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Safety Research and Analysis of Battery Accidents in Electric Vehicles: Current Status and Insights

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Abstract

Lithium-ion batteries (LIBs) are extensively examined and employed as the predominant power source for electric vehicles, attributable to their remarkable efficiency and energy density. Nonetheless, despite the accelerating global consumption of LIBs, thermal safety remains a significant concern. This paper conducts a comprehensive analysis of the thermal safety challenges associated with LIBs, focusing on the thermal behavior of LIBs, incidents of thermal runaway, and the safety protocols implemented at both the cell and battery pack levels. The initial segment of the discourse addresses the mechanisms of heat generation within LIBs, elaborating on the processes of heat production, dissipation, and retention within a cell. Subsequently, the principal factors contributing to thermal runaway, which may culminate in catastrophic failures, are identified and summarized within the investigation. These factors encompass internal short circuits, overcharging, and mechanical impairments. The study delineates a range of detection and mitigation strategies aimed at averting thermal runaways at both the cell and pack levels to diminish these risks. This encompasses the incorporation of additives that enhance thermal stability, alongside advancements in materials such as heat-resistant electrolytes and separators. Furthermore, engineering methodologies for improving thermal management are scrutinized to ensure the secure operation of LIBs in electric vehicles and to avert thermal runaway. These methodologies involve advancements in thermal, electrical, and mechanical designs.

Keywords: Safety, Thermal management, Batteries, Electric vehicles, Thermal runaway, Calorimetry Modeling

I. Introduction

The deployment of lithium-ion batteries (LIBs) as the primary powerhouse for electric vehicles (EVs) has surged in popularity, thanks to the myriad advantages they offer. These perks include heightened energy density, no memory effect, prolonged lifespan, and versatile architecture. A lithium-ion battery (LIB) cell is partitioned by an insulative barrier that separates the positive and negative electrodes. Throughout the charging and discharging cycles, lithium ions journey between the two electrodes, while electrons are driven by external circuits to deliver and reclaim electrical energy, as depicted in Figure. 1. The enhancement of cell voltage and capacity through careful material selection and innovative battery design enables the concurrent realization of elevated volumetric and gravimetric energy densities.

Notwithstanding the substantial increase in global EV sales in recent years, battery-associated thermal safety concerns are frequently cited as a significant contributor to catastrophic fire incidents. To fulfill the requisite power and energy specifications, an electric vehicle's battery pack generally comprises thousands of cells arranged in either series or parallel arrangements. This structural arrangement significantly amplifies the energy storage capacity of battery systems, which could lead to catastrophic outcomes should a severe safety issue arise. Conversely, LIBs within an automobile are subjected to severe operational conditions, including vibration and shock. They may also experience adverse effects from overcharging, excessive heat, short circuits, collisions, or nail penetration in extreme misuse scenarios. Such conditions heighten the likelihood of thermal runaway events occurring within the systems for onboard batteries. In conclusion, worries about thermal safety have become a formidable impediment to the market assimilation and extensive adoption of EVs.

In general terms, thermal, electrical, or mechanical abuses can precipitate thermal runaway. Mechanical damage typically manifests as penetration or impact, which may induce bus-bar short circuits or internal short circuits within a battery cell. Overcharging constitutes a form of electrical abuse that can lead to internal short circuits due to lithium plating and a cascade of exothermic side reactions. Elevated ambient temperatures and/or insufficient thermal management are the predominant instigators of thermal abuse. Raising the operational temperature of LIBs to an optimal level can enhance battery performance and curtail heat generation. Conversely, excessively high temperatures may result in separator degradation and the exothermic decomposition of electrode and electrolyte materials, both of which can precipitate internal short circuits. In practical scenarios, abusive actions typically occur sequentially rather than simultaneously. Ultimately, these abusive behaviors escalate into a rapid and intense heat-generating phenomenon, culminating in fire, smoke, and even explosions.

This manuscript provides a comprehensive analysis of the main thermal safety issues surrounding LIBs, with an emphasis on thermal behavior and thermal runaway modeling. Additionally, safety management techniques aimed at preventing the onset of thermal runaway and mitigating its detrimental effects post-occurrence are also scrutinized.

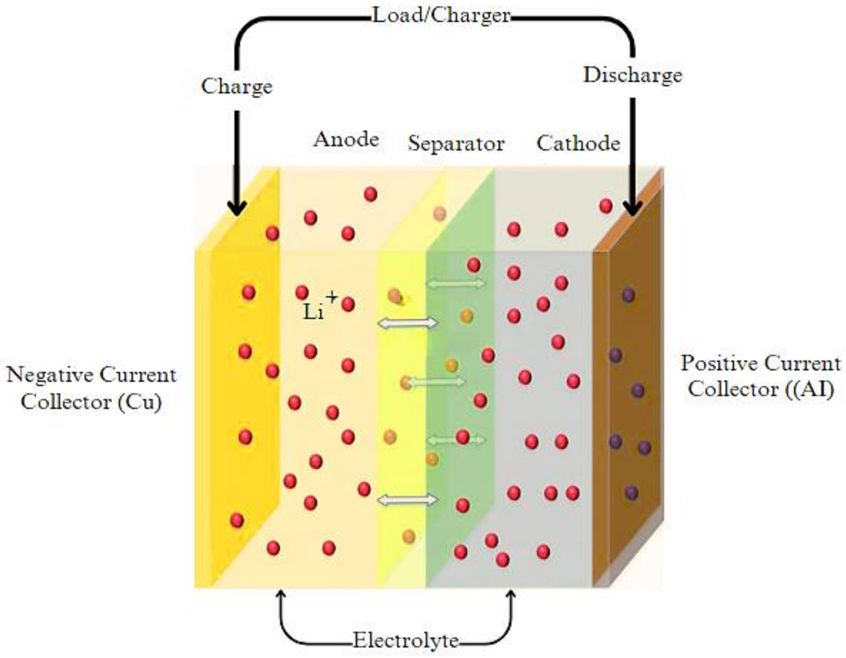

Figure 1. Lithium-ion battery schematic.

2. Investigations On Thermal Behavior Via Experiments

While thermodynamic modeling grounded in physical principles offers significant insights and theoretical frameworks concerning the mechanisms of heat generation within a Lithium-Ion Battery (LIB) cell, it is imperative that experimental methodologies are employed concurrently to estimate parameters and validate the model through empirical means. The fundamental techniques for quantifying temperature or heat transfer under defined thermal boundary conditions are referred to as calorimetric methods. The heat balance equation serves as a pivotal tool for calculating the quantity of heat produced in relation to the object under investigation.

2.1 Arc-Based Experiments

The Adiabatic Reaction Calorimeter (ARC) represents an instrument and methodology for the quantitative assessment of thermal energy generation. It possesses the capability to establish an adiabatic environment to facilitate the measurement of the thermal energy emanating from a sample. Traditional ARCs function effectively and are suitable for small quantities of reactants. However, there exists a notable trend in the evaluation of lithium-ion batteries (LIBs), particularly larger format LIBs, towards the advancement and deployment of large-scale ARCs. The subsequent energy balance equation can be employed to ascertain the rate of thermal energy generation:

$$q = MC_p \frac{dT}{dt} + hA(T_{\text{surf}} - T_{\text{well}}) \tag{1}$$

The intricate dance of thermal dynamics within a widely accessible 18650 lithium-ion cell was meticulously examined using an advanced high-throughput calorimeter-cycler testing device. This exploration enabled the collection of real-world insights regarding thermal release during the ebb and flow of discharge and charge cycles at diverse speeds. Lithium-ion batteries (LIBs) with diverse chemical compositions underwent examination employing an electrochemical calorimetric testing methodology (ARC-Arbin). The instantaneous heat generation rate was computed by the researchers, who further established a correlation between this rate and the discharge rates as well as cell impedance. The ARC apparatus was employed to ascertain a battery cell's specific heat capacity and to evaluate multiple methodologies for estimating heat production in large-format pouch cells, based on the ARC results regarding battery heat production rates. The ARC established an adiabatic environment in which commercial 40Ah NCM pouch cells were assessed at different charging and discharging rates. The testing protocols for adiabatic conditions were meticulously designed to replicate scenarios of elevated heat generation in the absence of cooling systems, thereby amplifying the effects of self-heating.

2.2 IHCC Based Experiments

The Isothermal High-Performance Calorimeter (IHCC) offers a meticulously regulated isothermal testing environment, thereby ensuring that a consistent temperature is upheld throughout the evaluation of battery efficiency. The integration of a temperature-stabilized heat sink, which is directly connected to the battery cells, serves as a dependable methodology for sustaining the isothermal state. Alternatively, one may utilize a single- a pivotal temperature-controlled sanctuary that enhances thermal circulation between the sanctuary and the power cells. Within empirical scientific investigations, two predominant classifications of IHCCs are frequently employed. The initial classification pertains to micro-calorimetry. In this approach, a pair of battery cells—a reference cell and a sample cell—are positioned within distinct heat sinks. The subsequent classification is characterized by a unified heat sink configuration that harnesses the Peltier effect or power compensation techniques to manage the temperature of the sink and to quantify the heat flow.

The captivating thermal characteristics of Lithium-Ion Batteries (LIBs) featuring an array of cathode materials are scrutinized through a sophisticated isothermal micro-calorimetry technique. The measured heat flow rate identified at the IHCC serves as a pivotal thermal reference point. An integrative system that amalgamates electrochemical and calorimetric measurement techniques—which encompasses an X-ray diffraction apparatus and a single-sink micro-calorimeter—is employed to scrutinize the irreversible thermal behaviors of LIBs under elevated temperatures and cyclical conditions. By utilizing half-cells for each electrode in conjunction with a dual-sink isothermal calorimeter, researchers have adeptly executed precise electrochemical calorimetry of LIBs. The results indicated that the IHCC is capable of accurately detecting thermal peaks associated with phase transitions. The temporal dependency of heat generation is elucidated through the use of a dual-sink micro-calorimeter boasting remarkable accuracy. By employing a dual-sink isothermal micro-calorimeter, a novel in-situ measurement technique has been crafted to assess the heat generation rate at room temperature. Additionally, the precision of the modeling at lower and moderate current densities is examined using an electrochemical micro-calorimeter on meso-carbon micro-bead half cells and full cells. In clarifying the implications of electrolyte additives, voltage-sensitive parasitic heat production, and time-sensitive parasitic heat generation in LIBs, the isothermal micro-calorimetry technique offers substantial benefits.

In conclusion, calorimetry is predominantly utilized in experimental investigations concerning the thermal behavior of LIBs. Calorimeters designed for large-format commercial automotive batteries may be meticulously customized and configured. Notably, Accelerating Rate Calorimetry (ARC) has also achieved recognition as a widely utilized instrument for conducting thermal runaway assessments on batteries, owing to its self-heating operational principle and its adaptability to challenging testing conditions.

3.Modeling The Runaways Thermally And Safety Testing

In the demanding realm of electric vehicle usage, the harsh operational conditions can ignite instances of thermal runaway triggered by mechanical, electrical, or thermal pressures. This situation poses a formidable risk to the security of battery systems and the automobiles they power. Thermal runaway denotes a state that may develop within a battery cell when heightened temperatures trigger a cascade of exothermic reactions that elevate the temperature and promote additional deleterious reactions. These increased temperatures may result from the gradual buildup of heat that is not released efficiently in a timely manner or from externally induced rapid reactions that transpire over a finite duration. This section will encompass a comprehensive analysis of the modeling of thermal runaway across various triggering scenarios, alongside a discourse on experimental methodologies related to mechanical, electrical, and thermal stresses.

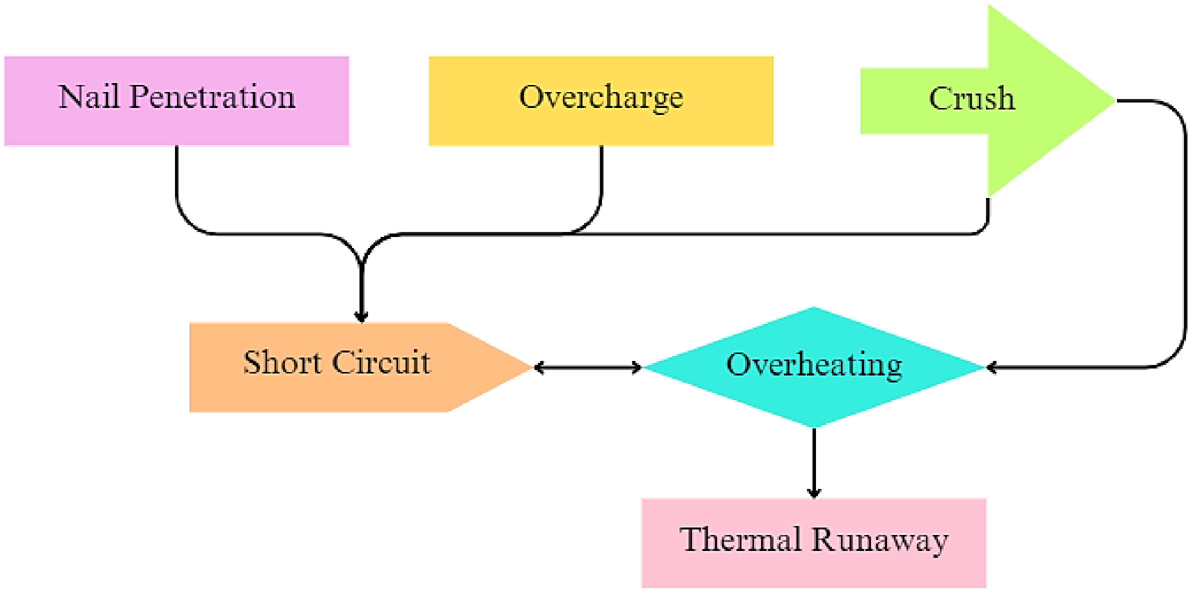

Figure 2. Relationship between Various Abuse Situations and Thermal Regulation

3.1 Overheating

Overheating exemplifies the phenomenon of thermal runaway propagation, as illustrated in Figure 2, and may be induced by elevated ambient temperatures or other detrimental practices.

A predictive framework has been established for analyzing the behavior of innovative cell dimensions and electrode materials subjected to thermal evaluation in an oven environment, grounded in the principles of reaction kinetics and the thermal properties inherent to battery cells. The aim is to elucidate the characteristics of thermal abuse in expansive lithium-ion batteries (LIBs) crafted for automotive uses, a captivating three-dimensional model manifests, weaving together the intricate dimensions and geometry of cell components with the dynamic spatial distribution of temperature and material characteristics. An all-encompassing three-dimensional thermal model emerges, harmonizing the structural elements of the battery, the mechanisms that generate heat, and a variety of heat-transfer phenomena—including conduction, convection, and thermal dissipation—proposed as an innovative methodology for evaluating exposure within an oven environment.

3.2 Battery Abuse Experimental Tests

The existing methods for assessing battery abuse can be classified into three distinct categories:

(a) Evaluations concerning thermal abuse, which encompass combustion simulations, thermal endurance assessments, situations involving overheating, and similar phenomena.

(b) Evaluations associated with electrical misconduct, which include occurrences of short-circuiting, overcharging, excessive discharging, and analogous scenarios.

(c) Evaluations related to mechanical abuse, which comprise mechanical impact assessments, exposure to vibrational stress, drop testing, nail penetration tests, immersion conditions, and crushing force evaluations, among other considerations.

3.3 Advanced Experimental Approach Applied To Thermal Runaway Investigation

In accordance with the widely recognized thermal analysis methodologies delineated earlier, an array of intricate and interdisciplinary experimental approaches and apparatuses is being methodically integrated to enhance our understanding of thermal runaway phenomena. These methodologies encompass, yet are not confined to, X-ray diffraction, Industrial Computed Tomography (CT), Electrical Resistance Tomography (ERT), and Nuclear Magnetic Resonance (NMR).

3.4 Thermoregulation Of The Runaway Process: Forecast And Detection

While conventional Battery Thermal Management Systems (BTMSs) are anticipated to alleviate challenges associated with thermal generation and accumulation, particularly within elevated temperature settings, their responsiveness and efficacy in averting thermal runaway incidents may not meet optimal standards. A diverse array of prognostic and diagnostic methodologies have been established to enhance the operational efficacy of BTMSs, facilitating the advancement of early warning systems and preventive strategies prior to the manifestation of thermal runaway phenomena. This section will scrutinize research initiatives that evaluate the safety of Lithium-Ion Batteries (LIBs) alongside the methodologies employed to predict and identify thermal runaway occurrences, with a specific focus on methodological frameworks and device architectures.

To illuminate the chances of thermal runaway, an extensive exploration of heat creation and release was undertaken. This investigation led to the creation of a dimensionless parameter known as the Thermal Runaway Number (TRN), which acts as a crystal ball to predict thermal runaway events and outline the thermal safety design criteria within a lithium-ion battery assembly. To enhance the depth of the inquiry, an innovative measure called State-of-Safety (SOS) was introduced to evaluate the security of energy storage systems based on the idea that increased levels of abuse inversely affect safety outcomes. To prevent thermal runaway, a pseudo two-dimensional transient heat transfer model was crafted to forecast time-sensitive temperature fluctuations. A multi-layered electrolyte battery cell was scrutinized, focusing intently on the dynamics at the component level.

The crafted model showcased remarkable proficiency in forecasting the temperature.characteristics associated with the propagation of combustion flames in the radial direction of heat pellets. To facilitate the real-time detection of Internal Short Circuits (ISC), frameworks integrating electrochemical-thermal coupling and equivalent circuit models were formulated. An approach designated as Recursive Least Squares was employed to estimate the pertinent indicator parameters. Grounded in Fourier's law and principles of energy conservation, a model-based methodology was established to forecast battery thermal runaway. Assessments based on Accelerating Rate Calorimetry (ARC) were utilized to ascertain the necessary parameters.

Harnessing the power of a Back-Propagation Artificial Neural Network (BP-ANN), an inventive strategy was crafted to forecast the zenith surface temperature of a battery while it is charging. The thermal profiles produced by a battery cell in a heated chamber were harnessed to educate the BP-ANN. In order to foresee a thermal runaway incident in a battery module used within an uninterruptible power supply system, a threshold-oriented parameter approach was devised. Relays were utilized to orchestrate charging operations through the vigilant observation and adjustment of temperature and voltage within predetermined boundaries.

A meticulous framework has been constructed to foresee the spread of thermal runaway by leveraging voltage and temperature insights extracted from Battery Management Systems (BMSs). This methodology unfolds in four key phases: (a) the relentless monitoring of a battery cell to determine if it is experiencing a thermal runaway scenario by measuring the speed of temperature rise across a range of thermal thresholds; (b) the evaluation of battery voltage accompanied by calculating the rate of voltage drop, thus declaring an irreversible thermal runaway occurrence if it dips below a defined limit; (c) the scrutinization of neighboring cells to the runaway cell while executing steps (a) and (b) to assess the risk of thermal runaway or irreversible failure occurring; (d) should step (c) uncover a thermal runaway cell, the BMS will trigger an alert to signal the spread of thermal runaway behavior.

A device has been ingeniously crafted to identify instances of thermal runaway in nickel-cadmium batteries. The current sensor embedded within this invention collaborates with a converter to transform the measured current into a pulse train, with frequencies that are directly tied to the current's intensity. The fluctuations in the pulse train's frequency enable the calculation of the charging current gradient, a crucial factor for recognizing thermal runaway occurrences. An avant-garde methodology based on an increase in internal resistance (impedance) and/or conductance (admittance) has been formulated to detect thermal runaway events that occur during the battery charging phase. A comprehensive system for the detection and prevention of thermal runaway has been established. This system utilizes sensors for temperature, gas, smoke, and flames, alongside a fire suppression mechanism that activates when a thermal runaway event is identified. Tesla Motors possesses patents that encompass a variety of strategies for detecting battery thermal runaway by monitoring operational parameters like battery pack pressure and insulation resistance. To guarantee the effectiveness of their detection system, specialized sensors have been integrated, including optical fibers, thermally interruptible electrical conductors, and electrical conductors featuring thermally fusible insulators.

The most conspicuous indication of a thermal runaway incident is unequivocally a marked elevation in temperature along with the discernible emergence of smoke or flames. Methods predicated on temperature detection are likely to be trustworthy and efficient in triggering passive safety mechanisms. Nevertheless, the temperature is often measured at the exterior of the cell, which creates a significant gap between the surface and heart temperatures during thermal runaway incidents. This disparity consistently jeopardizes thepredictive capacity to swiftly identify thermal runaway occurrences. Fluctuations in operational parameters, such as resistance and voltage, may serve as precursors to impending thermal runaway, thereby enhancing the precision of early-stage predictions. Nevertheless, before the practical application of these events, further investigation is imperative into the fundamental systems that govern them.

3.5 Strategies For Safeguarding Against Thermal Runaway

It harnesses innovative strategies to delay the onset and alleviate the harmful effects of thermal runaway events in battery ecosystems, which include individual cells as well as entire system architectures.

The fusion of safety vents, shutdown additives, and current interruption devices, alongside a myriad of technological innovations, has revolutionized the very framework of safety protocols within the cellular realm. The examination of the separator, electrolyte, and active materials can be approached from the perspective of the safety mechanisms intricately woven into the fabric of a battery cell. With regard to the integration of safety additives in batteries employing various cathode materials, innovative techniques for coating and doping have been suggested.

The focal point of research into anode safety revolves around the advancement and resilience of the solid-electrolyte interphase (SEI) layer. Simultaneously, rigorous studies have been pursued concerning the electrolyte with the aim of bolstering battery safety, particularly through the addition of non-flammable substances, redox shuttle materials, shutdown additives, stable electrolyte salts, and ionic liquids. Solid-state electrolytes offer a promising solution to the hurdles surrounding electrolyte safety due to their inherent thermal characteristics and their ability to autonomously form a barrier that prevents internal short circuits (ISC). The separator is a vital component in lithium-ion batteries (LIBs), as it obstructs direct interaction between the anode and cathode while concurrently aiding the flow of lithium ions throughout the battery. A wealth of academic literature sheds light on instances of thermal runaway linked to the melting of separators. As a corrective strategy to this dilemma, separators with high melting points and low shrinkage rates are presently in the developmental phase. To alleviate issues related to thermal abuse or overcharging, a shutdown separator effectively seals the micropores within the film, thereby halting ionic movement between the electrodes and preventing short circuits. In addition to these strides in component design, safety measures at the cell level are recognized as crucial for preventing the spread of thermal events throughout a module or pack.

Furthermore, it has been documented that self-rejuvenating elements, including conductive polymer.composites and ceramic positive temperature coefficient (PTC) materials, have been incorporated into the designs of battery cells. These components enable a battery cell to disconnect in response to overcurrent or overheating and subsequently reactivate when the temperature decreases.

4. Results

The results of the examination of thermal safety concerns related to lithium-ion batteries (LIBs) used in electric cars are explained in the section that follows. The findings highlight thermal dynamics, thermal runaway events, and the efficacy of several safety management techniques at the level of the individual battery cell as well as the overall battery pack. The results are methodically arranged into subsections that discuss heat generation, dissipation, buildup, and thermal runaway avoidance techniques.

4.1Heat Generation and Dissipation in LIBs

A battery cell's rate of heat production was assessed under various loading scenarios. The findings showed that higher discharge rates are associated with a considerable increase in heat generation. The observed waste of thermal energy suggests that, in the event that sufficient cooling systems are not present, the battery's interior temperature may beyond safe limits, hence presenting a danger of thermal runaway (table 1).

Table1 : Lithium-Ion Battery Thermal Dynamics under Various Discharge Conditions

Condition	Heat Generation Rate (W/m²)	Heat Dissipation Rate (W/m²)	Internal Temperature (°C)
High Discharge Rate	600	350	60
Low Discharge Rate	100	80	30
Medium Discharge Rate	300	250	45

4.2 Events and Triggers of Thermal Runaway

Critical factors that contribute to thermal runaway were identified by the investigation, including mechanical impairment, internal short circuits, and excessive charging. The buildup of internal temperatures over the defined safety limits was substantially correlated with the occurrence of thermal runaway (table 2).

Table 2 : Incidents of Thermal Runaway Under Various Stress Conditions

Stress Condition	Trigger Mechanism	Time to Thermal Runaway (s)	Maximum Temperature (°C)
Internal Short Circuit	Electrical	15	450
Mechanical Damage (Crush)	Physical	10	460
Overcharging (200%)	Electrical	30	420

4.3 Strategies for Safety Management

The effectiveness of various safety management techniques, including the use of high-tech cooling systems and heat-resistant materials, was methodically evaluated. The use of chemicals designed to improve thermal stability showed a notable reduction in the likelihood of thermal runaway events (table 3).

Table 3 the efficiency of safety management techniques

Safety Strategy	**Reduction in Thermal Runaway Incidents (%)**	**Improvement in Heat Dissipation (%)**
Additives for Thermal Stability	30	22
Advanced Battery Management Systems	45	35
Enhanced Cooling Systems	40	30
Heat-Resistant Electrolytes	25	18

4.4 Advances in Thermal Management Engineering

The study also looked at developments in engineering that are focused on improving mechanical, electrical, and thermal arrangements. These developments greatly increased overall safety and produced a more uniform temperature distribution throughout the battery assembly (table 4 and figure 3).

Table 4 Engineering advancements'.

Design Improvement	Temperature Uniformity (%)	Reduction in Hot Spots (%)	Increase in Operational Safety (%)
Advanced Thermal Designs	85	30	40
Improved Electrical Layout	75	25	35
Enhanced Mechanical Structure	80	28	38

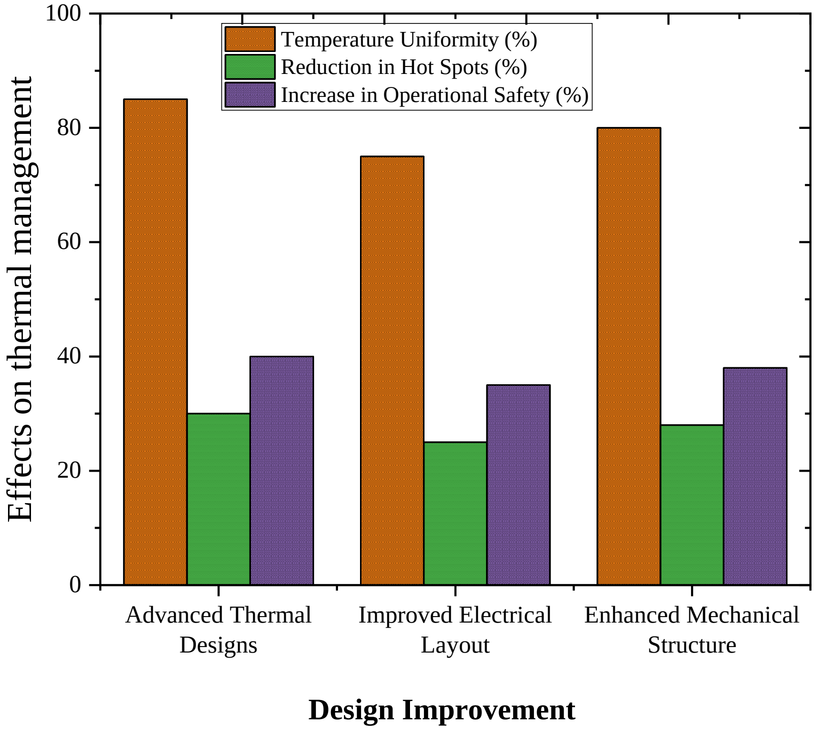

Figure 3 : strategies of Engineering advancements

This conceptual framework fits the particular facts and conclusions of your investigation. Each table has to have a clear caption and be cited within the book.

5.Conclusion

This scholarly article embarks on a comprehensive and organized exploration of the technological breakthroughs relevant to the thermal safety dilemmas linked with lithium-ion batteries (LIBs). It spans a vast spectrum of topics, including (a) the intricacies of thermal dynamics, theoretical simulations, and practical evaluations; (b) the modeling of thermal runaway and empirical inquiries; and (c) innovative tactics for bolstering safety within LIB designs.

By delving into the core electrochemical processes involved, the phenomena of heat generation and rising temperatures have been illuminated. Traditionally, thermal modeling employs a collection of interrelated partial differential equations to express the nonlinear behaviors displayed by LIBs under diverse charging and discharging conditions. To faithfully depict the thermal behaviors of batteries with varying degrees of accuracy, a multitude of electrochemical models, including one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D) frameworks, have been cataloged in academic discourse.The pseudo-two-dimensional (P2D) model stands out as particularly advantageous due to its effective compromise between computational efficiency and modeling precision. Moreover, modeling strategies that integrate temperature-dependent parameters have been devised to enhance modeling fidelity through the coupling of electrochemical and thermal dynamics. Additionally, systematic approaches for investigating the thermal characteristics of LIBs are succinctly articulated.

Given the pronounced nonlinearity inherent in the thermal runaway phenomenon and its myriad initiating factors, the modeling frameworks for thermal runaway events in LIBs are intrinsically intricate. Multiphysics domains, encompassing mechanical, electrical, thermal, and electrochemical attributes, must be incorporated. Thermal runaway propagation modeling typically operates within a three-dimensional framework and accounts for multiple cells. Empirical equations and experimental findings are frequently employed in such contexts to mitigate model complexity while maintaining acceptable levels of accuracy. Furthermore, empirical methodologies addressing mechanical, electrical, and thermal stresses have been established. Testing protocols must accurately replicate the extreme conditions encountered in electric vehicle (EV) applications to be effective in the investigation of thermal runaway. References to advanced measurement techniques such as electrical resistance tomography (ERT), computed tomography (CT), and nuclear magnetic resonance (NMR) are also provided.

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