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Short Communication

Effects of heating rate and State of Charge of Thermal Runaway in Pouch Li-ion Battery Cells

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Abstract

This study investigates the impact of heating rate and state of charge (*SoC*) on thermal runaway in pouch Li-ion battery cells. Thermal runaway is a critical safety concern in Li-ion batteries, leading to catastrophic failure and potential hazards. By systematically varying the heating rates and *SoC* levels, we analyse the onset temperatures, reaction kinetics and the severity of thermal runaway events. Our findings indicate that higher heating rates accelerate the onset of thermal runaway, reducing the reaction time and increasing the severity of thermal events. Additionally, cells at higher *SoC* levels exhibit lower onset temperatures and more violent thermal runaway reactions due to increased stored energy and electrolyte decomposition. These results highlight the importance of controlling heating rates and *SoC* to enhance the safety and stability of Li-ion battery systems. The provides valuable insights for the development of safer battery management systems and thermal safety protocols.

Keywords: Thermal runaway; Heating rate; State of charge (*SoC*); Li-ion battery; Pouch cells

Introduction

Thermal runaway is a critical safety concern in lithium-ion (Li-ion) batteries, particularly in high-energy-density applications such as electric vehicles, consumer electronics, and grid storage. This phenomenon occurs when a battery cell experiences an uncontrolled increase in temperature, leading to exothermic reactions that can further elevate the temperature, potentially resulting in catastrophic failure, fire, or explosion [1]. Understanding the factors that influence thermal runaway is essential for developing safer and more reliable battery systems.

Two significant factors affecting thermal runaway in Li-ion batteries are the heating rate and the state of charge (*SoC)*. The heating rate, or the speed at which a battery cell is subjected to increased temperatures, can influence the onset and progression of thermal runaway. Rapid heating can lead to a quicker onset of exothermic reactions, giving less time for heat dissipation and increasing the severity of thermal events. Conversely, slower heating rates may allow more time for heat management and mitigate the intensity of the reactions [2].

The state of charge (*SoC)* refers to the amount of energy stored in the battery relative to its capacity. Higher levels mean more stored energy, which can contribute to more severe thermal runaway events due to the increased availability of reactive material and higher potential for electrolyte decomposition [3]. Lower *SoC* levels generally result in less severe thermal events but can still pose significant risks depending on other factors such as battery chemistry and design.

This study aims to systematically investigate the effects of varying heating rates and (*SoC)* levels on thermal runaway in pouch Li-ion battery cells. By analysing the onset temperatures, reaction kinetics, and severity of thermal events under different conditions, we seek to provide a comprehensive understanding of how these factors interact and influence the safety and stability of Li-ion batteries. This knowledge is crucial for informing the design of safer battery management systems and developing effective thermal safety protocols [4].

In the heating rates and state of charge (*SoC)* levels affect thermal runaway in pouch Li-ion battery cells. By examining onset temperatures and reaction severity, we aim to understand their interaction and influence on battery safety, aiding in the design of safer battery management systems.

Thermal runaway & heating rate

Thermal runaway in pouch Li-ion battery cells, focusing on the effects of heating rate and state of charge (*SoC)*. Thermal runaway is a critical issue leading to potential fire or explosion in batteries. We examine how different heating rates and *SoC* levels influence the onset temperature and severity of thermal runaway events. Faster heating rates and higher *SoC* levels tend to lower the onset temperature and increase the reaction's intensity, making the batteries more prone to catastrophic failure [5]. The findings aim to enhance battery safety by providing insights for better battery management systems (Table 1 & 2).

Table 1: Effect of heating rate on onset temperature.

Heating Rate (°C/min)	Onset Temperature (°C)	Severity of Thermal Runaway
1	150	Low
5	140	Medium
10	130	High

Table 2: Effect of state of charge (SoC) on onset temperature.

SoC %	Onset Temperature (°C)	Severity of Thermal Runaway
20	160	Low
50	140	Medium
100	120	High

These tables summarize the relationship between heating rate, *SoC* and thermal runaway characteristics, demonstrating how increased heating rates and higher lower the onset temperature and increase severity [6].

State of Charge (*SoC*)

State of Charge (*SoC)* is a critical parameter in lithium-ion (Li-ion) batteries that indicates the current energy level relative to the battery's total capacity. It is typically expressed as a percentage, where 100% *SoC* means the battery is fully charged, and 0% *SoC* means it is fully discharged. Monitoring *SoC* is essential for optimizing battery performance, ensuring safety, and prolonging battery life (Table 3, Figure 1); [7,8].

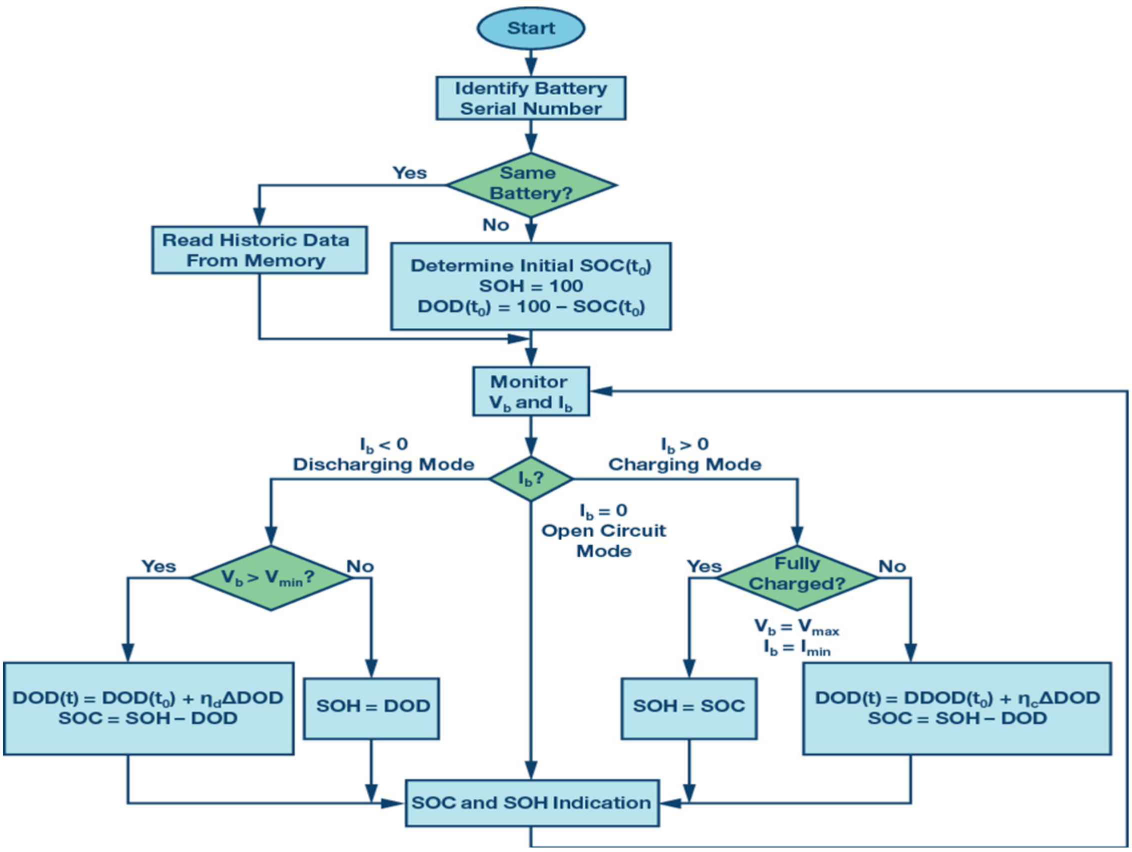

Figure 1: Working of State of Charge (SoC) of Li-ion battery.

Table 3: Methods for estimating state of charge (SoC) [8].

Method	Description	Advantages	Limitations
Voltage Measurement	Uses the open-circuit voltage (*OCV*) to estimate *SoC*	Simple and cost-effective	Affected by temperature and load
Coulomb Counting	Measures the charge entering and leaving the battery	High accuracy over short periods	Drift over time, requires recalibration
Model-Based	Combines data from various sensors and uses algorithms to estimate *SoC*	High accuracy, compensates for errors	Complex and requires significant processing power

In the SoC involves studying its impact on battery behaviour, including efficiency, capacity fade, and thermal characteristics. Accurate estimation helps in developing effective Battery Management Systems that can prevent overcharging and deep discharging, both of which can lead to battery degradation or failure. Researchers use various methods to estimate such as voltage measurement, coulomb counting, and advanced algorithms that combine multiple data points for improved accuracy.

Li-ion battery

Li-ion batteries are rechargeable energy storage devices commonly used in portable electronics, electric vehicles, and renewable energy systems. Their popularity stems from their high energy density, lightweight, and long lifespan.

a) **Working:** Li-ion batteries consist of the following main components:

b) **Cathode:** Made from lithium metal oxides (e.g., $LiCoO_2$, $LiFePO_4$). During discharge, lithium ions move from the anode to the cathode, generating electrical current.

c) **Anode:** Usually composed of graphite. During charging, lithium ions intercalate into the graphite structure.

d) **Electrolyte:** A lithium salt solution in an organic solvent that facilitates the movement of lithium ions between the electrodes.

e) **Separator:** A porous membrane preventing the direct contact of the anode and cathode, thus avoiding short circuits, while allowing ion flow.

f) **Current collectors:** Aluminium for the cathode and copper for the anode, which help in conducting the electric current to the external circuit [9,10].

Key points features and comparisons

Table 4; [11]

Table 4: Comparison of cathode materials [11].

Material	Energy Density (*Wh/kg*)	Safety	Cost (*$/Wh*)	Cycle Life (cycles)
$LiCoO_2$ (LCO)	150 - 200	Medium	High	500 - 1000
$LiFePO_4$ (LFP)	90 - 120	High	Medium	2000+
$LiMnO_2$ (LMO)	100 - 150	Medium	Medium	1000-2000
NCM (*Nickel Cobalt Manganese*)	150 - 220	Medium	Medium	1000-2000

Explanation

a) $LiCoO_2$: Offers high energy density but is costly and has moderate cycle life.

b) $LiFePO_4$: Known for its safety and long cycle life, albeit with lower energy density.

c) $LiMn_2O_4$: Balanced performance with medium energy density, cost, and cycle life.

d) *NCM*: Provides high energy density and good cycle life, with moderate safety and cost.

Table 5

Table 5: Li-ion battery specifications.

Parameter	Specification
Nominal Voltage	3.6 - 3.7V
Energy Density	150 - 250Wh/kg
Charge/Discharge Efficiency	80 - 90%
Operating Temperature	-20 to 60 °C
Cycle Life	500 - 2000+ cycles

Explanation

a) **Nominal voltage:** Typically, between 3.6 - 3.7 volts, suitable for a variety of applications.

b) **Energy density:** High energy density (150 - 250Wh/kg) allows for longer usage times in portable devices.

c) **Efficiency**: Good charge/discharge efficiency (80 - 90) ensures minimal energy loss during operation.

d) **Temperature range:** Operates effectively across a broad temperature range (-20 to 60 °C).

e) **Cycle life:** Varies from to over cycles, depending on the specific chemistry and usage patterns [12,13].

Li-ion batteries are integral to modern technology due to their favourable properties. The choice of materials for the cathode and anode, along with the design of the electrolyte and separator, determines the battery's performance, cost, and lifespan. The tables provided help in comparing different cathode materials and understanding the general specifications of Li-ion batteries.

Pouch cells for li-ion batteries

Recent advancements in Li-ion battery technology have focused on pouch cells due to their flexibility, lightweight, and high energy density. Pouch cells, characterized by their soft, laminated packaging, offer significant advantages over traditional cylindrical and prismatic cells, including better space utilization and reduced weight [14,15].

Key innovations

a) Enhanced electrolytes: Researchers are developing solid-state and gel polymer electrolytes to replace conventional liquid electrolytes. These new electrolytes improve safety by reducing flammability and enhancing thermal stability [16].

b) High-capacity cathode materials: Novel cathode materials such as high-nickel *NCM* (Nickel Cobalt Manganese) and *NCA* (Nickel Cobalt Aluminium) are being explored. These materials promise higher energy densities and longer cycle lives compared to traditional cathodes like $LiCoO_2$.

c) Silicon anodes: Incorporating silicon into graphite anodes is a promising approach to increase energy density. Silicon can theoretically store more lithium ions, resulting in higher capacities. In the challenges like volume expansion and stability are being addressed through nano structuring and advanced binder technologies [17,18].

Advanced Manufacturing Techniques: New techniques such as dry electrode coating and roll-to-roll processing are being developed to enhance manufacturing efficiency and reduce costs. These methods also improve the environmental sustainability of battery production.

Benefits and applications

The research on pouch cells aims to deliver batteries that are safer, more efficient, and longer lasting. These advancements are particularly beneficial for electric vehicles, portable electronics, and grid storage solutions. The flexible design of pouch cells allows for customized shapes and sizes, making them ideal for a wide range of applications. In the ongoing research in pouch cell technology is set to revolutionize the Li-ion battery industry, driving forward innovations in energy storage and sustainability [19,20].

Conclusion

Thermal runaway in pouch Li-ion battery cells is significantly influenced by the heating rate and state of charge *(SoC)*. Studies indicate that higher heating rates accelerate the onset of thermal runaway, leading to more severe reactions and greater safety hazards. Conversely, lower heating rates allow for better heat dissipation, reducing the risk of catastrophic failure. The state of charge also plays a crucial role; cells with higher *SoC* are more prone to thermal runaway due to the increased energy density and the larger amount of reactive material. Cells at higher *SoC* exhibit more vigorous exothermic reactions, which can rapidly escalate into thermal runaway. In the managing the heating rate and carefully monitoring the state of charge are critical for enhancing the safety of pouch Li-ion batteries. Implementing thermal management systems and *SoC* control strategies can mitigate the risks associated with thermal runaway, ensuring safer operation of these high-energy storage devices.

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