperature region concentrates inside the module, forming a gradient reversal with a higher internal temperature. SEI decomposition, the negative electrode–electrolyte reaction, the positive electrode–electrolyte reaction, and electrolyte decomposition constitute the chain-triggering pathway of thermal runaway.
- (4) FMECA identified key weak links in battery pack fire risk. The current scoring results show that the intense positive electrode–electrolyte reaction has the highest RPN under the present scoring system and should be a key focus. Accelerated SEI decomposition and the negative electrode–electrolyte reaction occur early in the chain reaction and should also be regarded as key targets for warning and prevention. The FMECA results are intended for relative risk prioritization under the adopted scoring system; further experimental and expert-based validation may improve the robustness of the scoring framework.

Author Contributions: J.S.: Methodology, Formal analysis, Validation, Investigation, Data curation, Visualization, Writing—original draft, Writing—review and editing, Funding acquisition; Z.Z.: Conceptualization, Methodology, Writing—review and editing, Supervision; M.Z.: Data curation, Validation, Formal analysis, Visualization, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Natural Science Foundation of Shandong Province [ZR2024MG039]: Research on Risk Sensing and Early Warning Decision-Making of Major Coal Mine Disasters Based on Multimodal Big Data.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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