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Thermal Management in Lithium-Ion Batteries for Heat Distribution and Performance in Series and Parallel Configurations

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Abstract - Spontaneous thermal runaway has become a pressing concern in the thermal management of lithium-ion batteries, particularly during high discharge rate operations. This study systematically examines the thermal and electrochemical behaviours of lithium-ion batteries under varying discharge rates. The research is conducted in two phases. Initially, experimental discharge tests were performed to characterize the electrochemical properties and thermal responses at different discharge conditions. Subsequently, a one-dimensional electrochemical model coupled with a three-dimensional heat transfer framework was developed and validated against experimental data using numerical simulation software. The validated model was further employed to analyse the heat distribution of batteries configured in series and parallel. Critical temperature thresholds triggering thermal runaway were identified under various C-rate conditions, providing valuable insights into the thermal control and safety of lithium-ion battery systems.

***Keywords*:** Lithium-ion batteries, Heat distribution, Series and parallel configurations, Critical temperature thresholds, High discharge rates

1. Introduction

Since the late 21st century, technological advancements have continued to progress at an unprecedented rate, fostering significant improvements in various sectors, including communication, transportation, healthcare, and industrial automation. These developments have not only enhanced the convenience and efficiency of daily human activities but have also revolutionized economic and societal structures, shaping a more interconnected and sophisticated global landscape [1-3]. However, the rapid acceleration of technological growth has simultaneously exacerbated critical global issues, including environmental degradation, resource depletion, and the increasing carbon footprint associated with industrial and consumer activities. The extensive consumption of fossil fuels, which historically served as the primary source of energy for industrial and transportation sectors, has led to severe ecological consequences, including climate change, air pollution, and adverse effects on biodiversity. In response to these challenges, global efforts have intensified toward the development of sustainable energy solutions, with a strong emphasis on renewable energy sources such as solar and wind power. These energy alternatives are increasingly being integrated into national energy frameworks to mitigate dependence on non-renewable resources and reduce carbon emissions [4, 5]. One of the most significant transformations within the energy sector has been the shift from conventional internal combustion engine vehicles to electrically powered transportation systems, which rely on advanced energy storage technologies. This transition stems from the growing recognition of the detrimental environmental effects associated with gasoline and diesel-powered engines, including greenhouse gas emissions and inefficient fuel consumption. Among various energy storage solutions, lithium-ion batteries have emerged as a cornerstone technology in the development of electric vehicles due to their superior electrochemical properties, including high operating voltage, extended cycle life, and substantial energy density. These batteries provide efficient energy storage and discharge mechanisms, making them particularly suited for applications requiring stable and high-power electrical output. The continuous innovation in lithium-ion battery technology has significantly contributed to the expansion of the electric vehicle market, driving improvements in battery efficiency, longevity, and charge-discharge rates [6-9].

In recent years, extensive research has focused on optimizing cathode materials to enhance the energy density and operational voltage of lithium-ion batteries. Various cathode compositions, including lithium cobalt oxide (LCO), nickel manganese cobalt (NMC), nickel cobalt aluminum (NCA), lithium manganese oxide (LMO), and lithium iron phosphate (LFP), have been investigated to achieve improved electrochemical performance and increased thermal stability [10]. Despite the advantages associated with high energy density cathode materials, they tend to generate substantial thermal energy during discharge processes. This heat accumulation can negatively impact battery efficiency, accelerate degradation, and reduce overall energy utilization rates. Consequently, within a comprehensive energy supply system, the battery thermal management system (BTMS) plays a critical role in maintaining optimal operational conditions, preventing overheating, and ensuring long-term stability. Several studies have been conducted to analyse the thermal behaviour of lithium-ion batteries under varying discharge rates and operational conditions. Özdemir Tanılay et al. [11] investigated the thermal characteristics of batteries using an electrochemical-thermal coupled model, providing insights into heat generation mechanisms and energy dissipation efficiency. Similarly, He Tengfei et al. [12] employed experimental techniques and numerical simulations to develop simplified models for 18650 cylindrical lithium-ion batteries, proposing multiple frameworks to predict electrochemical reactions and thermal non-uniformity. These studies underscore the significance of integrating thermal management strategies within lithium-ion battery systems to optimize performance and enhance safety in practical applications.

This study systematically examines the self-heating phenomena of 18650 cylindrical lithium-ion batteries through an integrated approach that combines experimental methodologies and numerical simulations, aiming to optimize battery thermal management for improved efficiency, safety, and reliability in energy storage applications. Given the increasing demand for high-performance lithium-ion batteries in electric vehicles and other power-intensive technologies, understanding their thermal behaviour under varying discharge conditions is crucial. To achieve this, controlled discharge experiments will be conducted to empirically determine electrochemical and thermal properties, providing essential data on voltage fluctuations, internal resistance, thermal dissipation, and heat accumulation. These experimental findings will serve as the foundation for validating numerical models, ensuring the reliability of computational simulations. In parallel, a one-dimensional electrochemical model will be employed to analyze charge transport mechanisms, phase transitions, and energy conversion processes within the battery system, with the results validated against empirical discharge curves. Additionally, a three-dimensional cylindrical framework will be integrated with the electrochemical model to enable a spatially resolved thermal analysis, allowing for the evaluation of temperature distribution, conductivity, and dissipation across interconnected batteries in series and parallel configurations. By investigating heat generation and accumulation in these configurations, the study will provide insights into optimizing thermal regulation strategies and mitigating performance degradation caused by excessive heating. The findings will contribute to the advancement of battery cooling technologies and energy storage optimization, ensuring the sustainability of lithium-ion battery applications in transportation and other high-power industries while laying a foundation for future developments in thermal management systems.

2. Methodology

Lithium-ion batteries consist of key components, including an anode, cathode, separator, electrolyte, and current collector, enclosed within a protective casing to ensure stability. The separator prevents direct contact between electrodes while allowing lithium-ion transport through the electrolyte for energy conversion. During discharge, lithium ions move from the anode to the cathode, generating electrical power, while charging reverses this process using an external power source. This study investigates the self-heating behaviour of 18650 cylindrical lithium-ion batteries through experiments, numerical simulations, and mathematical modelling to enhance thermal management for improved efficiency and safety. Controlled discharge tests will be conducted using the CT-4008T battery testing system. Numerical simulations will model electrochemical and thermal interactions, incorporating a one-dimensional electrochemical model for charge transport analysis and a three-dimensional cylindrical framework to evaluate spatial heat generation. Mathematical equations will describe charge conservation, heat conduction, and electrochemical kinetics, enabling predictive analysis of self-heating effects. By integrating experimental data, simulations, and modelling, this study aims to optimize battery thermal management, ensuring improved reliability and performance in applications such as electric vehicles and energy storage systems.

2.1. Experimental procedure

To systematically analyse the thermal behaviour and self-heating characteristics of lithium-ion batteries, this study will conduct controlled discharge experiments on 18650 cylindrical lithium-ion cells utilizing the CT-4008T battery testing system, as illustrated in Figure 1. The experiments will be performed under a strictly regulated ambient temperature of 25°C, without external convection, to ensure accurate thermal assessments. Variations in battery temperature will be monitored using high-precision T-type thermocouples with an accuracy of ±1°C, while the CT-4008T system will provide voltage and current measurement accuracy of ±0.05%, thereby ensuring precise characterization of key performance parameters, including voltage fluctuations, current profiles, and discharge efficiency. Discharge cycles at constant current rates of 0.5C, 1C, and 2C will be conducted to evaluate the impact of discharge intensity on temperature dynamics and voltage response, offering valuable insights into electrochemical interactions and thermal dissipation efficiency. The findings of this study will contribute to the advancement of battery cooling technologies and thermal management strategies, thereby enhancing the efficiency, reliability, and longevity of lithium-ion batteries in high-power applications, such as electric vehicles.


Fig. 1: Battery testing equipment.

2.2. Numerical simulation

This study seeks to rigorously validate the accuracy of the proposed model by performing comprehensive error analysis through numerical simulation software and experimental measurements. By systematically comparing simulated data with empirical results, the study aims to identify discrepancies, optimize model performance, and ensure the reliability of key electrochemical parameters. These validated parameters will serve as a foundation for subsequent configurations involving battery series and parallel connections, thereby enhancing predictive accuracy and system efficiency. The methodological framework is illustrated in Figure 2.

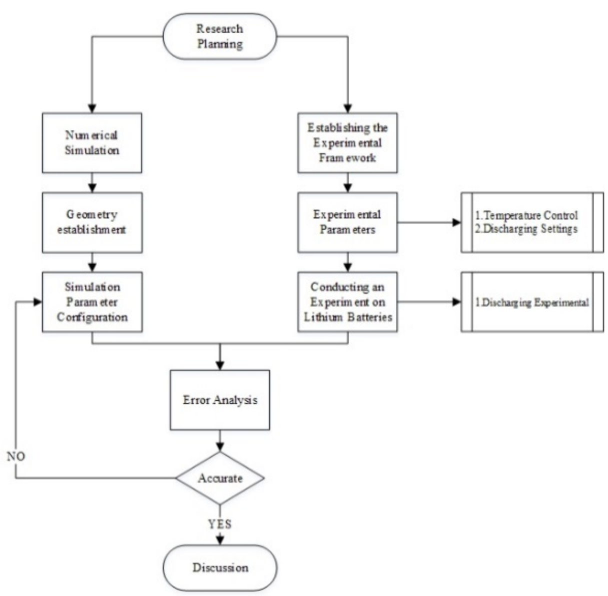


Fig. 2: Research Methodology Flowchart.

The development of the numerical simulation model is grounded in a detailed understanding of electrochemical parameters and their associated outcomes in conjunction with the geometric configurations of the battery cells. These electrochemical parameters play a critical role in governing battery behaviour and performance under varying conditions. In this study, the key electrochemical parameters utilized for simulation analysis will be referenced from the established dataset provided in tables, ensuring consistency with prior research findings and industry standards. The integration of these validated parameters within the model will facilitate accurate thermal and electrical performance predictions, contributing to the advancement of battery management strategies and optimization methodologies as shown in these tables 1.

Table 1: Geometric, electrochemical, and thermal model parameters.

Symbol	Unit	Ncc[a]	Nc[b]	Separator	Pc[c]	Pcc[d]
L	μm	10	170	13	80	15
r_p	μm	~	11	~	2.5	~
H_{cell}	mm	64.93				
r_{cell}	mm	9.1				
d_{model}	mm	3.95				
L_{shell}	mm	0.4				
Electrochemical parameters						
ε_s	~	~	0.511	~	0.54	~
ε_e	~	~	0.31	0.42	0.29	~
$C_{s,init}$	$molm^{-3}$	~	14870	~	11952	~
$C_{s,max}$	$molm^{-3}$	~	31507	~	48000	~
C_e	$molm^{-3}$	1200				
σ_s	Sm^{-1}	~	100	~	91	~
D_s	m^2S^{-1}	~	33	~	34	~
α_a	~	~	0.5	~	0.5	~
α_c	~	~	0.5	~	0.5	~
k	$m^{2.5}mol^{-0.5}S^{-1}$	~	2.334e-11	~	1e-10	~
Υ	~	~	1.5	1.5	1.5	~
Thermal parameters						
C_p	$JKg^{-1}K^{-1}$	385	750	~	1250	900
ρ	Kgm^{-3}	8960	2300	~	4740	2700
λ	$Wm^{-1}K^{-1}$	395	1.04	0.3344	5	237
ε	~	0.6				

2.3. Mathematical model and Equations

Each equation shall be presented on a separate line, with a blank line both preceding and following it to enhance readability. In addition, all equations must be accompanied by clear definitions of the symbols and expressions used in the accompanying text. The mathematical model under consideration includes the following components: diffusion of lithium ions within the solid phase, charge conservation in the solid phase, mass conservation in the liquid phase, electrode kinetics, and a three-dimensional thermal model. Furthermore, each equation should be numbered consecutively along the outer right margin, as illustrated in Eqs. (1) to (3) below. In this context, the governing system of equations can be written as follows:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u}) \tag{1}$$

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right)\mathbf{u} = -\nabla P + \rho \mathbf{g} + \frac{1}{c}\mathbf{J} \times \mathbf{B} \tag{2}$$

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right)e = -P\nabla \cdot \mathbf{u} + \rho\mathbf{u} \cdot \mathbf{g} + \frac{1}{\sigma}\mathbf{J}^2 \tag{3}$$

3. Discussions & Results

Initial conditions for fully charged 18650 cylindrical lithium-ion batteries were systematically examined through discharge tests conducted at an ambient temperature of 25°C. Discharge experiments were carried out at three distinct rates —0.5C, 1C, and 2C—and the corresponding voltage predictions from the electrochemical-thermal coupled model were compared with experimental observations (see Figure 3). The analysis reveals that the model accurately reproduces the discharge profiles under the various conditions. Moreover, the agreement between the model predictions and the experimental data was quantified using the coefficient of determination, yielding values of 0.971, 0.976, and 0.961 for the 0.5C, 1C, and 2C discharge rates, respectively. These outcomes substantiate the model's effectiveness in simulating the performance of lithium-ion batteries under diverse discharge conditions.

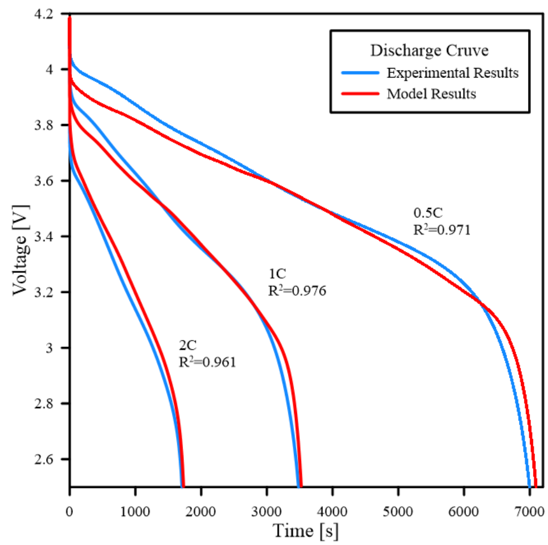


Fig. 3: Comparison of Voltage between Model and Experiment

During the discharge process, electrochemical reactions generate thermal energy within the battery. Variations in environmental temperature can adversely affect both the discharge efficiency and the battery's lifespan. Consequently, the present study investigates the temperature variations induced by these electrochemical reactions in a single battery operating under an ambient temperature of 25°C. Figure 4 presents the temperature distribution within the battery. The analysis demonstrates that the temperature is uniformly dispersed under all examined conditions, while the magnitude of the released heat energy increases with the C-rate. Notably, under a 2C discharge condition, the maximum temperature at the center reaches 51.7°C, underscoring the critical importance of effective thermal management in high-performance battery applications. Furthermore, the simulation outputs and experimental measurements, as shown in Figure 5, reveal a strong concordance between the predicted surface temperature curve and the actual observations. With coefficients of determination of 0.77, 0.95, and 0.97 for the respective conditions, these findings validate the accuracy of the model parameters prior to battery modularization in subsequent studies.

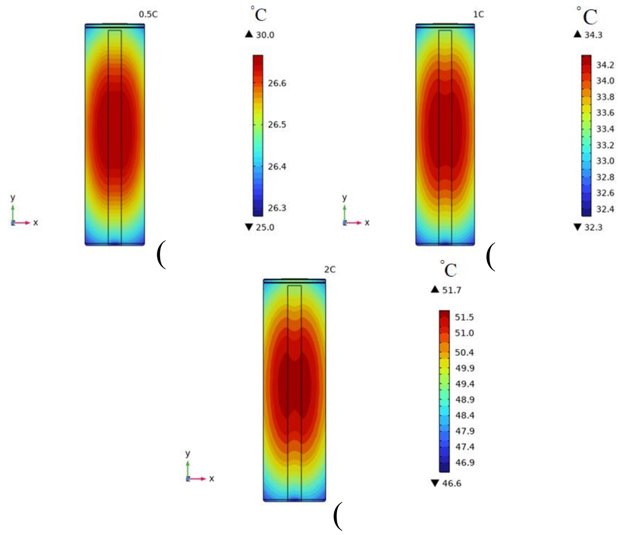


Fig. 4: Temperature distribution (a) 0.5C (b) 1C (c) 2C

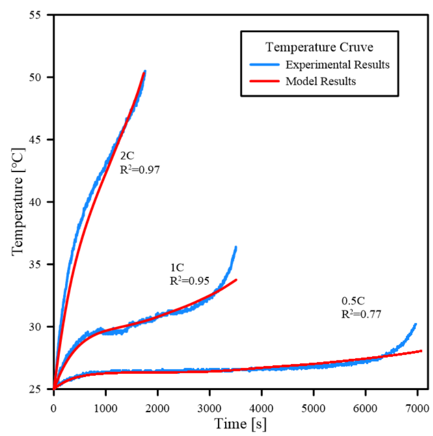
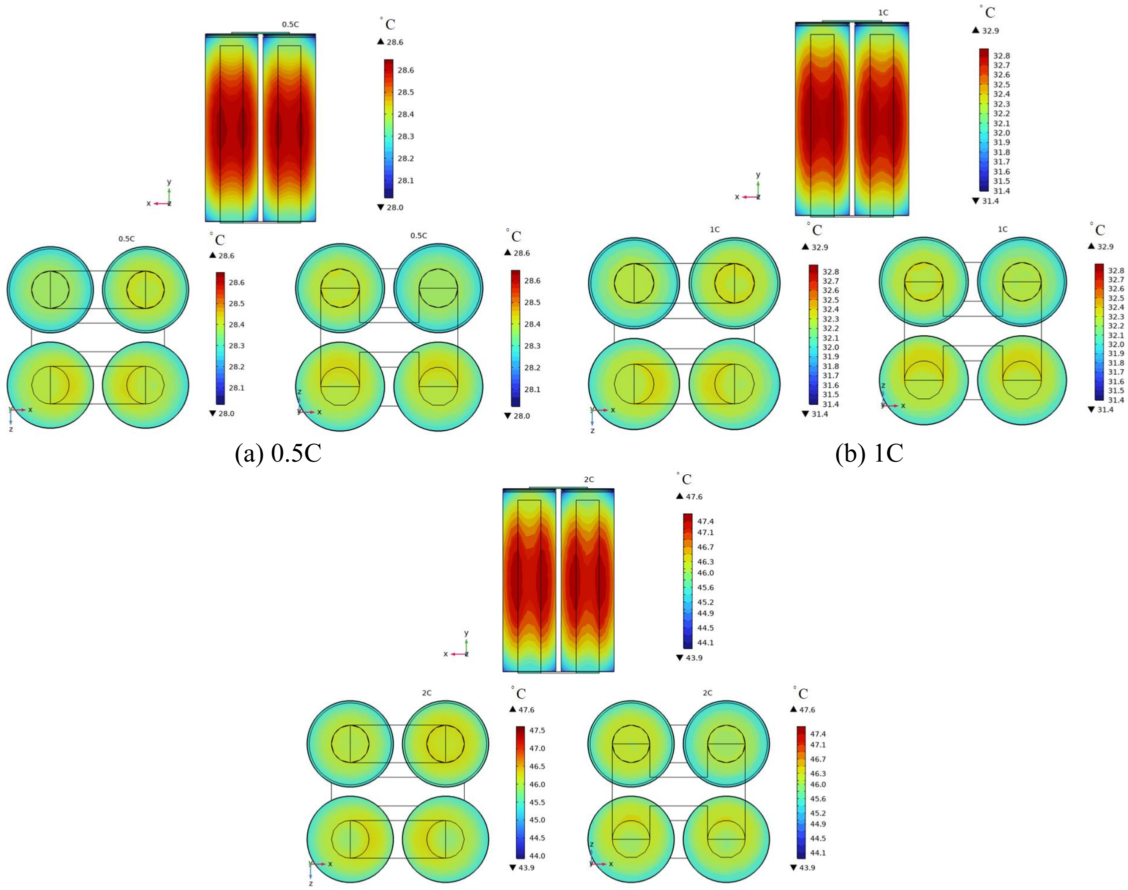


Fig. 5: Comparison of Temperature between Model and Experiment

To elucidate the thermal behaviour of battery modules, this study first conducted comprehensive simulations on individual battery cells. Subsequently, a simplified module configuration comprising two series-connected cells and two parallel-connected cells was employed to observe the overall heat distribution as shown in the Fig. 6. The simulation results demonstrated that the temperature distributions across three distinct C-rates closely corresponded to those identified in the single-cell analyses. Furthermore, a detailed examination of the thermal conditions at the positive and negative terminals—evaluated along the XZ plane for both series and parallel configurations—revealed that, in the absence of forced convection, terminal temperatures exhibited a continuous increase. This persistent thermal escalation is likely to detrimentally affect the battery's lifespan and may ultimately precipitate thermal runaway within the entire battery module.



(a) 0.5C (b) 1C

(c) 2C

Fig. 6: 2 series and 2 parallel connections

4. Conclusion

Constructing a one-dimensional electrochemical model requires a thorough understanding of the battery's geometric, electrochemical, and thermal parameters. These parameters are essential for accurately simulating the behavior of a lithium-ion battery. Comparisons between experimental and simulated voltage and temperature curves yielded determination coefficients for voltage of 0.971, 0.976, and 0.961, and for temperature of 0.77, 0.95, and 0.97, respectively. Although the temperature error at the 0.5C discharge rate is slightly higher, the maximum relative error is only 7%, which is acceptable. Under discharge rates of 0.5C, 1C, and 2C, the temperature distribution within a single battery follows a consistent internal-to-external diffusion pattern. Notably, at lower discharge rates, the maximum internal temperature reaches only 30°C, compared to 51.7°C at 2C. Operating at lower discharge rates helps maintain battery efficiency, prolong its lifespan, and ensure overall safety. Furthermore, to evaluate the thermal effects after battery modularization, a simplified configuration with two cells in series and two cells in parallel was simulated. The results indicate that, in the absence of forced convection, even a slight increase in the discharge rate beyond the highest rate studied may induce hazardous conditions, potentially leading to thermal runaway.

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