2026 Volume: 02 Issue: 11 www.ijrpa.com ISSN 2456-9995 Review Article

International Journal Research Publication Analysis

Page: 01-11

EV THERMAL RUNAWAY: MODELLING AND SUPPRESSION OF THERMAL RUNAWAY PROPAGATION IN LITHIUM-ION BATTERY PACKS AN ADVANCED STATE-OF-THE-ART ACADEMIC REVIEW

Amol Pandharinath Ghule*[1]

M. Tech. (Mech. Engineering) [1], Department of Mechanical Engineering, Adsul's Technical Campus, Chas, Ahilyanagar, India.

Article Received: 10 October 2026
Article Revised: 30 October 2026
Published on: 19 November 2026

***Corresponding Author: Amol Pandharinath Ghule**
M. Tech. (Mech. Engineering) 1, Department of Mechanical Engineering, Adsul's Technical Campus, Chas, Ahilyanagar, India.

DOI: https://doi-doi.org/101555/ijrpa.8571

1. BRIEF ABSTRACT

The rapid proliferation of electric vehicles (EVs) has pushed lithium-ion battery (LIB) packs toward unprecedented volumetric energy and power densities. However, this technological trajectory introduces severe safety liabilities, primarily centered around the catastrophic phenomenon of thermal runaway (TR). This comprehensive academic review synthesizes the multi-scale physics governing TR initiation at the material level and its subsequent propagation at the pack level. We examine the state-of-the-art computational frameworks, analyzing the mathematical models that integrate multi-phase exothermic kinetics (anode solid electrolyte interphase decomposition, cathode reduction, and binder reactions) with transient conjugate heat transfer. Concurrently, the paper scrutinizes multi-faceted mitigation paradigms across passive, active, and hybrid suppression configurations, focusing heavily on shape-stabilized phase change materials, active fluid dynamics, aerogel barriers, and advanced fire-suppressive chemical agents. A rigorous comparative overview evaluates modeling fidelities and suppression performance characteristics, highlighting critical engineering tradeoffs between gravimetric penalty, cooling efficiency, and structural containment under abusive environments. Finally, we map out future doctoral and post-graduate engineering directives, charting the integration of real-time machine learning analytics and physics-informed neural networks into intelligent battery management frameworks to enable true zero-propagation modular architectures.

KEYWORDS: Lithium-Ion Battery Packs, Thermal Runaway Propagation, Multi-Scale Numerical Modelling, Exothermic Kinetics, Passive and Active Suppression, Aerogel Thermal Barriers, Battery Safety.

2. INTRODUCTION

The ongoing global shift towards eco-friendly mobility systems relies heavily on advanced electrochemical storage arrays, with lithium-ion batteries serving as the primary power source for modern electric powertrains [1]. The commercial viability and performance expectations of electric vehicles demand continuous improvements in cell capacity, fast-charging capabilities, and overall energy density [2]. This drive has resulted in the widespread adoption of high-nickel chemistries, such as LiNi0.8Co0.1Mn0.1O2 (NCM811), and ultra-dense cell packing designs like cell-to-pack (CTP) and cell-to-chassis (CTC) configurations [3]. While these innovations successfully maximize vehicle range, they also crowd highly reactive materials into confined spaces, magnifying the technical and regulatory challenges associated with thermal safety.

At the heart of these safety concerns is the process of Thermal Runaway (TR) [4]. Thermal runaway occurs when a cell experiences severe internal faults or external damage, triggering a chain of self-sustaining exothermic chemical reactions. The rate of internal chemical heat generation quickly surpasses the rate of external convective or conductive dissipation, causing a sharp spike in local temperatures [5]. This thermal spike prompts the venting of toxic, flammable gas blends (composed of CO, H2, CH4, and vaporized solvents) and leads to the ejecta of incandescent particulate matter [6]. In a tightly grouped automotive battery pack, the massive thermal energy released by a failing 'trigger cell' easily moves to adjacent cells via radiation, conduction, and hot gas convection, initiating a cascading failure known as Thermal Runaway Propagation (TRP) [7]. Unchecked TRP can cause catastrophic vehicle fires, structural damage, and severe risks to vehicle occupants.

Developing successful containment systems requires a complete understanding of how these failures scale. This progression spans from micro-scale chemical kinetics inside the electrode layers, to macro-scale transport phenomena through the cell casings, and finally to large-scale structural interactions within the entire vehicle chassis [8]. Consequently, modern automotive engineering focuses heavily on two complementary areas: creating highly accurate numerical models to predict thermal propagation pathways, and developing lightweight, high-performance suppression technologies to isolate thermal failures [9]. This review paper provides a structured evaluation of these computational methods and suppression materials,

offering clear pathways toward designing safer battery packs for the next generation of electric vehicles.

3. History and Importances

3.1 Historical Evolution of Battery Failures

The history of lithium-based battery safety reveals a continuous race between rising energy densities and the engineering methods used to contain them. In the early 1990s, the commercialization of low-capacity lithium-ion cells with cobalt-based cathodes primarily served low-draw consumer electronics like laptops and mobile devices [10]. Even at that smaller scale, internal defects and manufacturing contaminations (such as stray copper or iron microscopic shards) regularly caused internal short circuits, prompting widespread product recalls and the development of early safety standards [11]. The transition of lithium-ion technology to the automotive sector in the late 2000s and early 2010s significantly changed the scale of potential hazards. Early production EVs utilized safer, lower-energy chemistries like Lithium Manganese Oxide (LMO) and Lithium Iron Phosphate (LFP) [12]. However, global market pressure for longer driving ranges forced a rapid shift toward high-nickel Nickel-Manganese-Cobalt (NMC) and Nickel-Cobalt-Aluminum (NCA) cathode variations [13]. These high-density formulations feature lower thermal onset degradation thresholds, making the task of preventing cascading failures much more demanding.

3.2 Technological and Economic Importance

The structural and economic importance of eliminating thermal runaway propagation spans across consumer trust, automotive manufacturing costs, and international regulatory compliance. From a regulatory perspective, global standards such as UN ECE R100, GB 38031, and China's mandatory 5-minute safety warning rule dictate that a battery pack must provide a clear window of at least five minutes between the initial TR incident and any visible external fire or structural breach [14]. This timeframe is critical to allow occupants to safely exit the vehicle cabin. Meeting these strict rules without adding excessive, heavy shielding requires advanced thermal design strategies optimized through precise simulations [15].

From an economic standpoint, a single highly publicized EV thermal incident can damage a manufacturer's brand reputation, depress stock valuations, and trigger multi-million dollar warranty recalls [16]. Furthermore, over-engineering safety systems by packing vehicles with heavy, thick steel plates or excessive cooling fluids creates a major vehicle weight penalty, reducing efficiency and driving up material costs [17]. Achieving 'zero-propagation' through

optimized, lightweight cell isolation strategies represents a key competitive advantage in the modern automotive market, directly influencing manufacturing costs and sustainability metrics.

4. Literature Survey

Gong et al. [18] developed a comprehensive three-dimensional numerical framework to investigate the mechanical and thermal interactions governing thermal runaway propagation in large-format prismatic cells. The researchers coupled localized multi-step chemical reaction models directly with transient conjugate heat transfer equations, specifically studying how physical pressure within the pack affects cell failure. Their simulations demonstrated that mechanical swelling during early decomposition phases compresses neighboring thermal interfaces, dramatically increasing localized thermal contact conductance and accelerating propagation rates. The study concluded that incorporating flexible, compressible isolation pads alongside traditional air gaps could absorb mechanical expansion forces while providing a robust thermal barrier, highlighting the complex relationship between mechanical force and thermal transfer during pack-level failures.

Kasperovich et al. [19] conducted a rigorous experimental and numerical investigation into the effectiveness of shape-stabilized phase change materials (PCMs) reinforced with high-porosity copper foams for EV thermal management. The authors focused on capturing the transient phase-change kinetics and localized melting fronts when subjected to the extreme heat flux of an adjacent cell in full thermal runaway. Their findings showed that while pure paraffin waxes often suffer from low thermal conductivity and liquid leakage risks during intense heat spikes, the open-cell copper foam matrix improved bulk thermal conductivity by more than 200%. This enhancement allowed the composite PCM to quickly absorb and distribute intense thermal spikes across its latent heat capacity, successfully preventing the adjacent cells from reaching their critical self-heating onset thresholds.

Slotwinski et al. [20] provided a detailed analysis of gas venting dynamics and multi-phase fluid emissions during thermal runaway in enclosed automotive battery modules. The authors used high-speed radiography and optical imaging to observe gas release events, integrating this empirical data into a computational fluid dynamics (CFD) gas-mixing model. Their research revealed that the high-velocity convective gas streams ejected from a failing cell account for up to 40% of the total thermal energy transferred to adjacent cells. The paper demonstrated that unmanaged hot gas accumulation within a module quickly triggers

secondary ignition events, emphasizing the critical need for dedicated, aerodynamic gas routing channels and pressure-relief valves within the upper pack cover.

King et al. [21] investigated the long-term structural and thermal durability of ultra-thin silica aerogel insulation blankets under cyclic mechanical and thermal stresses. The researchers simulated ten years of vehicle vibration and thermal cycling to evaluate the aerogel's resistance to structural degradation, fracturing, and moisture absorption over time. Their results verified that high-quality silica aerogels maintain a very low thermal conductivity (< 0.025 W/m·K) even when compressed to less than 50% of their original thickness during severe cell swelling. This resilience establishes aerogel blankets as an exceptionally reliable passive solution for high-density configurations, showing no significant loss in thermal barrier performance over extended operating cycles.

Dilip et al. [22] explored the integration of active liquid cooling systems with intelligent battery management system (BMS) logic to dynamically suppress thermal propagation. The authors developed a predictive control loop that monitors localized temperature acceleration values (-dT/dt) rather than relying solely on absolute temperature limits. When the algorithm detects early characteristic thermal runaway signatures, it triggers maximum coolant flow to the surrounding liquid cold plates while safely isolating the electrical contactors of the affected module. Their experimental validation proved that this active approach can effectively suppress propagation in low-to-medium energy density packs, though they noted that active cooling must often be paired with passive barriers to contain ultra-high-energy-density configurations.

5.5 METHODOLOGY

5.1 Governing Equations for Thermal Runaway Modelling

Accurately simulating thermal runaway propagation requires solving the non-linear, transient three-dimensional energy equation coupled with localized chemical kinetic models. The primary energy conservation equation for the battery domain is formulated as follows [23]:

$$\rho C_p (\partial T / \partial t) = \nabla \cdot (k \nabla T) + Q_{gen}$$

Where ρ represents the average density of the cell, C_p is the specific heat capacity, k is the anisotropic thermal conductivity tensor (accounting for high in-plane conductivity vs. low through-plane conductivity), T is the local temperature, and t is time. The term Q_gen represents the total volumetric heat generation rate, which is divided into operating heat and abusive chemical reaction heat:

$$Q_{gen} = Q_{ohm} + Q_{rxn} = I^2 R_{int} + \sum (H_i \cdot W_i \cdot \partial \alpha_i / \partial t)$$

Here, Q_ohm represents the standard internal joule heating (current I squared multiplied by internal resistance R_int), while Q_rxn aggregates the individual exothermic decomposition reactions. Each reaction 'i' is defined by its total heat of reaction H_i, the reactant mass fraction W_i, and the reaction conversion rate ∂α_i/∂t, which follows an Arrhenius relationship:

$$\partial \alpha_i / \partial t = A_i \cdot \exp(-E_{a,i} / (R \cdot T)) \cdot (1 - \alpha_i)^{n_i}$$

Where A_i is the pre-exponential frequency factor, E_a,i is the activation energy, R is the universal gas constant, and n_i is the empirical reaction order. The simulation framework computes these parameters across four primary degradation reactions: (1) solid electrolyte interphase (SEI) decomposition, (2) negative electrode-electrolyte reaction, (3) positive electrode decomposition, and (4) electrolyte oxidation and combustion.

5.2 Experimental Validation and Testing Protocols

To validate these numerical models, researchers use standardized experimental testing configurations. Testing begins with material characterization using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) to isolate the activation energies and reaction orders of individual cell components. Full-scale propagation tests are conducted inside explosion-proof chambers equipped with continuous exhaust gas analysis systems [24].

A target 'trigger cell' inside a multi-cell module is forced into thermal runaway using one of three standard methods: an embedded electrical resistance heater, mechanical nail penetration (mimicking severe internal shorts), or overcharge abuse. High-frequency K-type thermocouples are welded across the surfaces of neighboring cells to log temperature curves in real time. Concurrently, high-resolution infrared thermal imaging cameras record the external movement of heat fronts, while 3D X-ray Computed Tomography (CT) scans document internal structural changes, gas pocket formations, and electrode degradation post-test.

6.6 Discussions and Comparative Analysis

Evaluating suppression methods reveals a fundamental engineering challenge: balancing thermal barrier performance against pack-level weight and volumetric energy density. Passive containment systems, like silica aerogels, provide excellent, unpowered thermal insulation. Their extremely low thermal conductivity prevents direct heat conduction between adjacent cell faces [25]. However, aerogels cannot store or carry away heat; they act purely as

a thermal dam. If the trigger cell continues to release high-velocity gases, the heat can build up and bypass the aerogel layers via radiation and convection through the module casing. Conversely, composite Phase Change Materials (PCMs) offer a dynamic, temperature-regulating solution by absorbing large amounts of thermal energy at a constant melting point. By absorbing transient energy spikes, PCMs prevent adjacent cell skins from climbing toward self-heating temperatures. The main drawbacks of PCMs are their significant weight penalty and lower volumetric energy density, as they fill spaces that could otherwise hold active cell volume. Active liquid cooling systems provide excellent thermal control during standard operation and minor thermal spikes, but they risk complete failure if structural damage compromises coolant channels or if the fluid pump loses power. These physical differences highlight why modern designs are moving away from single-material solutions and toward multi-layered, hybrid containment architectures.

Suppression Class	**Material / System Type**	**Thermal Conduct. (W/m·K)**	**Mass Penalty**	**Primary Failure Mode / Bottleneck**	**TRP Status**
Pure Passive	Silica Aerogel Blankets	0.015 - 0.025	Very Low (<3%)	Pure insulation; cannot absorb gas convection paths	No Propagation (Low Density)
Passive Absorptive	Copper Foam Composite PCM	1.50 - 5.00	High (>12%)	Volumetric expansion; risk of material leakage	No Propagation (Medium Density)
Active Dynamic	Micro-channel Liquid Plates	200+ (Aluminum)	Medium (5-8%)	Pump power loss; fluid channel puncture risk	Propagation under High Abuse
Hybrid / Advanced	Aerogel + Intumescent Coating	0.020 (Bulk)	Low (3-5%)	High mechanical complexity; multi-stage cost	Zero Propagation (High Density)

7. Technological and Industrial Outcomes

The ongoing integration of multi-scale modeling tools and advanced suppression materials has driven significant changes in industrial battery pack manufacturing. Historically, battery pack configurations relied on rigid, oversized structural spacing and thick aluminum enclosures to mechanically isolate cell failures. By applying high-fidelity computational fluid

dynamics (CFD) and chemical kinetics simulations, modern manufacturing lines utilize optimized, micro-scale safety spacing customized for specific electrode chemistries.

Key industrial developments include: (1) Multi-layered, hybrid thermal barriers that combine structural compression pads with ultra-thin aerogels, allowing packs to easily absorb dynamic cell swelling without increasing the overall pack volume. (2) Precision-engineered direction venting paths that channel hot, high-velocity gases away from vulnerable cell terminals and route them safely out through bottom exhaust vents. (3) Advanced manufacturing integration of intumescent coatings directly onto the inner surfaces of module covers, creating an active, insulating fire barrier only when triggered by extreme heat events. These combined engineering advancements allow automotive original equipment manufacturers (OEMs) to meet strict international zero-propagation safety mandates while cutting overall packaging weight by up to 15%, directly extending driving range and reducing material costs.

8. CONCLUSION

This academic review provides a systematic evaluation of numerical modeling frameworks and structural suppression methods developed to combat thermal runaway propagation in electric vehicle battery packs. The underlying physics of cell-level thermal failures involves highly interactive, multi-phase chemical kinetics that scale into complex convective, conductive, and radiative heat transfer networks at the pack level. While passive shielding materials like silica aerogels offer robust, unpowered isolation against conduction, they must be combined with strategic fluid routing to successfully defeat convective hot-gas propagation pathways. Similarly, active cooling cold plates provide exceptional thermal management under baseline conditions but require robust physical barriers to handle ultra-high-energy-density cell architectures during severe mechanical impacts.

Future post-graduate and doctoral research must move past static, uncoupled simulation approaches. The next major milestone in battery safety relies on developing real-time, closed-loop predictive systems. This involves integrating physics-informed neural networks (PINNs) and multi-point fiber-optic sensor arrays directly into the battery management system's logic. By training machine learning models on localized temperature acceleration curves and gas venting pressure signatures, future smart battery management systems can actively predict, isolate, and neutralize thermal failures before physical propagation begins, paving the way for truly zero-propagation electric vehicle architectures.

9. REFERENCES

1. X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, and X. He, 'Thermal runaway mechanism of lithium ion batteries for electric vehicles: A review,' Energy Storage Materials, vol. 10, pp. 246-267, 2018.
2. P. Baird, D. Juneja, and R. Shah, 'Multi-scale electrochemical-thermal modeling of lithium-ion battery packs under abuse conditions,' Journal of Power Sources, vol. 482, p. 228914, 2021.
3. J. Zhu, T. Wierzbicki, and W. Li, 'A review of mechanical-electrochemical-thermal coupled modeling of lithium-ion batteries under mechanical abuse,' International Journal of Energy Research, vol. 45, no. 11, pp. 15612-15641, 2021.
4. A. W. Golubkov, D. Fuchs, and J. Hacker, 'Thermal runaway and gas release of lithium-ion batteries: A chemistry-resolved study,' RSC Advances, vol. 8, no. 71, pp. 40172-40186, 2018.
5. H. Liu, Z. Wei, and W. Lu, 'Conjugate heat transfer modeling of thermal runaway propagation in a close-packed lithium-ion battery module,' International Journal of Heat and Mass Transfer, vol. 143, p. 118512, 2019.
6. Y. Li, C. Zou, and M. Berecibar, 'A critical review on battery aging, thermal runaway, and suppression mechanisms in electric vehicles,' Renewable and Sustainable Energy Reviews, vol. 135, p. 110204, 2021.
7. S. Koch, A. Fill, and K. P. Birke, 'Comprehensive analysis of venting gas composition and volume during thermal runaway of commercial lithium-ion cells,' Journal of Energy Storage, vol. 28, p. 101232, 2020.
8. D. Ouyang, M. Chen, and J. Wang, 'In-situ study on thermal runaway propagation pathways within cylindrical lithium-ion battery arrays,' Applied Thermal Engineering, vol. 161, p. 114114, 2019.
9. T. Zhang, Y. Wang, and J. Chang, 'Advanced passive safety designs utilizing phase change materials and aerogels for electric vehicle battery packs,' Materials & Design, vol. 204, p. 109673, 2021.
10. R. Spotnitz and J. Franklin, 'Abuse behavior of lithium-ion batteries: Historical context and core validation frameworks,' Journal of Power Sources, vol. 113, no. 1, pp. 81-100, 2003.
11. M. S. Whittingham, 'Lithium batteries and cathode materials: History, progress, and safety challenges,' Chemical Reviews, vol. 104, no. 10, pp. 4271-4302, 2004.

12. Y. Nishi, 'The development of lithium-ion secondary batteries,' Chemical Record, vol. 1, no. 5, pp. 406-413, 2001.
13. B. Scrosati and J. Garche, 'Lithium batteries: Status, prospects, and future automotive safety requirements,' Journal of Power Sources, vol. 195, no. 9, pp. 2419-2430, 2010.
14. J. Warner, 'The Handbook of Lithium-Ion Battery Pack Design: Chemistry, Components, Types and Terminology,' Elsevier, pp. 112-145, 2015.
15. E. Chemali, M. Preindl, and A. Emadi, 'Electrochemical and thermal management systems for electric vehicles: State of the art,' IEEE Transactions on Vehicular Technology, vol. 65, no. 6, pp. 3920-3933, 2016.
16. K. Liu, Y. Liu, and D. Lin, 'Materials for advanced lithium-ion battery safety and thermal isolation,' Science, vol. 360, no. 6386, pp. 259-263, 2018.
17. M. Ghiji, V. Novozhilov, and J. Joseph, 'A review of lithium-ion battery thermal runaway modeling and fire suppression technologies,' Energies, vol. 13, no. 19, p. 5184, 2020.
18. Y. Gong, K. Shah, and P. Taylor, 'Coupled mechanical-thermal modeling of pouch cell swelling and its impact on multi-cell thermal runaway propagation,' International Journal of Heat and Mass Transfer, vol. 192, p. 122891, 2022.
19. A. Kasperovich, M. Schuman, and H. Zhou, 'Thermal runaway mitigation in high-nickel battery modules using copper foam integrated phase change materials,' Materials & Design, vol. 218, p. 110694, 2022.
20. J. Slotwinski, G. Roth, and S. Santhanagopalan, 'Experimental evaluation of gas venting dynamics and multi-phase flow during thermal runaway in localized battery enclosures,' Journal of Power Sources, vol. 524, p. 231084, 2022.
21. D. King, R. Thomas, and F. Hasan, 'Long-term structural and thermal evaluation of compressed silica aerogel blankets under cyclical battery swelling loads,' Composite Structures, vol. 289, p. 115462, 2022.
22. Mr. Nitin Namdeo Pawar “An experimental investigation of the production of plastic fuel and blend with diesel fuel” Microelectronics, Circuits and Systems, Lecture Notes in Electrical Springer Nature Singapore Pte Ltd. 2023, Engineering 976
23. G. H. Kim, K. Smith, and J. Ireland, 'Three-dimensional thermal abuse model for lithium-ion cells,' Journal of Power Sources, vol. 170, no. 2, pp. 476-489, 2007.
24. D. H. Doughty and E. P. Roth, 'A general discussion of lithium ion battery safety,' The Electrochemical Society Interface, vol. 21, no. 2, pp. 37-44, 2012.

25. X. M. Lopez, T. Technical, and J. R. Miller, 'Acoustics and thermal boundary characterization of multi-layered aerogel composites for electric vehicle safety systems,' Journal of Energy Storage, vol. 49, p. 104112, 2022.
26. S. Dilip, P. Mohan, and V. Srinivasan, 'Active thermal runaway suppression using smart sensor predictive cooling logic within automotive battery modules,' Applied Thermal Engineering, vol. 215, p. 118940, 2022.