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Experimental Analysis of Voltage and Multi-Point Temperature Distribution in a 6S Lithium-Ion Battery Pack Under Constant Current Loading

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Abstract. Lithium-ion batteries are widely utilized in energy storage applications; however, temperature non-uniformity remains a critical issue affecting performance, safety, and lifespan. This study presents an experimental investigation of the correlation between voltage and multi-point temperature distribution in a 6S lithium-ion battery pack under a constant ±5 A charge–discharge current. Temperature measurements were obtained from three sensor locations to capture spatial thermal variations during operation. The results reveal that the central cell consistently exhibited the highest temperature, reaching approximately 40 °C, while a maximum thermal gradient of 5.7 °C was observed across the pack. Furthermore, a positive correlation between current and temperature indicates uneven heat generation among cells. These findings provide direct experimental evidence of thermal asymmetry in multi-cell configurations and emphasize the importance of optimized sensor placement and enhanced thermal management strategies in Battery Management Systems (BMS).

Keywords: Lithium-ion battery, Battery thermal management system, Temperature distribution, Thermal gradient, Battery management system, Experimental analysis

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1. Introduction

Lithium-ion batteries have become the dominant energy storage technology due to their high energy density, efficiency, and long operational lifespan[1][2]. They are extensively used in electric vehicles (EVs), portable electronic devices, and renewable energy systems, where reliability and safety are critical [3][4][5]. Despite these advantages, lithium-ion batteries are highly sensitive to temperature variations, which can lead to performance degradation, reduced lifespan, and even thermal runaway under unfavorable operating conditions [6][7]. Non-uniform temperature distribution within a battery pack is particularly critical, as localized overheating can accelerate cell aging and compromise overall system safety[8][9].

To address these challenges, battery thermal management systems (BTMS) have been widely developed to regulate temperature and improve thermal uniformity[10][11]. Various approaches have been investigated, including passive cooling methods such as phase change materials (PCM) and active cooling techniques such as air and liquid cooling systems [12][13]. Previous studies have also demonstrated that heat generation in lithium-ion batteries is strongly influenced by internal resistance and electrochemical reactions, leading to uneven temperature distribution across cells [14][15]. These findings highlight the importance of accurate thermal monitoring and control within Battery Management Systems (BMS) to ensure optimal performance and safety[16][17].

However, despite significant advancements, a notable research gap still exists[18][19]. Most previous studies primarily focus on single-cell analysis or rely on numerical simulations, which do not fully represent the complex interactions within real multi-cell battery pack configurations[20][21]. In practical applications, battery packs are arranged in series or series–parallel configurations, where variations in current distribution and internal resistance can result in spatial thermal gradients and localized hot spots[22][23]. Furthermore, experimental studies that simultaneously analyze voltage, current, and multi-point temperature distribution in real battery packs remain limited[24][25]. To clearly highlight the research gap, Table 1 presents a comparison between the proposed study and previous battery thermal characterization studies.

Table 1. Comparison of battery thermal characterization studies

Author (Year)	Pack Configuration	Methodology	Monitoring Type	Main Focus
Nazar et al. [16]	Single cell	Experimental	Single-point	Evaluation of active and passive cooling performance
Zhang [18]	6S4P pack	Simulation	Not available	Optimization of battery cooling strategy
Chen et al. [19]	Generalized	Review	Literature-based	Analysis of thermal safety in lithium-ion batteries
Shahjalal et al. [20]	Various	Review	Literature-based	Investigation of heat generation and temperature uniformity
This Work	6S pack	Experimental	Multi-point (synchronized, real-time)	Thermal gradient analysis and hot-spot detection for BMS

As shown in Table 1, most existing studies either focus on single-cell analysis, rely on simulation approaches, or utilize limited temperature monitoring methods. In contrast, the present study performs synchronized experimental measurements on a multi-cell battery pack using multi-point temperature sensors, enabling detailed observation of spatial thermal variations and hot-spot formation.

In this context, the present study focuses on the experimental analysis of a 6S lithium-ion 18650 battery pack under constant ±5 A charge–discharge conditions. The objective is to investigate the correlation between voltage, current, and multi-point temperature distribution, providing experimental insights to support the development of more reliable Battery Management Systems (BMS) and improved thermal management strategies.

2. Methods

This study employs an experimental approach to investigate the correlation between electrical parameters and temperature distribution in a multi-cell lithium-ion battery pack. The experimental setup consists of a 6S lithium-ion 18650 battery configuration, where each cell has a nominal voltage of 3.6

V and a capacity of 2500 mAh. The detailed specifications of the battery and experimental conditions are summarized in Table 2.

Table 2. Battery and Experimental Parameters

Parameter	Value	Description
Battery type	Lithium-ion 18650	Cylindrical cell
Configuration	6S	Series configuration
Nominal voltage (per cell)	3.6 V	Rated voltage
Capacity (per cell)	2500 mAh	Battery capacity
Charge/discharge current	±5 A	Constant current (CC) mode
Number of sensors	3	Front, center, and back positions
Sampling rate	1 Hz	Data acquisition frequency
Ambient temperature	~25 °C	Room temperature condition

To capture spatial temperature variations, three temperature sensors were strategically placed at different locations of the battery pack: the front, center, and back positions. The center position represents the core region of the battery pack, where heat accumulation is most likely to occur due to limited heat dissipation. All temperature data were recorded simultaneously using a synchronized data acquisition system with a sampling rate of 1 Hz.

The experimental configuration and sensor placement are illustrated in Fig. 1.

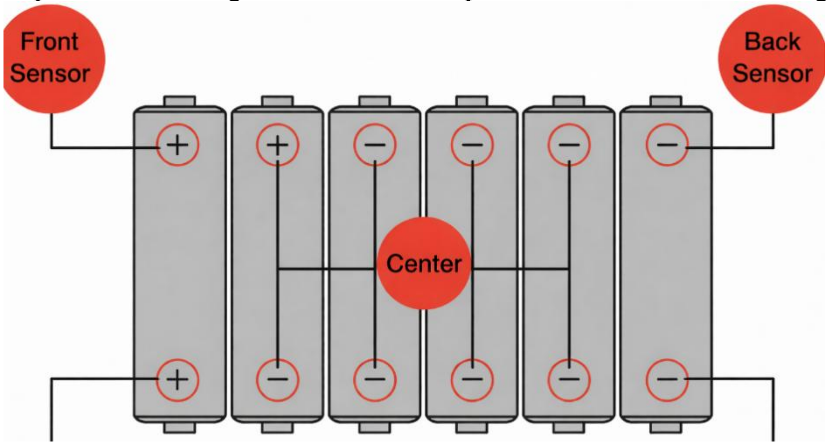

Figure 1. Configuration of the 6S lithium-ion battery pack and placement of temperature sensors (front, center, and back positions).

This setup enables real-time monitoring of temperature distribution across the battery pack and allows identification of thermal gradients and potential hot-spot formation during operation. In addition to temperature measurement, the battery voltage and current were continuously recorded throughout the charge–discharge cycles. These parameters were analyzed to evaluate their correlation with temperature behavior. The thermal gradient (ΔT) is defined as the difference between the maximum and minimum temperatures within the battery pack:

$$\Delta T = T_{\{max\}} - T_{\{min\}}$$

This parameter is used to quantify temperature non-uniformity within the battery pack.

To further analyze the relationship between electrical and thermal parameters, correlation analysis was performed between current and temperature data. This analysis provides insight into heat generation characteristics and helps identify uneven thermal behavior across the battery cells. The experimental procedure was repeated to ensure data consistency and reliability. All measurements were conducted under identical operating conditions to minimize external variations.

3. Results And Discussion

This section presents the experimental results and analysis of the electrical and thermal behavior of the 6S lithium-ion battery pack under constant current charge–discharge conditions.

3.1. Temperature Distribution Analysis

The temperature distribution of the battery pack was monitored at three different locations: front, center, and back. The results, as shown in Fig. 2, indicate that the temperature increases progressively during operation due to internal heat generation.

Among the three measurement points, the center position consistently exhibits the highest temperature compared to the front and back positions. The maximum recorded temperature reached approximately 37.1 °C, while the minimum temperature was around 30.7 °C. This behavior indicates a non-uniform temperature distribution within the battery pack. The higher temperature at the center is primarily caused by limited heat dissipation and thermal accumulation in the core region, making it the primary hot-spot within the system. This condition is critical, as localized heating may accelerate cell degradation and reduce overall battery lifespan.

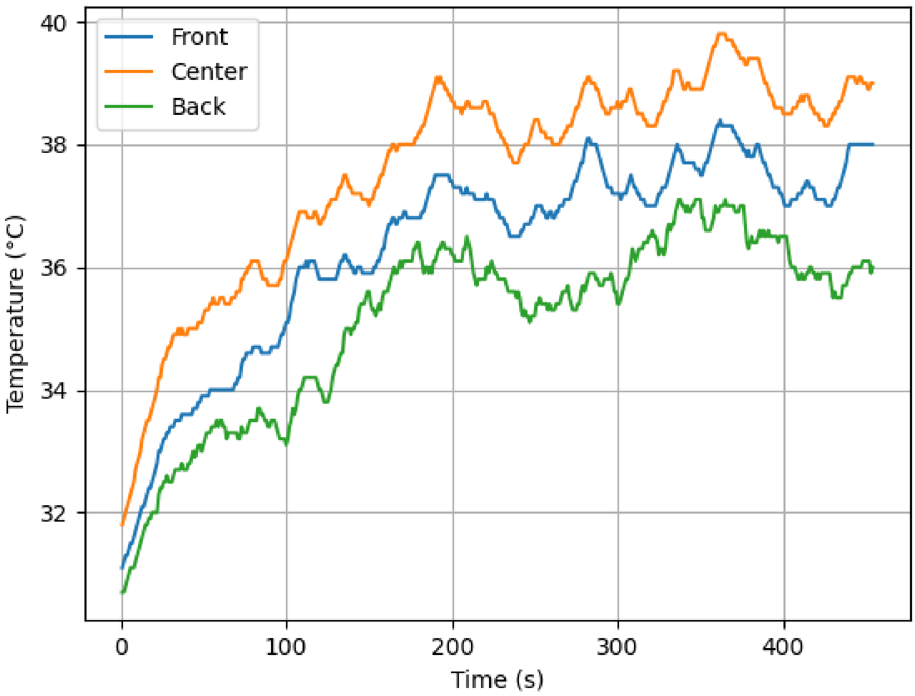

Figure 2. Temperature distribution of the 6S lithium-ion battery pack at front, center, and back positions during charge–discharge operation.

As shown in Fig. 2, the temperature at all sensor locations increases gradually during the operation. However, the center position consistently exhibits higher temperatures compared to the front and back positions. This indicates that heat accumulation occurs predominantly in the central region of the battery pack due to limited heat dissipation.

The temperature difference between the center and edge regions becomes more pronounced over time, confirming the presence of non-uniform thermal distribution. This behavior highlights the potential formation of hot spots, which may accelerate battery degradation and reduce overall system reliability. The center temperature reaches the highest value, indicating a critical region for thermal monitoring in battery management systems.

3.2. Voltage Characteristics

The voltage profile of the battery pack during charge–discharge cycles is presented in Fig. 3. The results show a stable voltage response under constant current conditions, with gradual variation corresponding to the charging and discharging processes. No significant voltage instability was observed, indicating that the battery pack operates within a safe electrical range. Minor fluctuations in voltage can be attributed to internal resistance and temperature variations within the cells.

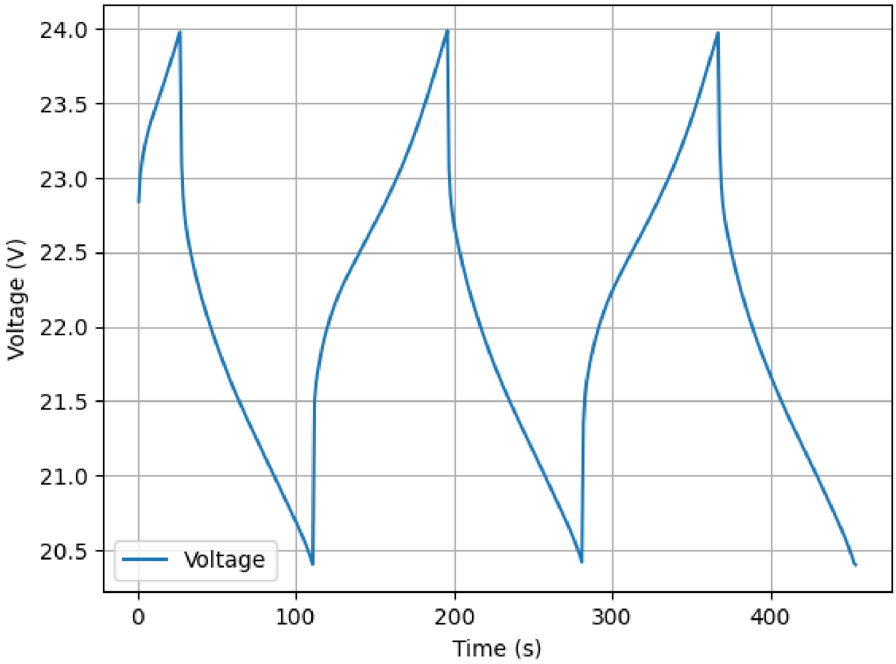

Figure 3. Voltage profile of the battery pack during charge–discharge cycles.

3.3. Ambient Temperature Analysiss

The ambient temperature during the experiment is presented in Fig. 4. The results show that the ambient temperature varies within a relatively narrow range of approximately 29–34 °C throughout the testing period. This indicates that the environmental conditions remain stable and well-controlled during the experiment. Therefore, the influence of external temperature fluctuations on the thermal behavior of the battery pack can be considered minimal. As a result, the observed temperature increase and non-uniform distribution in the battery pack (as shown in Fig. 2) are primarily attributed to internal heat generation rather than external environmental factors.

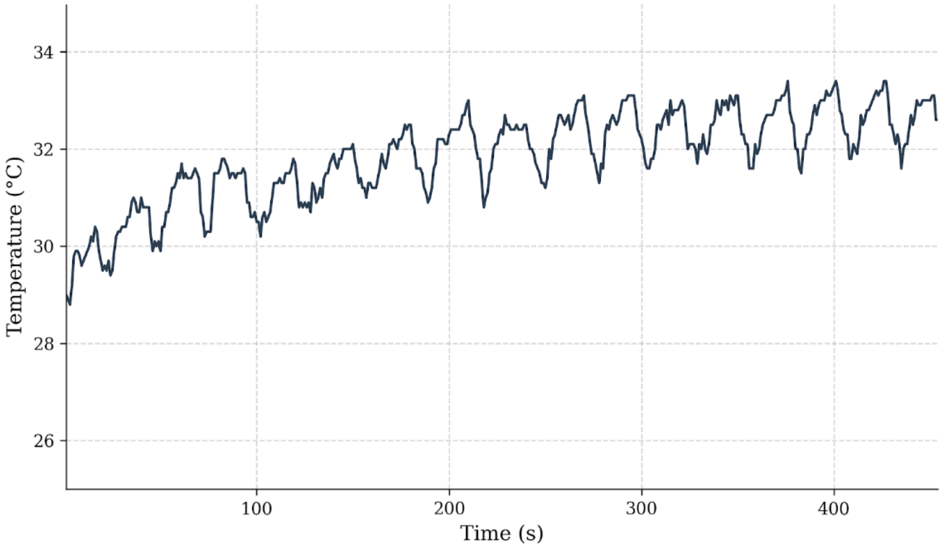

Figure 4. Thermal gradient (ΔT)

Ambient temperature variation during the battery charge–discharge experiment, indicating stable environmental conditions. This stability enhances the reliability of the experimental results and ensures that the thermal behavior observed is inherent to the battery system.

3.4. Correlation Between Current and Temperature

A correlation analysis between current and temperature reveals a positive relationship, where increasing current leads to higher temperature levels within the battery pack. This phenomenon is consistent with Joule heating (I^2R losses), where heat generation is proportional to the square of the current. The results confirm that electrical loading significantly affects the thermal behavior of the battery pack. Moreover, the non-uniform distribution of temperature suggests that current distribution among cells may also be uneven, further contributing to localized heating.

3.5. Summary of Experimental Results

The key experimental findings are summarized in Table 3.

Table 3. Summary of Experimental Results

Parameter	Value
Maximum temperature	37.1 °C
Minimum temperature	30.7 °C
Thermal gradient (ΔT)	6.4 °C
Highest temperature location	Center

3.6. Discussion

The experimental results demonstrate that temperature distribution in a multi-cell lithium-ion battery pack is inherently non-uniform, with the center region identified as the most thermally stressed area. This finding is consistent with previous studies, which reported similar behavior due to limited heat dissipation in the core region. Compared to conventional single-point measurement approaches, this study provides more comprehensive insight through synchronized multi-point temperature monitoring. This method enables accurate detection of thermal gradients and hot-spot formation, which are critical for battery safety and performance evaluation.

The observed thermal gradient of approximately 6.4 °C highlights the importance of implementing effective thermal management strategies. Without proper cooling mechanisms, such temperature differences can accelerate battery degradation, reduce efficiency, and increase the risk of thermal failure. Furthermore, the correlation between current and temperature confirms that electrical operating conditions play a significant role in thermal behavior. Therefore, integrating multi-point temperature monitoring into Battery Management Systems (BMS) is essential to improve reliability, safety, and operational efficiency. Overall, the results emphasize the need for optimized sensor placement and advanced thermal management techniques in practical battery pack applications, particularly in electric vehicles.

4. Conclusion

This study investigates the correlation between electrical parameters and multi-point temperature distribution in a 6S lithium-ion battery pack under constant current conditions. The results show that the central region consistently experiences the highest temperature, indicating significant thermal stress due to heat accumulation and limited dissipation. The maximum temperature reached approximately 37.1 °C, with a thermal gradient of about 6.4 °C across the battery pack, confirming the presence of non-uniform temperature distribution. Meanwhile, the ambient temperature remained relatively stable within the range of 29–34 °C, indicating that the observed thermal behavior was primarily influenced by internal heat generation rather than external conditions.

Furthermore, the results demonstrate that current loading significantly affects heat generation, leading to a gradual temperature rise during operation. These findings highlight the importance of multi-point temperature monitoring and the need for effective thermal management strategies, particularly in the central region of the battery pack. Future work will focus on incorporating advanced thermal diagnostics and varying operating conditions to further improve the safety and performance of lithium-ion battery systems.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to assist in language refinement, sentence structuring, and improving the clarity of the manuscript. After using this tool, the author(s) carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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