DETECTION AND MONITORING OF THERMAL RUNAWAY IN LITHIUM-ION BATTERIES

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that the thesis entitled "**DETECTION AND MONITORING OF THERMAL RUNAWAY IN LITHIUM-ION BATTERIES"** contains literature survey and original research work by the undersigned candidate, as a part of his MASTER OF ENGINEERING IN AUTOMOBILE ENGINEERING under the DEPARTMENT OF MECHANICAL ENGINNERING, studies during academic session 2021-2023.

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CERTIFICATE OF RECOMMENDATION

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CERTIFICATE OF APPROVAL

The foregoing thesis, entitled " ***DETECTION AND MONITORING OF THERMAL RUNAWAY IN LITHIUM-ION BATTERIES*** *" is hereby approved as a creditable study in the area of Automobile Engineering carried out and presented by AJIT DAS in a satisfactory manner to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is notified to be understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed and conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.*

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TABLE OF CONTENTS

Nomenclature and subscripts

Ah	Ampere Hour
BMS	Battery management system
BTMS	Battery thermal management system
CO	Carbon Monoxide
CO2	Carbon Dioxide
C-rate	Charging rate
DC	Direct Current
emf	electromotive force
EV	Electric Vehicles
HC	Hydrocarbon
LCO	Lithium Cobalt Oxide
LFP	Lithium iron phosphate
Li	Lithium
LIB	Lithium-ion battery
LiPF6	Lithium Hexafluorophosphate

LMO Lithium manganese oxide

mAh Milliampere Hour

MQTT Message Queuing Telemetry Transport

NMC Lithium Nickel Manganese Cobalt Oxide

PCM Phase Changing Material

PPM Parts Per Million

PPM/s Parts Per Million Per Second

SEI Solid electrolytic Interface

SOC State of Charge

SOH State of Health

TR Thermal Runaway

V Voltage

°C/s Degree Celsius Per Second

List of Figures

List of Tables

Chapter 1

INTRODUCTION

In the current global scenario, depletion of fossil fuels is a significant concern, and vehicle emissions are contributing to environmental degradation and health problems. Therefore, electric vehicles (EVs) have become increasingly popular among consumers, and different types of EVs, such as Hybrid Electric Vehicles, Plug-In Hybrid Electric Vehicles, and Lithium-Ion Battery (LIB) Electric Vehicles have been developed.

The energy storage system of EVs must meet various requirements, such as faster charging capacity, good mileage, and high performance. Li-ion batteries are one of the most suitable options for EVs due to their higher charge density and light weight. Additionally, they have a lower self-discharge rate, meaning they can retain their charge for an extended period. However, heat generation is a significant concern with Li-ion batteries, which can lead to thermal runaway (TR) and potentially catastrophic failure. The TR can arise from a variety of abusive conditions, including nail penetration, excessive charging, and excessive discharging. For design a battery pack it is important to consider the propagation speed of TR in a single li-ion battery module. The timing between the first noticeable TR and completion of TR event need to know for design a better battery thermal management system (BTMS). That's why testing a single module to investigate the onset temperature of TR and the temperature rising rate also the pressure generation, is required to understand the propagation process to scaling it on large battery pack level.

The testing of li-ion battery can be categorized as Life cycle testing, Abuse testing, Performance testing, Environmental and durability testing, Transport testing. To examine the methods and causes of thermal runaway in battery systems, one of the crucial tests is the overcharging abuse test.

In practical scenario overcharging of a battery can occur due to failure of charging system and charger or failure of battery management system. That's why detection and control system must be required to mitigate the occurrence of thermal runaway.

Therefore, to understand the occurrence of thermal runaway due to overcharging we have to understand the working of li-ion battery its chemistry, how charging and discharging is work how overcharging and over discharging occur and how thermal runaway is occurring due to overcharging of the battery.

1.1 Component of LIB

Lithium-ion battery is an electro-chemical cell it converts chemical energy into electrical energy and electrical energy into chemical energy that produce power. A lithium-ion battery is made of anode, cathode, electrolyte, separator and two current collectors. Some brief description of all the components is given bellow.

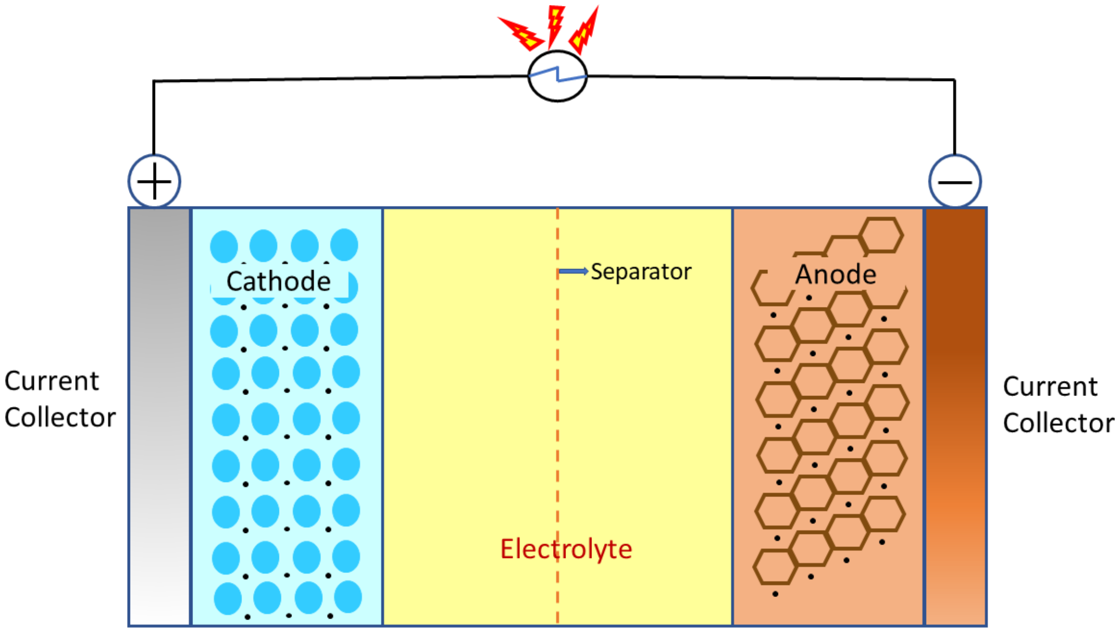


Figure 1: Diagrammatic representation of Components of Li-ion Battery

1.1.1 Cathode

The cathode is the positive electrode of lithium-ion battery. The cathodes are mainly metal oxide of lithium which act as a storage of lithium-ions. The metal oxides are lithium cobalt oxide ($LiCoO_2$/LCO), lithium iron phosphate ($LiFePO_4$/LFP), lithium manganese oxide ($LiMn_2O_4$/LMO). Different cathode material has different advantage and dis advantage. Out of these, $LiCoO_2$ is utilised frequently due to its excellent electrical properties. In this experimental study, an LCO lithium-ion battery was used.

1.1.2 Anode

Anode is the negative electrode of the lithium-ion battery. Generally, it made of graphite and soft or hard carbon. During charging the li-ion are intercalating in the structure of the graphite anode and stored. During discharging the stored li-ion moves back to the metal oxide cathode.

1.1.3 Electrolyte

The electrolyte is liquid or gel-based conducting medium which allow the movement of lithium ion between anode and cathode. It basically a lithium salt like $LiPF_6$ combined with HC solvent. Electrolyte also act as a separator between anode and cathode to prevent short circuit.

The electrolyte also plays a significant role in the development of solid electrolyte interface or SEI layers. The electrolyte reacts with the graphite or carbon anodes as the initial electrochemical reactions start to take place inside the cell. On the surface of the anode, a portion of the lithium starts to form the SEI layer.

1.1.4 Separator

A separator is a thin film type plastic or ceramic material layer that separate the anode and cathode from direct electrical contact to prevent short circuit. If due high temperature the separator melts and anode and cathode come into contact, then short circuit will occur that leads the battery to thermal runaway.

1.1.5 Current collectors

Lithium-ion battery has two current collectors one for cathode and one for anode. Current collector is basically conductive material that's collect current and distribute it, produce by the movement of li-ion. It is made of metal foil, for anode side copper and for cathode side aluminium is used. It is used to provide electrical connection for external circuit.

1.2 Working of Li-ion Battery.

Li is highly reactive in nature in its pure form, but it is quite stable in metal oxide form means cathode. When li-ion is taken-out from its metal oxide it become unstable and try to gain its stable condition. When li-ion is start to move one electrode to another electrode free electrons are created and its start to flow from one electrode to another electrode through the external circuit then electrical current starts to flow.

1.2.1 Charging of Li-ion Battery

When an external power source or charger is connected to li-ion battery and external voltage is applied, the lithium-ion is starts to move from cathode to anode through the electrolyte. The li-ions reach to the anode which is made of graphite and intercalated into the structure of carbon. At the same time the free electron flows through the external circuit and charge the battery. When all the li-ion reached to the anode then battery is fully charged.

1.2.2 Discharging of Li-ion Battery.

When the power source is removed and a load is connected, the li-ion trapped in the structure of graphite anode is wants to move their stable state at cathode. At that time electron is flows through external circuit by powering the load. When all the li-ion moves to the cathode, the battery is totally discharged.

1.3 Overcharging of Li-ion battery

Over charging can be happen in lithium-ion battery when the charger is out of order to voltage control. It also occurs if the BMS is failed to stop when the voltage of the charger or the power source is much higher than maximum voltage of the li-ion battery and it allow to charge the battery beyond its maximum voltage, the battery is over charged.

1.4 Thermal runaway of Li-ion Battery

When Li-ion batteries experience various forms of abuse, such as mechanical abuse like crushing or penetrating, electrical abuse like external short circuits or overcharging and over discharging, and thermal abuse like excessive heating **[1]**, the LIB's temperature increases. The components of Li-ion battery like cathode, anode and electrolyte undergo some chemical reaction that produce heat. This heat has the potential to speed up the reactions even more, starting a vicious cycle that raises the temperature quickly. If the temperature reach to 80-90 C, the SEI layer starts to decompose due to some exothermic reaction.

Due to decomposition of SEI layer some flammable gasses are release and pressure increase inside the battery in temperature is further increase. When the temperature reaches 130 C the separator starts to melt and the two electrode comes in contact which causes internal short circuit. Due to this more exothermic reaction occur between the two electrode and electrolyte and lot of flammable gases and oxygen release.

The battery can explode and catch fire if the internal pressure becomes too high. This phenomenon is called Thermal runaway of Li-ion battery. The occurrence of thermal runaway shown in Fig. 2.

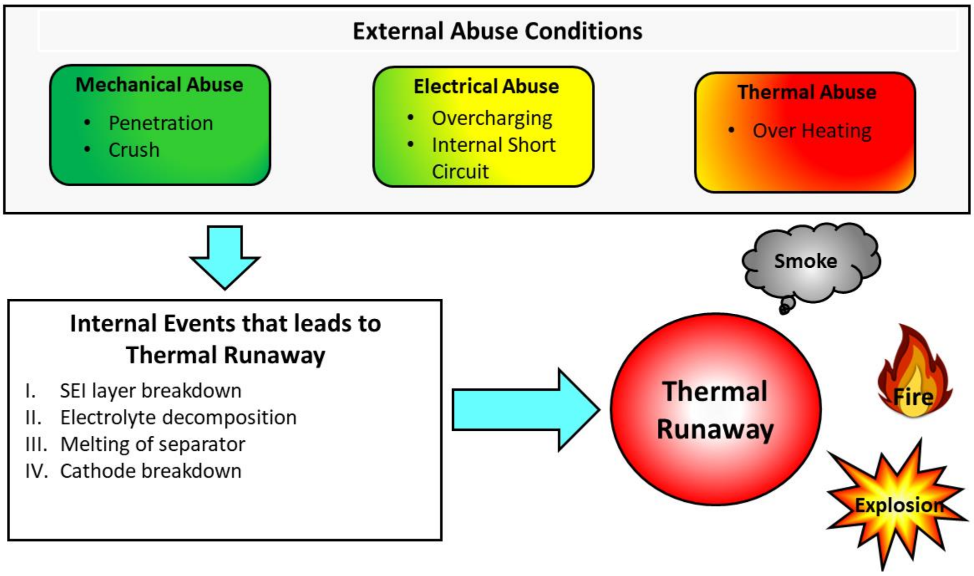


Figure 2: Representation of the Occurrence of Thermal Runaway in Li-ion battery

1.4.1 Thermal runway due to Overcharging

Overcharge of a battery is generally occurred when the charger is out of order and continue to charging the battery even its fully charge or BMS fails to stop charging after the maximum rated voltage of the battery. During overcharging heat and gas generation is a common phenomenon. Ohmic heat is responsible for heat generation inside the battery. Due to the additional energy delivered to the battery during overcharging, thermal runaway caused by overcharging is harsher than other abuse conditions. The test conditions have an impact on the overcharge result, at higher C-rate the battery get explode and catch fire and for lower C-rate only swelled.

Overcharging mechanism have some side reaction, due to overcharging excessive Li-ion intercalate in the anode causes lithium dendrite at the surface of anode. Excessive amount of lithium de-intercalated from the cathode causes the cathode breakdown which leads the battery to produce heat and release oxygen. Massive gases are produced as a result of the electrolyte's accelerated breakdown due to oxygen release. The increased internal pressure may cause the cell to vent. Due the excessive pressure inside the battery it may explode and catch fire.

Chapter 2

LITERATURE REVIEW

For design a battery pack it is important to consider the propagation speed of TR in a single li-ion battery module. The timing between the first noticeable TR and completion of TR event need to know for design a better battery thermal management system (BTMS). That's why testing a single module to investigate the onset temperature of TR and the temperature rising rate also the pressure generation, is required to understand the propagation process to scaling it on large battery pack level.

Researchers have already done some experimental study to perform early detection of TR by creating different abuse condition. Some experimental studies are discussed below.

2.1.1 Review on TR due to overheating

Battery can get over heated externally when the battery is installed near heat source such as engine. When get over heated due to some external heat source it may lead to TR.

Amano et al. **[2]** studied 19 experiments were conducted using 25 pouch cells of li-ion battery with NMC cathode. Al the experiments were done inside an air-tight reactor vessel with a volume of 100 dm^3. The study carried out in two series of test series 1uses a heating plug and series 2 uses a heating plate to initiate thermal runaway with different state of charge (SOC). The study shows how thermal runaway varies with respect to the type of ignition source. They found that Lower SOC level like less than 50% shows lower tendency to thermal runway, also lower gas released. In case higher SOC like 90% to 100 % shows higher tendency to thermal runaway, the pressure rising rate and the temperature rise rate also higher in case of higher SOC level. Amount of gas released is greater with higher SOC.

Aiello et al. **[3]** investigate thermal runaway propagation with four 41 Ah li-ion pouch cells (100% SOC). The heating process was done by a flat steel heater. At the beginning TR was triggered in a 1st cell then the TR will propagate to the adjacent cells by a cascade effect and by the time throughout the whole module. He concludes that the melting point of the separator 135°C to 170°C. Which causes internal short circuit and thermal runaway occurs. The peak temperature of the battery can reach 1100°C.

Wang et al. **[4]** studied an experiment on thermal runaway and ignition with 50 Ah NMC LIBs. An *in-suit calorimeter* was used for this experimental study. Heating of the batteries ware done by two different method using cylindrical heater and electrical furnace. Parameters like surface temperature, heat release, gas emission and mass loss have been measured and analysed. The onset temperature of TR for a Li-ion battery heated with electrical furnace was greater than heated with cylindrical heater. Electric furnace exhibited more heat release than cylindrical heater as TR occurs more when battery was heated with high heating power and high heating area

Wang et al. **[5]** conducted a series of test to examine the thermal behaviour of single cell 18650 li-ion battery using a *cone calorimeter*. The experimental test investigates TR characteristics of a single battery with different state of charge (SOC) and different incident heat fluxes. And the result of the study revealed that high SOC have higher thermal hazard

From the last few reviews, it has been found that State of Charge (SOC) is a key factor in inducing Thermal Runaway (TR).Mao et al. **[6]** studied self-heating reaction of li-ion battery using the *standard accelerating rate calorimeter*. The experiment was carried out with a single 18650 type li-ion battery with different SOC. The study investigates the initial temperature (onset) for self-heating and thermal runaway triggering temperature. He also concludes that the onset self-heating temperature decrease with higher SOC and the delay period of thermal runaway decrease with SOC. Zhong et al. **[7]** performed a series of experimental test using modified cone calorimeter with 18650 type li-ion battery. A self-made heater was used to heat evenly the LIBs. The heater was made hollow copper cylinder surrounded by a stainless steel. In this study heat release rate, gas generation, voltage variation was investigated. He noticed same thing that for constant heating power the triggering temperature of TR decrease with SOC. Lower SOC battery needs higher net heat

Gao et al. **[8]** has done some interesting experiment which will helps to design a battery pack. He carried out three experiments with 4, 24 Ah li-ion battery connected in parallel using two different heaters in an anti-explosion box. The experiments investigate thermal runaway propagation within a battery stack connected in parallel. He found that TR propagates more in case of parallel than series module

2.1.2 Review on TR due to Penetration

Mao et al **[9]** investigates a series of test by nail penetration using 18650 type li-ion battery. They analysed how the fire behaviour change with different SOC different penetration speed, depth and position. The investigation shows that tr occur in the battery when the temperature surpasses 233°C.TR increase with SOC of the battery, when the nail is penetrated at the centre of the battery the higher temperature and higher heating rate and faster thermal runaway propagation occur.

2.1.3 Review on TR due to Overcharging

Over charging can be happen in lithium-ion battery when the charger is out of order to voltage control. Over charging can create unstable condition inside the battery it can increase pressure and cause thermal runaway. Some experimental study on overcharging is reviewed bellow.

Huang et al. **[10]** has done comparison experiment using a prismatic li-ion cell and a pouch li-ion cell with same capacity and voltage range to investigate how TR occur during overcharging. He concludes that the prismatic cell has less thermal behaviour and overcharge tolerance as compared to pouch cell, but the prismatic cell has better TR buffering characteristics because of safety valve.

Yuan et al. **[11]** explore effect of overcharging on the Aged LIB, the experiments' goal is to demonstrate the thermal runaway (TR) behaviour of batteries with various levels of ageing. In this study 18650 type commercial LMO battery is used with different capacity retention rates (CRRs). The results of the study indicated that the trigger time for thermal runaway in batteries was negatively correlated with the CRR. Batteries with CRRs of 86.7%, 80.8%, and 75.2% took 28.2%, 32.5%, and 52.0% longer than a fresh battery, respectively, to reach the temperature that triggers thermal runaway. Additionally, these aged batteries took 54.1%, 91.8%, and 115.1% longer than a fresh battery to reach the point where lithium plating occurs. The deposition of manganese oxide on the cathode surface and the phenomenon of lithium plating on the anode surface were identified as contributing factors to the reduction of reversible lithium inside the battery. As the battery ages, the amount of reversible lithium decreases, which explains the delayed trigger time for thermal runaway. The study's findings serve as a guide for designing batteries' charging safety and TR control strategies.

Zhang et al. **[12]** have done an experimental study to examine the effect of slight overcharging on a Li-ion battery. He further investigated the degree of degradation and thermal stability of the battery. In this study 18650 type NMC battery of capacity 3500mAh is used. The results indicate that a single slight overcharge is give little impact on the cell capacity and it significantly degrade the thermal stability of the battery. More significantly, the characteristic temperature of thermal runaway, in particular the self-heating temperature, significantly decreases along with overcharging, which means that even a small overcharge significantly reduces the thermal stability of the cell.

Wang et al. **[13]** conducted some overcharging experimental test of aged 25Ah prismatic type LFP battery. The experiment is done with different state of health under different charging rates. In this paper, experimental phenomenon as cell voltage, temperature and pressure is comprehensively studied to examine the properties of overcharge to thermal runaway. The result conclude that the battery explodes when the SOH is equal or higher than 80% under 10 or more than that. But in case of lower C-rate and lower SOH no Exploration occur.

Sun et al. **[14]** investigate a comparative study of thermal runaway using different overcharging condition. The experimental study is done with two over charging condition one is direct over charging to TR and another is overcharging still safety valve open-standing- recharge. The experiment is conducted with LFP battery module, to detect TR condition surveillance camera, infrared imager, temperature detector and gas detector is used. The result sows that in both charging condition that the battery module's heat dissipation is far worse than that of a single battery cell, and that heat is easily collected under overcharge conditions, making it more likely that thermal runaway may occur. When the battery module loses control, it will emit a strong flame and a lot of high-temperature smoke, which contains substances like H2, CO, CO2, HCl, HF, SO2, and others.

From the above review it is notable that C-rate and SOH is key factor in overcharging experimental test. Liu et al. **[15]** presented the aging effect of li-ion battery under slight over charging cycle and experimental research is done to examine the thermal stability of the battery. The study utilised an Extended Volume Accelerating Rate Calorimeter to examine the thermal stability of aged batteries. According to the findings, batteries get less stable as they age. As a result of lithium plating during overcharging, the anode is crucial in the changes in thermal stability. As a result of cathode structure deterioration, the cathode dominates the stability after 70% SOH. Also, Ouyang et al. **[16]** conducted series of experimental test to examine fire behaviour and TR characteristic of LIB under overcharging and over dis-charging test. During the study voltage, current, capacity and cell surface temperature is measured. He draws the conclusion that TR occurs more frequently with higher C-rates.

From the above experimental studies, it is known that TR can occur due to various abusive condition mainly overheating, penetration and over charging. The occurrence of TR, depends on the charging rates (C-rates), Sate of charge (SOC) and state of health (SOH). In overheating and penetration test higher SOC shows more catastrophic failure also in overcharging test higher C-rates shows more fast temperature rise in the battery. In a battery pack, when TR triggered in once cell then TR will propagate to the adjacent cells by a cascade effect. Therefore, it is required to stop the propagation of TR one cell to another cell. This is only achievable with a suitable Battery Thermal Management System (BTMS), which can keep the battery temperature within a safe range and also keep the battery pack's temperature uniform **[17-18]**

2.2 Classification of BTMS

The battery thermal management system can be categorised according to power usage, coolant type, and coolant-battery contact. There are also other cooling techniques include mist cooling, hydrogel cooling of cells, thermoelectric cooling, and cooling using heat pipes. In some cases, a single cooling system is unable to give propre cooling to the battery pack so, combination of some cooling system is required to obtain the required outcome.

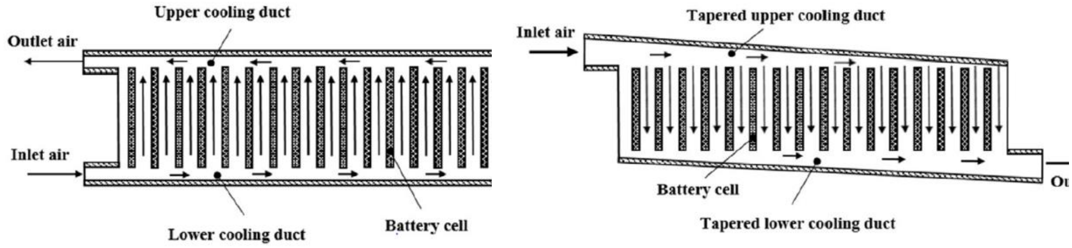
2.2.1 Classification based on Power Consumption

Cooling systems require power to operate effectively. Based on their power consumption, cooling systems can be categorized into two types: active cooling and passive cooling **[18]**.

Active cooling techniques utilise external energy sources to speed up cooling. Forced air cooling, liquid cooling, and cooling with refrigeration units are a few examples of active cooling systems. These cooling techniques are effective, but because they need external energy, they are referred to as active cooling systems. On the other side, passive cooling systems can achieve cooling without the use of external electricity. These systems depend on phase-changing materials, heat pipes, or natural convection. Compared to active cooling, passive cooling is more energy-efficient, but it has practical application and heat absorption capacity restrictions. **[17-18].**

2.2.2 Air cooling

Air cooling can be classified as forced cooling and natural convection-based cooling. The simplest cooling method for batteries is air cooling. It benefits is being lightweight, simpler in design, leak-proof, safe, and easy to maintain. However, air has a poor capacity to absorb heat, which some time restricts its use. Also, natural convection is some time unable to keep the temperature within the desired range. In order to improve the capacity of air cooling, several computational and experimental investigations have been conducted. These include changing the air flow channel, using fans/blowers, exhaust fans, positioning the inlet and outlet for the movement of air within the pack, and using fins.



(a) U-type duct (b) Z-type duct

Figure 3: Schematic of "U-type" and "Z-type" flow battery pack. **[20]**

Researchers have shown that U type ducts and horizontally oriented battery packs, such as those depicted in Fig. 3, have greater heat dissipation capacities due to their enhanced thermal contact surface and short air flow paths. **[19-20]**

2.2.3 Liquid Cooling

This type cools more effectively than air-cooled devices since it employs liquid as the coolant. In current commercial applications, it is most favoured. Liquids of all kinds, including water, water mixed with ethylene glycol, liquid metal, and Nano fluids, can be employed.

De-ionized water was employed by Gou et al. **[21]** in their vapour chamber cooling technique due to its high heat-absorbing capacity and non-reacting copper nature. Hosseinzadeh et al.'s **[22]** comparison of using mineral oil against a water-glycol mixture as a coolant medium. Average cell temperature, maximum temperature gradient, and cooling power need were the variables used in the comparison. It was found that water-glycol cooling outperforms oil cooling in terms of cooling and power usage. According to Yang et al. **[23]**, liquid metal cooling uses less electricity and maintains a lower temperature than water cooling under the same flow conditions.

2.2.4 PCM cooling

Although active cooling has been covered up to this point, it is having some complexity because it consumes power to run compressor, blower fan. These, restrictions were removed by the introduction of passive method cooling, or PCM cooling. PCM is a substance that absorbs or releases heat by switching between states at a specific temperature.

PCM material is able to absorb a large quantity of heat in the form of latent heat during the solid-liquid transition. The phase-changing material (like paraffin wax) absorbs the heat released during operation in the form of sensible and latent heat. When the temperature of the PCM is higher than the solidus temperature, indicating that the PCM is solid, the heat is initially absorbed as sensible heat in the solid zone. When the PCM starts to melt and reaches the mushy zone, it starts to absorb heat as latent heat. When all of the PCM has melted it then absorbs heat once more in the form of sensible heat. Therefore, it is clear that additional power consuming equipment is not required to carry out the cooling. Thus, it is referred to as a passive cooling method. Additionally, through modifying PCM cooling systems, researchers have attempted to increase their performance. Here are some examples of them.

Ramandi et al. **[24]** compared passive cooling techniques using PCM for two different configurations, including one that used a single PCM shell around the batteries with a thickness of 2mm and another that used double series PCM shells around the LIB with a thickness of 1mm each. Both of these configurations were insulated to prevent heat from the environment from escaping. Both designs made use of four distinct PCM. Exergy analysis and computational fluid dynamics (CFD) were used to compare the two systems. Overall, it was discovered that the single shell type was less energy efficient than the double PCM configuration.

In addition to performing a numerical investigation to determine the best fin shape (rectangular, trapezoidal, triangular, I-shape, or T-shape), Choudhari et al. **[25]** also conducted an analytical investigation to estimate the maximum temperature reached under operational conditions for various current rates. They also discovered that a key PCM covering thickness can be increased to get the maximum heat transmission. Beyond the critical point, adding PCM material is not as useful. The numerical and analytical results were found to be in good agreement.

The methods listed above are a few ways to regulate the thermal load on the battery and battery pack. These methods assist in keeping the battery temperature within the ideal range (15°C–40°C) and the desired range (5°C) for the battery pack temperature gradient. If the battery is not kept within the ideal range, Thermal Runaway (TR) may be induced, which has already been addressed. The cell could be harmed by thermal runaway, which could potentially result in dangers including leaks, fires, and explosions. Damages like this result in system failure and could hurt the person using the device. Therefore, early TR detection becomes crucial. The early detection of TR therefore becomes critical from the perspective of the safety of the cell, the device, and the user of the device.

2.3 Early detection of TR

Early TR detection can occasionally be utilised to minimise both the severity and onset of TR. Early detection can be accomplished in a variety of methods, such as by monitoring surface temperature and internal temperature of the cell, monitoring cell voltage, real time monitoring the impedance and gas release from the battery **[26]**

2.3.1 Early detection by monitoring cell temperature

During TR, the battery temperature rises so monitoring temperature is an important parameter to detect TR in a battery. Temperature measurement can be done by using thermocouple, thermal resistance, optical fibre sensor, impedance temperature measurement, infrared thermography, liquid crystal thermography etc. Among these sensor thermocouple and thermal resistance are more suitable because these sensors are highly sensitive, small in size and lower in cost. Some detection method of TR using temperature measurement is described bellow

K-type thermocouple is used in various experiment to measure surface temperature of the cell [**2-11].** Christensen et al **[27]** have done four 3-D thermal coupling model using DUALFOIL and FLUENT and validate it with experimental measurement. In experimental study they used thermistor to measure the temperature of the battery. According to Raijmakers et al **[28]** thermocouples utilising the Seebeck effect have been employed more frequently because of its robustness, low cost, small size, and wide measurement range, than thermistors in terms of measuring battery temperature.

But in case of battery pack there are thousands of cells, to monitor the temperature of each cell with thermocouple is quite difficult **[29]**. There are several methods to monitor the cell temperature of battery stack, some are listed below

Table 1: Different methods or sensors use to monitor cell temperature

Author	Methods (sensors) used to monitor cell temperature	Remarks
Nascimento et al [30]	Utilised fibre Bragg grating optical sensors	According to the results for this particular application, fibre Bragg grating sensors are a better option for the real-time monitoring of the battery surface temperature as well as a useful tool for failure detection and an optimised management in batteries because they have a better resolution and a rise time 28.2% lower than the K-type thermocouples.
Yang et al [31]	Utilised optical frequency domain reflectometry (OFDR)	A standard SMF-28e optical fibre may attain 1 cm of spatial resolution with an uncertainty of 0.7 C, according to experimental verification.

2.3.2 Early detection by monitoring cell voltage

Monitoring the cell voltage is one of the important methods for early detection of TR. Because at the initial state of TR the separator of the battery gets melted and internal short-circuit occur. These is reason for change in cell voltage and impedance also. According to Lamb et al **[32]** for different abusive condition, voltage drop does not follow the same pattern. For mechanical abuse, such as nailing, leads to an immediate drop in voltage to 0 V. Overcharging causes the voltage to continuously increase before eventually dropping to 0 V. Over discharging results in a gradual voltage decrease to 0 V. Overheating causes the voltage to gradually drop to 0 V, typically accompanied by the thermal runaway (TR) process.

Duan et al. **[33]** described a threshold-based method for fault diagnosis of battery overvoltage and undervoltage. He determines a suitable threshold value is challenging due to the complex working environment of batteries. To solve this problem adaptive thresholds that account for aging and other factors are proposed.

Lai et al. **[34]** published a method for early ISC identification based on measurements of voltage and temperature. In order to determine the TR, voltage and temperature readings were converted to electrochemical status.

Even while voltage decrease is a typical aspect of battery thermal runaway, its regularity is weak, and major voltage changes only happen once thermal runaway has already begun. To make thorough decisions and offer early warnings for thermal runaway, it is also required to combine voltage drop signals with other characteristic data. Those methods are described in the table below.

Table 2: different methods of early detection of TR along with voltage monitoring

Author	Method of detection	Remarks
Zhang et al. [35]	Detection of internal short circuit is done by **monitoring the charging current** of the cell	The suggested internal short circuit detection method is extremely effective and efficient in detecting early-stage internal short circuit, providing enough of time for putting countermeasures into place and improving battery system safety.
Srinivasan et al [36]	Suggested a method of early detection of TR by **monitoring internal impedance** of the cell	As result it can be noticed that in the early stages of the battery's TR, it was possible to notice that the temperature changed gradually, but the impedance phase shift was abnormal. As a result, it is thought that the TR warning can be successfully realised by monitoring the internal impedance.

2.3.3 Early detection by monitoring gas release from the cell.

However, the methods listed above are difficult and unreliable. The effectiveness of the entire system may be impacted if one component fails. Gas detection technology is thus a good additional method of TR detection. To convert the project into a LIB pack. In order to quantify the primary gas component using gas chromatography, Golubkov et al. **[37]** conducted an experimental test of thermal runaway on a li-ion battery. The conclusion he draws is that H2, CO_2, CO, and hydrocarbons are the primary components of gases.

Su et al. **[38]** done and experimental overcharging test on commercially used Li-ion battery and proposed a method of early detection of thermal runaway using acoustic signal during gas venting. He showed that detecting of acoustic signal is more efficient than other detection process like temperature and voltage.

Cai et al. **[39]** proposed a method of early detection of thermal runaway by monitoring the amount of gas released from the battery. They have done some simulation using COMSOL and conclude that monitoring of gas concentration is more efficient as compared to surface temperature of the cell.

Lammer et al. **[40]** proposed that the amount of CO2 generated is proportional to the amount of SEI that is depleted as a result of the SEI layer breaking down. The study found that the gas sensing methodology is substantially quicker and more promising than the surface temperature monitoring method in terms of early TR detection.

2.4 Research gap

A survey of the literature revealed that the catastrophic event known as thermal runaway can have an impact on li-ion battery applications. The incident of thermal runaway of li-ion battery can be occur due to some abusive condition like electrical abuse, thermal abuse and mechanical abuse. From the literature review some cooling technique of the battery is known as air cooling, liquid colling and PCM cooling. Sometimes, these cooling techniques are not alone to prevent the thermal runaway. So, research on early detection is required to stop thermal runaway. Some researchers have been proposed the method of early detection by monitoring cell temperature, cell voltage and gas leakage from the battery experimentally and numerically. From these methods of monitoring the amount of gas leakage is one of the promising methods for early detection. So, following gaps are found after reading the literature:

- Lot of experimental study have been done on battery but limited number of studies using overcharging has been performed to understand the propagation of thermal runaway.
- The use of many sensors in combination for early detection of thermal runaway has not yet been thoroughly studied. Additionally, a suitable thermal runaway mitigation strategy is not suggested.

2.5 Objective

The following objectives are set for the present work based on the literature review and the research gap mentioned above:

- Develop an experimental setup for battery overcharging to examine the process of thermal runaway in the battery.
- Use of several sensor together like temperature sensor, gas sensor and voltage sensor to monitor and early detect the thermal runaway of li-ion battery
- Finally, propose a process of mitigation of thermal runaway followed by overcharging the li-ion battery.

Chapter 3

METHODOLOGY

3.1 Experimental setup

The current study aims to detect thermal runaway in an 18650 lithium-ion battery by conducting an overcharging experiment. To do this, a DC power supply is utilized, which can maintain a constant current during the test while using different charging rates (C-rates). The battery's temperature is monitored using a K-type thermocouple with a temperature sensor, while the gas generation is measured using CO and CO2 sensors. In addition, a voltage sensor is being used to continuously track the cell's voltage, while a microcontroller with an integrated Wi-Fi module is used to connect each sensor and wirelessly send data to a base system.

To ensure safety, the battery is kept inside a transparent cubical box, and a battery holder is used to hold the battery and prevent any explosions. The CO and CO2 sensors are mounted inside the box to monitor the amount of gas generated at any instant. The schematic of the setup is shown in Fig. 4.

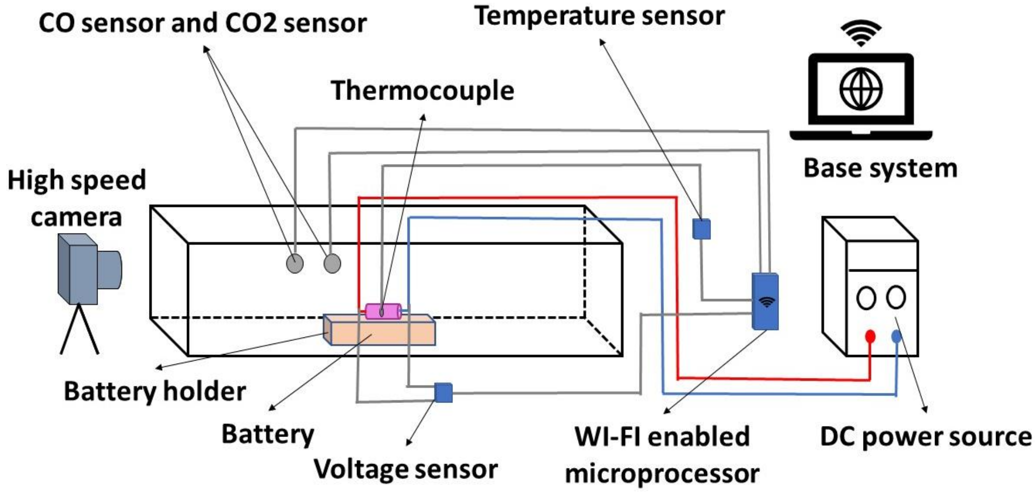


Figure 4: Schematic of the experimental set-up during over-charging test

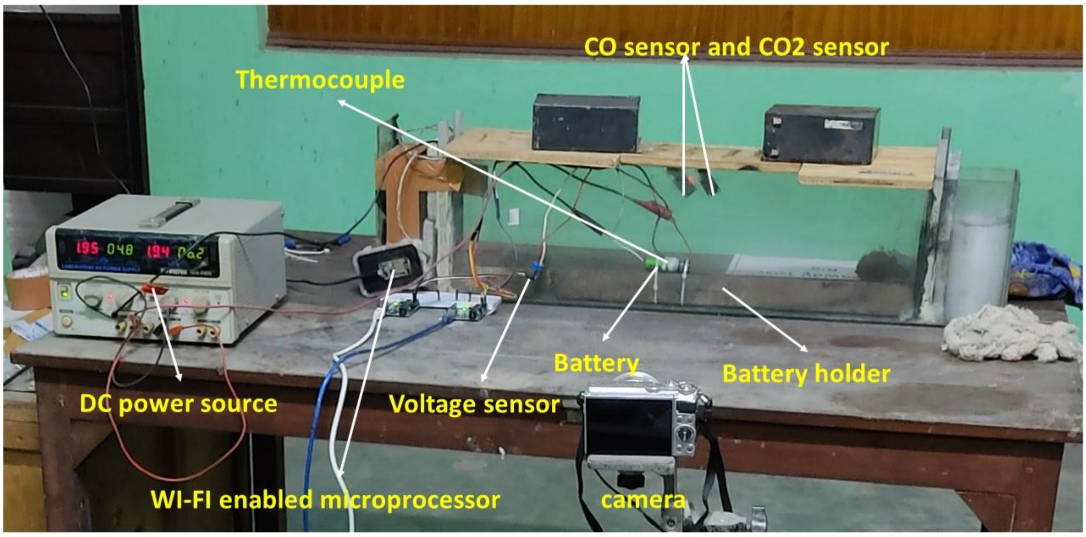


Figure 5: Picture of experimental setup

3.2 Cell description

In the current study, the battery cell used is an 18650 cylindrical type with a rated capacity of 2600 mAh and a nominal voltage of 3.7V. The cathode chemistry used in the battery is LCO, while the anode electrode is made of Graphite. The battery has a height of 65mm, a diameter of 18mm, and a weight of approximately 45 grams. All the specification of the battery is given in the table 3.

Table 3: Specification of a cell.

Sl. No.	Parameters	Values
1.	Cathode material	LCO
2.	Anode material	Graphite
3.	Electrolyte	Lithium hexafluorophosphate ($LiPF_6$)
4.	Capacity of a cell	2,600 mAh
5.	Nominal voltage of a cell	3.7 V
6.	Cell type	18650 (Cylindrical)
7.	Height of a cell	65 mm
8.	Diameter of a cell	18 mm
9.	Weight of a cell	45 g approx.

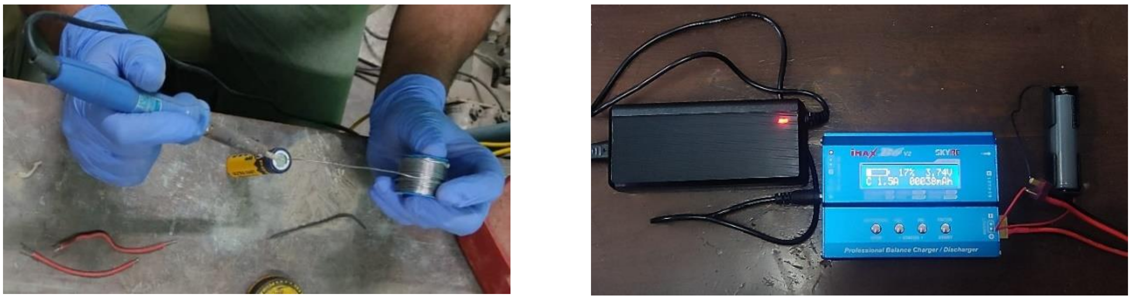
It is important to note that this battery does not have any internal overcharging protection device, which makes it suitable for this study's purpose of inducing thermal runaway through overcharging. However, it is important to exercise caution and follow proper safety protocols during the experiment to prevent any potential accidents or damage to equipment. The picture of the cell is given in the Fig. 6.

Figure 6: 18650 lithium-ion cells used in this study

3.3 Cell preparation

To prepare a cell for an overcharging test, there are several steps that need to be taken. First, the positive and negative terminals of the cell must be connected to two wires using soldering. This is done so that the cell can be connected to a DC power supply. The soldering process should be carried out with care to avoid damaging the cell or creating a short circuit.

Once the wires have been soldered to the cell, each battery must be charged to 100% and then discharged to 0% using a battery charger/discharger. This ensures that the cell is in a consistent state before the overcharging test begins. Charging and discharging the cell in this way helps to reduce variability in the results and allows for easier comparison of performance between different cells. Once the cell has been charged and discharged, it is ready for the overcharging test. Figure 7 represents the preparation process of the battery.



a ***b***

Figure 7: Preparation process of the battery ;(a) Soldering process of the cell (b) Charging and discharging of the cell

3.4 Sensors and other equipment

For conducting an overcharging test on a battery, a DC power supply from GW INSTEK is utilized, which has two channels and can provide current up to 3 A and voltage up to 30 V. To measure the concentration of gases generated from the battery, MQ CO and CO2 sensors are employed. Additionally, a K-type thermocouple with a MAX6675 temperature sensor is used to monitor the temperature of the cell during the test. To monitor the voltage of the cell, a voltage sensor is incorporated. All these sensors are connected to an ESP8266 microcontroller with an in-built Wi-Fi module, which collects the data from all the sensors and sends it to a base system. This allows for real-time monitoring of the battery's performance during the overcharging test. Also, a high-speed camera called the Photron FASTCAM UX 100 Mini was utilized to record the events of gas release during thermal runaway

3.4.1 Description of DC power supply

To overcharge the battery a GW INSTEK GPS-3033 power supply is used. The GPS-3033 can provide 180 W output power. It has two channel CH1 and CH2 both can provide output current 0-3A and voltage 0-30V. If the two channels are connected in parallel, it can produce current 0-6A and voltage 0-30V and if the terminals are connected in series is produce voltage 0-60V and current 0-3A. Figure 8 shows the picture of DC power supply.

Figure 8: DC power supply

3.4.2 Description of CO sensor

To measure CO level in ppm, a MQ 7 gas sensor is used. The sensor can measure concentration of carbon monoxide (CO) in air. It can detect level of CO in between 20 PPM to 2000 PPM and the sensor have high sensitivity and fast response time so this sensor is suitable for this work to measure PPM of CO released from the battery. The working of this sensor depends on the chemiresistor, the chemirsistor is SnO2 which is one type of semiconductor which have free electron. In clean air oxygen molecule attract the free electron and no current conduct and give output voltage zero. When it contacts with toxic gases like CO the free electron detached from the surface of SnO2 and it gives output voltage. The sensor gives analogue output voltage it can be calibrate with PPM of gas level.

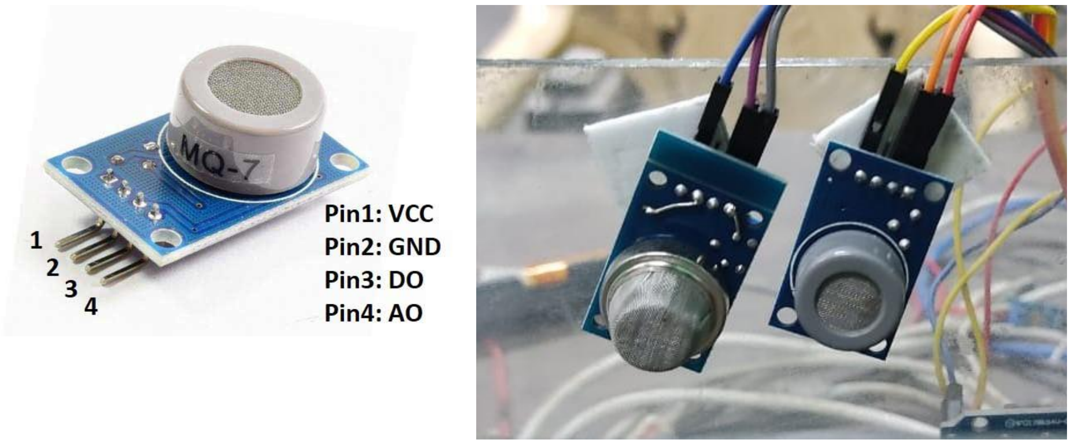
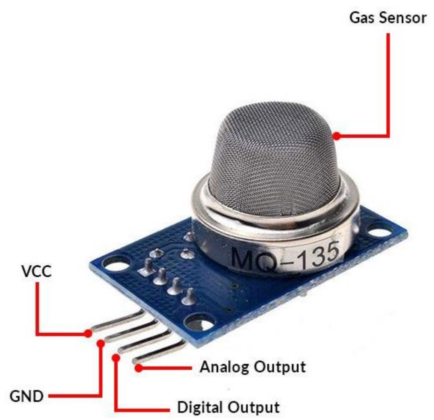


Figure 9: CO gas sensor

3.4.3 Description of CO2 sensor

In this study MQ135 gas sensor is used to monitor the PPM level of CO2 release from the battery. The MQ135 is basically an air quality measuring sensor it can detect ammonia, benzene, alcohol. But it is also use to measure smoke and CO2 in the air. It can measure 100 PPM to 1000 PPM of gases in the air. The working principle of this sensor is same as MQ7 CO sensor it also gives analogue voltage output.

At the initial stage of this study, the MQ135 sensor was used to measure the concentration of CO2. Since it can measure a variety of gases, the MH-Z19 sensor was used for further study. This MH-Z19 sensor is only use to measure CO2. Also, the measuring range of this sensor is much higher than MQ135 sensor. The picture of the CO2 Gas sensor is shown in the Fig. 10.



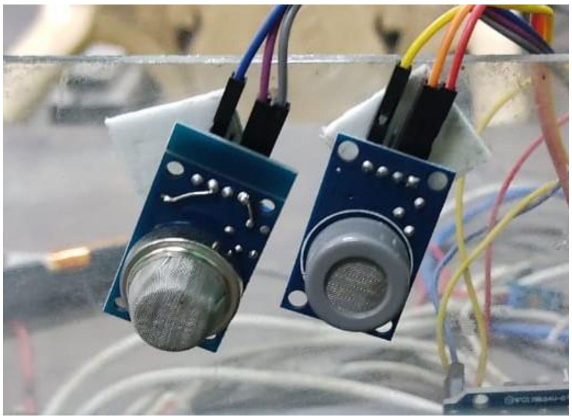


Figure 10: CO2 gas sensor

3.4.4 Description of thermocouple and temperature sensor

For temperature measurement, a K-type thermocouple and a MAX6675 temperature sensor is used. The thermocouple works on the principle of Seebeck effect. Basically, a thermocouple is a two dissimilar metal wire which is joined together at one end. If the temperature of the junction changes, an emf is induced in mV. For different temperature different emf induced in the wire. Here the MAX6675 sensor used to convert the mV output from the thermocouple into temperature data by a linear relation. It converts the emf into temperature valve, with a microcontroller. Figure 11 represents the picture of temperature sensor

Figure 11: Temperature sensor

3.4.5 Description of voltage sensor

In overcharging Test of li-ion battery, a digital multi meter can be uses to measure voltage of the battery. But as the battery is overcharging so its voltage will rise by the time. It is difficult to measure and store voltage of the battery using a multi meter as the voltage is changes with time. To overcome this problem a voltage sensor module is used to monitor the cell voltage. This sensor can measure voltage 0-25 V. this sensor is connected with a microcontroller to collect the voltage data with time. In Fig. 12 the picture of voltage sensor is shown.

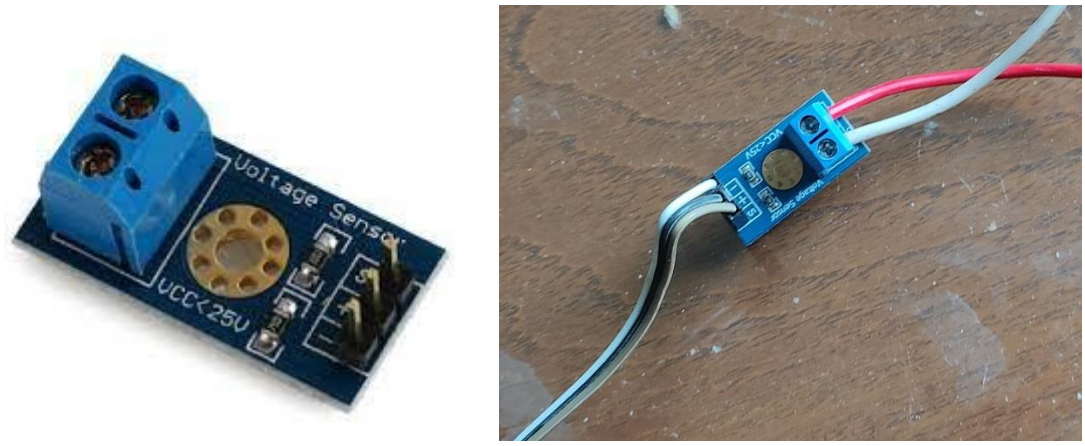


Figure 12: Voltage sensor

3.4.6 Description of microcontroller

In this study, the ESP8266 NodeMCU microcontroller is used to collect all the sensor data. It has an inbuilt Wi-Fi module through which it can send data wirelessly to the base system. It has 15-pin header with access to GPIOs, SPI, UART, ADC, and power pins. All the sensors are connected to this sensor using a jumper wire. The microcontroller collects data from all of the sensors and sends it to the base computer using the MQTT protocol. The data collection process using the MQTT protocol is described in the 3.6 section. The picture of the microcontroller is shown in the Fig.13.

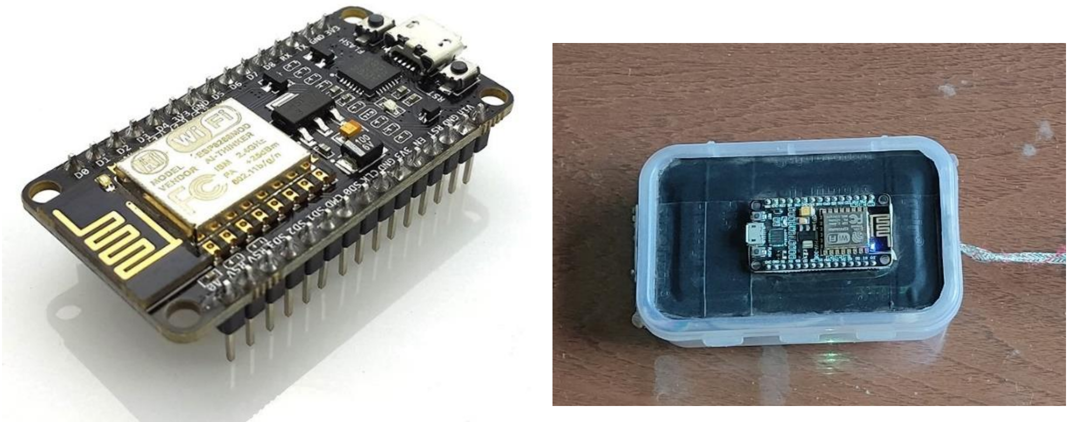


Figure 13: Microcontroller

3.4.7 Description of High-speed camera

The ***Photron FASTCAM Mini UX100*** high-speed camera is used to record the event of venting of the battery and gas release. The camera can capture in a maximum frame rate of 2 lac fps. Tamron SP 24-70mm F/2.8 Di VC USD model: A007N 70 mm lens is used and the video was captured at 12500 fps and at a resolution of 1280 x 240.The video is taken using a software named photron fastcam viewer (PFV). Figure 14 shows the picture of high-speed camera.

Figure 14: High-speed camera

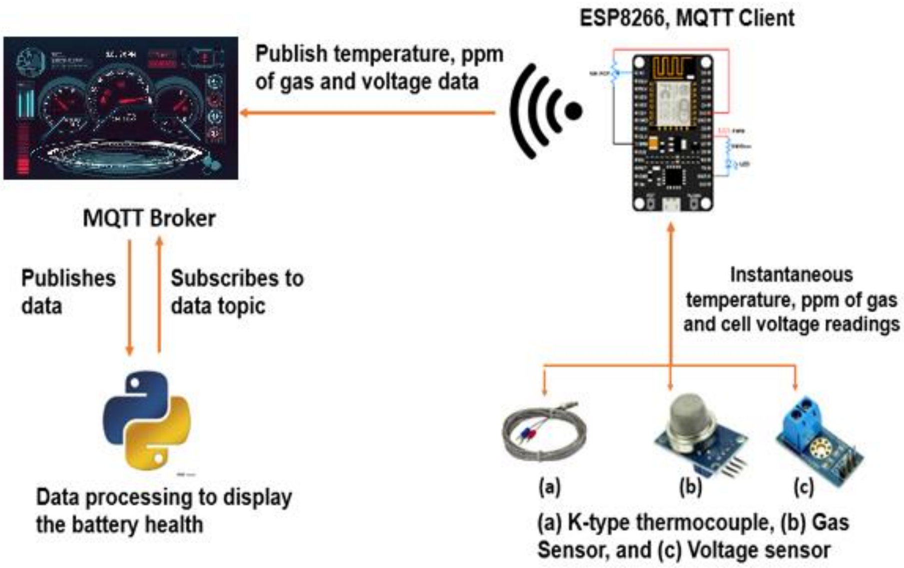
3.5 Experimental procedure

The experiment was carried out at various C-rates of 1C, 1.5C, and 2C. The battery was overcharged by setting the voltage of the DC power supply to 20V, which allowed it to charge above 4.2V. The constant current overcharging was done with the current set at the desired C-rate. Only one channel of the DC power supply is utilized, and the output current is set to 2.6A for the 1C-rate. However, for the 1.5C and 2C-rates, the two channels of the power supply must be connected in parallel. This arrangement ensures that the current from the two channels adds up, allowing the appropriate current to be acquired. The two probes of the power supply are then connected to the two terminals of the battery. To monitor the cell voltage during experiment the voltage sensor is connected to the terminals of the battery. To record the surface temperature of the battery a thermocouple is attached to the middle surface of the battery using Teflon tape. Then the battery is kept on a holder and the whole thing is kept inside a transparent cabinet to maintain safety during the overcharging test. CO and CO2 sensor is mounted inside the cabinet to measure the PPM of gas during the process. All the sensors are connected to a ESP8266 microcontroller which send the sensor data wirelessly to the base computer using MQTT protocol. The experiment is done unlit the thermal runaway of the battery is occurring. To ensure data collection accuracy, the power source is turned off after the battery TR occurs.

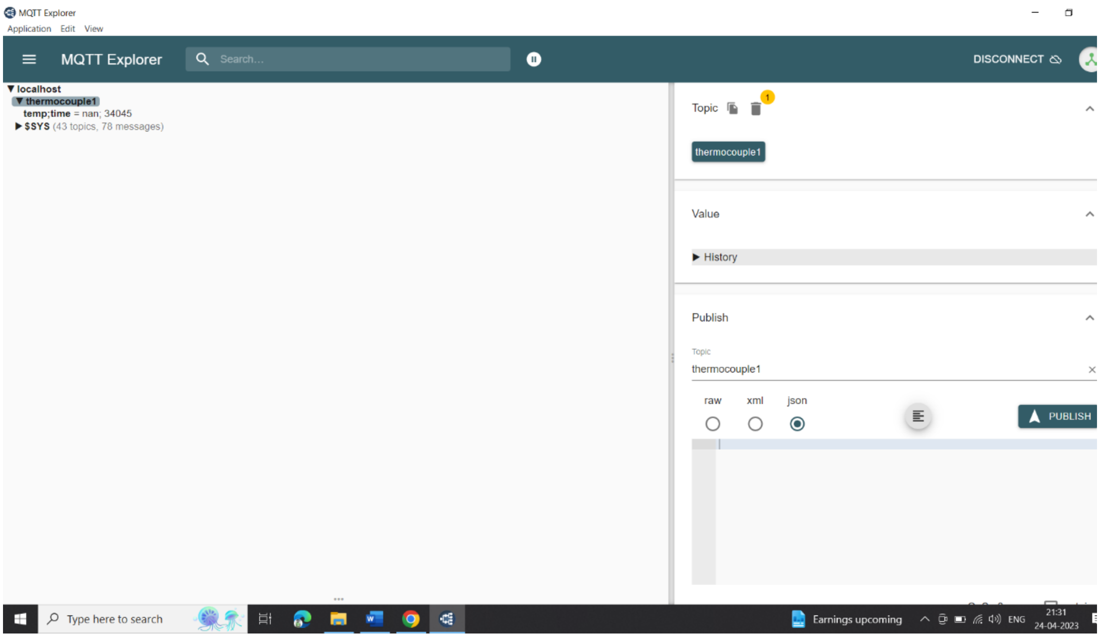
3.6 Data collection process using MQTT

During the experiment all the sensors' data have to collect for further analysis of TR phenomenon. To collect the data in real-time, A ESP8266 microcontroller is used. The microcontroller has in-built Wi-Fi module with it, that send the collected data wirelessly to the base computer. To retrieve the data from the microcontroller, the MQTT protocol has been used as a broker. The MQTT protocol is a light weighted massaging protocol which work on publisher and subscriber method. In our case the ESP8266 is a publisher, that publish the data collected from the sensors and the computer is subscribed to the ESP that can access the data published by the publisher.

MQTT acts as a broker in this case, connecting the publisher and subscriber. The published data can be viewed in real time using the software called MQTT explorer. A python code is utilised to store the data as a text file so that it can be used later. The flow chart of this process and the interface of the software is shown in the Fig .15.



a



b

Figure 15: (a) Flow chart of data collection process (b) Interface of MQTT explorer

Chapter 4

RESULTS AND DISCUSSIONS

The overcharging experiment is carried out with three C-rates: 1C-rate, 1.5C-rate, and 2C-rate. In this experiment, the battery is overcharged until it reached its maximum temperature, at which point gas leakage and thermal runaway occurred. During this process, the cell temperature and voltage are monitored, as well as the amount of gas leakage. The effects of C-rate on cell temperature, voltage and gas leakage are compared and early detection of thermal runaway is done.

4.1 Effect of C-rates on cell temperature

This section describes the impact of various charging rates on the battery's health and temperature during an experimental overcharging test. It is crucial to remember that overcharging a battery can result in a reduction in its performance and lifespan as well as safety risks like thermal runaway. Therefore, in this work the overcharging of the battery is done at constant current under three different C-rates as 1 C-rate, 1.5 C-rate and 2 C-rate. In all the experiment battery thermal runaway achieved. Figure 16 depicts the cell's temperature variation over time at various C-rates. For all the C-rates the temperature vs time graph follows same trend. The heat generation inside the side battery due the ohmic heating is greater than the heat escape from the battery, so the temperature of the battery rises. The speed of temperate rise depends on the C-rates as the charging current is higher at 2 C-rate, it takes less time to trigger thermal runaway than other C-rates. At the initial stage of overcharging the cell temperature increases gradually till 70 °C after that it increases abruptly that leads the cell to TR. The peak point of the curves is showing the point of TR occurrence.

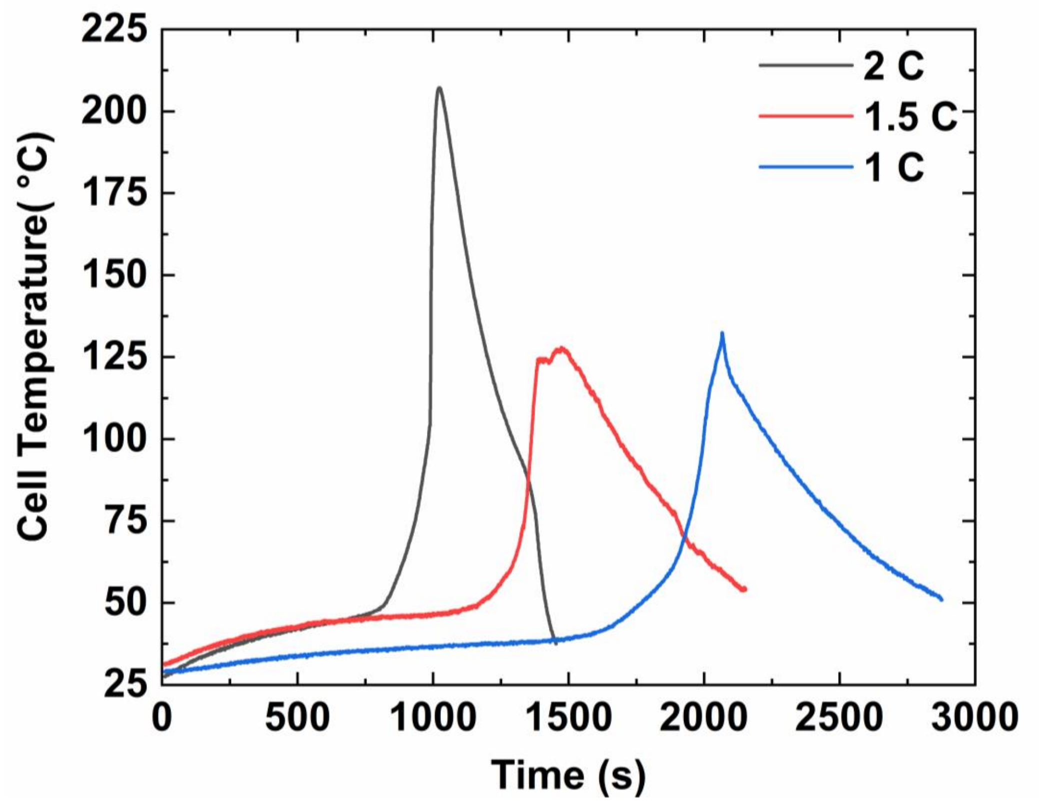
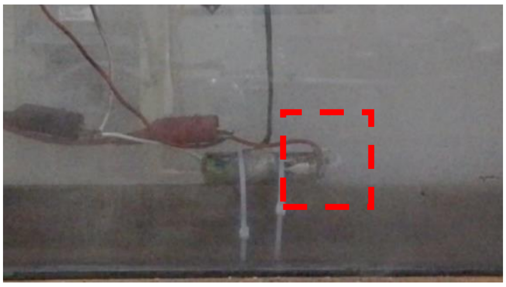


Figure 16: Temperature profile of the cell operating at different charging rates

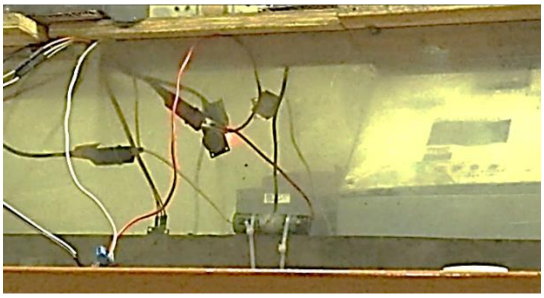
It can be noticed from the Fig. 16 that at 2C-rate the peak temperature of the battery is higher as compared to lower C-rates. Furthermore, greater C-rates are more hazardous in nature. In the case of a 1 C-rate gas release from the battery alone, there is no explosion; in the case of a 1.5 C-rate gas release followed by an explosion; in the case of a 2 C-rate gas release followed by an explosion of the battery; and finally, the gases catch fire. The TR phenomenon of li-ion battery during over charging test at 1 C and 2 C-rate is shown in the Fig. 17 and 18 respectively

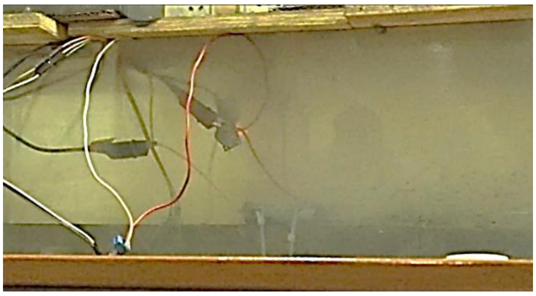
(a) **(b)**



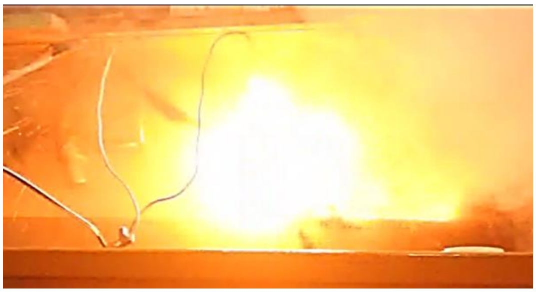
(c)

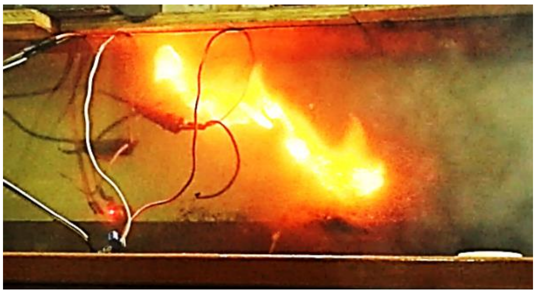
Figure 17: The progression of thermal runaway triggered by over-charging at 1 C-rates: (a) instant just before gas leak gas begins, (b) when battery get swelled and (c) gas leakage





(a) **(b)**





(c) **(d)**

Figure 18: The progression of thermal runaway triggered by over-charging at 2 C-rates: (a) instant just before gas leak gas begins, (b) when gas leak begins, (c) explosion occurs and (d) gases catches fire

Additionally, the thermal runaway of the cell occurred at approximately 1037 seconds for a 2 C-rate compared to 2056 seconds for a 1 C-rate. As a result, the period at which thermal runaway occurred varied greatly depending on the charging rate, with the 2C-rate causing thermal runaway to occur much faster than the 1C-rate. This emphasises how crucial it is to thoughtfully choose the charging rate for a particular battery, based on its characteristics and application requirements.

4.2 Effect of C-rates on cell voltage

This section explains how the battery's voltage changes at various C-rates during the overcharging test. It was indicated in the previous section that the battery's voltage rises when it is linked to a DC power source that permits charging. The battery will charge normally if the DC power source voltage is set to the maximum voltage of the battery. The voltage of the DC power source must be set higher than the battery's maximum voltage in order to overcharge this battery. The charging current, or C-rates, determines how quickly batteries charge and overcharges. For this experiment on overcharging a battery, the output voltage of the DC power supply is set at 20V. To maintain a constant initial voltage for each battery, the batteries are discharged. Here, a voltage versus time curve has been plotted for 1C-rate, 1.5C-rate, and 2C-rate in Fig. 18. The volage curve has a consistent shape across all C-rates. The fully depleted battery has enough free space on the anode side to intercalate the Li-ion, therefore the voltage rises quickly at the beginning of the operation. The voltage curve almost flattens out after reaching a particular voltage and being fully charged, then the voltage increases quickly and the battery is overcharged, which causes TR. In every situation, it can be observed that all of the batteries have been overcharged, reaching the maximum set voltage of 20 V and entering a state of thermal runaway. Like temperature, for 2C-rate the voltage reaches to maximum voltage faster than other two C-rates.

It is important to note in Fig. 19 that, during the overcharging test, voltage rapidly reduces for all C-rates immediately before the thermal runway. This occurrence occurred as a result of the battery's electrolyte decomposing during the overcharging process and forming a resistive solid electrolyte interface (SEI) on the anode, which causes the voltage to drop sharply shortly before the thermal runway **[11]**. Same observation was found in experiment also. This phenomenon can be used as early detection of thermal runaway of the battery during over charging test.

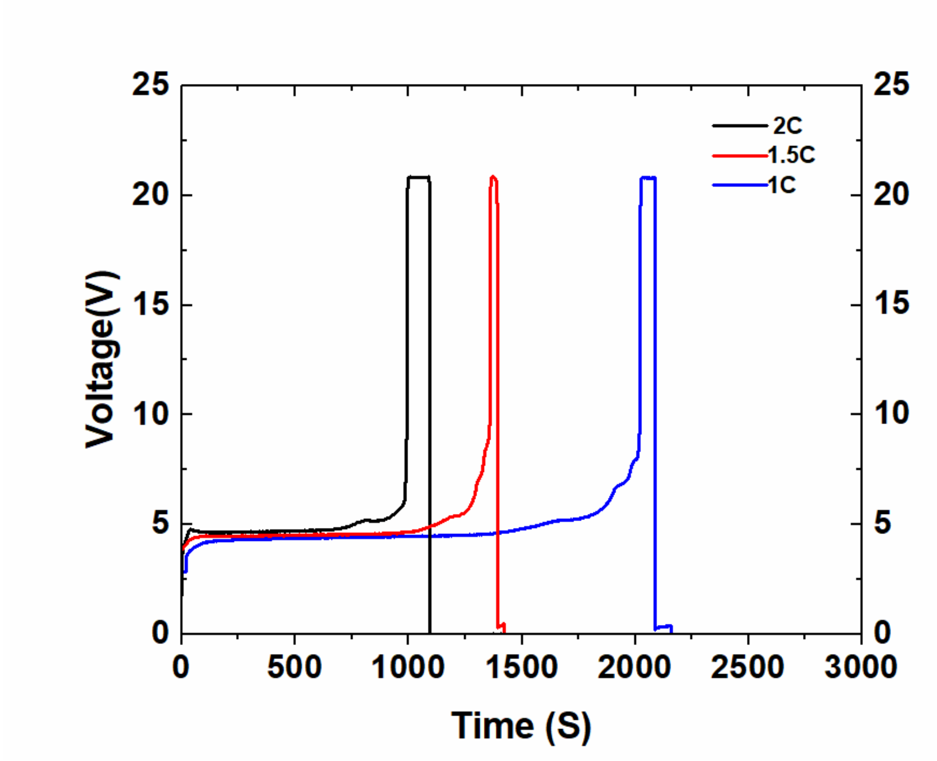
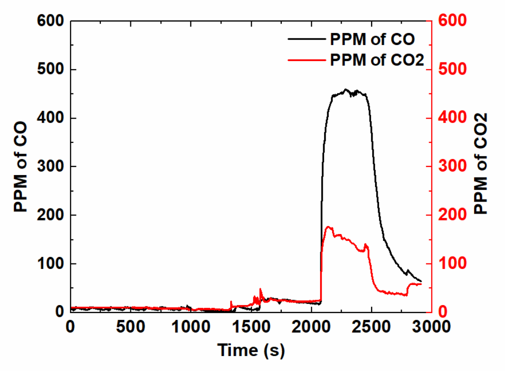


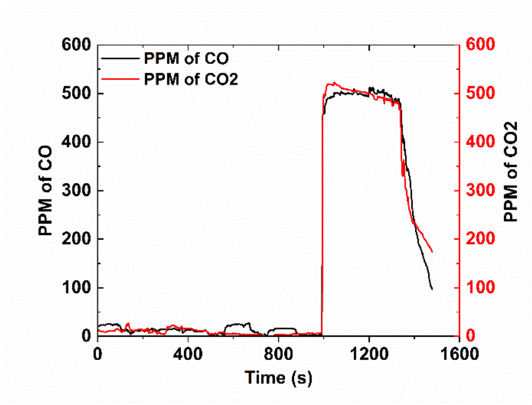
Figure 19: Voltage profile of the cell operating at different charging rates

4.3 Effect of C-rate on CO and CO2 release

As stated in Section 4.1, when TR occurs, gas is released from the battery; therefore, it is crucial to measure the PPM of gas release from the battery in order to detect and mitigate TR. Several major gases, primarily CO2 and CO, as well as H2 and HF are release from battery during thermal runaway [37]. As a result, assessing the levels of CO and CO2 helps for the detection of TR.

In this experiment a CO sensor and a CO2 sensor is attached inside the cabinet to measure the PPM of gas leakage from the battery for 1C and 2C-rates. The SEI layer starts to break down and leak gases, primarily CO and CO2, when the cell temperature hits the threshold limit of 80°C to 110°C. According to the degree of SEI layer disintegration, CO and CO2 gas emissions increase. In Fig. 20, it can observe that the amount of CO2 leakage is greater in 2C-rate than 1C-rate. But the amount of CO generation is same for both C-rates. The occurrence of thermal runaway is indicated by the abrupt, sharp rise in the PPM level of gases. Early detection of thermal runaway can be done by monitoring the PPM level of gas leakage this is explained in the following section,

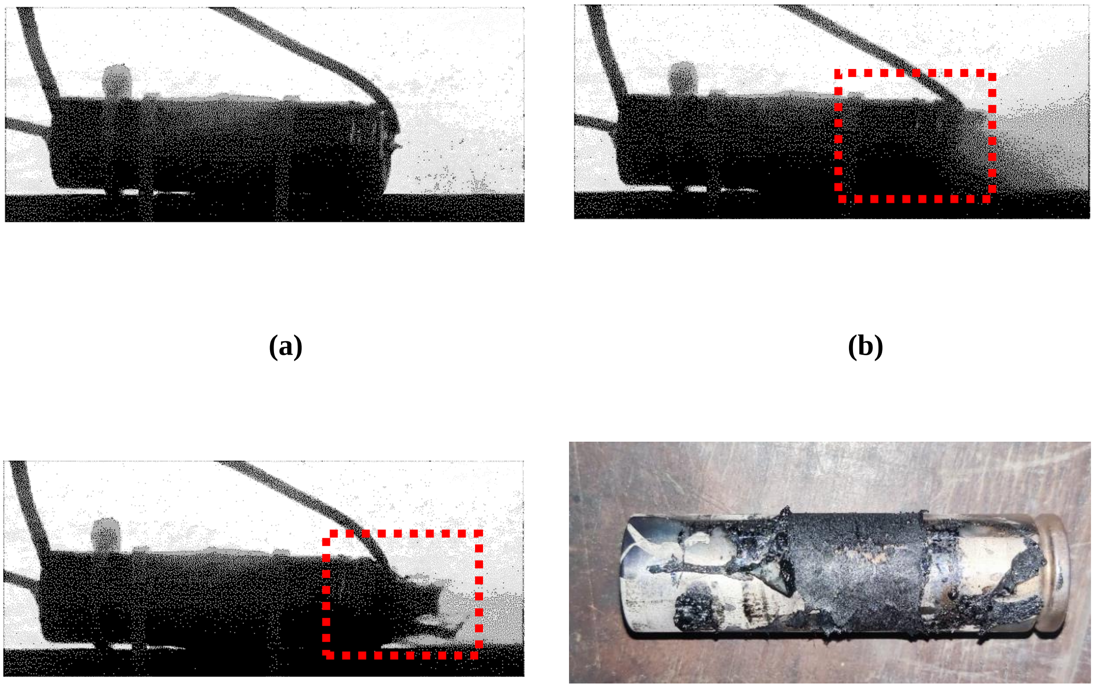




(a) **(b)**

Figure 20: Quantification of the CO and CO2 gas release at (a) 1C-rate, and (b) 2 C-rate

The high-speed camera records the event of progression of the thermal runaway at 2000 frames per second. Figure 21 describes the propagation of thermal runaway and gas release process during thermal runaway. In Fig. 21 (a), the battery is stable before the onset of thermal runaway. As the temperature of the cell rises, the battery swells up slightly and the safety valve breaks, releasing gas as shown in Fig. 21 (b). Next, the battery's positive terminal ruptures as seen in Fig. 21 (c), and gases escape at a high velocity. Finally, the cell catches fire and continues to burn until the entire electrodes have been depleted, as seen in Fig. 21 (d).



(a) (b) (c) (d)

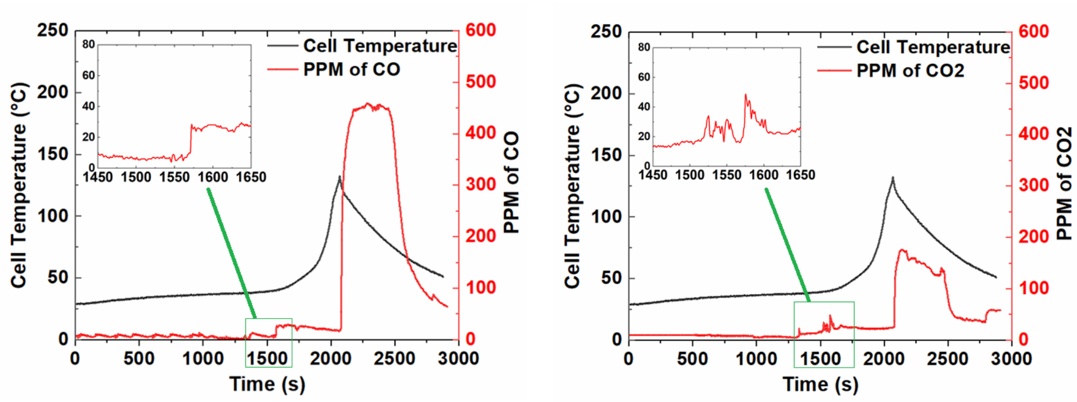
Figure 21: The progression of thermal runaway triggered by over-charging: (a) instant just before gas leak gas begins, (b) when gas leak begins, (c) positive terminal rupturs and gas escape at high speed and (d) thermal runaway undergone battery

4.4 Early detection of thermal runaway

In this section, early detection of thermal runaway which is occurring due to over-charging is performed. Two methods are proposed to detect thermal runaway based on gas detection technique and monitoring cell temperature. The methods are described in subsequent sections.

4.4.1 Based on Gas detection

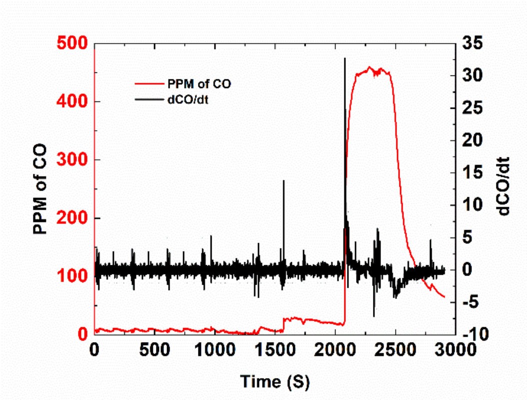
Gas leakage occurs during the overcharging test, which happens just before thermal runaway in the early stage. This is caused by the decomposition of the SEI layer, resulting in the release of gas, primarily CO and CO2. To track early detection of the thermal runaway PPM of gas leakage monitored in this section. When the cell undergoes overcharging test at 1 C-rate, it can be noticed in the Fig. 22 that between 1500 and 1550 seconds, specific spikes in the ppm level CO2 and CO curve are seen. After then, it stabilises before growing significantly larger during a thermal runaway. This increase suggested that the cell could experience thermal runaway. Therefore, this phenomenon can be used as early detection of thermal runaway. But it is difficult to quantify the value of abnormal spikes occur in the CO and CO2 curve because the quantity of gas release is not same for all C-rates as discussed in the section 4.3. So, monitoring the variation of gas level with time will more reliable for early detection of thermal runaway.

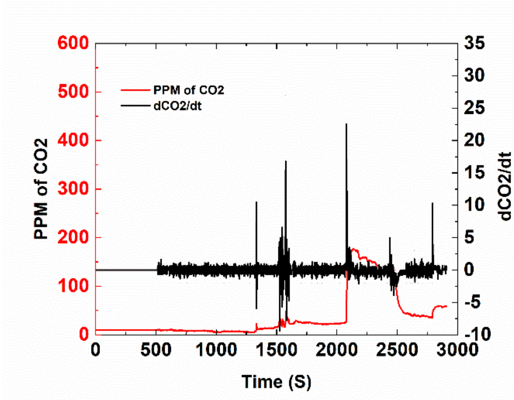


(a) (b)

Figure 22: Early detection of thermal runaway at 1 C-rate by tracking (a) CO gas and (b) CO2 gas

For early detection of thermal runaway, variation of gas level with time is monitored in overcharging test for 1C-rate. Figure 23 shows the rate of change of CO and CO2 level with time. In this figure it can be noticed that rate of change of CO and CO2 level is almost same till 1500s. But just after 1500 s a certain spike occur on both of dCO/dt and dCO2/dt curve which indicates the gas leakage at that time. After that it stabilised and a spike occur at the time of thermal runaway. The occurrence of spike in dCO/dt and dCO2/dt curve, before 500s of thermal runaway can be use as early detection of thermal runway.





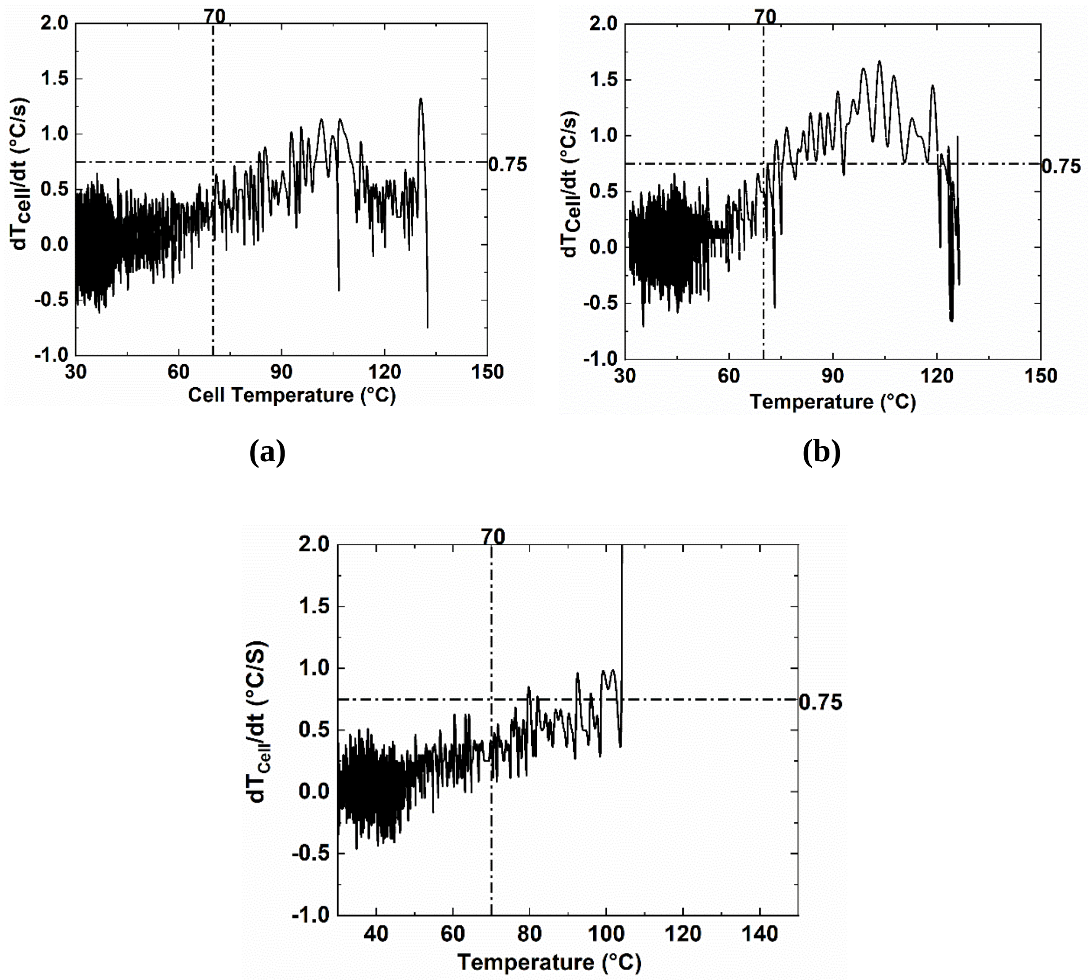
(a) **(b)**

Figure 23: Early detection of thermal runaway at 1 C-rate by tracking (a) rate of CO gas and (b) rate of CO2 gas release

4.4.2 Based on surface temperature detection of the battery.

According to literature review, the TR of the li-ion battery initiate after the battery surface temperature reaches 70 °C. Beyond this critical temperature, an imbalance arises between the joule heating caused by overcharging and the heat dissipation, leading to an accelerated rise in temperature. To identify thermal runaway, one effective approach involves monitoring the rate of temperature increase in the cell. During overcharging tests at both 1 C-rate 1.5 C-rate and 2 C-rate, the rate of temperature increase is continuously tracked relative to the cell's temperature. The fig 24 shows the variation of the rate of temperature increase (dT_{cell}/dt) with respect to temperature. It is noticeable in the fig 24 that the value of dT_{cell}/dt remains below 0.75 °C/s before reaching the cell temperature 70 °C for all C-rates. When the temperature crossed 70 °C the value of dT_{cell}/dt exceeds the 0.75 °C/s threshold then leading occurrence of thermal runaway after a certain period time. So, rising the value of dT_{cell}/dt above 0.75

°C/s after the cell temperature reaching 70 °C indicates the occurrence of thermal runaway.



(a) (b)

(c)

Figure 24: Early detection based on tracking cell temperature at (a) 1 C-rate (b) 1.5 C-rate and (c) 2 C-rate

Therefore, early detection of thermal runaway can be accomplished using the techniques covered in sections 4.4.1 and 4.4.2. A relay module can use to stop the overcharging of the battery by considering the threshold condition of the battery's surface temperature.

Chapter 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusions

In this experimental investigation, a method of early detection of thermal runaway that is caused by overcharging is described. The overcharging experiment is carried out with different C-rates as 1C, 1.5C and 2C-rates using constant current. During operation, a temperature sensor with a K-type thermocouple, as well as CO and CO2 sensors, are fitted to keep track of the cell temperature and ppm levels of gases. As a result, thermal runaway is early detected utilising gas detection techniques and monitoring the cell temperature. Using this method of early detection of thermal runaway, a mitigation method is proposed to control the overcharging and stop the Occurrence of TR. The following are the study's main findings:

i. The occurrence of thermal runaway depends on by the charging rate. Thermal runaway occurred in the cell at a charging rate of 1 C in about 2056 s, whereas thermal runaway occurred at charging rate of 2 C in about 1037 that is less than half the time needed for a charging rate of 1 C.

ii. Thermal runaway occurred in the cell for all the three charging rates. But for 2C-rates, the maximum temperature being reached. This suggests that a faster and more severe thermal runaway could be caused by charging at higher rates.

iii. During the overcharging experiment at both the 1C and 2C-rates, the production of CO and CO2 was compared. The PPM level of CO2 gas was found to be lower at the 1C-rate than at the 2C-rate. However, the CO concentrations were essentially the same at both the 1C and 2C-rates.

iv. This study's key finding is that spikes in the CO2 and CO curve appear 500 seconds before thermal runaway at the 1C-rate. These unexpected spikes indicate the initiation of thermal runaway. So, early detection of thermal runaway is possible using gas detection techniques.

v. During the overcharge experiment, an important observation was made: once the cell temperature reached 70°C, which is the temperature at which exothermic reactions start to occur, the rate of temperature increase was observed to surpass 0.75°C/s. Therefore, these specific threshold values serve as a significant parameter for detecting the occurrence of thermal runaway.

5.2 Future Scope

- In this experimental study the mitigation strategy for overcharging induced thermal runaway was developed. However, battery may undergo thermal runaway because of other abusive condition too. Therefore, to combat thermal runaway sprinkler or an emergency cooling system may be integrated via relay module.
- In future digital twin model can be developed to monitor battery health.

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