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Thermal and electrical analysis of 26650 li-ion batteries in series connection using the NTGK model and virtual simulations

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Abstract: Lithium-ion batteries are extensively used in various renewable sources such as renewable energy storage systems, electric vehicles, and portable electric vehicles due to their storage properties. However, since they are significantly affected by ambient temperature, their lifetime and safety issues in general negatively affect their electrical performance. In order to ensure that batteries achieve their optimum potential, it is necessary to understand the interaction between charge and discharge rates and temperature changes very well. In this study, the electrical characteristics of 26650 lithium-ion batteries were analyzed in series under different environmental conditions and different discharge rates. To understand the relationship between environmental temperatures and battery performance, Newman, Tiedemann, Gu, and Kim (NTGK) evaluated the effectiveness of previously used models in predicting these effects. The Ansys Battery Ntgk model was used to predict the temperature behavior and voltage variations under different outdoor temperature conditions. In this study, four ambient temperatures (273 K, 283 K, 298 K, and 318 K) and four discharge rates (0.5C, 1C, 1.5C, and 2C) were investigated to study the thermal characteristics and voltage variations. The mesh independence study was carried out in detail at the beginning of the analysis to validate the simulation results. The results indicate that the discharge time decreases significantly due to increased internal resistance and electrochemical side reactions. The 1S1P battery design reaches a maximum internal temperature of 303.2 K at 273.15 K ambient temperature and 336.7 K at 318.15 K ambient temperature, while the 2S1P battery design exhibits an even higher maximum temperature of 341.3 K at an ambient temperature of 318.15 K, indicating that compound heat buildup occurs in series connections.

Keywords: 26650 lithium-ion battery; voltage output; thermal behavior; ambient temperature; NTGK model; ANSYS simulation; electric vehicles; thermal management systems.

1. Introduction

Because of its high energy density, extended cycle life, and low self-discharge rates, lithium-ion (Li-ion) batteries are at the forefront of energy storage technology and are extensively utilized in portable electronics, electric vehicles (EVs), and renewable energy systems. Lithium-ion batteries are critical for applications where high reliability and efficient operation are desired. Lithium-ion batteries are widely used in many areas today due to their high energy density, long life, and low maintenance requirements [1,2]. However, thermal management is crucial for batteries to operate efficiently and safely. Especially at high discharge rates and variable environmental conditions, the effects of internal heat generation and ambient temperature on the voltage balance and thermal efficiency of batteries are examined in detail by researchers [3,4]. Therefore, Thermal Management Systems (TMS) are being developed to prevent overheating and keep temperature imbalances under control. An ineffective thermal management system shortens the life of the battery, while also causing energy losses and safety risks.

In this context, methods such as phase change materials (PCM), hybrid cooling systems, and numerical modeling techniques continue to be developed to increase the thermal performance of batteries [5,6]. PCMs can also maintain temperature balance by preventing overheating of batteries thanks to their high heat storage capacities. Studies have shown that metal fins integrated into PCM systems increase the heat conduction of

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these materials and make the temperature distribution more balanced [3]. Especially in applications requiring high power such as electric vehicles, the use of PCMs with liquid cooling or thermoelectric modules ensures safe and efficient operation of batteries [6,7].

The Newman, Tiedemann, Gu, and Kim (NTGK) model, developed to understand the electrochemical and thermal behaviors of batteries, stands out with its ability to accurately predict temperature changes and voltage behaviors in different environmental conditions [8,9]. This model contributes to the optimization of battery management systems (BMS) and to ensuring battery safety. In addition, hybrid cooling systems combining active and passive cooling methods are also being investigated to improve thermal management [7]. It is stated in the literature that PCM-based thermal management systems provide effective temperature control at high discharge rates and balance heat dissipation [5,8]. In addition, finned systems have been shown to reduce temperature differences by increasing heat transfer in battery modules.

Numerical modeling and dynamic simulation techniques are widely used to better understand and improve the thermal and electrical performance of batteries [4,6]. These methods allow the development of new generation thermal management systems by examining how batteries respond to different discharge rates and environmental conditions. In addition, the mechanical and thermal interactions of batteries have been examined in detail and the effects of temperature changes on battery life and current characteristics have been revealed.

In order to further improve the thermal management performance of batteries, metallic PCM integration providing fast thermal response has been proposed, and new micro-fin designs have been developed to increase heat dissipation in high-density battery modules [10]. These innovations are considered as important steps to close the gap between battery technologies and industrial applications [10,11].

Despite all these developments, the relationship between internal heat generation, battery voltage and ambient temperature has not been fully answered in the literature.. Therefore, new studies based on advanced modeling approaches and experimental validations are needed to analyze the thermal and electrical behavior of batteries more comprehensively. In this study, the electrical and thermal behavior of 26650 lithium-ion batteries under different environmental conditions is investigated using the NTGK model. The simulation results combined with theoretical frameworks contribute to the development of effective thermal management systems for applications such as electric vehicles, renewable energy systems, and portable electronics [12,13].

Despite the large number of studies on the thermal and electrical behavior of lithium-ion batteries, research on the application of the NTGK model in series-connected configurations of type 26650 batteries under different ambient temperatures has been limited. Previous studies have mostly focused on single-cell simulations or experimental verifications and do not fully integrate numerical modeling techniques to evaluate the voltage behavior and thermal variations in multicell systems. To address this gap, this research aims to perform detailed simulations of 26650 batteries using the NTGK model to evaluate their thermal and electrical performance under different environmental conditions and discharge rates. The findings will contribute to optimizing battery thermal management strategies for real-world applications.

Most previous studies have focused on single-cell lithium-ion battery simulations or performed analyses based on experimental data without integrating detailed electrochemical-thermal modeling techniques. However, this study presents a comprehensive approach by evaluating the thermal and electrical performance of series-connected 26650 cells through the NTGK model. The novelty of this study lies in the detailed numerical modeling approach and the examination of multi-cell configurations under varying environmental conditions, which have not been extensively studied in the literature. Furthermore, this study contributes to understanding the complex interactions between voltage behavior, heat accumulation, and discharge conditions, which are crucial for optimizing battery thermal management in practical applications such as electric vehicles and energy storage systems. A key innovative aspect of this study is the implementation of the use Virtual Battery Connection method, which eliminates the need for physical busbars in series-connected battery configurations. Traditional bus-bar connections introduce additional weight and resistive losses, which can negatively impact overall system efficiency, particularly in weight-sensitive applications such as electric vehicles (EVs) and aerospace battery systems. By utilizing a virtual connection approach, this study provides a lightweight and computationally efficient alternative, ensuring a more accurate representation of real-world battery pack behavior without the added complexity of physical interconnections. Furthermore, unlike previous research that primarily focuses on either experimental or simplified numerical modeling approaches, this study integrates the Newman, Tiedemann, Gu, and Kim (NTGK) model with advanced numerical simulations to offer a more precise analysis of the thermal and electrical performance of series-connected 26650 lithium-ion cells under various ambient temperature and discharge conditions. These findings contribute to the optimization of battery pack design, enhancing performance and safety in high-power applications such as electric vehicles, renewable energy storage, and aerospace systems.

2. Materials and Methods

The following table provides a list of symbols and their corresponding definitions used throughout the mathematical modeling and numerical analysis sections of this study. This nomenclature ensures clarity in the interpretation of equations and parameters presented in the manuscript.

2.1. Battery Specification and Configuration

Commercially available 26650 lithium-ion (Li-ion) batteries with a 5000 mAh capacity and a nominal voltage of 3.7 V were used in this investigation. Unlike the traditional busbar connection method, the serial connection of battery packs is achieved using the virtual connection model in Ansys Fluent. By eliminating the resistance losses caused by hardwired busbar connections, this new technique has made it possible to accurately simulate the series or parallel connection behavior of batteries. In this study, the following assumptions were made in the numerical analysis:

Battery Materials and Homogeneity: The battery components (cathode, anode, separator) were assumed to be homogeneous and isotropic in terms of thermal and electrical properties.

Heat Generation and Dissipation: The heat generation was considered primarily due to Joule heating and electrochemical reactions, while radiation heat transfer was neglected.

Electrochemical Kinetics: The NTGK model parameters were derived from experimental discharge data, assuming uniform reaction kinetics within the battery structure.

No Aging Effects: Battery degradation effects such as capacity fade and resistance growth over repeated cycles were not included in the model.

Ambient Conditions: The ambient temperature was considered uniform, with no external forced convection applied unless explicitly stated in the simulation conditions.

These assumptions were necessary to ensure computational efficiency while maintaining accuracy in predicting thermal and voltage behavior.

2.1.1 Equations of the Battery Model Used in Numerical Analysis

In this work, the thermal and electric fields of the battery are solved in the CFD domain at the battery cell scale using the following differential equation

$$\partial(\rho C p T)/\partial t - \nabla\cdot(k\nabla T) = \sigma_+|\nabla\varphi_+|^2 + \sigma_-|\nabla\varphi_-|^2 + \dot{q}_{Ech} + \dot{q}_{SHORT} + \dot{q}_{abuse} \quad (1)$$

$$\nabla.(\sigma_+\nabla\varphi_+) = -(j_{ECh} - j_{short}) \quad (2)$$

$$\nabla.(\sigma_-\nabla\varphi_-) = j_{ECh} - j_{short} \quad (3)$$

where σ+ and σ- are the effective electric conductivities for the positive and negative electrodes, φ+ and φ_- are phase potentials for the positive and negative electrodes, j_{ECh} and $\dot{q}$Ech are the volumetric current transfer rate and the electrochemical reaction heat due to electrochemical reactions, respectively, j_{short} and $\dot{q}$ $\dot{q}$SHORT are the current transfer rate and heat generation rate due to battery internal short-circuit, respectively, $\dot{q}$abuse and is the heat generation due to the thermal runaway reactions under the thermal abuse condition [16].

NTGK is a simple semi-empirical electrochemical model. The volumetric current transfer rate is related to the potential field by:

$$j_{ECh} = \frac{Q_{nominal}}{Q_{ref} Vol} Y[U - V] \quad (4)$$

where denotes the active zone's volume of a single battery; V is the battery cell voltage, which is either obtained directly from the circuit network solution method or calculated as φ_+ - φ_- from the MSMD solution method; $Q_{nominal}$ is the battery total electric capacity in Ampere hours; and Q_{ref} is the capacity of the battery that is used in experiments to obtain the model parameters Y and Y.U and U are functions of the battery depth of discharge (DoD):

$$DoD = \frac{Vol}{3600 Q_{nominal}} \int_0^t j dt \quad (5)$$

For a given battery, the voltage-current response curve can be obtained through experimentation. Then Y and U in Equations 6 and 7 can be fitted, in theory. There are two approaches to specifying functions [16]:

Y and U can be fitted from testing data as functions of DOD and temperature explicitly before simulations. The relationship between Y/U and DOD/temperature can be provided:

$$U = \left(\sum_{n=0}^{5} a_n (DoD)^n\right) - C_2\left(T - T_{ref}\right) \quad (6)$$

$$Y = \left(\sum_{n=0}^{5} b_n (DoD)^n\right) \exp\left[-C_1\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad (7)$$

where C_1 and C_2 are the battery-specific NTGK model constants.

Y and U are not predetermined. Instead, the relationship between current and voltage from raw test data is stored, and Y and U are calculated dynamically during the simulation.

Model parameters are battery specific. You can use the Y and U parameters from a tested battery with a capacity Q_{ref} for a battery with a different capacity $Q_{nominal}$

as long as the battery's material is the same. If the model parameters are from the battery that is analogous to the one you are simulating, then capacities $Q_{nominal}$ and Q_{ref} will be the same.

The electrochemical reaction heat $\dot{q}_{Ech}$ is calculated as

$$\dot{q}_{Ech} = j_{ECh} = \left[U - V - T\frac{dU}{dT} \right] \quad (8)$$

The Li-ion cell specifications, material properties for the NTGK model, U and Y coefficients, and material properties are listed [16] in ▶**Tables 1 to 3** respectively.

2.2. Simulation Model

For in-depth thermal and electrochemical simulations, the Newman, Tiedemann, Gu, and Kim (NTGK) model was used. The NTGK model offers a semi-empirical framework that can precisely forecast battery cell temperature rise, voltage behavior, and thermal distribution under a range of operating circumstances. To guarantee accurate findings, simulations were carried out using ANSYS Fluent, using the virtual connection and the NTGK modeling technique.

To ensure the accuracy of the numerical model, a mesh independence test was conducted by evaluating different element counts ranging from 20,000 to 50,000. As shown in ▶**Table 1**, the maximum internal temperature and voltage results stabilize when the mesh size reaches 40,256 elements, with negligible variation observed in the 50,000-element case. Increasing the mesh density beyond this point resulted in only a 0.1 K difference in maximum temperature, which falls within an acceptable numerical error range. However, computational time increased significantly, from 2500 seconds for 40,256 elements to 3100 seconds for 50,000 elements, without yielding substantial improvements in accuracy.

Table 1. Effect of Mesh Density on Temperature and Voltage Predictions

Mesh Elements	Maximum Temperature (K)	Voltage (V)	Computational Time (s)
20,000	318.9	3.72	1800
30,000	316.1	3.74	2200
40,256	316.7	3.75	2500
50,000	316.6	3.75	3100

Previous studies have demonstrated that 20,000 mesh elements are sufficient for accurate thermal heat flux distribution prediction in an electric vehicle battery cell [18]. However, other works have shown that more refined mesh structures (38,777 to 45,604 elements) provide enhanced accuracy in complex battery thermal simulations [19]. Considering these findings, a 40,256-element mesh was selected as the optimal balance between computational efficiency and numerical precision in this study. Our results confirm that finer mesh sizes beyond this threshold contribute to excessive computational costs without a significant accuracy gain.

Therefore, the selection of a network with 40,256 mesh elements has provided an appropriate numerical model to ensure computational efficiency.

The mesh independence study, the thermal behavior study for a single battery were conducted with the NTGK model. In these tests, maximum temperature was chosen as the main evaluation criterion. As a result of the analysis, it was decided that a network structure

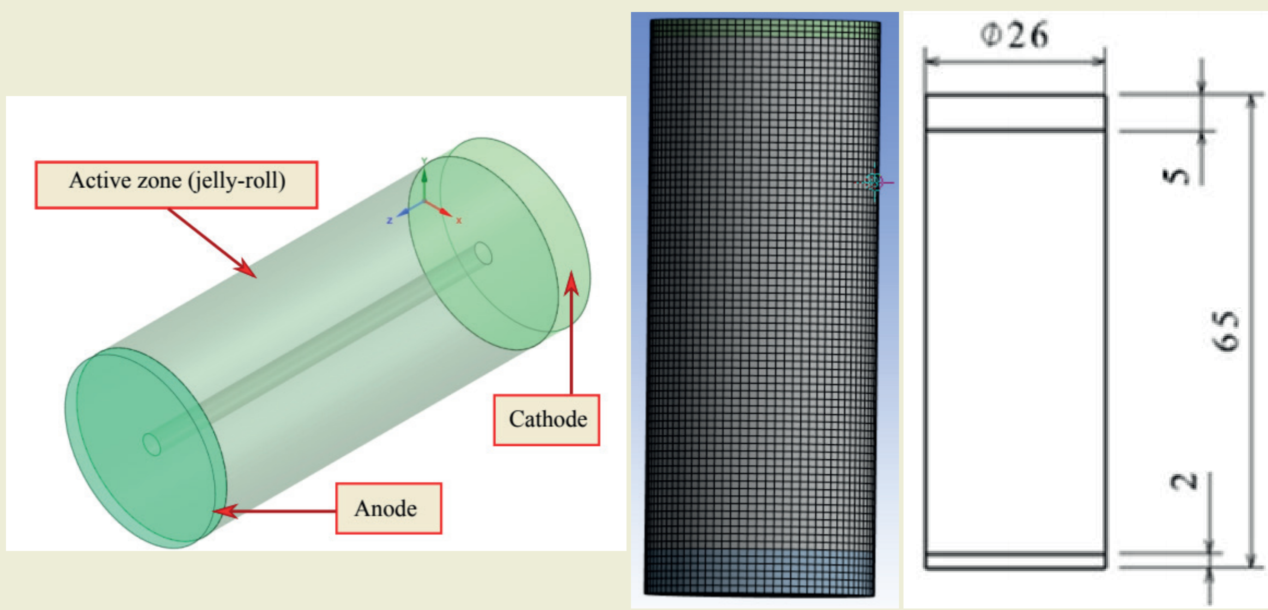

Figure 1. Battery details for Newman, Tiedemann, Gu, and Kim (NTGK) model

consisting of approximately 40256 elements is the optimal value in terms of both computational efficiency and accuracy of results in single-cell battery simulations. This network structure provided sufficient ktireter to model the thermal and electrical behavior of the battery with sufficient accuracy. A comprehensive diagram of the 26650 Li-ion battery used in the study is shown in detail in ▶**Figure 1** using the NTGK framework. The diameter of the battery used in this study was modeled as 26 mm and the height as 65 mm."The mesh independence test indicated that a mesh size of 40,256 elements provided an optimal balance between computational efficiency and accuracy. This is in agreement with previous studies on battery thermal modeling, where similar element counts (ranging from 35,000 to 50,000 elements) were reported to achieve mesh-independent solutions [17]."

2.3. Virtual Simulation Setup

A virtual series connection of the batteries was modeled to replicate realistic operating conditions.

Table 1. 26650 Li-ion battery Specification [14]

Parameter	Specification
Nominal Voltage	3.7 V
Nominal Capacity	4 Ah
Maximum Discharge Rate	2C
Maximum Charge Rate	1C
Dimensions (Diameter × Height)	26 mm × 65 mm
Mass	88 g
Cathode Material	LiCoO2
Anode Material	Graphite
Charging Voltage Limit	4.2 V
Cut-off Voltage	2.75 V
Emissivity	0.8

Simulations incorporated ambient temperatures of 273.15 K, 283.15 K, 298.15 K, and 318.15 K, and discharge rates of 0.5C, 1C, 1.5C, and 2C. Key input parameters, such as heat generation rate and thermal conductivity of the battery components, were included to ensure accuracy.

The selected ambient temperature ranges correspond to real-world operating conditions that lithium-ion batteries frequently encounter in various applications. 273.15 K (0°C) represents cold winter conditions, particularly relevant for electric vehicles (EVs) operating in high-latitude regions or elevated terrains where low temperatures can significantly impact battery performance. 283.15 K (10°C) reflects mildly cold conditions, typical of early spring or late autumn, where battery efficiency starts to improve but remains affected by moderate temperature variations. 298.15 K (25°C) represents standard room temperature, a benchmark condition widely used in laboratory settings and industrial applications to evaluate battery performance under ideal circumstances. 318.15 K (45°C) simulates high-temperature scenarios, such as summer conditions in warm climates or situations where EVs are exposed to prolonged sunlight, leading to increased heat accumulation within the battery pack. Understanding battery behavior across these temperature ranges is crucial for optimizing thermal management strategies and ensuring reliable performance under diverse environmental conditions.

2.4. Battery Specifications

The following table summarizes the key specifications of the 26650 Li-ion battery used in the study:

Table 2. Battery material properties[14]

Property	Jelly Roll (Active Zone)	Positive Tab (Aluminum)	Negative Tab (Steel)
Density (kg/m³)	2226	2719	8030
Specific Heat (J/kg-K)	1197	871	502.48
Thermal Conductivity (W/m-K)	27	202.4	16.27
Electrical Conductivity (S/m)	1.19×10^6, 9.83×10^5	3.54×10^7	8.33×10^6

Table 3. U and Y coefficients for the NTGK model [14]

U	a0: 4.0682, a1: -1.2669, a2: -0.9072, a3: 3.7550, a4: -2.3108, a5: -0.1701
Y	b0: 16.5066, b1: -27.0367, b2: 237.3297, b3: -632.603, b4: 725.0825, b5: -309.8760

The U and Y parameters used in the NTGK model were obtained from experimental discharge tests conducted under controlled environmental conditions. In order to investigate the behavior of the batteries depending on the temperature and discharge rate, numerical studies were performed at four different ambient temperatures (273 K, 283 K, 298 K, and 318 K) and four different discharge rates (0.5C, 1C, 1.5C, and 2C). The obtained numerical data were used to determine the parameters of the NTGK model. In this process, the Y(DOD, T) and U(DOD, T) functions, which explain the effects of deep discharge (DOD) and temperature (T) on the internal resistance and open circuit voltage of the battery, were optimized by the least squares method.

In order to test the accuracy of the model, a control study was performed for the battery data at temperatures of 288.15 K and 308.15 K and discharge rates of 0.75C and 1.25C. When the simulation results were compared with the experimental data, the root mean square error (RMSE) between the voltage and temperature values predicted by the model and the experimental results was found to be 0.678 V. These results showed that the NTGK model can successfully predict the thermal and electrical behavior of the battery over a wide operating range.

Table 4. Use Virtual Battery Connection

mp 1
nS 2
tab_n_1 tab_p_1
tab_n_2 tab_p_2

Structural series and parallel connections without busbars involve connecting battery cells directly via their terminals or conductive surfaces, eliminating the need for additional busbar components. This approach reduces the overall weight and cost of the battery pack, resulting in a simpler and more compact design. However, varying current paths and connection interfaces can affect thermal dissipation and electrical resistance, and require careful optimization of connection geometry and materials. Tools such as Fluent simulate the thermal and electrical performance of such configurations, allowing the design to be evaluated and optimized for improved efficiency and reliability.

3. Results and Discussion

This chapter investigates the thermal and electrical performance of series-connected 26650 lithium-ion cells under different ambient temperatures and discharge rates. Using the NTGK model and advanced virtual simulation techniques, the analysis sheds light on critical performance metrics such as voltage stability, discharge time, heat dissipation, and maximum temperatures. The findings reveal the complex interactions between battery internal heat generation, environmental factors, and discharge rates, highlighting their combined impact on battery performance. The results are examined for different cell configurations, such as 1S1P and 2S1P, and the thermal and electrical behavior of these structures under realistic operating conditions are analyzed. Particular focus is placed on the identification of key performance thresholds such as critical temperatures and voltage drops, emphasizing the role of these parameters in the design of efficient thermal management systems (TMS). Furthermore, the decisive effects of ambient temperature variations on discharge efficiency, heat accumulation, and voltage stability over time are evaluated in detail.

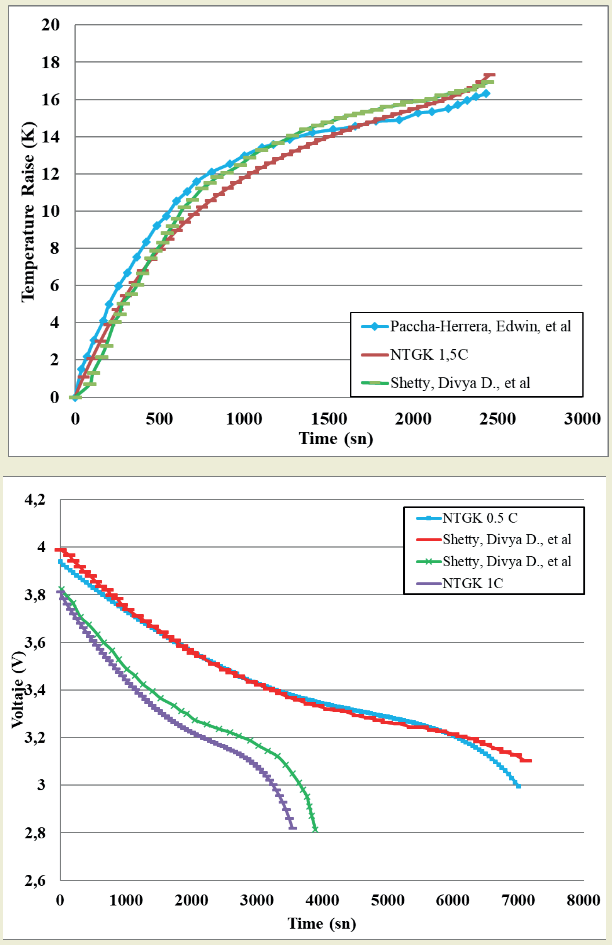

Figure 2. Validation with reference values

▶**Figure 2** verifies the accuracy of the NTGK model by comparing the simulated voltage outputs with reference values. The results obtained at 1C discharge rate show that the model is able to predict the voltage behavior with high accuracy under different operating conditions. The maximum deviation is within ±0.5%, which supports the reliability and predictive power of the model. The strong agreement between simulation data and experimental results proves the robustness of the NTGK model and its ability to accurately represent real-world thermal-electrical dynamics. Increasing voltage difference over time causes polarization increase and uneven charge distribution due to the increase in battery internal resistance and depletion of active lithium ions. This process directly affects the electrochemical balance of the battery, leading to voltage instability and performance losses.

To further evaluate the accuracy of the NTGK model, additional simulations were performed under different ambient temperatures (283.15 K and 318.15 K) and discharge rates (0.5C and 2C). These analyses were performed to verify how well the model can represent the thermal and electrical behavior of the batteries under different operating conditions. The additional tests provided a comprehensive comparison of the model's predictive capability in various scenarios and demonstrated the consistency of the NTGK model in voltage prediction. Furthermore, a cross-validation method was applied using an independent dataset, and discharge profiles that were not included in the original parameterizations were evaluated during this validation process. The findings demonstrate the complex interactions between internal heat generation, environmental factors, and discharge rates, emphasizing their combined impact on battery performance.

Although additional simulations at different temperatures and discharge rates were not performed within the scope of this study, the validation results presented in ▶**Figure 2** show that the NTGK model can accurately capture the correct operation of the system under the tested conditions. Future work will focus on improving the reliability of the model by covering a wider range of temperatures and discharge rates and testing the robustness of the system at higher battery temperatures.

3.1. 1S1P Battery Pack

This figure illustrates the discharge behavior of a 1S1P battery under various ambient temperatures. At a 2C discharge rate, the discharge time decreases significantly as the ambient temperature rises, dropping from approximately 3600 seconds at 273.15 K to around 2500 seconds at 318.15 K. Lower ambient temperatures provide greater voltage stability throughout the discharge process, while higher temperatures result in more rapid voltage drops. This behavior is attributed to increased internal resistance and thermal effects at elevated temperatures. These results underscore the necessity for effective thermal management systems to minimize performance degradation and ensure voltage stability, especially in high-temperature environments.

At higher temperatures, the increased internal resistance restricts efficient charge transport, leading to enhanced voltage losses and reduced discharge efficiency. Additionally, the electrochemical reaction rate accelerates, intensifying undesired side reactions such as electrolyte decomposition and SEI layer breakdown. These processes further contribute to performance degradation, increasing resistive heat generation and hastening capacity fade. As a result, the sharp decrease in discharge time between 298.15 K and 318.15 K is primarily driven by these thermally induced changes, emphasizing the importance of optimized cooling strategies to mitigate excessive heat buildup and ensure prolonged battery lifespan.

▶**Figure 4** presents the maximum internal temperatures of the 1S1P battery setup across different ambient

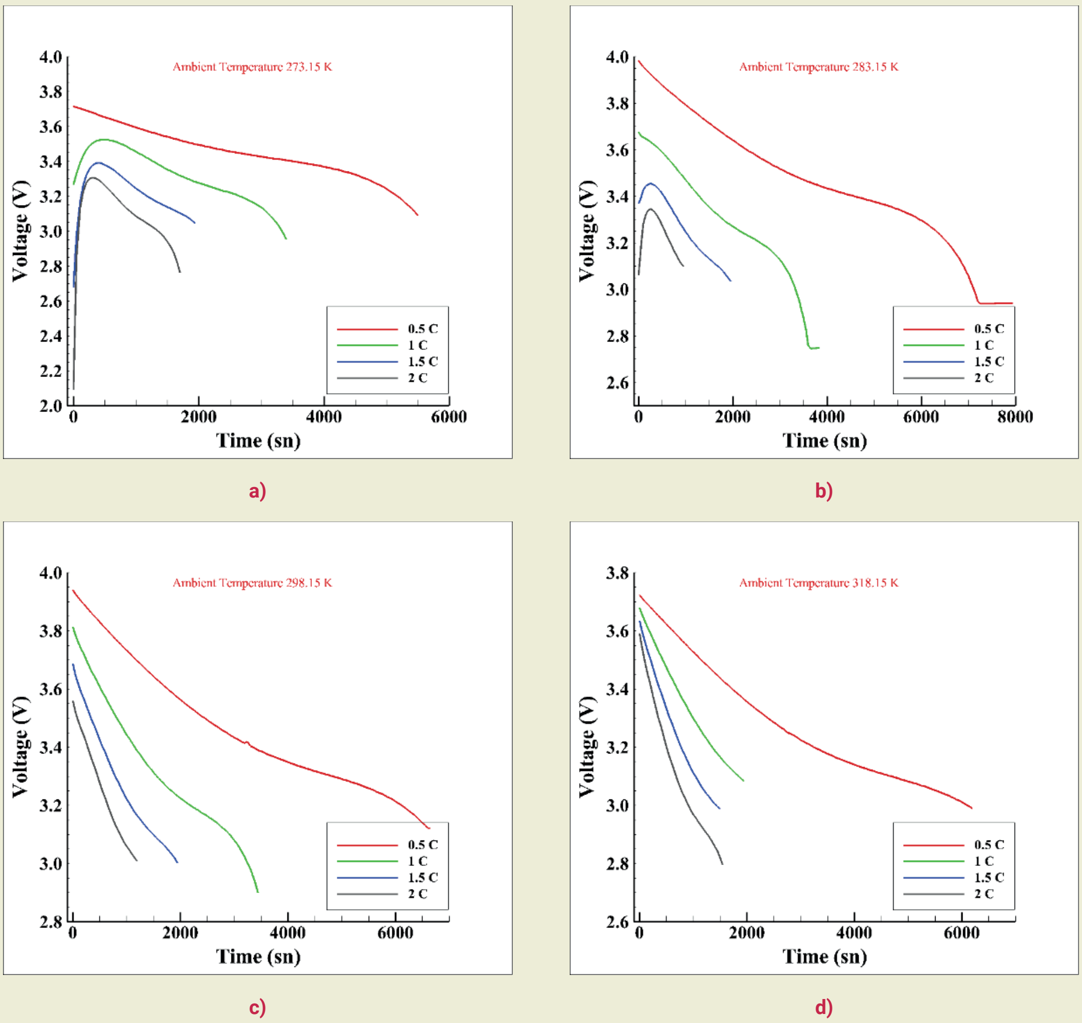

Figure 3. Discharge data of 1S1P battery for different ambient temperature (a-273.15 K b-283.15 K c-298.15K d- 318.15 K)

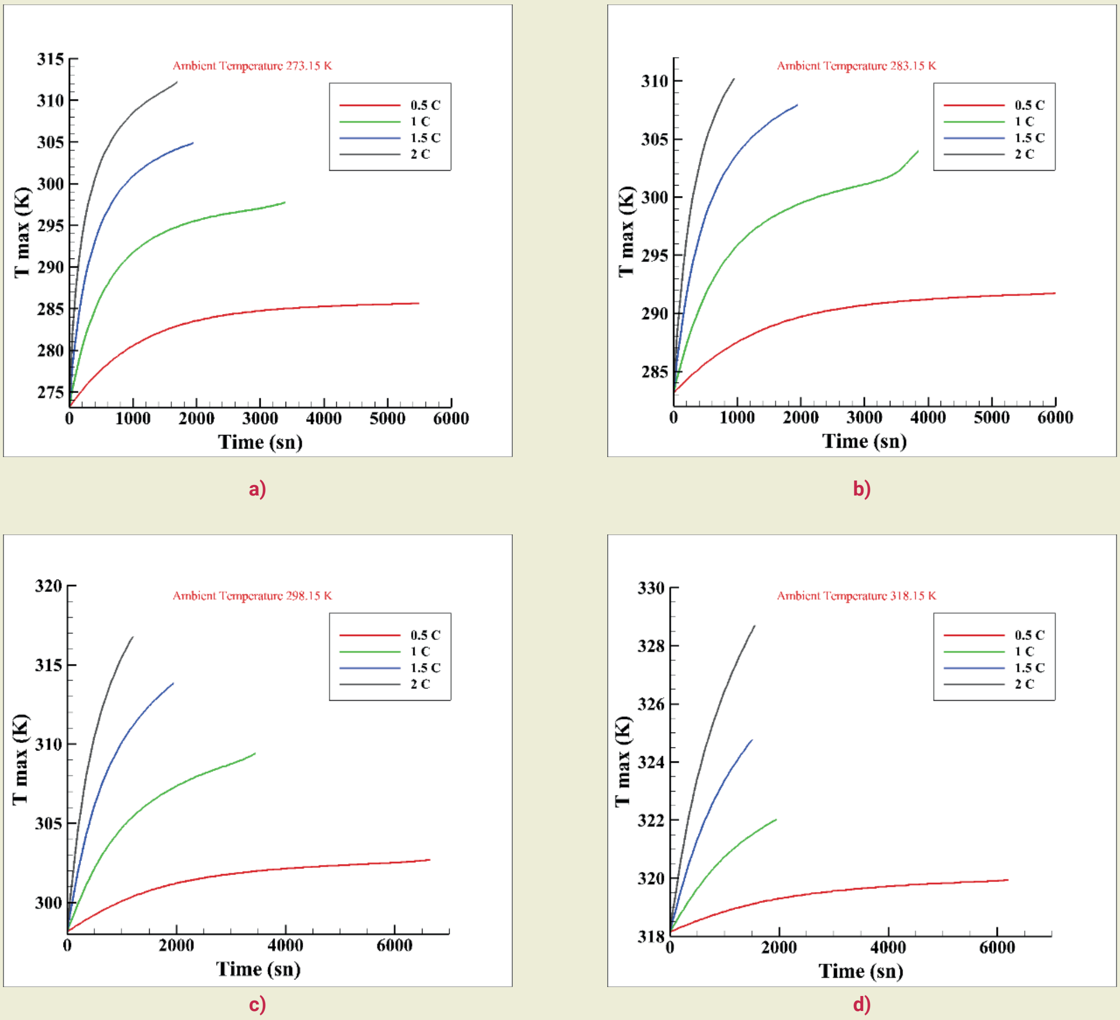

Figure 4. Maximum temperature information for 1S1P battery at different ambient temperature (a-273.15 K b-283.15 K c-298.15K d- 318.15 K)

temperatures and discharge rates. At a 0.5C discharge rate and 273.15 K, the peak temperature is recorded at 303.2 K. As the ambient temperature rises to 318.15 K with a 2C discharge rate, the maximum internal temperature increases significantly to 336.7 K. This stark rise in temperature highlights the compounding effect of higher discharge rates and elevated ambient conditions on thermal stress. The findings emphasize the importance of advanced cooling solutions to control the internal temperature and prevent thermal runaway in lithium-ion batteries operating under demanding conditions.

This figure provides a thermal map of the 1S1P battery configuration at an ambient temperature of 298.15 K and a 1.5C discharge rate. The distribution shows localized hotspots where heat accumulation is more pronounced, with temperatures peaking around the central regions of the battery.

These hotspots indicate uneven thermal dissipation, which can compromise battery performance and safety over time. The figure highlights the need for improved thermal uniformity and efficient heat dissipation mechanisms in battery designs. The temperature distribution observed in ▶**Figure 5** highlights localized heat accumulation in specific regions of the 1S1P battery configuration at an ambient temperature of 298.15 K and a discharge rate of 1.5C. The primary reason for these hotspots is the non-uniform distribution of cur-

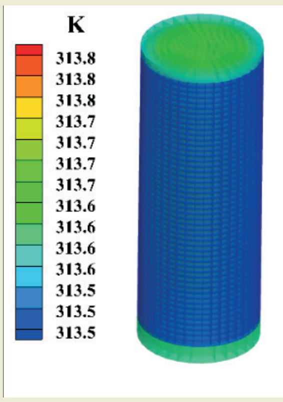

Figure 5. Maximum temperature distribution for 1S1P battery at 298.15 K ambient temperature and 1.5 C discharge information

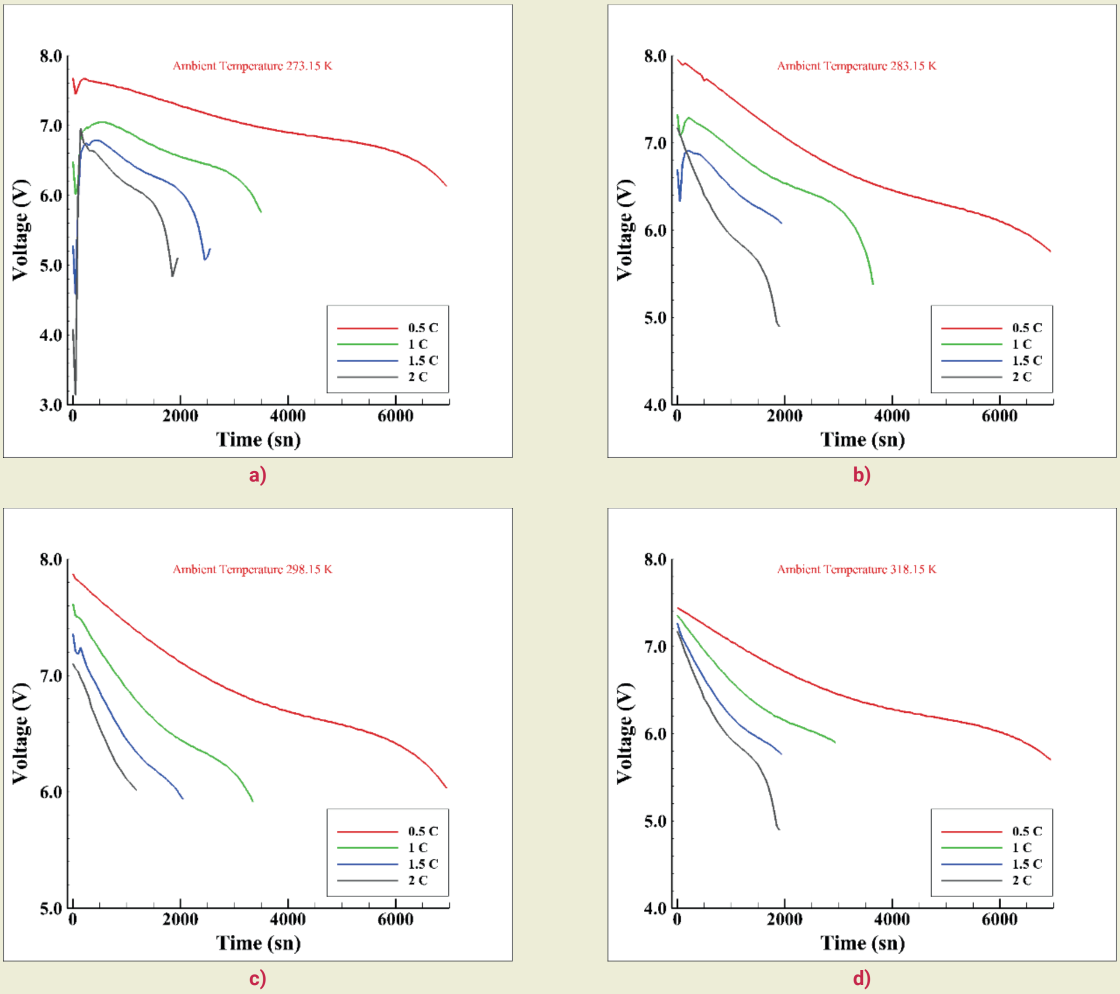

Figure 6. Discharge data of 2S1P battery paket for different ambient temperature (a-273.15 K b-283.15 K c-298.15K d- 318.15 K)

rent density within the battery. The positive and negative electrode tabs, where electrical connections are made, act as localized heat sources due to increased contact resistance and high current density in these areas. Furthermore, the anisotropic thermal conductivity of battery materials leads to uneven heat dissipation, with the electrode regions exhibiting higher thermal buildup than the separator and casing.

In a single-cell (1S1P) configuration, the overall heat dissipation is relatively more uniform compared to multi-cell arrangements. However, localized thermal buildup still occurs due to the non-homogeneous nature of electrical and thermal conductivity within the cell structure. The cylindrical battery geometry further exacerbates this issue, as heat tends to accumulate near the central core region, where thermal dissipation is more restricted. The results highlight the necessity for optimized cooling techniques, such as enhanced tab cooling, heat spreaders, or phase change materials, to mitigate hotspot formation and ensure uniform temperature distribution.

3.2. 2S1P Battery Pack

Figure 6 examines the discharge behavior of a 2S1P battery configuration under different ambient temperatures. Similar to the 1S1P setup, the discharge time decreases as ambient temperature increases, reducing from approximately 4200 seconds at 273.15 K to about 3100 seconds at 318.15 K for a 2C discharge rate. The voltage profile shows a more pronounced drop at the end of the discharge cycle under higher temperatures, highlighting the amplified impact of ambient conditions on series-connected batteries. These results point to the necessity of effective cooling systems for maintaining voltage stability and maximizing discharge duration in multi-cell configurations.

The significant reduction in discharge time between 298.15 K and 318.15 K can be attributed to the increased internal resistance, accelerated side reactions, and thermal effects on electrochemical processes. At moderate temperatures (273.15 K–298.15 K), ion transport and electrolyte viscosity gradually improve, leading to stable discharge performance. However, as the temperature rises beyond 318.15 K (45°C), the internal resistance increases due to accelerated electrolyte decomposition and degradation of the solid electrolyte interphase (SEI) layer. Additionally, excessive thermal energy enhances parasitic reactions, leading to faster voltage drops and reduced available capacity. These factors collectively result in a steeper decline in discharge time at high temperatures, highlighting the need for effective cooling strategies to maintain battery stability in high-temperature environments.

This figure illustrates the maximum internal temperatures of the 2S1P battery configuration under varying ambient temperatures and discharge rates. At 0.5C and 273.15 K, the peak temperature is 304.7 K, while at 2C and 318.15 K, it rises sharply to 341.3 K. The higher temperatures in the 2S1P configuration compared to 1S1P demonstrate the compounded thermal challenges of series-connected batteries, where heat accumulation from multiple cells exacerbates thermal stress. These results underline the importance of implementing advanced cooling strategies, such as hybrid thermal management systems, to ensure operational safety and efficiency in high-capacity battery systems. A key factor in lithium-ion battery safety is the identification of critical temperature thresholds that may increase the risk of thermal runaway. While the highest ambient temperature examined in this study was 318.15 K, this research suggests that significant thermal instability begins at temperatures exceeding 333.15 K (60°C). At this point, electrolyte decomposition accelerates, leading to increased gas generation and internal pressure buildup within the battery cell. If the temperature continues to rise beyond 373.15 K (100°C), exothermic reactions between the electrolyte and electrode materials can trigger thermal runaway, a self-sustaining chain reaction that can result in catastrophic battery failure, including cell venting, fire, or explosion.

In the 2S1P configuration, where heat accumulates due to the series connection, localized hotspots may cause certain regions within the battery pack to exceed safe operating temperatures, leading to non-uniform degradation and increased thermal stress. To mitigate these risks, advanced cooling strategies such as liquid cooling, phase change materials (PCM), or thermally conductive coatings should be considered, particularly for applications exposed to high ambient temperatures. Furthermore, integrating early warning systems, such as thermal sensors and BMS algorithms, can help de-

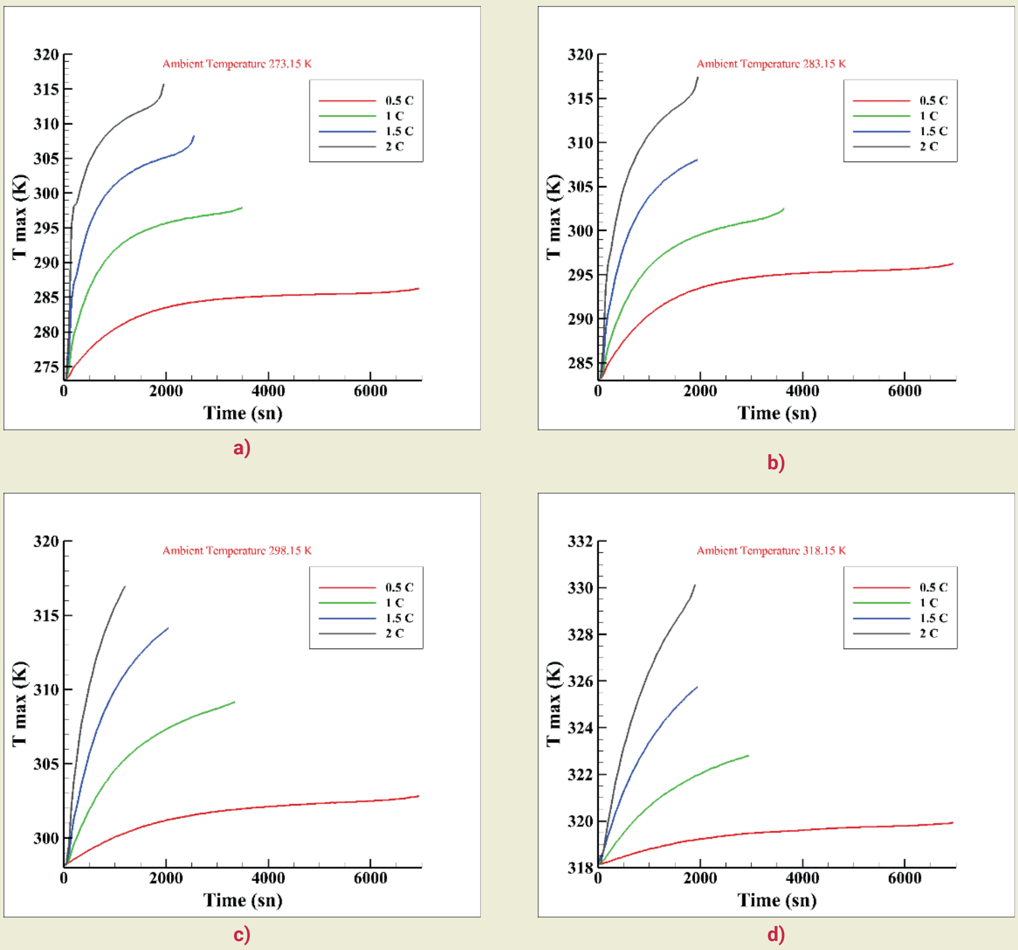

Figure 7. Maximum temperature information for 2S1P battery paket at different ambient temperature (a-273.15 K b-283.15 K c-298.15K d- 318.15 K)

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tect temperature anomalies and prevent hazardous conditions before they escalate.

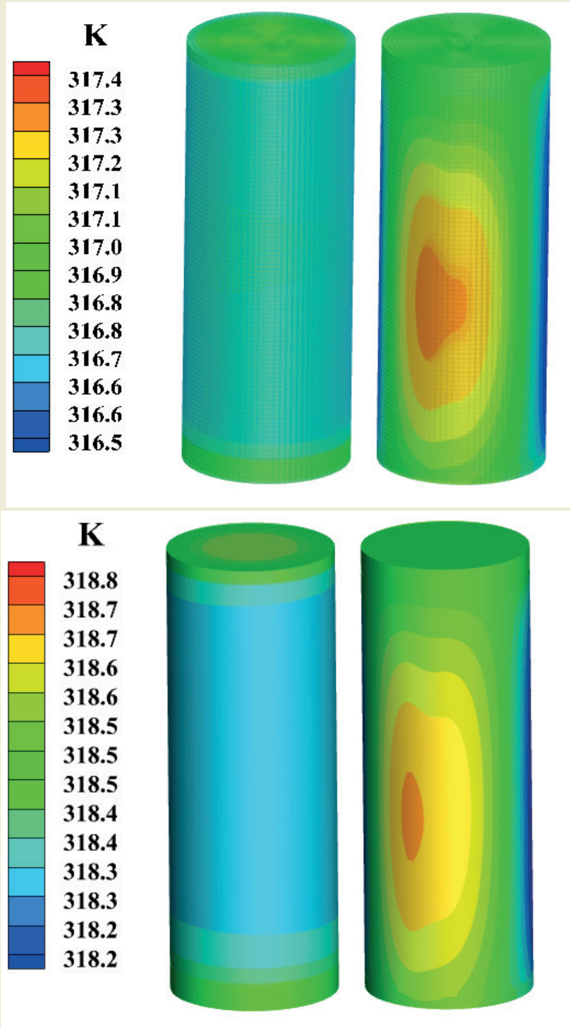

Figure 8. Maximum temperature distribution for 2S1P battery paket at 283,15 and 298.15 K ambient temperature and 2 C discharge information

For different external conditions, the heat distributions on the batteries are shown with thermal maps for 2S1P battery designs at ambient temperatures of 283.15 K and 298.15 K under a 2C discharge rate. The highest temperatures obtained as a result of numerical modeling are 317.4 K and 318.2 K, respectively. The hot spot formation in ▶**Figure 8** shows the thermal difficulties of a 2S1P battery pack operating at ambient temperatures of 283.15 K and 298.15 K with a 2C discharge rate. Compared to the 1S1P battery pack, the 2S1P pack is formed as a result of the combination of heat generated in each cell. By this logic, the difference will increase more at higher discharge rates (2C), where the need for more current demand will increase and the pack will be exposed to higher differential temperature.

Furthermore, the connection points between the cells serve as additional resistance sources, contributing to higher localized temperature spikes at the interconnection regions. The uneven heat dissipation observed in the thermal map is due to the asymmetric positioning of electrode tabs and variations in thermal conductivity between different battery layers. The results highlight the importance of thermal management techniques such as improved interconnection materials, heat dissipation coatings, or active cooling methods (e.g., forced air or liquid cooling systems) to minimize thermal gradients and ensure uniform temperature distribution across the battery pack. Battery Management Systems (BMS) that integrate temperature-dependent control algorithms can significantly benefit from these findings. The results highlight the importance of adaptive thermal management techniques, such as variable coolant flow rates, active cooling mechanisms, and real-time temperature monitoring, to mitigate excessive heating in high-power applications. Furthermore, series-connected battery configurations can utilize these insights to optimize cell balancing algorithms, ensuring uniform charge distribution and preventing localized thermal stress. This study's findings can be directly applied to the development of next-generation BMS for electric vehicles, grid-scale energy storage, and aerospace propulsion systems, where precise thermal regulation is critical for operational efficiency and safety.

4. Conclusion

This study analyzed the thermal and electrical performance of 26650 Li-ion batteries in 1S1P and 2S1P configurations under different environmental temperatures and discharge rates using the NTGK model and virtual simulations. The batteries exhibited different thermal and electrical behaviors depending on the environmental conditions and load levels; in particular, temperature rise and high discharge rates caused the battery internal temperatures to reach critical levels and accelerated voltage drops. In the 1S1P configuration, at 0.5C at 273.15 K, the battery was stable for 5500 seconds to maintain its internal temperature at 285.6 K, whereas at 2C, this time was reduced to only 1700 seconds and the temperature increased up to 312.2 K. This indicates that at high discharge rates, electrochemical reactions inside the battery accelerate and energy losses are converted into heat. Similarly, at 283.15 K, the temperature remained at 294.2 K when the battery was operating at 0.5C for 7950 seconds, but at 2C it lasted only 1000 seconds to reach 310.2 K. This trend was also observed at 298.15 K, where the internal temperature of the battery operating at 0.5C for 6650 seconds was 302.7 K, while at 2C it increased to 316.8 K in 1200 seconds. The highest increase in the internal temperature of the battery occurred at an ambient temperature of 318.15 K, where the battery reached 319.9 K for 6200 seconds at 0.5C and 328.7 K for 1550 seconds at 2C.

When the 2S1P configuration was analyzed, it was observed that the series connection caused a compound heat accumulation inside the battery. At 273.15 K, the internal temperature reached 286.3 K in 6950 seconds at 0.5C, while at 2C the temperature increased to 315.7

K in 1950 seconds. The main difference observed here is that although the battery life is longer than that of 1S1P, the temperature increase becomes more pronounced. At 283.15 K, at 0.5C, the battery operated for 6950 seconds, raising its temperature to 317.6 K, while at 2C, it reached 317.4 K in 1950 seconds, showing that batteries reach a certain temperature threshold at high discharge rates. At 0.5C at 298.15 K, the battery only reached 302.8 K in 950 seconds, while at 2C it reached 316.9 K in 1200 seconds. The highest temperature was measured at 318.15 K, where at 0.5C the battery temperature was 319.9 K in 6950 seconds, while at 2C it rose to 330.1 K in only 1900 seconds. This shows that at high ambient temperatures, batteries heat up rapidly, and safe operating limits can be exceeded.

The voltage analysis clearly demonstrated the sensitivity of the batteries to temperature and discharge rates. In the 1S1P configuration, the voltage was found to be 3.087 V at 0.5C at 273.15 K and decreased to 2.760 V at 2C. This decrease is related to the increasing internal resistance and the temperature-dependent variation of ion motions inside the battery. At 283.15 K, the voltage at 0.5C remained at 2.941 V, while at 2C it was measured as 3.096 V. At 298.15 K, the voltage at 0.5C was 3.121 V, while at 2C it decreased to 3.007 V. The largest voltage loss was observed at 318.15 K, where the voltage at 0.5C was 2.988 V, while at 2C it decreased to 2.795 V.

In the 2S1P configuration, higher total voltage values were obtained, but the voltage drop was accelerated by the temperature effect. At 273.15 K, the battery reached 6.125 V at 0.5C and decreased to 5.098 V at 2C. At 283.15 K, the voltage was measured as 5.754 V at 0.5C and decreased to 5.089 V at 2C. At 298.15 K, the voltage was 6.026 V at 0.5C and 6.008 V at 2C. At 318.15 K, the voltage remained at 5.699 V at 0.5C, while it decreased to the lowest value of 4.894 V at 2C. This decrease indicates that at high temperatures, electrode materials lose performance, and side reactions inside the battery increase.

The findings show that at high temperatures and high discharge rates, the internal temperature of the batteries approaches critical thresholds, and heat accumulation increases, posing a risk to battery safety. In particular, the temperature reaching 330.1 K at a 2C discharge rate and 318.15 K ambient temperature highlights the need for an effective thermal management strategy. Therefore, the application of advanced thermal management solutions such as liquid cooling, phase change materials and hybrid cooling systems in battery packs can control the internal temperature of the battery to extend the life and maintain safe operating limits. Furthermore, the integration of temperature-oriented intelligent algorithms in BMS can play a critical role in preventing battery overheating by tracking instantaneous temperature changes. This study highlights the necessity of optimized cooling strategies to maintain thermal and electrical balance in battery packs and provides important guidance for future battery technologies.

Future research can expand on these findings by conducting experimental validation to further confirm the accuracy of the NTGK model under varying environmental conditions. Additionally, investigating the application of the Use Virtual Battery Connection method in larger-scale battery packs and multi-module configurations can provide deeper insights into its scalability and practical feasibility. Moreover, integrating machine learning-based thermal management algorithms into battery simulations could enable predictive control strategies that enhance overall system efficiency. Finally, exploring alternative cooling methods, such as PCM or immersion cooling, could further optimize temperature regulation in high-performance battery applications.

Nomenclature

Symbol	Definition	Unit
Q	Battery capacity	Ah
Rint	Internal resistance	Ω (Ohm)
T	Temperature	K
I	Discharge current	A
V	Terminal voltage	V
Y(DOD,T)	TGK model parameter function	-
U(DOD,T)	Open-circuit voltage function	V
SOC	State of charge	%
DOD	Depth of discharge	%
P	Power dissipation	W
Cp	Specific heat capacity	J/kg·K
k	Thermal conductivity	W/m·K

Research ethics

Not applicable.

Author contributions

The author solely conducted all stages of this research.

Competing interests

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Data availability

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