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by Ashutosh Ranjan

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Design and Development of Thermal Runaway Chamber for Testing and Investigation of Hazardous Gases and Safety of Li-ion Batteries

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by

Ashutosh Kumar Ranjan
(Roll no. 24/PSY/06)

Under the supervision of
Prof. M. Rizwan
(Professor)
Co-supervisor
Dr. Sikandar Ali Khan
(Assistant Professor)



To the
Department of Electrical Engineering
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Sahbad, Daulatpur, Main Bawana Road, Delhi-110042. India

May, 2026



DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)
Shahbad, Daulatpur, Main Bawana Road, Delhi-42

CANDIDATE'S DECLARATION

I Ashutosh Kumar Ranjan (24/PSY/06) hereby certify that the work which is being presented in the thesis entitled “**Design and Development of Thermal Runaway Chamber for Testing and Investigation of Hazardous Gases and Safety of Li-ion Batteries**” in partial fulfillment of the requirements for the award of the Degree of Master of Technology, submitted in the Department of **Electrical Engineering with Power System specialization**, Delhi Technological University is an authentic record of my own work carried out during the period from 2024 to 2026 under the supervision of Prof. M. Rizwan and co-supervision of Dr. Sikandar Ali Khan.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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CERTIFICATE BY THE SUPERVISOR(s)

Certified that Ashutosh Kumar Ranjan (24/PSY/06) has carried out their search work presented in this thesis entitled **“Design and Development of Thermal Runaway Chamber for Testing and Investigation of Hazardous Gases and Safety of Li-ion Batteries”** for the award of **Master of Technology** from Department of Electrical engineering, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

Signature

Prof. M. Rizwan

Professor

Department of Electrical
Engineering, Delhi Technological
University, Delhi-110042

Signature

Dr. Sikandar Ali Khan.

Assistant Professor

Department of Electrical
Engineering, Delhi Technological
University, Delhi-110042

Date:

ABSTRACT

Li-ion batteries are widely utilised in EVs and portable devices due to their ability to store significant energy and their longevity. If they overheat, they can become very hazardous and may ignite or burst. This research examines the reasons Li-ion batteries overheat and the impact on their performance. It also explores methods to prevent this from occurring. The research revealed that charging Li-ion batteries excessively, short circuits, and elevated temperatures are among the primary causes of Li-ion battery failures. Employing systems to cool Li-ion batteries and managing them with Battery Management Systems (BMS) can significantly enhance the safety and reliability of Li-ion batteries. These systems are capable of identifying issues promptly. Prevent major mistakes from occurring. We must continue researching and developing technology to ensure lithium-ion batteries are safe and environmentally friendly. Li-ion batteries play a crucial role. The results indicate that thermal runaway begins with a chain of exothermic reactions, encompassing Solid Electrolyte Interphase (SEI) breakdown, electrolyte deterioration, separator malfunction, and cathode breakdown, potentially raising cell temperatures above 200–300°C and posing fire or explosion risks. The research also emphasizes that sophisticated thermal management systems can lower battery temperatures by around 25–35°C, and AI-driven monitoring methods can deliver early alerts 5–10 minutes prior to critical failure. Moreover, battery monitoring models based on deep learning, such as GRU-RNN and BiGRU-RNN, were assessed for real-time evaluation of battery health. Experimental findings from the use of 18650 lithium-ion batteries under LA92 and US06 driving cycles showed that the GRU-RNN model performed better, presenting MSE values of 0.0013 and 0.0011, RMSE values of 0.0018 and 0.0017, and processing times of 8.7 s and 10.05 s, respectively, surpassing the BiGRU-RNN model in terms of both precision and computational efficiency. The research finds that preventing thermal runaway necessitates superior battery materials, efficient thermal control, smart Battery Management Systems (BMS), and AI-driven monitoring methods. Integrating real-time sensing with machine learning enhances battery safety, reliability, and performance, facilitating the safer use of lithium-ion batteries in electric vehicles and energy storage systems.



DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)
Shahbad, Daulatpur, Main Bawana Road, Delhi-42

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2. , D. Kumar, H. Raj, A. Kumar, A. K. Ranjan M. Rizwan, and A. K. Panwar, "A comprehensive review on thermal runaway in lithium-ion batteries: Triggers, gas emissions, and safety implications," in Proc. 2nd Int. Conf. Sustainable Power and Energy Research (ICSPER 2025), Srinagar, India, Jul. 12, 2025.

Patent

3. D. Kumar, A. K. Ranjan M. Rizwan, M. Singh, and A. K. Panwar, "Testing chamber for evaluating thermal runaway behaviour of energy storage modules," Indian Patent Application IN202611009870 A1, published Mar. 13, 2026

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List of Symbols and Abbreviations

Abbreviations	Full form
AI	Artificial Intelligence
BMS	Battery Management System
FTIR	Fourier Transform Infrared Spectroscopy
GC-MS	Gas Chromatography–Mass Spectrometry
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LIB	Lithium-ion Battery
ML	Machine learning
NCA	Nickel Cobalt Aluminium Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
SEI	Solid Electrolyte Interphase
SOC	State of Charge
SOH	State of Health
SS304	Stainless Steel 304
TES	Thermal Energy Storage
TR	Thermal Runaway
VOCs	Volatile Organic Compounds

Chapter 1: Introduction

1.1 Overview of Energy Storage Technologies

Energy storage technologies are essential for closing the gap between energy production and consumption over time, especially in a time when switching to renewable energy sources is very important. Technologies are providing an overall assistance in the integration of renewable energy (intermittent wind/solar) into the grid, as well as providing support for improving the overall reliability and stability. Energy storage encompasses a varied and diverse group of methods for Energy Storage; it represents a range of mechanical, electrochemical, thermal, or chemical. These classifications of methods consist of mechanical, chemical, thermal, and electrochemical systems, each suited for different applications related to energy systems. Chemical energy can be produced from electricity through a chemical reaction for the purpose of long-term storage. When chemical energy needs to be used again for energy production, the chemical energy can be converted back to electrical energy. Chemical storage represents one of many methods by which chemical storage may be performed; additionally, chemical storage technologies such as hydrogen fuel cells have a very high density of storage capability relative to other chemical storage technologies, but also require significant investment to build and develop the necessary infrastructure to produce and distribute [1]. Technologies known as thermal energy storage, such as molten-salt storage, store thermal energy that can be utilized directly for heating and cooling or later transformed into electrical power. The decoupling of energy supply from immediate demand is made possible by TES systems, which are essential to the integration of renewable energy.

1.2 Li-ion Battery Working Principle

When an external load is applied, the complex processes of lithium-ion migration and electron flow begin, governing the fundamentals of lithium-ion batteries' operation. An electrolyte, a separator, and two electrodes anode and cathode make up the basic parts of a Li-ion battery, as shown in Fig. 1.1 Graphite and carbon compounds usually make up the anode, while lithium metal oxides like lithium cobalt oxide (LCO),

lithium iron phosphate (LFP), or lithium nickel manganese cobalt oxide (NMC) make up the cathode. There is a porous membrane separator between the anode and the cathode that electrically isolates the two electrodes; as a result, electrons are unable to flow through it. Although the electrolyte may be solid or liquid, most lithium-ion batteries use liquid electrolytes. The electrolyte is used to soak the anode and cathode. Li^+ is one of the ions carried by the electrolyte [2]. To efficiently collect and conduct the electrical current, the anode and cathode's active materials are applied to a current collector, which is usually made of copper or aluminium.

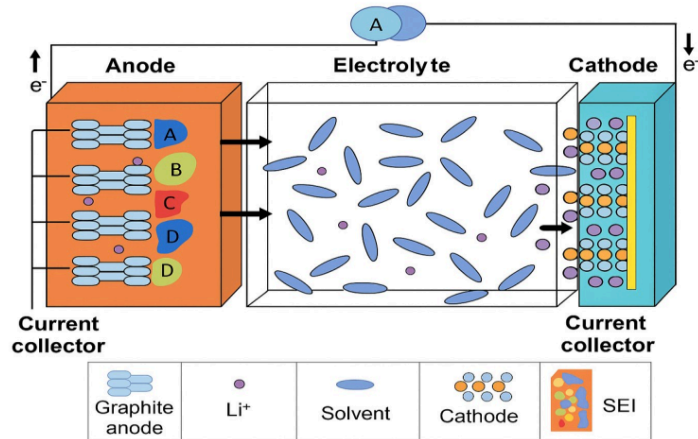
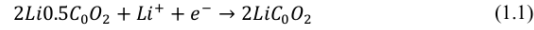


Fig. 1.1 Schematic diagram of li-ion battery [3].

Lithium ions are intercalated inside the graphite layers of the anode when it is completely charged. In the process of discharging or powering a device, lithium ions leave the anode and move through the electrolyte in the direction of the cathode. The lithium ions travel to the cathode via the separator's nanopores. The electrical energy needed to operate the gadget is produced concurrently by the release of electrons, which move through the external circuit. The migrating electrons recombine with the ions at the cathode, while the lithium ions intercalate into the lithium metal oxide structure as they arrive. In the process of charging, the opposite takes place. After

leaving the cathode and moving through the electrolyte, lithium ions re-intercalate into the anode. The power source forces the appropriate electrons to go across the external circuit before they recombine with the ions at the anode [4]. The following is an example of a discharge reaction for an LCO cathode chemistry:

Reaction at positive electrode (cathode):



Reaction at the negative electrode (anode):



The positive and negative electrodes are commonly referred to as the "cathode" and "anode," respectively; however, this classification is only accurate during a battery's discharge cycle. The anode really becomes the positive electrode and the cathode the negative electrode when their polarity switches during the charging process. By physically separating the electrodes while allowing lithium ions to migrate, the separator plays a crucial part in preventing a short circuit between the anode and cathode. These parts are used to create battery cells in a variety of shapes and sizes, including prismatic, pouch, and cylindrical cells [5]. One battery cell may be used, or several cells may be connected in series within a module, depending on the particular use case. It is possible to arrange many cells in parallel to boost a battery system's capacity. A group of these connected modules makes up a full battery system for automotive applications.

1.3 Types of Li-Ion Battery

1.3.1 Cylindrical Type Cell

Cylindrical lithium-ion cells use a "jelly-roll" design, where long strips of anode, separator, and cathode get rolled up together and packed inside a metal can usually stainless steel or aluminium. During manufacturing, the electrodes are first coated with active materials on current collectors (copper for the anode, aluminium for the cathode), then dried, pressed flat, and cut to size, shown in Fig. 1.2. Once that done, the layers are rolled up, tabs are attached, and the roll slides into the cylindrical can. In a dry room, workers inject the electrolyte, then seal the cell with a cap that includes safety features. Next comes formation cycling, which helps build the SEI layer. Afterward, every cell gets graded for capacity and impedance. These cells are tough,

easy to cool, and fit right in with automated production. That's why you will see them everywhere, from electric vehicles to power tools to big battery packs. Still, their round shape doesn't pack perfectly tight, so it will end up with some empty space between cells in a module.



Fig.1.2 Cylindrical Type Battery [6].

1.3.2 Prismatic Type Cell

Prismatic lithium-ion cells come in tough, rectangular metal cases usually aluminium. Instead of winding the electrodes, manufacturers cut the anode and cathode into rectangles, layer them with separators, and stack everything inside the case. They weld tabs onto the ends of the stack, inject electrolyte in a dry room, then seal up the top with a laser or resistance welder. Like other cells, these go through formation and aging to fine-tune performance.

The prismatic type battery packed tightly and have flat sides, which makes it easier to design battery modules and packs shown in Fig.1.3. That's why observe them a lot in electric vehicles and energy storage setups. Still, they're not perfect. The way stress spreads inside is tricky, and if they don't stack everything just right, there's a higher chance of short circuits.

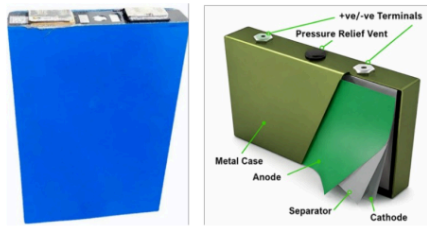


Fig. 1.3 Prismatic Type Cell [6]

1.3.3 Pouch Type Cell

Pouch-style lithium-ion cells lack a metallic casing. The electrodes are contained within a pouch crafted from laminated aluminum-plastic film. To produce these cells, individuals initially create sheets for the anode and cathode. They achieve this by coating, drying, and then calendaring. Arrange them in a flat rectangle. Tabs are welded onto the ends of the anode and cathode sheets.

Then they placed the stack inside the pouch. As illustrated in Fig. 1.4, workers use heat to seal three sides of the pouch. They subsequently inject the electrolyte through the exposed edge and vacuum seal it to eliminate any gas bubbles. Once the pouch type lithium-ion cell undergoes formation and aging, it is prepared for installation in a module. Lithium-ion pouch cells are the lightest among all cell types. They can effortlessly accommodate various spaces and forms. This makes pouch-style lithium-ion cells ideal for devices such as smartphones, tablets, drones, and compact electric vehicle batteries. Pouch-type lithium-ion cells aren't the most durable. They may be delicate

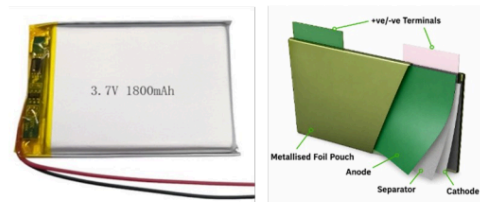


Fig. 1.4 Pouch Type Cell [6]

1.4 Li-ion Batteries are Categorised by the Cathode-Based

Lithium-ion batteries are classified by their cathode composition into LCO, LFP, NMC, and NCA families because the cathode composition dominates the battery's performance with respect to energy density, power, cycle life, thermal stability, safety, and cost. By segregating battery cells based on their positive-electrode composition, engineers, manufacturers, and designers can easily and quickly pick the best chemistry for various applications. For instance, LFP cells are selected for applications that demand safety and long life (like home storage systems and buses), NMC and NCA are used for high energy, long range EVs, and LCO cells are used for portable devices that are small and have high energy demands. Since different cathode families compose batteries that are built and designed with similar chemistry, this approach to classification simplifies standards, testing, and recycling protocols and regulations.

1.4.1 Li-NMC (Lithium Nickel Manganese Cobalt Oxide, LiNiMnCoO_2)

The NMC material is an oxide-based cathode that contains nickel, manganese, and cobalt in order to achieve a good balance between high energy density, acceptable power density, and cycle life. The various NMC ratio formulations (like 111, 532, 622, and 811) control the amount of nickel to maximize energy density while sacrificing stability and cycle life.

1.4.2 Li-NCA (Lithium Nickel Cobalt Aluminium Oxide, LiNiCoAlO_2)

NCA uses a nickel-dominant layered oxide containing trace quantities of cobalt and aluminum offering exceedingly high energy and excellent power density. It is utilized in long-distance EVs where maximum range is essential, but it exhibits reduced thermal stability and a shorter lifespan compared to LFP and NMC need effective thermal management and battery management systems.

1.4.3 LFP (Lithium Iron Phosphate, LiFePO_4)

The LFP chemistry is based on an iron phosphate cathode, which uses a type of olivine structure. The material is extremely thermally stable, safe, and durable, cycling for more than 3000 to 6000 cycles. It is free of cobalt and nickel, making it less expensive

and environmentally friendly; however, the battery provides reduced specific energy and lower voltage compared to NMC/NCA cells.

1.4.4 LCO (Lithium Cobalt Oxide, LiCoO_2)

It is among the oldest Li-ion chemistries that have excellent volumetric energy density and constant voltage output, hence widely used in smartphones, laptops, and small electronic gadgets. Nevertheless, LCO is less thermally stable and has a short cycle life and high cost owing to cobalt, which makes it unsuitable for large-scale applications.

1.5 Summary

Energy storage systems are crucial elements for electric vehicles, large-scale energy storage solutions, and portable electronic devices. Energy storage systems can be classified according to their operational modes, which consist of mechanical, thermal, and electrochemical systems. Among these categories, electrochemical energy storage systems, such as LIBs, often carry thermal runaway risks linked to their high energy density and intricate electrochemical reactions. Thermal runaway is an exothermic process that results in heat generation due to overcharging, internal short circuits, physical stress, and elevated temperatures. The reaction process results in the breakdown of electrolytes, degradation of the separation film, release of oxygen from the cathode, and eventually overheating, which presents fire and explosion risks. Conversely, mechanical energy storage systems such as pumped hydro and compressed air do not face thermal runaway issues since they do not involve any chemical reactions. Moreover, the thermal stability of lithium-ion batteries relies on the composition of their cathode material; hence, LFP batteries possess greater thermal stability compared to NMC and NCA. Therefore, efficient battery management systems (BMS), thermal management systems (TMS), and predictive health monitoring strategies are essential to avert thermal runaway risks in modern energy storage solutions.

Chapter 2: Literature survey

A literature survey is a thorough and comprehensive examination of the many studies conducted by many scholars on a chosen topic, together with a summary of their findings. The formation and characteristics of nanoparticles have drawn the interest of several scientists, technologists, and engineers in contemporary civilization. Fundamental studies on 18650 cells were carried out by Golubkov et al. (2014), who supplied vital quantitative information for chamber design. Their main discovery was that the minimal chamber size required to dilute explosive combinations is directly determined by the 1.5 litres of gas that a single cell can create per Amp-hour capacity. They determined that carbon dioxide (CO₂), carbon monoxide (CO), hydrogen (H₂), and other hydrocarbons were the main gas components, emphasising the need for sturdy, pressure-rated structures and design that is explosion-proof [7].

In his research on the thermal and gaseous characteristics of large pouch Li-ion power batteries during thermal runaway, K. Zou et al. (2021) discovered that TR resulted in exceedingly elevated internal temperatures, a sudden rise in pressure, and considerable quantities of hazardous gases, mainly CO, CO₂, H₂, and lighter hydrocarbons. Gas generation increases with cell capacity, the study noted, posing serious safety issues for exhaust behaviour, gas management, and thermal runaway chamber design [8].

The mechanics of Li-ion battery thermal runaway were reviewed by Jiaqiang E. et al. (2024), who identified gas venting, heat accumulation, and misuse triggers as important variables. The discovery that TR generates significant amounts of poisonous and combustible gases (CO, HF, and hydrocarbons) highlighted the necessity of validated models to forecast gas generation and enhance safety [9].

Strategies to reduce Li-ion battery thermal runaway were reviewed by X. Feng (2020). TR produces heat, smoke, fire, and dangerous gases when it is activated by mechanical, electrical, or thermal abuse. introduced the time-sequence map (TSM) as a tool for determining intervention spots and stages. Stable separators, non-flammable electrolytes, electrolyte additives, thermal barriers, and intelligent BMS are some of

the suggested remedies. concluded that prevention requires a combination of system-level and material-level approaches [10].

The best technique for giving an ultra-early warning of thermal runaway in lithium-ion batteries is gas monitoring, according to Wang et al. (2024). The authors point out that the creation of gas starts before electrical impulses or temperature changes. CO₂, volatile organic molecules, and CO are identified as appropriate markers in the paper. Temperature and electrical signal monitoring, on the other hand, are limited by their inability to be timely and their uneven heat distribution. The three phases of thermal runaway are also described in the paper, and it is recommended that future gas sensors be smaller and operate at low temperatures [11].

The trigger method used to start thermal runaway in a large-format lithium-ion battery has a considerable impact on gas production, mass loss, and maximum temperature, with an impact like the cell's state of charge, according to study by Willstrand et al. (2023) The large cell format has a minor effect on other evaluation factors, but it enhances the impacts of other trigger techniques, the study also found. Additionally, the test atmosphere had minimal impact on the outcomes, according to the authors [12].

According to Feng et al. (2018), the primary barrier to the widespread adoption of lithium-ion batteries in electric vehicles is safety. They discovered that thermal runaway, which results in an internal short circuit and is caused by mechanical, electrical, or thermal abuse, is the main safety issue. The study suggests a three-tiered protective strategy to lessen this, emphasizing early warning, passive defense, and improving materials' inherent thermal stability [13]. Inconsistencies in lithium-ion battery gas emission data are caused by experimental procedure flaws and data misinterpretation, claim Nilsson and Tidblad et al. (2024). The review emphasized that analyzing vent gases is essential for grasping the fundamentals of runaway, as these gases indicate the types and quantities produced. The researchers discovered that the combination of gases influences their flammability and toxicity. They seek information to improve their understanding of gas emissions from LIBs. [14].

Liao et al. published a paper in 2019. It was stated that lithium-ion batteries continue to pose a danger due to their tendency to overheat. Liao et al. examined various methods to monitor lithium-ion batteries. They measured the temperature and the surrounding air near the batteries. They examined the voltage as well. Liao et al. discovered that monitoring the air can indicate if the battery will overheat. This is due to the fact that issues can arise with the battery and create air before there are changes in temperature or voltage. Liao et al. discussed measures we can take to prevent this from occurring. They mentioned we can make changes to the system or only to a single battery at a time. Liao et al. provided numerous concepts to enhance the safety of lithium-ion batteries [15]. The study conducted by Shahid and Agelin-Chaab (2022) indicates that thermal runaway (TR) presents a significant safety concern for lithium-ion batteries. The authors elaborate on how TR initiates, how it disseminates, and how the gases emitted are characterized. The study also addresses the need for effective heat management systems to prevent TR. It explores methods to reduce damage following a TR incident and stresses the importance of mathematical and numerical models in predicting TR [16].

Finegan et al. (2017) created a controlled internal short-circuit (ISC) apparatus that enabled the accurate and consistent triggering of shorts at specific locations within the cell. The capacity to conduct experiments in a regulated setting gives researchers the chance to assess thermal runaway impacts resulting from the position of a short circuit. Employing high-speed x-ray technology, the researchers demonstrate that a short circuit in the jellyroll's center results in quicker heating and a more intense event compared to when a short circuit happens at the jellyroll's outer edge. This research offers an enhanced insight into reproducible experiments in controlled settings that examine thermal runaway, while also supplying additional proof that internal shorts are the main reason for catastrophic failure [17]. To comprehend how the dimensions of the cell and the method employed for external heating influenced the thermal runaway characteristics of NMC cells, Wang et al. (2019) examined the impact of cell size and external heating. The results of their research indicated that localized heating could create significantly more pronounced rupture patterns compared to evenly distributed heat within the cell, leading to an increased flame height following rupture.

Larger cells produce significantly more heat compared to smaller cylindrical cells due to their considerably greater volume of active material. This leads to significantly more intense fire activity [18].

The researchers McKerracher et al. discussed this in 2021. They discussed methods to prevent lithium-ion batteries from overheating and igniting. They believed that enhancing the separators by adding substances to the electrolyte and utilizing the battery management system for intervention would be effective concepts. Researchers discovered certain plastics that do not shrink when heated, along with new separators featuring a ceramic coating that can prevent the battery from short-circuiting in high temperatures. To genuinely prevent the battery from overheating, the manufacturers should utilize specific materials and intelligent systems that can monitor the battery and prevent it from reaching excessive temperatures, according to McKerracher and others. Currently, individuals are working to prevent the battery from overheating in the first place, rather than simply taking measures to safeguard it once it has begun to overheat, according to the research findings. The safety of lithium-ion batteries is extremely crucial. Researchers, such as McKerracher et al., focus on the safety of lithium-ion batteries and are seeking methods to avert thermal runaway in these batteries [19]. In 2022, Tran et al. [20] conduct a review of thermal runaway models. They examined various models such as reduced-order models, data-driven ML predictors, electrochemical-thermal interconnected models, and physics-based thermal-chemical models. Thermal runaway models are significant. The research indicated that combining temperature, voltage, gas detection, and sound emission sensors can assist in predicting when thermal runaway is imminent. Thermal runaway remains an issue. The team encountered several difficulties, such as a lack of standardized datasets and issues with scaling test results from small cells to larger battery packs. Enhancements are necessary for thermal runaway models. This research laid the groundwork for developing safety measures, modelling, and diagnostics related to thermal runaway.

Gu et al. carry out a study in 2025. They coined the phrase State of Safety, abbreviated as SOS. They discovered that mechanical strain is an effective indicator of potential problems before they worsen. What they observed was that the strain alterations occur

in a manner that you can anticipate prior to noticing any shifts in the voltage or temperature. They developed a method to assess factors that can indicate if a thermal runaway will occur several hours in advance. This innovative method employs strain and additional sensor information, including temperature, voltage, power, and capacity. This research is significant as it demonstrates how intelligent diagnostics and sensing can prevent negative events from occurring. It implies that individuals can take action on an issue before it worsens to the point of causing significant harm. State of Safety is a concept as it may aid in averting disastrous failure. The concept of State of Safety illustrates how this can function [21].

¹⁹ Zhang et al., 2023, published a critical review of early warning systems and thermal runaway prediction. They discussed sensor-based methods, such as gas, strain, pressure, and acoustic detection, and compared them with hybrid, sophisticated data-driven models like neural networks and hybrid physics-ML frameworks. From their study, one can know that there is no single sensor to predict thermal runaway reliably; rather, a multimodal approach gives the best result. They also discussed the gap between achievement in practical applications, which is brought on by ageing and operating environmental factors. For the essential application, the focus is on the importance of robust and early warning systems [22].

Feng et al. [22] note that the thermal runaway process is a sequence of events, hence terming it a multi-stage process involving SEI breakdown, separator melting, internal short circuiting, cathodic O₂ release, electrolyte combustion, and venting with gas release. The authors further analyse the behaviour of different battery chemistries during thermal runaway tests, where they also discussed differences in the likelihood of oxygen release from nickel-rich cathodes. They further recommended the analysis that needs to be done in order to correlate propagation behavior both at module and pack levels. This would serve as good material and resource for information regarding thermal runaway in EV batteries.

According to He et al. (2024), the authors provide an updated overview of the mechanisms responsible for the aging and the current generation of Ni-rich Li-ion batteries. It was observed that at higher temperatures, batteries do eventually generate

more energy. The authors also gave a detailed description of each process involved in the dissolution of the electrolyte, cathode structural breakdown, leakage of oxygen, and deterioration of the SEI.

The authors emphasized the significant safety risks connected with utilizing old or second-life batteries since deterioration reduces thermal stability. The authors also discussed innovative ways to lessen the impact of temperature on batteries, such as employing heat-resistant materials for electrodes and enhancing performance by adding chemicals to the electrolyte using additive manufacturing techniques. The evolving nature of TR mechanisms as batteries change in terms of their chemistry and service life was a crucial finding in this study [23].

In 2018, Feng and colleagues conducted research on the factors that cause lithium-ion batteries in electric cars to overheat and ignite. They examined what happens when these batteries sustain damage from things like being crushed or exposed to excessive energy, as well as what happens when a short circuit occurs within the battery. According to the study, batteries can become overheated due to mechanical, electrical, or thermal degradation. This frequently occurs due to internal short circuits. According to the researchers, an excessively heated battery can set off a series of events that include the separator failing, the electrolyte degrading lithium, and the generation of heat [24].

Yang Hu, et al. [25] conducted research in 2022. They aimed to assess the effectiveness of heat insulation and heat dissipation in preventing runaway incidents in lithium-ion battery modules from escalating. The research consisted of four configurations in a limited area. These consisted of: no protection, with thermal insulation, with thermal dissipation, and with both thermal insulation and thermal dissipation. They utilized plates to retain the heat and additional plates with fins to dissipate the heat. The researchers examined the battery temperature, how the voltage varied, how the flames acted, and the surrounding temperature when the batteries overheated.

Their findings revealed that heat insulation slowed the runaway but did not reduce the likelihood of the batteries catching fire. Heat dissipation on the hand reduced the

battery temperature and prevented large flames from developing. Utilizing both heat insulation and heat dissipation simultaneously proved to be the most effective. It halted the runaway and significantly decreased the risk of fire and the temperature increasing near the batteries. Yang Hu, et al. discovered that this method effectively ensures the safety of lithium-ion battery modules.

Xuning Feng, et al. conducted research in 2019. They examined the effects of excessive heat on lithium-ion batteries. The scientists employed instruments to observe the behaviour of various lithium-ion batteries when subjected to high temperatures. They discovered that lithium-ion batteries can reach three temperature levels when overheating. The scientists conducted tests on lithium-ion batteries and on the components that comprise these batteries. They were curious about how heat is generated when lithium-ion batteries overheat. They discovered that lithium-ion batteries overheat due to the interactions between the components of the battery when temperatures rise. The issues are not originating from within the battery. The research additionally indicated that when the component that divides the sections of the battery overheats, it can cause the battery to become even hotter [26].

Lithium-ion batteries can be rendered safer by considering these crucial temperatures. This data can assist individuals who create lithium-ion batteries and the mechanisms that maintain their temperature. In 2018, a study was conducted by Xiang Liu, et al. [27] They examined the effects of excessive heat on lithium-ion batteries. These batteries contained separators composed of PET and ceramic. They discovered that these batteries can become excessively hot even when there are no significant issues occurring internally. The primary cause of this occurrence is the manner in which the components of the battery communicate with one another. When the battery becomes excessively hot, the component that generates electricity emits oxygen. This oxygen subsequently interacts with the section of the battery that absorbs electricity. This generates a significant amount of heat. Makes the battery become even hotter researcher discovered that this is typically what leads to excessive heating in lithium-ion batteries. Lithium-ion batteries pose significant risks when they overheat. The research indicated that the interaction among the various components of the lithium-ion battery are what cause it to overheat [27].

In 2018, a study was conducted by Andriy Kvasha, Cesar Gutiérrez, et al. They examined the behavior of various lithium-ion battery types when subjected to excessive heat. The batteries that were evaluated were composed of materials: NCA/Graphite, LFP/Graphite, and NCA/LTO. The research indicated that every battery became heated and ignited regardless of their stored energy levels. As the batteries stored more energy, they heated up more quickly. The LiFePO₄/Graphite battery was reliable. This is due to the LiFePO₄ component of the battery being excellent at maintaining a cool temperature. The NCA-based batteries lacked stability. They emitted oxygen when overheated, causing them to ignite easily. The research also indicated that the liquid within the battery is crucial. It has the potential to ignite. Cause the battery to overheat [28].

In 2016, a study was conducted by Krishna Shah, et al. [29]. They aimed to determine when lithium-ion batteries would become overheated. They devised a research ²³referred to as the Thermal Runaway Number, abbreviated as TRN. This research assists in forecasting when a battery will overheat. The research discovered that it centered around equilibrium. If a battery generates a lot of heat and cannot dissipate it, it will become overheated. However, if the battery can dissipate the heat, then it will be fine. The researchers discovered that if the Thermal Runaway Number exceeds one, the battery will overheat. A Thermal Runaway Number below one indicates the battery is safe. The researchers discovered that improved heat dissipation in the battery enhances safety. This indicates that the battery won't overheat quickly. The researchers provided suggestions on designing batteries. These suggestions assist individuals in creating effective batteries. The Thermal Runaway Number is crucial as it assists in maintaining lithium-ion batteries within safe temperature ranges. The contributions of Krishna Shah and his team are crucial for the production of lithium-ion batteries.

In 2015, Carlos F. Lopez et al. performed a study. They investigated the impact of overheating on lithium-ion battery modules and how this heat is distributed. They tested the assembly of the modules by modifying the distance between the cells, changing the tab designs, relocating the vents, and choosing various insulation materials. They found that when the cells are not closely spaced, the heat does not dissipate much. They think it's wise to keep a minimum of 2 mm gap between the cells

for enhanced safety of the modules. The researchers noted that some kinds of tabs are more effective than others. The tabs that extend outwards are superior to the ones that are all twisted. This occurs because they do not allow a significant amount of electricity to enter the malfunctioning cell. They also discovered that certain types of cells are more prone to ignite a fire. The cells with vents on the side can transfer flames and heat to adjacent cells. They discovered that certain kinds of insulation can genuinely make a difference. These insulators can prevent heat and flames from reaching the cells. This reduces the chances of heat dispersing and creating issues with the lithium-ion battery modules [30].

In 2015, a study was conducted by Judith A. Jeevarajan, et al. They examined the effects of overheating in lithium-ion battery modules and the manner in which this heat disperses. They experimented with assembling the modules by adjusting the proximity of the cells, altering the tab designs, repositioning the vents, and selecting different types of insulation. They discovered that when the cells are not too near one another, the heat does not dissipate significantly. They believe it's a good idea to maintain at least 2 mm of space between the cells for greater safety of the modules. The researchers observed that certain types of tabs outperform others. The tabs that extend outwards are superior to the ones that are all twisted. This occurs because they do not allow a significant amount of electricity to enter the malfunctioning cell. They also discovered that certain types of cells are more prone to ignite a fire. The cells with vents on the side can transfer flames and heat to adjacent cells [31]. They discovered that certain kinds of insulation can genuinely make a difference. These insulators can prevent heat and flames from reaching the cells. This reduces the chances of heat dispersing and creating issues with the lithium-ion battery modules.

2.1 Research Gap of Thermal Runaway

Extensive research gap has been conducted to investigate the TR behaviour of LIBs, focusing on abuse condition such as overcharging external heating internal short circuit and mechanical deformation. Previous have successfully identified the key mechanism responsible for thermal runaway, including SEI decomposition, separator failure electrolyte decomposition, and cathode oxygen release. Most investigations have been performed under the controlled laboratory condition at the cell level,

whereas the thermal propagation behaviour in battery module and pack level system has not been comprehensively explored. Furthermore, existing thermal runaway models often consider thermal, electrochemical, and mechanical effect separately, resulting in limited prediction accuracy under the practical operating condition.

Moreover, despite BMSs being able to track battery characteristics like voltage, current, and temperature, creating dependable early-warning methods that can forecast thermal runaway before critical reactions begin is still a major challenge. Recent developments in machine learning and artificial intelligence have demonstrated encouraging outcomes for battery health assessment; nevertheless, their use for real-time thermal runaway forecasting with multi-parameter datasets remains constrained. Additionally, the thermal safety properties of new battery chemistries, such as high-nickel cathodes and advanced high-energy-density cells, remain to be completely comprehended.

It is essential that we conduct research on lithium-ion battery systems. This study must involve observing various elements simultaneously through computer simulations to forecast outcomes and examining the transfer of heat. This is necessary to identify issues early and stop Li-Ion battery systems from overheating. Addressing these issues will make Li-Ion batteries safer and more dependable. This is crucial for employing lithium-ion batteries in cars and for energy storage. We aim to implement lithium-ion batteries in these applications on a large scale.

Chapter 3: Thermal Runaway

3.1 Introduction

Lithium-ion batteries offer numerous advantages, yet they also pose significant safety concerns, particularly regarding thermal runaway. A perilous scenario termed "thermal runaway" is characterized by a series of exothermic reactions that generate substantial heat when activated sequentially.

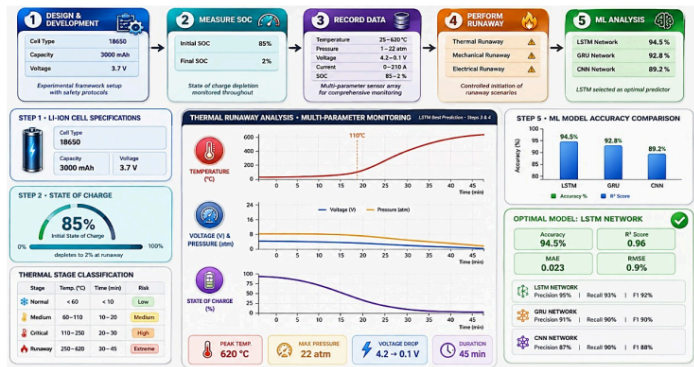


Fig. 3.1 Procedure Framework of the Thermal Runaway

This occurrence is highly hazardous as it can cause significant damage to the battery and lead to fires or explosions. In the automotive sector, thermal runaway poses significant risks as it can ignite intense, prolonged fires that are hard to extinguish. These flames provide wider threats to passengers and the environment in addition to jeopardising vehicle safety [32]. Mechanical, electrical, and thermal abuse are some of the ways that this series of chemical events might begin.

The Thermal Runaway Analysis Framework details the entire procedure for examining lithium-ion battery malfunction in severe circumstances. Initially, a lithium-ion battery of type 18650, with a capacity of 3000 mAh and a voltage of 3.7 V, is chosen and set up with appropriate safety measurements described in Fig. 3.1 The battery state of charge (SOC) is tracked from 85% down to 2% throughout the experiment. Various factors including temperature, pressure, voltage, current, and SOC are continuously

monitored. In thermal runaway, the temperature swiftly escalates from 25°C to 620°C, pressure surges to 22 atm, while voltage declines from 4.2 V to 0.1 V, signalling battery malfunction. Thermal, mechanical, and electrical runaway experiments are conducted to examine various failure scenarios. The gathered data is evaluated through machine learning models such as LSTM, GRU, and CNN, with the LSTM model reaching the highest accuracy of 94.5% in forecasting thermal runaway behaviour. In summary, the framework aids in comprehending battery safety, failure processes, and early identification techniques for more secure energy storage systems.

3.2 Triggering Mechanism of Thermal Runaway

A number of abuses, including mechanical abuse (crushing or puncturing), thermal abuse (extreme external heating), and electrical abuse (overcharging, overdischarging, or short circuits), can cause thermal runaway in lithium-ion batteries are illustrated in Fig. 3.2.

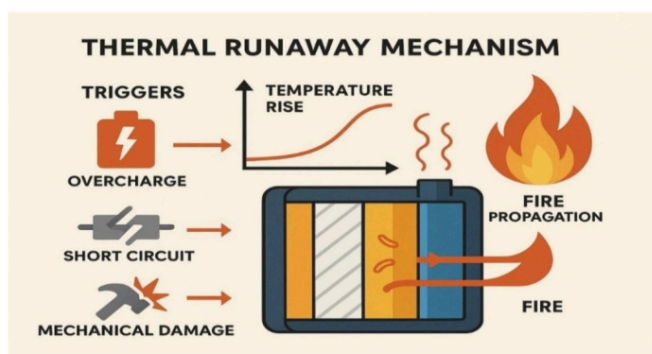


Fig. 3.2 Mechanism of the Thermal Runaway

These circumstances increase the battery's internal temperature and harm its protective layers. An internal short circuit could result from the separator melting as the temperature rises and the SEI layer on the anode disintegrating and releasing heat.

This short causes the materials in the battery to become chemically unstable, which significantly speeds up the production of heat. The electrolyte may catch fire and the

cathode may leak oxygen shown in Fig. 3.3. The self-accelerating cycle that can cause an explosion, fire, or uncontrollably high temperatures is created when these reactions produce heat more quickly than it can escape.

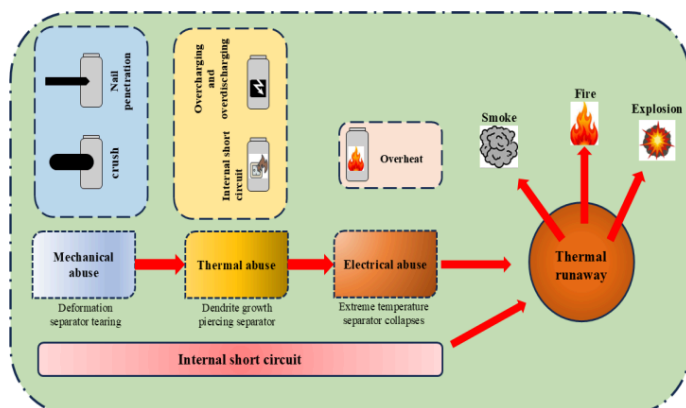


Fig. 3. 3 Thermal runaway Triggering Methods.

3.2.1 Thermal Abuse

Mechanical abuse can include cell bending, compression, punching, and shell casing damage, which can occur during collisions. The main line of defense against mechanical and thermal stress is a cell's case. Thus, it is essential to the cell's general mechanical behaviour that the cell is protected during safety accidents. It is important to comprehend this element and take it into consideration while designing and choosing LIB materials. A reaction with the electrolytes and active ingredients may be started if the substance ruptured the separator or if the shell was damaged [33].

This may lead to exothermic reactions and material breakdown. These side reactions have the potential to produce flammable gases and particles that can cause additional combustion and fire in addition to releasing heat. Through this process, thermal runaway can begin to spread from one cell to another and eventually spread throughout an entire battery pack.



Fig. 3.4 Schematic Illustration of the Thermal Abuse

The overheating in the lithium-ion cells is explained by the Fig. 3.4 of the heated battery. A battery's internal chemical reactions quicken and start generating excessive heat when it is exposed to temperatures higher than its safe functioning range. The battery's separator and electrolyte are harmed by this excess heat, which raises the risk of failure. Continuous temperature increases may cause battery enlargement, gas leakage, fire, or explosion. Thermal abuse from external heat sources is depicted in the illustration with the external flame or heat gun. Heat from the surroundings is absorbed by batteries that are exposed to heaters, fire, sunlight, or other hot surfaces. As a result, the battery's materials deteriorate and the internal temperature rises quickly. Overheating from the outside can start the cell's breakdown processes, which could ultimately result in thermal runaway. High ambient temperatures are depicted in the Fig. 3.4 with the sun. The external temperature raises the internal chemical processes when batteries are used or stored in high-temperature environments. This results in increased pressure buildup, faster electrolyte breakdown, and a shorter battery life. Long-term exposure to high temperatures damages the battery's internal structure and increases instability. The battery in the attached photo has inadequate heat dissipation. Batteries inherently generate heat as they are charged and discharged. Heat builds up inside the cell if it is unable to escape due to poor ventilation or inadequate cooling.

Trapped heat boosts internal temperatures, destroys delicate parts, and increases the likelihood of runaway reactions and thermal collapse. Heat transfer between neighbouring cells is explained by the illustration of one damaged cell influencing another. Fig. 3.4 describes Thermal propagation is a chain reaction that occurs when one battery cell fails and is extremely hot, spreading the heat to neighbouring cells. Battery packs may experience several cell failures as a result. High charge or discharge rates at high temperatures are represented by the battery that is attached to a charging device. Excessive internal heat from rapid charging or high current flow can harm the separator, raise internal resistance, and cause thermal runaway.

Thermal runaway is explained by the photos in the lower sequence. Internal battery components are harmed by excessive heat, which also speeds up chemical reactions and increases heat generation. As temperature and pressure build uncontrollably, the battery may emit gasses, catch fire, or explode.

The wide cross-section of the battery reveals interior damage from thermal usage. Elevated temperatures have the potential to melt the separator, induce internal short circuits, release gasses, and raise cell pressure. The battery may vent, catch fire, or explode if the pressure is too high.

3.2.2 Mechanical Abuse

Thermal abuse can happen at temperatures that are too high or too low. In most lithium-ion cells, the electrolyte becomes more viscous at temperatures lower than 5 °C, which hinders the mobility of lithium ions. Internal resistance within the cell rises as a result. The likelihood of lithium ions effectively intercalating into the anode is reduced under these circumstances. Lithium plating is a procedure whereby they instead deposit straight onto the anode's surface. Lithium plating usually arises when charging is done at low temperatures or too quickly. The anode's lithium deposit may produce complex, branch-like metallic structures called dendrites. With each charging cycle, these dendrites, which were initially tiny, might gradually enlarge. Dendrites run the danger of puncturing the separator as they enlarge. A short circuit occurs when dendrites penetrate through the separator thereby creating a straight path for electrons to travel from the anode to the cathode.

Thermal runaway can be caused by short-circuiting. When lithium-ion batteries are at high temperatures, they face different challenges than when they are at room temperature. At high temperatures thermal runaway will have a greater probability of occurring due to the faster chemical reactions taking place within the cell. In the case of thermal runaway, the breakdown of electrolyte components and deterioration of the electrodes will occur; this will result in decreased capacity and efficiency. The next section will explain the chemical reactions that occur during thermal runaway.



Fig. 3.5 Schematic Illustration of the Mechanical Abuse

Compression or crushing damage is indicated by the Fig. 3.5 of the crushed battery. The inside layers of the battery may flex or fracture if it is pressed sufficiently, resulting in an internal short circuit that produces heat. The battery exhibits puncture damage due to the pointed object that penetrated it. The separator between the electrodes may be ruptured by battery penetration, causing direct contact inside the cell and a potentially hazardous short circuit. Impact or drop damage occurs when a slanted battery falls to the ground. The danger of failure can be increased by a forceful impact from a drop that damages the internal structure, cracks components, or misaligns electrodes. The picture of the battery helps us understand what bending stress is. When a battery is bent much it can hurt the inside layers and damage the thing that keeps everything separate. This can cause problems like circuits and getting too hot.

In the Fig. 3.5 the compressed battery illustrates the concept of deformation. When a battery is compressed tightly, it can compromise the entire integrity of the cell. This can harm the internal components of the battery and render it unstable. The image of the vibrating battery illustrates the effects of vibration damage on a battery. If a battery is shaken excessively or for an extended period, it may damage or dislodge its internal components. This may lead to issues over time, such as wear and tear damage, within the battery and heat accumulation. The images of batteries at the bottom illustrate the effects of batteries being damaged in a certain manner. This type of harm affects the internal components of the battery, including the separator and the electrodes. May lead to a short circuit. When this short circuit occurs, it causes the battery to heat up rapidly. As the temperature continues to rise, the chemical processes within the battery spiral out of control. This may lead to smoke, flames, or potentially an explosion.

The big picture of the battery that has been cut open shows what kind of damage can happen inside a battery when it is physically abused. When a battery is damaged it can tear the separator make the electrodes not line up right and cause circuits inside the battery. Sometimes little pieces of metal called lithium dendrites can. The pressure inside the battery can build up. If the damage is very bad the battery can release gases, catch on fire or even explode. The battery Fig. 3.5 and the large battery cross-section are examples of what mechanical abuse can do to batteries. Mechanical abuse is very bad for batteries. Can cause a lot of problems like thermal runaway and explosions. Batteries that are damaged in a way can be very dangerous so it need to be careful, with them.

Nail-penetration and battery-crush tests are two common mechanical abuse methods used to evaluate the safety and failure behavior of lithium-ion batteries. In a nail-penetration test, a sharp metallic nail is driven into the battery cell and makes direct contact with the electrodes to intentionally create an internal short circuit. This abrupt short, which results in rapid heat, gas release, and often thermal runaway, helps researchers better understand how puncture-related failures occur. The battery crush test is performed to measure how a li-ion battery works when a force is applied to the exterior of the Li-ion Battery. The way a Li-Ion Battery fails under this type of testing is due to an increase in pressure that results in a short circuit. This type of test allows

engineers to gain an understanding of how Li-Ion Batteries will react in simulated environments similar to a crash in the automotive industry, via a tool being used to puncture a Li-Ion Battery, or a structural compression.

3.2.3 Electrical Abuses

Lithium-ion batteries can undergo a variety of abusive electrical conditions that can create excessive energy accumulation and heat. The three most common are: Over-charging, Over-discharging, Rapid charging. The thermal dissipation produced from these three abusive conditions deteriorates the capacity and power of lithium-ion batteries through the internal resistance and electrochemical reactions that occur during charge/discharge cycling, while also posing a significant risk to safety [33].

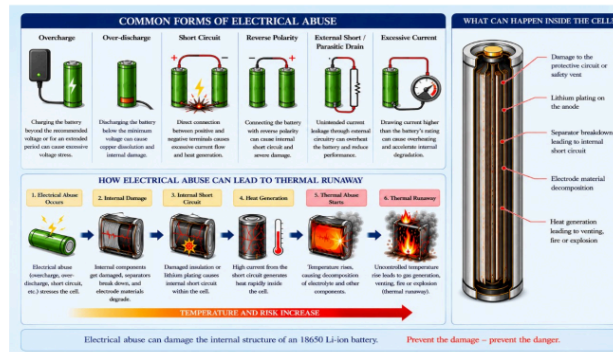


Fig. 3.6 Schematic Illustration of the Electrical Abuse

The Fig. 3.6 of batteries at the bottom show what happens when batteries are treated roughly. When batteries are damaged it hurts the parts inside like the separator and electrodes and this can make them touch each other in the wrong way. This is called a circuit. The short circuit makes the battery get very hot quickly. As the heat keeps building up the chemical reactions inside the battery get out of control. This can make the battery start smoking, catch fire or even explode.

The pictures also show what happens when lithium-ion batteries are used in the way. At the time of charge a battery much it gets too hot inside and this stresses the battery. If you use up all the power in a battery it can hurt the inside of the battery by making

the voltage too low. If the wires inside the battery get tangled up or if put the wires in the way it can make too much heat and hurt the battery. If something is draining the battery when it is not being used it can make the battery not work well. Continuously use of battery much it can get very hot inside and this can make the battery get old faster. The pictures, at the bottom show how using a battery in the way can hurt the separator and electrodes make them touch each other in the wrong way and build up heat, which can make the battery get too hot, catch fire or explode. The Fig. 3.6 of the inside of a battery shows what can go wrong like the separator breaking down lithium building up gas forming and pressure building up which can make the battery vent, catch fire or explode.

When a lithium-ion battery is charged above its maximum voltage limit, which is usually greater than 4.2 V per cell, overcharge takes place. More lithium than the electrodes can safely hold is forced into them by excessive charging. Lithium plating, electrolyte breakdown, gas production, and quick heat production result from this. The cell may vent, swell, catch fire, or go into thermal runaway if the temperature keeps rising. Overcharge testing verifies Battery Management System (BMS) protection circuits and aids in determining safe charging limits. When the battery voltage falls below the permitted cut-off (typically less than 2.5 V), overdischarge occurs. The copper current collector dissolves at very low voltages, forming copper ions that deposit as metallic copper when the cell is recharged. Internal short circuits, capacity loss, and long-term cell damage result from this. In addition to increasing internal resistance and weakening cell structure, severe overdischarge can cause failure in subsequent cycles.

An external short-circuit occurs when the positive and negative terminals are connected directly through a channel with very little resistance. This allows a very high current to flow rapidly, rapidly heating interior materials. The electrolyte may evaporate, the separator may melt, and the internal pressure of the cell may rise. An explosion, fire, or venting could occur if it is not controlled. External short-circuit tests simulate accidental shorts caused by faulty wiring, metal tools, or damaged battery packs.

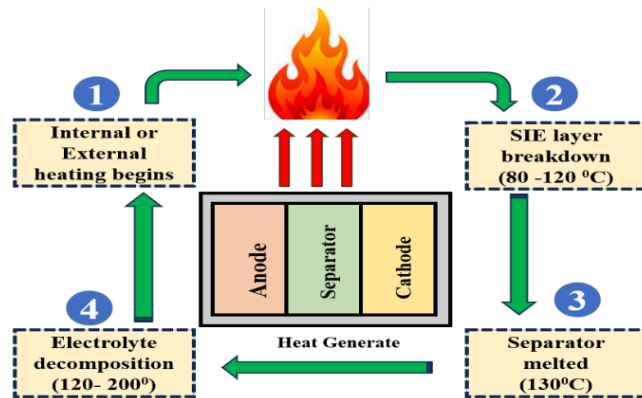


Fig3.7 Process to Thermal Runaway takes place

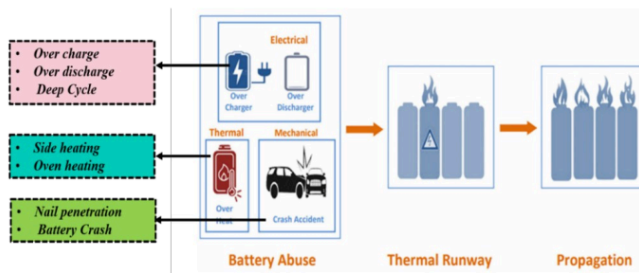


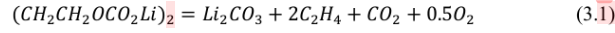
Fig. 3.8 Parameters under Thermal Runaway Abuses.

3.3 Analysis of Thermal and Gas Production Behaviour

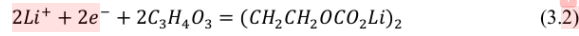
Chain reactions may result from exothermic reactions made possible by the high temperature under thermal abuse circumstances. Fig. 3.7 and Fig. 3.8 shows these reactions, which can occur both with and without an ISC. There are four primary processes that are producing heat. The breakdown of the SEI layer, the anode-electrolyte reaction, the cathode-electrolyte reaction, and the electrolyte breakdown. The Fig. 3.9 shows exothermic reactions for a typical LIB with a graphite anode,

LiC_0O_2 cathode, and the electrolyte of ethylene carbonate ($C_3H_4O_3$) and lithium hexafluorophosphate ($LiPF_6$) will be covered in the ensuing subsections. The reactions will differ significantly for other materials used as battery cathodes.

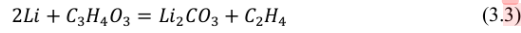
The SEI layer is thermally sensitive and may decompose when exposed to high temperatures. This usually happens first. The SEI layer can decompose as:



The SEI decomposition starts at a temperature of 90-120°C [34]. As a consequence, the anode surface may react with the electrolyte to form a new SEI layer

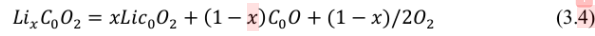


The SEI decomposition leads to direct contact between the lithium in the anode and the electrolyte, resulting in the formation of lithium carbonate (Li_2CO_3) and ethylene (C_2H_4)

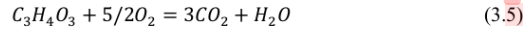


This reaction takes place at approximately 100 °C.

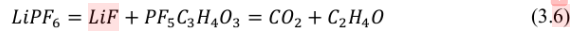
At high temperatures, the cathode starts to decompose [104]:



Moreover, the oxygen produced during cathode decomposition can instigate a direct reaction between the cathode and the electrolyte.



Lastly, the carbonate and salt in the electrolyte can disintegrate under high temperatures [34].



These chemical processes are primarily exothermic and result in the production of gases such as ethylene and oxygen.

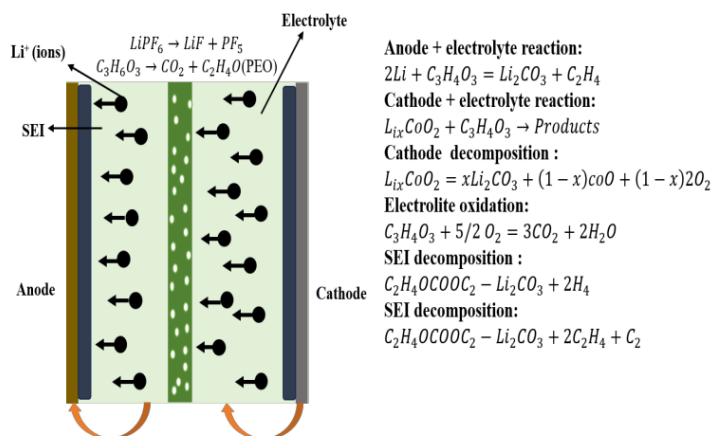


Fig. 3. 9 Configuration and Thermal Runaway Reaction for a Typical LIB[3]

3.4 Thermal Runaway Chamber Design and Fabrication

The high-temperature resistant stainless steel (SS304) used to construct the chamber has planned venting routes, thermal insulation, and other features. For the safe collection and tracking of released gases, these venting pathways are meant to be connected to hazardous gas sampling bags and a data logger. Pressure sensors are set up to track internal chamber pressure during the battery abuse test, and heating elements and thermocouples are integrated to create a controlled heating environment.

An artificial intelligence (AI)-based infrared camera is set up to take and analyse thermal pictures of the batteries being tested, evaluate the thermal data, and spot anomalous heating patterns that could be signs of TR events in real time. To measure the concentration of important gases, such as O_2 , CO , CO_2 , H_2 , H_2O , C_2H_2 , CH_4 , C_2H_6 , and volatile organic compounds (VOCs), several electrochemical gas sensors are set up. Additionally, the sample ports for FTIR and gas chromatography mass spectrometry (GC-MS) are incorporated, enabling thorough gas characterisation. The chamber is made to mimic mechanical, electrical, and thermal damage scenarios as well as support rapid charge/discharge aging. The design also incorporates validation

procedures such sensor calibration, leak testing, and initial trials with dummy cells following construction.

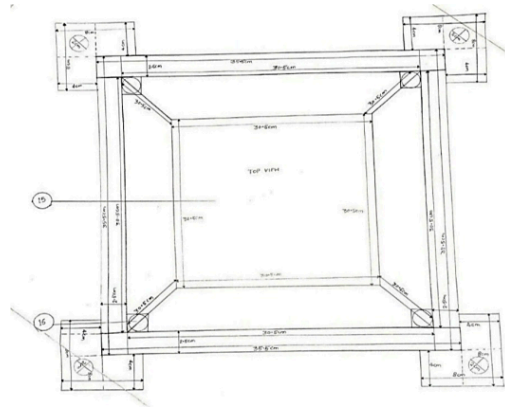


Fig. 3.10 Sketch view of the Thermal Chamber with Dimensions

Additionally, this system includes an external battery management system that is communicatively connected to the battery being tested. BMS generates SOC, SOH, cell voltage data, identify and implement cell balancing measures, and provides error codes from individual cells. The BMS's ability to record thermal data, gaseous or pressure measurements as well as electrical characteristics on a continuous basis and synchronize this data with BMS data allows you to create a regulated and reproducible method using prescribed testing standards. These standards detail the SOC, SOH and cause of triggering. Other measurements include the rate at which pressure builds up, how gas escapes through vents, how quickly temperature changes, and when (i.e. onset time) the temperature begins to rise. This all combines into a design that not only protects against injuries caused by the release of hazardous gasses, but also provides the means to collect accurate and repeatable estimates of where the hazardous levels exist. Furthermore, this design addresses weaknesses in past studies by generating high-quality reproducible datasets that support both modelling and machine learning.

3.4.1 Description Thermal Runaway Chamber with Component ⁷

An integrated thermal runaway testing chamber was designed to enable the testing of lithium-ion batteries under different types of abuse. The thermal runaway testing chamber is constructed from SS304 stainless steel, has one squared off to provide greater stability, and has a layer on the interior to protect the thermal runaway chamber from high-temperature materials. The thermal runaway testing chamber is covered with a sealed top cover secured by screw fasteners at each of the corners and additional holes to accommodate for the installation of sensors, screws, and wiring.

The thermal runaway testing chamber design incorporates K-type thermocouple sensors to provide real-time measurements of the temperature of both the thermal runaway testing chamber and battery throughout the entire test process. Thermal runaway testing chamber has two pressure sensors that constantly and continuously monitor both the amount of pressure present inside the thermal runaway testing chamber and the amount of gases being released during the testing process, while there are also two nozzle ports for the release of gases to conduct post-test analysis (e.g., gas sampling), as well as for conducting (e.g., gas chromatographic mass spectrometry) analyses of gases present during thermal battery failures. Electrochemical sensors detect gases that may be released during testing as a result of a thermal runaway failure or explosion of the test battery. Helical Thermal Elements, which are located within the centred of the thermal runaway testing chamber, heat to temperatures above approximately 1,000 degrees Celsius. Data loggers display test results, and gas sampling bags collect gases for post-analysis. Screw holes secure the upper plate to create a vacuum at the chamber's corners shown in Fig. 3.11. The square-shaped thermal chamber is constructed from SS304 stainless steel. Computer systems are used to display all collected data graphically or numerically. During tests, a pressure gauge or sensor measures the gas pressure emitted by the Li-ion battery. Real-time temperature data is recorded by a temperature control unit and sensors. The inner heat-protection sheet, made of SS304 stainless steel, houses the Li-ion battery during testing. Top sheets form an airtight, vacuum-proof enclosure, with cut slots for connecting wires and sensors. Screw holes allow securing the inner heat-protection

sheet and creating a vacuum when covered by the upper sheet. An AI-powered infrared camera captures real-time Fig. 3.9 of the entire thermal chamber.

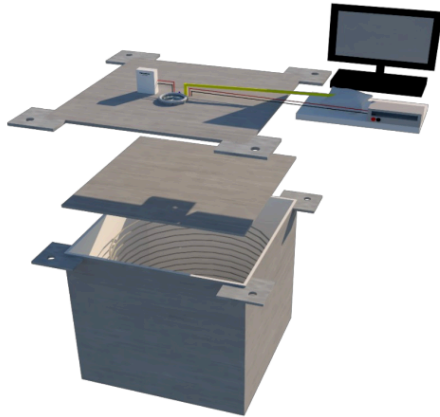


Fig. 3. 11 Outlook of the Thermal Chamber in open side

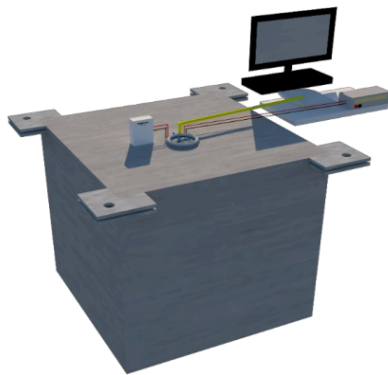


Fig. 3. 12 Final Outlook of the Chamber with the Data Acquisition System

3.4.2 Experimental Battery Mounting System

The Fig. 3.12 shows an experimental mounting system used to investigate thermal runaway in lithium-ion batteries. An exploded view displays the final constructed arrangement as well as the module components. Following a rigid module framework that provides mechanical support, a mica insulation plate is used to isolate the battery both electrically and thermally during testing. An optional heating plate is provided to initiate a controlled thermal runaway and externally heat the lithium-ion battery sample. To measure deformation or variations in internal pressure when the battery is subjected to mechanical or thermal stress, an optional stress sensor can be installed. The LIB cell is placed in the centre of each plate. To enable gas venting or sensor access, a fixture opening plate is placed on the outside. When all the parts are put together, they are compressed into a small experimental module with outward-extending electrical and sensor leads. During thermal runaway testing, this configuration guarantees safe containment, exact heating control, and precise stress and thermal behaviour measurement.

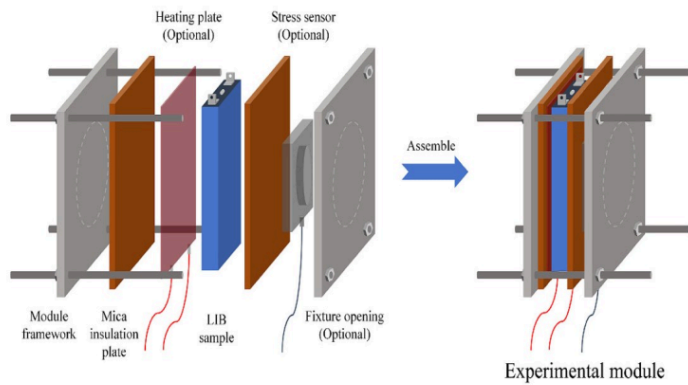


Fig. 3. 13 Battery Mounting System

3.5 Data Acquisition System

A Data Acquisition System (DAQ) is utilized to gather and assess information regarding batteries in real time. It examines factors such as temperature, voltage, current, gas emissions, and pressure. This is carried out to determine if there is an issue with the battery that might lead to a problem. The Data Acquisition System features sensors that convert the battery's activities into signals. A computer then analyzes these signals. The Data Acquisition System gathers all this data, and then specialized software along with Artificial Intelligence (AI) and Machine Learning (ML) analyze it. This assists us in determining whether a battery will fail. The primary purpose of utilizing a Data Acquisition System is to receive an alert if there is an issue with the battery. This assists in stopping the battery from overheating. It additionally enhances the battery's lifespan and performance. The Data Acquisition System plays a crucial role for lithium-ion batteries.

3.5.1 Temperature sensor

The temperature sensor plays a crucial role in the monitoring system of lithium-ion batteries. This occurs because when an issue arises with the battery, it typically begins with a rapid increase in temperature. The temperature sensor constantly monitors the temperature of the lithium-ion battery during charging or usage. This ensures the battery operates safely. In this project, utilize temperature sensors such as thermistors, or thermocouples. Utilize them due to their ability to quickly sense minor temperature fluctuations. The temperature sensor is placed close to the lithium-ion battery cells to measure the heat precisely. It connects to the Raspberry Pi 5 through an Analog-to-Digital Converter module. This is due to the fact that the Raspberry Pi 5 can solely comprehend signals. The temperature sensor can gauge temperatures from approximately -40°C to 1000°C . This indicates it can sense both low and extremely high temperatures that could lead to issues. The system measures the temperature 10 times each second. This allows us to track and assess the temperature over time.

When the temperature sensor detects that the temperature is excessive, it transmits a warning signal to the control system. The control system may activate cooling systems, trigger an alarm, or disconnect the lithium-ion battery. This prevents the battery from

overheating and creating issues. The temperature sensor is an element of the lithium-ion battery monitoring system as it aids in maintaining the battery's safety.

3.5.2 Voltage and Current Sensor

The voltage of the lithium-ion battery cells must be verified. This is the point at which the voltage sensor is utilized. It gauges the voltage of every cell and the entire battery pack. This is crucial for both charging and discharging.

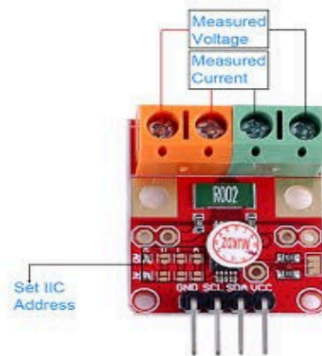


Fig 3.14 Voltage Current Sensor [35]

The sensor continuously monitors the voltage. Ensures it remains in a secure range. The voltage range for each cell is from 2.5 V to 4.2 V. Should the voltage exceed or drop below this range, the battery cells may become unstable. This may lead to overheating or potentially a thermal runaway. The voltage sensor is linked to the Data Acquisition system and the Raspberry Pi 5. This allows for monitoring and scrutiny. The current sensor measures the electricity flowing into and out of the battery system. It acts as a guardian that watches for any problems. Sensors that employ Hall-effect or shunt resistors are effective for this function. They are fast and accurate. The current sensor measures the current based on the load and charging condition. It helps in detecting problems like overcurrent, excessive power flow, and short circuits. Such matters can generate heat. The sensor connects to the Raspberry Pi through an Analog-to-Digital Converter module. This allows for immediate data gathering and safety

monitoring of the lithium-ion battery cells and the complete battery pack. The voltage sensor and the current sensor work together to ensure the battery system's safety.

3.5.3 Gas Sensor, Pressure Sensor and Battery Management System

The gas monitoring system employs the MiCS-6814 and MiCS-5524 sensors to identify dangerous and flammable gases emitted during lithium-ion battery overheating and thermal runaway. The MiCS-6814 identifies gases like carbon monoxide (CO), nitrogen dioxide (NO₂), ammonia (NH₃), methane (CH₄), and hydrogen (H₂), whereas the MiCS-5524 primarily responds to carbon monoxide, hydrocarbons, and methane vapors released during electrolyte breakdown. The Raspberry Pi 5 is linked to both sensors via the DAQ system for immediate gas monitoring and prompt thermal runaway identification. The pressure sensor constantly monitors the increase in internal battery pressure and identifies gas buildup resulting from chemical reactions within the battery under hazardous conditions. The Battery Management System (BMS) safeguards the battery against overcharging, deep discharge, excessive heat, and short circuits, in addition to carrying out cell balancing and real-time monitoring of voltage, temperature, and current. In unsafe operating conditions, the BMS can automatically sever the battery connection to avoid damage and enhance overall battery safety.

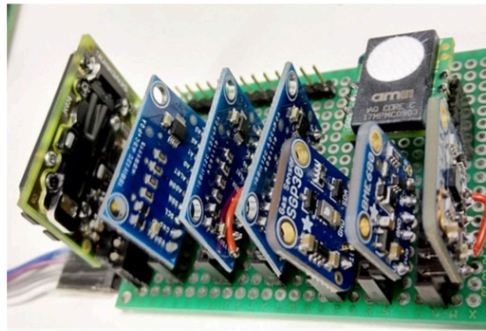


Fig 3.15 Gas Sensors [35]

3.5.4 Microcontroller, Communication Module, and AI Thermal Imager

Imager

The smart battery monitoring system employs the Raspberry Pi 5 as its main microcontroller. It collects real-time data from sensors that measure temperature, voltage, current, gas, and pressure through the DAQ and ADC modules, then assesses the data for evaluating battery safety. The Raspberry Pi 5 includes 8 GB RAM, built-in Wi-Fi, Bluetooth, USB ports, and rapid processing capabilities, making it perfect for Artificial Intelligence (AI), Machine Learning, and cloud surveillance tasks. The communication module employs Wi-Fi and Bluetooth technologies to transmit battery data to cloud platforms, mobile devices, and remote monitoring systems for real-time observation and alert generation. The system features an AI-powered thermal imager that monitors the temperature distribution on the battery's surface and identifies abnormal heat patterns during charging and discharging activities. The thermal imaging system continuously collects thermal data and uses AI algorithms to detect hotspots, rapid temperature rises, and possible thermal runaway events before a failure occurs. This intelligent integration improves early fault detection, remote monitoring, battery protection, and the complete safety of lithium-ion battery systems.

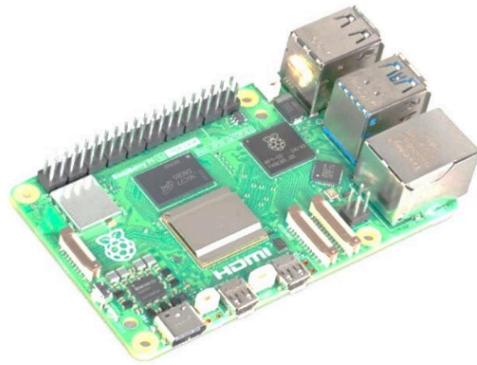


Fig 3.16 Raspberry Pi 5 [35]

3.6 Work Progress of the Thermal Runaway Chamber

The planning and engineering design process for the thermal chamber starts with the first step, "Proposed Design for the Thermal Chamber." The structural layout, dimensions, frame configuration, and mounting locations are prepared at this step using technical drawings and engineering sketches illustrated in Fig. 4.14. The objective is to create a chamber structure that guarantees mechanical strength and efficient thermal insulation while safely containing thermal runaway tests. Details like chamber size, material thickness, ventilation design, and sensor installation locations are decided upon during this step.

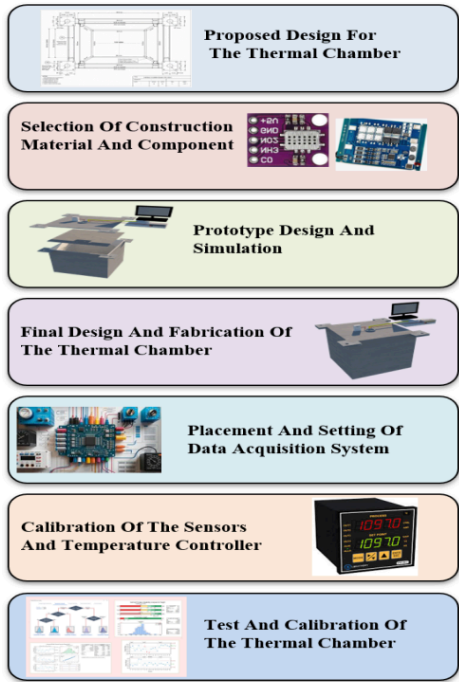


Fig. 3.14 Steps to work on the progress of the thermal runaway chamber.

The selection of suitable electronic and structural components required for the thermal chamber system is the focus of the second phase, "Choosing Construction Material and Components." The Battery Management System (BMS), temperature and humidity sensors, USB thermal camera, controllers, and electrical modules are examples of items that are selected based on their compatibility, robustness, sensitivity, and working range. Furthermore, during thermal runaway testing, the structural materials are chosen to withstand high temperatures, pressure, and corrosive gasses. Precise monitoring, safety, and consistent chamber performance are ensured by careful component selection.

Building a prototype model of the thermal chamber and evaluating its functionality with SketchUp and Blender comprise the third step, "Prototype Design and Simulation." Heat transfer, structural integrity, airflow distribution, and component layout are all examined using a three-dimensional model of the chamber. Potential flaws are found, chamber shape is adjusted, and the design's capacity to manage thermal runaway scenarios safely is assessed through simulation and visualization. Before manufacturing, this stage reduces design errors and improves the chamber's overall effectiveness.

"Final Design and Fabrication of the Thermal Chamber" is the name of the fourth stage. The Thermal Chamber is actually manufactured here. We create the Thermal Chamber using the outcomes of the prototype that we have already worked on. To construct it, and choose the components and materials. To assemble the insulation, sensor mounting, and electronic interfaces that comprise the structure. It requires a great care in doing this to ensure that it complies with the final design criteria. They ensure that everything is properly welded, machined, fastened, and aligned. The Thermal Chamber is robust in this manner. able to operate safely in extremely hot or extremely cold conditions. Temperature tolerance is a requirement for the Thermal Chamber.

The fifth stage involves the installation and configuration of the Data Acquisition System. The goal of this data collection system is to track occurrences over time. Devices for checking temperature, voltage, current, and air contribute data to the Data

Acquisition System. The technology and software used to keep track of these factors are set up to continuously log and present the measured data. By installing the Data Acquisition System and verifying its proper operation, we can gather precise data and have genuine confidence in the results of our research.

The sixth step involves preparing the sensors and the temperature controller. This phase is referred to as the Calibration of the Sensors and Temperature Controller. It's essential to test and ensure that all the sensors and control devices function properly to provide us with the necessary information. After that verify the temperature sensors, humidity sensors, thermal cameras, and controllers to ensure they are functioning correctly. Then evaluate them against tools that are aware of being precise. The temperature regulator must be modified to maintain a consistent temperature within the chamber. Calibrating in this way assists us in obtaining accurate measurements and ensures that the outcomes of our experiment are trustworthy during thermal runaway testing. Calibrating the Sensors and Temperature Controller is essential for obtaining accurate results.

The final step is to verify and confirm that the Thermal Chamber operates correctly. This is the moment we evaluate whether the Thermal Chamber functions as intended. The conduct trial runs to ensure that the Thermal Chamber is robust, maintains the correct temperature, and that the sensors function properly. Also aim to ensure it is safe for use. The test methods of utilizing the Thermal Chamber to ensure it can manage issues that could arise due to heat. It is essential to understand that the Thermal Chamber will provide us with the data during our experiments. Once the complete all the tests, adjust the Thermal Chamber and verify again to ensure everything is functioning properly. This ensures that the Thermal Chamber functions properly and complies with the testing standards. The Thermal Chamber must be dependable and comply with these standards.

Chapter 4: Result and Discussion

Research indicates that four primary forms of abuse can trigger thermal runaway in lithium-ion batteries: electrical abuse, thermal abuse, mechanical abuse, and internal abuse. Electrical abuse, including overcharge, over-discharge, short circuit, and rapid charging, generates excessive heat that may lead to internal failure. Thermal abuse takes place when battery temperatures exceed 150–200°C, triggering self-accelerating chemical reactions that can elevate temperatures to over 800–1000°C. Mechanical abuse, like crushing or nail penetration, can instantly harm the separator and result in swift thermal runaway. Battery failure can occur silently due to internal defects, aging, and the formation of dendrites.

4.1 SoC Estimation

The performance of State of Charge estimation for the LA92 driving cycle was evaluated using two network architectures: GRU-RNN and BiGRU-RNN. The results of the State of Charge estimation for both models are presented in Fig 4.1 and Fig 4.2. The employed performance metrics to evaluate the effectiveness of the models. These measurements consist of Mean Squared Error, Mean Absolute Error, Root Mean Squared Error, greatest error, and the duration taken to calculate the outcomes. They utilised these metrics to evaluate the accuracy and efficiency of the models. The metrics assist us in assessing how effectively the models can monitor the battery State of Charge while the vehicle is operated in various manners. The GRU-RNN model performed better than the BiGRU-RNN model. All the metrics we utilized had error values. The GRU-RNN model demonstrated a Mean Squared Error of 0.0013, a Mean Absolute Error of 0.0084, and a Root Mean Squared Error of 0.0018. This indicates that the State of Charge values estimated by the model closely matched the State of Charge values during the LA92 driving cycle.

The BiGRU-RNN model performed poorly. It contained mistakes. The Mean Squared Error was 0.0019, the Mean Absolute Error was 0.0168, and the Root Mean Squared Error was 0.0026. This is illustrated in Figure 10. Although the BiGRU-RNN model

considers data from both backward directions, it did not provide a more accurate estimation of the State of Charge for this dataset.

The State of Charge prediction curves indicate that the GRU-RNN model aligns more accurately with the State of Charge. It also manages fluctuations and temporary situations more effectively. The reduced error values and superior tracking performance indicate that the GRU-RNN model excels at comprehending the time-sensitive behavior of the battery. Overall, the findings indicate that the GRU-RNN model predicts the State of Charge more accurately and dependably than the BiGRU-RNN model during the LA92 driving cycle. The GRU-RNN model excels in forecasting the State of Charge. It is not as complicated. This provides a suitable option for real-time battery management systems in automobiles.

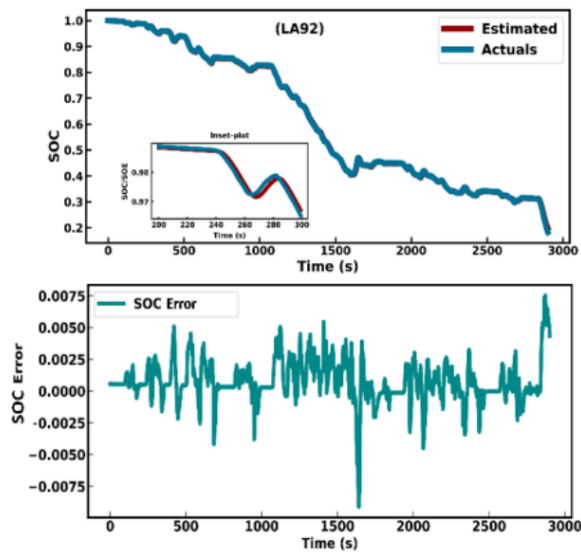


Fig 4. 1 Estimation performance of GRU-RNN under LA92 drive cycle [35]

The GRU-RNN exhibits superior computational efficiency, requiring 8.7seconds, while the BiGRU-RNN model requires 9.5 seconds.

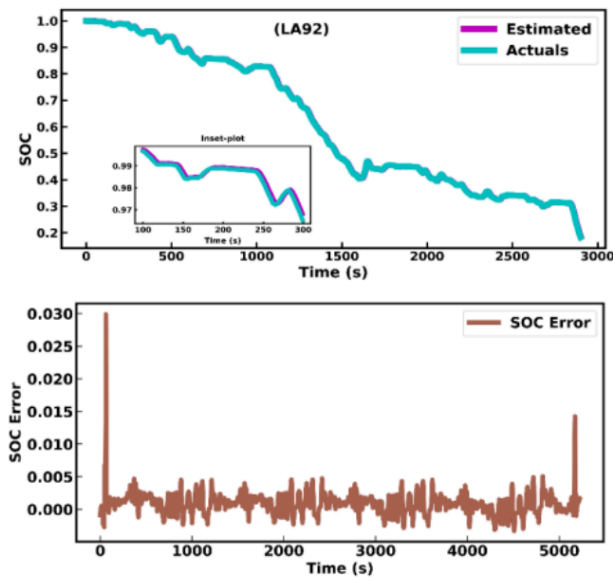


Fig 4. 2 Estimation performance of BiGRU-RNN under LA92 drive cycle [35].

The BiGRU-RNN model and the GRU-RNN model differ in their computational processes. This is due to the construction of the BiGRU-RNN model. The GRU-RNN model analyzes data in a single direction. The BiGRU-RNN model examines it in both forward and backward directions. This allows the BiGRU-RNN model to extract insights from the data, but it also increases the model's complexity. The BiGRU-RNN model requires energy to function and takes slightly more time to complete the task. This could render it less effective for applications such as Battery Management Systems, where quick determination of the state of charge is necessary.

The BiGRU-RNN model and the GRU-RNN model differ in their effectiveness as well. The GRU-RNN model had a slight error in its prediction of the state of charge, being off by just 0.0091. However, the BiGRU-RNN model erred more significantly, being off by 0.0306. This indicates that the BiGRU-RNN model is more prone to errors

during rapid changes, such as when the vehicle is operated similarly to the LA92 driving cycle. This can pose an issue as it complicates understanding the remaining battery life and when it will deplete. This is achieved using the BiGRU-RNN model along with the GRU-RNN model. The BiGRU-RNN model does not perform as well in that regard.

The GRU-RNN model performs well in terms of performance throughout the driving cycle. It contains a mistake, indicating that the GRU-RNN model can monitor SOC fluctuations effectively even when conditions are rapidly altering. The GRU-RNN model has metrics for MSE, MAE, and RMSE that assist the GRU-RNN model in producing predictions that are consistent. This implies that the GRU-RNN model can provide predictions with reduced variability. The GRU-RNN model provides us with quick results. This is crucial for us as we must make decisions and monitor situations constantly, making the GRU-RNN model extremely beneficial for this purpose. The findings clearly indicate that the GRU-RNN model outperforms the BiGRU-RNN model for SOC estimation in the LA92 driving cycle. The GRU-RNN demonstrates greater accuracy. Needs fewer calculations. It contains error rates as well. These benefits render the GRU-RNN a superior choice for estimating battery SOC.

The GRU-RNN improves battery control, energy effectiveness, and dependability in automobiles. The findings show that the GRU-RNN model is an appropriate choice for accurate SOC assessment under changing driving conditions. The GRU-RNN architecture operates efficiently across different circumstances. The GRU-RNN model provides accurate predictions. This study meticulously analyzed the creation, composition, identification methods, and risks associated with vent gas released during thermal runaway (TR) in lithium-ion batteries. The results showed that the main gases generated during TR are CO₂, CO, H₂, CH₄, C₂H₄ and other hydrocarbons that together account for more than 90% of the total gas quantity. The composition of gas is heavily influenced by factors such as batteries, chemistry, state of charge (SOC), and battery degradation, affecting toxicity, flammability, and risks of explosions. Vent gases can be recognized using steady-state techniques such as gas chromatography (GC) and GC-MS, alongside in-situ methods like Raman spectroscopic methods and FTIR analysis. The study indicated that vent gas temperatures could exceed 1000°C,

enabling heat transfer and increasing fire hazards. The danger of an explosion rises with an elevated SOC and can be assessed via reduced flammability limits, explosion thresholds, and overpressure evaluations. Even though it is perceived as thermally stable, Lithium Iron Phosphate (LFP) batteries were found to produce higher quantities of toxic and explosive gases when contrasted with NMC batteries during thermal escalation. The writers emphasized the significance of advanced real-time gas sensing technologies, an improved understanding of thermal runaway gas production processes and effective gas hazard mitigation strategies to improve the safety of lithium-ion batteries for energy storage and electric vehicle applications.

Chapter 5: Conclusion

Lithium-ion batteries face a safety issue known as thermal runaway. This is a worry as lithium-ion batteries are utilized in various applications, such as electric cars, mobile devices, and renewable energy storage systems. They are utilized in both aerospace and industrial industries. This research examined the reasons behind runaway, how it occurs, its effects, and methods to prevent it. The research discovered that thermal runaway occurs when a battery overheats and fails to cool off. This causes the temperature to increase rapidly and initiates reactions that generate heat. Such reactions may lead to undesirable outcomes, such as the emission of flammable gases, fires, explosions, and potential total battery failure. Understanding thermal runaway is crucial for enhancing the safety, reliability, and quality of lithium-ion batteries. Lithium-ion batteries must be secure to allow their use without concerns about overheating. The research discovered the factors that cause batteries to overheat and cease functioning. Many factors contribute to this, such as overcharging a battery or excessive heat from external sources. Occasionally, batteries are simply manufactured incorrectly. They become damaged. Occasionally, the small components within the battery link together in a manner they aren't supposed to. Overcharging and improper connections within the battery are issues that cause the battery to heat up rapidly and function improperly. The research also examined what occurs when a battery begins to overheat. Initially, the temperature rises. A unique layer within the battery begins to deteriorate. Next, the components that divide the sections of the battery begin to liquefy. Following that, the fluid within the battery begins to decompose and oxygen is emitted from one of the battery's components. All these events occurring cause the battery to become even hotter. Can lead to overheating of nearby batteries, causing them to malfunction as well. This might create an issue with the entire battery system. Runaway and battery failure refer to the situation when batteries overheat and cease functioning due to these issues. Battery malfunction is a concern since it can lead to significant harm. LFP batteries are extremely safe. They are more secure than batteries such as NMC and NCA. The materials used in a battery determine its safety. This encompasses the substances utilized for the electrodes and the electrolyte. The design

of the separator and the cell holds significance as well. Advanced Battery Management Systems are very advantageous. They have the ability to prevent problems from happening with the power source. Chillers and safety devices like fuses and pressure relief valves are also crucial. They help to stop the battery from becoming too hot. A battery can never be completely protected from overheating. The risk can be reduced. You can leverage tools and sophisticated systems to monitor the battery. Cutting-edge technologies, like solid-state batteries, are presently under development. They will improve the safety of Lithium Iron Phosphate batteries to a greater extent. Non-flammable electrolytes will also help. They will enhance the dependability and safety of upcoming lithium-ion energy storage systems.

5.1 Future scope

It is essential to enhance the safety of lithium-ion batteries. Future studies on runaway in lithium-ion batteries should focus on enhancing safety by developing innovative materials and improved monitoring systems. We can enhance battery safety by controlling heat. Solid-state batteries and specific fire-resistant materials can enhance the safety of lithium-ion batteries. This can greatly decrease the likelihood of issues arising with lithium-ion batteries. Improve their performance and extend their lifespan. We can enhance the safety of lithium-ion batteries by incorporating intelligence and machine learning into the systems that oversee them. This can assist us in assessing the health of lithium-ion batteries, detecting issues, and understanding when potential problems may occur with lithium-ion batteries before they arise.

We must investigate how heat transfers within large battery packs utilized in electric vehicles and energy storage systems on a substantial scale. We need to find methods to cool these batteries, such as utilizing special materials that can change phase and innovative safety devices that can prevent overheating. This will enhance the overall system performance and extend its lifespan. We need to make certain that safety standards and evaluations are implemented for the new batteries being manufactured. This is essential if we intend to use these batteries in daily life without problems. These developments will support us in developing energy storage solutions that are safer, more effective, and eco-friendly, which is vital for our future.

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- , D. Kumar, H. Raj, A. Kumar, A. Kumar Ranjan M. Rizwan and A. K. Panwar, "Robust State of Charge Estimation of Lithium-Ion Batteries Based on Hybrid Deep Learning Approach," 2025 IEEE Industry Applications Society Annual Meeting (IAS), Taipei, Taiwan, 2025, pp. 1-6, doi: 10.1109/IAS62731.2025.11061708.

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Robust State of Charge Estimation of Lithium-Ion Batteries Based on Hybrid Deep Learning Approach

Deepak Kumar
Center for Electrical Vehicles and Related
Technology, Department of Electrical
Engineering, Delhi Technological University,
Delhi, India
deepakvni63@gmail.com

Himanshu Raj
Department of Electrical Engineering, Netaji
Subhash University of Technology, Delhi,
India
himanshura8181@gmail.com

Dr. Astitva Kumar
Department of Electrical Engineering, Netaji
Subhash University of Technology, Delhi,
India
astitva.kumar@nsut.ac.in

Ashtosh Kumar Ranjan
Department of Electrical Engineering, Delhi
Technological University, Delhi, India
ashtoshkranjanss@gmail.com

M. Rizwan
Center for Electrical Vehicles and Related
Technology, Department of Electrical
Engineering, Delhi Technological University,
Delhi, India
rizwan@dce.ac.in

Anurish K. Panwar
Lithium-Ion Battery Technology Laboratory,
Department of Applied Physics, Delhi
Technological University, Delhi, India
anurish.phy@dtu.ac.in

Abstract—Lithium-ion batteries are widely used in many applications due to their high energy density, high efficiency, and excellent cycle capacity. The battery can operate more efficiently when the state of charge (SOC) is estimated with accuracy. To function safely and efficiently, Battery management system (BMS), which are increasingly common in electric vehicles (EV) & smart grid technologies, must assess their state of charge (SOC). In this research, an advanced intelligent hybrid approach consisting of a gated recurrent unit (GRU) network and a bidirectional gated recurrent unit (GRU) network with a recurrent neural network was presented. The features are automatically extracted by using the GRU and Bi-GRU network model which has been developed. The combined GRU-RNN and Bi-GRU-RNN network is studied. Under various drive cycles, SOC estimate is carried out to verify network suitability. The findings show that in terms of accuracy and computational efficiency, the GRU-RNN model frequently performed better than BiGRU-RNN. In the LA92 drive cycle, GRU-RNN demonstrated a 31.6% improvement in MSE, 50% in MAE, 30.8% in RMSE, and 70.2% reduced maximum error, with 8.4% reduction in computation time. In the US06 drive cycle, GRU-RNN demonstrated 21.4% enhancement in MSE, 20.2% in MAE, 10.5% in RMSE, and a 46.8% decrease in maximum error, along with 22.7% increase in computation efficiency. The findings indicate that the GRU-RNN model delivers a more accurate and effective approach for SOC estimation, rendering it far better for real-time applications where accuracy and rapidity are essential.

Keywords—Lithium-Ion Battery, State of Charge, Battery Management System, Electric Vehicle, Drive Cycle

I. INTRODUCTION

Electric vehicles (EVs) have emerged as a significant development in the quest for sustainable transportation, helping us to avoid the inherent financial and environmental problems caused by fossil fuels [1]. The LIBs is at the forefront of a technological revolution: its longevity, performance, and reliability are important for EV adoption and development. Thus, inaccuracy in estimation of battery parameters such as SOC, also responsible for the blast of EVs. In results, it hinder the advancement of EVs technology. Therefore, accurate SOC estimations helps to know the current status of the LIBs and prevent the battery from overcharging/discharging. This may also prevent LIBs from participating in the blast of EVs. In addition, it ensures the best performance and prolongs the lifespan of LIBs [2].

The battery's remaining capacity to its rated capacity is known as SOC. As it refers to the internal condition of the battery, this cannot be directly measured but must be examined by collecting information like battery capacity, voltage and current. Three categories are often used for SOC estimation: direct, model, and data-driven-based methods [3]. Accurately obtaining the battery SOC remains challenging because LIBs are highly time-varying and nonlinear [4]. There are significant constraints associated with direct measurement methods for SOC estimation, such as Coulomb counting and voltage-based estimation. Sensing inaccuracies and integration errors contributes to the progressive formation of errors in Coulomb counting, therefore providing a significant challenge to achieving overall precision [5]. Furthermore, it is very dependent on a precise starting SOC value; in the absence of this, the estimation might rapidly lose its reliability [6].

Model-based methods for estimating SOC, including electrochemical and equivalent circuit models, have many of shortcomings [7]. Often, such methods necessitate intricate models that might be computationally expensive, therefore posing difficulties for real-time SOC estimation. The precision of these methods is strongly influenced by appropriate parameter identification, which can vary significantly with variations in temperature, battery ageing, and operating scenarios [8]. The high sensitivity of the model parameters suggests that even minor mistakes in these parameters might result in substantial errors in the estimation of SOC. These models are also limited in their general application for various battery types because they must be specially adapted to distinct battery chemistry and combinations [9].

Data-driven methods, such as deep and machine learning and AI-based models, provide distinct advantages compared to direct measurement and model-based methods for SOC estimations [10]. These models may effectively manage intricate, non-linear correlations between SOC and battery parameters without requiring intricate physical models or precise beginning SOC values. In contrast to direct approaches, they exhibit less susceptibility to cumulative errors and exhibit more resilience to temperature fluctuations, load fluctuations, and ageing effects [11]. Data-driven methods are not dependent

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Patent

- D. Kumar, A. K. Ranjan M. Rizwan, M. Singh, and A. K. Panwar, “Testing chamber for evaluating thermal runaway behaviour of energy storage modules,” Indian Patent Application IN202611009870 A1, published Mar. 13, 2026.

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(71) Name of Applicant(s):
Delhi Technological University,

(72) Name of Inventor(s):
1. Kumar, Deepak
2. Ranjan, Ashutosh Kumar
3. Rizwan, M.
4. Singh, Madhusudan
5. Panwar, Amrish K.

(57) Abstract:

The present disclosure relates to a testing chamber (100) for energy storage modules (106). The testing chamber (100) includes a holder (104) disposed within an interior space (102) of the testing chamber (100) to secure the energy storage module (106), a heating element (110) to regulate temperature inside the testing chamber (100) for initiating thermal runaway and sensors (108A to 108D) for monitoring data associated with the energy storage module (106). The testing chamber (100) includes a cover (112) removably coupled to the testing chamber (100) for providing a pressure-controlled seal within the interior space (102), venting valve (114) coupled within the interior space (102) for controlled release of hazardous gases generated from the energy storage module (106) during thermal runaway and a controller to continuously monitor changes in the energy storage module (106) to detect a thermal runaway of the energy storage module (106).

Curriculum vitae

ASHUTOSH KUMAR RANJAN

Contact: +91 7089833393

Email: ashutoshranjancss@gmail.com

Linked In: www.linkedin.com/in/ashutosh-kumar-ranjan-207341258



PROFILE

Research-oriented Electrical Engineering- Power system, Post graduate with interests in lithium-ion battery safety, thermal management, energy storage systems, and renewable energy applications. Skilled in modelling, simulation, and analytical problem-solving with a strong motivation for advanced research in sustainable power technologies.

EDUCATION

DEGREE	INSTITUTE	YEAR	%/CGPA
M.TECH - PSY	Delhi Technological University, Delhi	2026	69.1%
B. TECH - EE	University of Lucknow, Lucknow	2023	64.9 %
12 th	Vidyut Mandal Hr. Sec school, Pali, Umaria, MP	2019	51.6%
10 th	Children Sin Sec School, Belaisha, Azamgarh, UP	2017	62.7 %

INTERNSHIP & WORK EXPERIENCE

- Internship at Locomotive Workshop, Rolling stock Workshop, Northern Railway, Charbagh, Lucknow (UP). The project I undertook was titled “Traction Motor” PoH (Periodic Overhaul) and testing, “3-phase induction motor” PoH (Periodic Overhaul) and testing.
- Project 1: GSM-Based Smart Energy Meter Billing System Using Arduino,
- Project 2: Multipurpose Solar-based Charging Station.

ACADEMIC ACHIEVEMENTS

Research article:

- Paper 1: Published in 2025 IEEE IAS Annual Meeting Incorporating the Industrial & Commercial Power Systems Asia Conference, New Taipei City, Taiwan.
- Paper 2: Accepted in “The 2nd International Conference on Sustainable Power and Energy Research (ICSPER 2025)”, NIT Srinagar.

Patent:

- Contributed to a patent application on “Testing Chamber for Evaluating Thermal Runaway Behaviour of Energy Storage Modules”, focusing on enhancing battery safety through real-time monitoring and control mechanisms (under review)

Workshops

- Attended a workshop on challenges in solar PV technologies, organised by Centre of Excellence for Electric Vehicles and related technology, EED, Delhi Technological University.
- Attended workshop on “Sustainable through Renewable Energy Solution considering NextGeneration Semiconductor Devices”, the Centre of Excellence for Electric Vehicles and related technology, EED, DTU
- Attended a workshop named GIAN (Global Initiative of Academic Network), organised by EED, Delhi Technological University, associated with the Ministry of Education, and scored an ‘A’ grade in the GIAN course.

Fellowship:

Teaching assistantship (TA), offered by the Department of Electrical Engineering, DTU.

SKILLS

- **Software:** LabVIEW, MATLAB, PSSE-33, MS Office, Visio, Cadence, etc.
- **Interests:** Power systems, Power Electronics, Smart Grid Systems, EV, Li-ion Battery Technology, Solving Critical Reasoning and Aptitude problems, and Managerial Skills.

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