symmetry

Review

Thermal Behavior Modeling of Lithium-Ion Batteries: A Comprehensive Review

Seyed Saeed Madani [1,*], Carlos Ziebert [1] and Mousa Marzband [2]

[1] Institute of Applied Materials-Applied Materials Physics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany; carlos.ziebert@kit.edu
[2] Net Zero Industry Innovation Centre, Campus Masterplan, Teesside University, Middlesbrough TS1 3BA, UK; m.marzband@tees.ac.uk
* Correspondence: seyed.madani@kit.edu

Abstract: To enhance our understanding of the thermal characteristics of lithium-ion batteries and gain valuable insights into the thermal impacts of battery thermal management systems (BTMSs), it is crucial to develop precise thermal models for lithium-ion batteries that enable numerical simulations. The primary objective of creating a battery thermal model is to define equations related to heat generation, energy conservation, and boundary conditions. However, a standalone thermal model often lacks the necessary accuracy to effectively anticipate thermal behavior. Consequently, the thermal model is commonly integrated with an electrochemical model or an equivalent circuit model. This article provides a comprehensive review of the thermal behavior and modeling of lithium-ion batteries. It highlights the critical role of temperature in affecting battery performance, safety, and lifespan. The study explores the challenges posed by temperature variations, both too low and too high, and their impact on the battery's electrical and thermal balance. Various thermal analysis approaches, including experimental measurements and simulation-based modeling, are described to comprehend the thermal characteristics of lithium-ion batteries under different operating conditions. The accurate modeling of batteries involves explaining the electrochemical model and the thermal model as well as methods for coupling electrochemical, electrical, and thermal aspects, along with an equivalent circuit model. Additionally, this review comprehensively outlines the advancements made in understanding the thermal behavior of lithium-ion batteries. In summary, there is a strong desire for a battery model that is efficient, highly accurate, and accompanied by an effective thermal management system. Furthermore, it is crucial to prioritize the enhancement of current thermal models to improve the overall performance and safety of lithium-ion batteries.

Keywords: lithium-ion batteries; thermal modeling; thermal behavior; temperature effects; thermal management

check for updates

Citation: Madani, S.S.; Ziebert, C.; Marzband, M. Thermal Behavior Modeling of Lithium-Ion Batteries: A Comprehensive Review. *Symmetry* **2023**, *15*, 1597. https://doi.org/10.3390/sym15081597

Academic Editor: Sergei D. Odintsov

Received: 28 July 2023
Revised: 11 August 2023
Accepted: 15 August 2023
Published: 17 August 2023

1. Introduction

Maintaining optimal operating temperatures for lithium-ion batteries (LIBs) is crucial to maximize their performance and ensure safe operation. Precisely monitoring temperature distribution within tightly sealed batteries during usage poses significant challenges [1]. To address safety concerns associated with lithium-ion batteries, extensive research has focused on thermal modeling at different levels, including cell, module, and pack levels. A notable study by Hoelle et al. [2] investigated and compared three empirical modeling approaches for predicting heat release during thermal runaway (TR) in a battery cell. The researchers employed a 3D-CFD framework to model a prismatic lithium-ion battery and compared the simulation results with autoclave calorimetry experiments. Additionally, the study examined the influence of critical parameters such as mass loss during TR, specific heat capacity, and thermal conductivity of the jelly roll. All three modeling approaches demonstrated high accuracy in reproducing experimental results, with varying levels of computational effort required. The study emphasized the importance of considering mass loss during TR, specific heat capacity, and thermal conductivity of the jelly roll to achieve precise simulation results. By highlighting the advantages and disadvantages of each modeling approach and identifying key modeling parameters, the research aimed to enhance TR and TR propagation simulation. These findings can be valuable for researchers and engineers in selecting appropriate models to design safer battery packs [2].

To meet the growing demand for safety and precise control in electric vehicles, there is an urgent need for a physics-based electrochemical model of lithium-ion batteries that can provide simple calculations and high accuracy across a wide temperature range, particularly for battery management systems (BMS). However, existing electrochemical models often prove too complex for practical use and lack the ability to accurately capture the battery cell's thermal characteristics. To address these limitations, Zhu, Guorong et al. [3] introduced a fractional-order model of lithium-ion batteries that considers both electrolyte polarization and thermal effects (FOMeT). The enhanced fractional-order model (FOM) incorporates electrolyte polarization, and a particle thermal model is introduced to describe heat generation and absorption within the cell. By combining the FOM considering electrolyte polarization with the particle thermal model, the researchers developed FOMeT, effectively coupling the cell temperature with lithium-ion dynamics. The study demonstrated that the proposed FOMeT model achieves high accuracy in predicting voltage and temperature across a wide range of temperatures (273.15 K to 318.15 K) and current loads (0.5 C to 2 C). This significant advancement in modeling contributes to improved battery management systems by providing a simplified yet accurate representation of lithium-ion battery behavior [3]. Electric vehicles face significant challenges in colder regions with low temperatures. To tackle this issue, Luo, Mingyun et al. [4] introduced a battery self-preheating system. Existing self-heating systems have limitations such as slow heating rates, complex control systems, single thermal management functions, and compromised safety. However, this study presented a conductive phase-change material (cPCM)-based self-preheating system that overcomes these drawbacks.

The self-preheating system presented in the study harnesses both the internal resistance of cells and the external resistance of the conductive phase-change material (cPCM) simultaneously. This innovative system achieves an impressive heating rate of 17.14 °C per minute and ensures excellent temperature uniformity, with a temperature difference of only 3.58 °C. The preheating process is safe within a battery capacity range of 20% to 100%, and when the battery pack is exposed to −20 °C, the effective electric energy increases significantly by 550% after preheating. Additionally, the researchers developed an energy conversion model that establishes a relationship between battery energy improvement and energy consumption during preheating. This model optimizes the preheating strategy, leading to maximum discharge energy. The study's findings demonstrate that the proposed self-preheating strategy effectively addresses low-temperature battery issues and maximizes the battery's effective electric energy. This advancement holds great promise for enhancing electric car performance in cold climates [4]. Accurate physical simulation of lithium-ion batteries plays a crucial role in gaining deeper insights into their operating mechanisms and potential state of health. However, calibrating reliable battery models proves complex due to the multitude of involved physical parameters. To address these challenges, Rabissi, C. et al. [5] conducted an extensive sensitivity analysis on the simulation of discharge, relaxation, and impedance spectroscopy tests. The focus of the analysis was on the response of the Doyle–Fuller–Newman model, which includes a thermal model to account for heat-transfer effects. The researchers investigated variations in 28 model parameters across approximately 160 combinations of temperature, battery state of charge, and C-rate. As a result of the sensitivity analysis, up to 14 parameters were identified as insensitive and could be reasonably excluded from model calibration. However, certain parameters exhibited diverse responses that could be maximized under specific conditions. To overcome these challenges and achieve accurate calibration, the researchers proposed an innovative method that combines two temperature levels and utilizes all three testing techniques (discharge, relaxation, and impedance spectroscopy). The combination of these techniques proved highly complementary and enabled fast and reliable calibration of the model. To demonstrate the efficacy of their proposed method, the researchers applied it to a commercial battery sample. The method facilitated a repeatable and physically sound calibration of the model parameters, as successfully demonstrated across a range of full discharges at 12 combinations of temperatures and C-rates. In comparison to a standard discharge-based calibration process, the proposed protocol showcased its strengths. Overall, this study underscored the significance of accurately calibrating lithium-ion battery models and proposed an innovative method that effectively addresses the challenges associated with model parameter calibration [5].

Despite the growing popularity of lithium-ion batteries (LIBs) in new energy vehicles, understanding the heat-generation patterns during their operation remains a challenging endeavor. Wu et al. [6] addressed this issue by introducing an electrochemical-thermal model (ETM) that assesses the heat-generation characteristics of cylindrical LIBs, considering discharge rates and the ratio of negative to positive electrode capacity (N/P ratio). To comprehensively research the thermal behavior of LIBs, the proposed ETM was validated using experimental data collected at ambient temperatures of 25 °C and 35 °C. The study further investigated the distribution profiles of heat-generation characteristics under various conditions using numerical simulations. Additionally, the research thoroughly analyzed the effects of different discharge rates and N/P ratios on battery heat generation. The results revealed that heat generation in the negative electrode plays a crucial role, and the impact of the reversible term on the total heat generation of the LIB cell cannot be ignored, especially at low discharge rates. Furthermore, the study observed that selecting an appropriate N/P ratio can enhance the total heat generation of LIBs, which proves beneficial for optimizing performance during the early stages of battery design and thermal management. Overall, this research significantly contributes to a better understanding of the heat-generation characteristics of LIBs during their operation. The proposed ETM provides valuable insights into the distribution profiles of heat generation under different conditions and emphasizes the influence of discharge rates and N/P ratios on battery heat generation. Such knowledge can be instrumental in optimizing LIB performance and developing effective thermal management strategies during battery design [6]. Accurate temperature prediction is crucial for improving battery performance and preventing thermal runaway in lithium-ion batteries. However, precise temperature estimation is challenging due to the complex nonlinear characteristics of heat generation and dissipation as well as the influence of external factors. In recent years, artificial neural networks (ANNs) have gained popularity in various aspects of lithium-ion battery research, including battery modeling, state-of-charge (SOC) estimation, residual life prediction, and battery temperature prediction. Nevertheless, there is limited research on temperature prediction for lithium-ion batteries with foam metal thermal management systems, and no consensus exists on the most suitable neural network architecture for this purpose. To fill this research gap, Wang et al. [7] utilized an artificial neural network approach to predict temperature changes in lithium-ion batteries within a metal foam thermal management system. They employed three types of neural networks, namely backpropagation neural network (BP-NN), radial basis functions neural network (RBF-NN), and Elman neural network (Elman-NN), to establish temperature prediction models. The study compared the performance of these different neural network models in temperature prediction and conducted performance tests under both sample and new conditions to validate the accuracy and effectiveness of the neural network thermal model. The results indicated that the Elman neural network model demonstrated better adaptability and generalization ability compared to the other neural network models. Moreover, the training time of the Elman neural network model was shorter, making it more suitable for temperature prediction in lithium-ion batteries with metal foam and forced air cooling systems. In summary, this research highlighted the application of artificial neural networks for temperature prediction in lithium-ion batteries with a metal foam thermal management system. The findings suggest that the Elman neural network model outperforms others in terms of adaptability, generalization, and training time, making it an effective choice for temperature prediction in such battery systems [7].

Cui et al. [8] introduced an innovative online method for estimating temperature distribution in lithium-ion batteries (LIBs), considering non-uniform heat-generation and boundary cooling effects. The researchers developed a thermal model for the tab area using the lumped parameter method, considering heat-generation and -transfer mechanisms. This tab thermal model served as the initial boundary condition for the core area of the battery. A difference equation was formulated using the heat balance method to describe temperature distribution within the core area. The researchers derived boundary conditions and a convection coefficient model for further calculations. They designed a disturbance observer to enhance temperature estimation accuracy. The proposed method outperformed traditional approaches, with an estimation error below 1.5 °C, offering valuable insights for battery modeling, parameter estimation, and thermal management in LIB systems [8]. Zhai et al. [9] conducted a series of experiments to investigate temperature distribution in a lithium-ion battery (LIB) using open-circuit voltage (OCV) tests, discharge rate tests, hybrid pulse power characteristic (HPPC) tests, and discharge temperature rise tests. They developed a thermal model (TM) incorporating a user-defined function (UDF) to account for variable heat-generation rate. The TM accurately predicted temperature rise at different discharge rates and offered valuable insights for LIB thermal management, aiding in the design of efficient cooling systems and optimizing battery performance [9]. Khaboshan et al. [10] researched the design of a high-performance battery thermal management system (BTMS) for lithium-ion batteries (LIBs) in electric vehicle (EV) applications. They employed a combination of phase-change material (PCM), metal foam, and fins in different configurations. The study investigated the effects of various fin shapes and identified the optimal BTMS configuration that achieved the lowest battery surface temperature and provided insights into the roles of different components in heat management. The research highlighted challenges in selecting an ideal fin shape for diverse environmental conditions [10]. Overall, these studies contributed significantly to the understanding and improvement of temperature distribution and thermal management in lithium-ion batteries, which are crucial for enhancing battery performance and safety in various applications.

Temperature plays a crucial role in influencing the performance and limitations of lithium-ion batteries (LIBs). Ma et al. [11] conducted a study to investigate the consequences of temperature on LIBs in both low and high temperature ranges. They discussed various techniques for monitoring internal battery temperature, highlighting the significance of temperature in LIB performance and the need for efficient temperature management. Feng and colleagues [12] presented a comprehensive review of approaches to address thermal runaway issues in LIBs. They introduced a time-sequence map to understand the progression of physical and chemical processes leading to thermal runaway and undesirable fires. This map aided in identifying transformation flows and developing effective strategies to prevent thermal runaway, enhancing the safety of LIBs for future applications. Zhang and colleagues [13] extensively investigated the thermal effects experienced by LIBs, including thermal runaway and battery performance in cold temperatures. They analyzed various heat-generation methods and assessed battery thermal management (BTM) strategies. The paper emphasized the importance of achieving uniform temperature distribution within battery packs to improve safety and extend battery lifespan, particularly for electric vehicles. Liao and colleagues [14] conducted a comprehensive review of monitoring and detection methods to improve the safety and robustness of LIB systems. They compared different approaches to identify the most effective methods for enhancing safety and reliability, focusing on identifying and tracking thermal runaway events. Patel and colleagues [15] provided a comprehensive review of battery thermal management systems, categorizing them as active and passive systems. They emphasized passive BTMS, particularly those utilizing phase-change material (PCM) and heat pipe technologies. The paper also explored hybrid BTMS, combining both active and passive techniques, and demonstrated their superior thermal management performance compared to individual approaches. In conclusion, these studies contributed valuable insights into understanding and addressing temperature-related challenges in LIBs. They emphasized the importance of precise temperature measurement, effective thermal management, and safety-enhancing strategies to optimize LIB performance and reliability across various applications.

Khaboshan et al. [10] outlined the development of a Battery Thermal Management System (BTMS) utilizing phase change materials (PCMs), metal foam, and fins to regulate battery surface temperatures during discharge. Four distinct BTMS configurations are formulated, with experimentation on various fin shapes (rectangular, triangular, trapezoidal, I-shape, and wavy fins). The application of a precise two-equation thermal model enhances the simulation of heat transfer between PCM and metal foam. The most effective BTMS integrates PCM, metal foam, and fins, resulting in a 3 Kelvin reduction in battery surface temperature and a maximum delay of around 470 seconds for PCM melting. The influence of diverse fin shapes on temperature is minimal, indicating the absence of a single optimal shape for all scenarios.

Li and colleagues [16] presented an overview of various EIS-based methods for predicting LIB temperature. These methods utilize impedance, phase shift, and intercept frequency to achieve high prediction accuracy, real-time performance, simplicity, and practicality. The study discussed the principles, advantages, disadvantages, and future directions of each method. Y. Kobayashi and colleagues [17] utilized an isothermal calorimeter to investigate the thermal behavior of a lithium-ion cell during charging and discharging processes. They prepared separate cells to distinguish between the thermal properties of the cathode and anode (graphite) materials. The study revealed unique thermal characteristics attributed to the distinct electrode materials and identified the gradual reduction in effective active material within the graphite electrode as the primary cause of capacity degradation after repeated cycles. Overall, these studies contribute valuable insights into the significance of temperature in LIB performance, the potential of EIS-based methods for temperature prediction, and the thermal behavior of different electrode materials. Understanding these aspects is essential for optimizing LIB performance and ensuring their reliable and efficient operation in various applications.

A. Pesaran and colleagues [18] developed a specialized calorimeter explicitly designed for accurately measuring heat generation in large battery modules. The calorimeter can accommodate battery modules with dimensions of up to 21 cm $\times$ 39 cm in cross-section and 20 cm in height, operating over a wide temperature range from -30 °C to +60 °C. It demonstrates high precision, capable of detecting small heat effects as low as 10 joules with an accuracy of 5%. The paper provided a detailed description of the calorimeter's design and functionality, along with calibration test results and test results obtained from a module replicating a lead–acid battery used in hybrid electric vehicles (HEVs). This research is crucial for understanding and managing thermal effects in large battery modules, especially in the context of hybrid electric vehicles [18]. Kong and colleagues [19] conducted a comprehensive review focused on advanced warning systems to prevent thermal runaway incidents in lithium-ion batteries (LIBs). They analyzed monitoring parameters used to detect thermal runaway and compared the sensitivity and robustness of multiple warning methods relying on these characteristic parameters. The study explored practical applications of early warning systems in various devices, such as portable devices, electric vehicles, and energy storage systems. Additionally, the researchers proposed potential future warning methods involving the integration of existing approaches with operational data from battery systems. This research contributes to the development of effective warning systems to enhance the safety and reliability of LIBs in diverse applications [19].

L. Guldbæk Karlsen and colleagues [20] conducted a literature study that focused on isothermal reaction calorimeters, exploring different types of equipment available. The review provides detailed descriptions and classifications of these instruments based on their measurement principles and design. Additionally, the study presented a case study of a new data treatment system implemented in a commercial bench-scale isothermal calorimeter, demonstrating how advanced data analysis techniques can enhance the accuracy and reliability of parameter determination in calorimetry experiments. This research contributed to a better understanding of available calorimeter equipment and showcased the potential for improved data analysis methods to advance the field of calorimetry.

The purpose of creating models to explore the thermal performance of batteries is to enhance our understanding of how batteries respond to and manage heat. These models aim to analyze, predict, and improve the thermal properties of batteries, which is a critical factor in enhancing their efficiency, operational quality, and safety. Through precise simulations and examinations of thermal elements, scientists and engineers can identify potential issues, develop more effective thermal control mechanisms, and ultimately improve the overall performance and reliability of battery systems. In our research, we extensively investigate various methodologies for battery modeling, with a particular focus on understanding the interactions and distinctions between thermo-electrochemical and thermal-electrical aspects. Our main objective is to conduct a comprehensive analysis of thermal behavior, temperature, and heat generation to develop accurate battery thermal models. Furthermore, we delve into a thorough investigation of existing strategies used in battery modeling to identify the challenges and discrepancies that researchers face. Our paper aims to provide an overview of modeling approaches that prioritize safety considerations, with a specific focus on the thermal aspects of battery behavior. Through this research, we hope to contribute to the development of safer and more reliable battery systems. By gaining a deeper understanding of thermal behavior, we can optimize battery performance, enhance safety protocols, and pave the way for more efficient and sustainable energy storage solutions.

2. Experimental Method for Thermal Analysis of Lithium-Ion Batteries

The experimental method for thermal analysis of lithium-ion batteries is essential for understanding their thermal behavior and optimizing their performance and safety. Table 1 provides a comprehensive compilation of detailed information on various experimental techniques used for this purpose. These experiments have contributed to advancing thermal analysis and modeling for lithium-ion batteries. Thermal analysis of lithium-ion batteries can be broadly classified into two main approaches: experimental and numerical methods. Both approaches involve studying the thermal behavior under normal operating conditions as well as abusive conditions. Factors such as heat generation, heat transport, storage mechanisms, and heat dissipation are considered in these analyses. Some investigations have utilized precise experimental setups, such as battery calorimeters, to accurately determine heat loss. These findings offer valuable inputs for thermal management systems and can be integrated with computational fluid dynamics simulations to enhance the thermal management of lithium-ion batteries. A key objective in the thermal design of lithium-ion batteries is to effectively mitigate heat generation and reduce the maximum temperature of battery cells under different conditions. Achieving these objectives simplifies the complexity of the thermal management system for lithium-ion batteries, leading to improved safety and performance. During the charging and discharging processes of lithium-ion battery cells, heat loss can be classified into two main sources: irreversible and reversible. The irreversibility of a lithium-ion battery cell, indicated by its overpotential, plays a significant role in determining heat losses. Additionally, the reversible entropic heat or entropy variation is another critical factor contributing to heat loss. Heat loss during both charging and discharging cycles can be further divided into two segments. Firstly, when a charge or discharge current is applied to the battery, the heat loss is referred to as heat loss during charging or discharging. Subsequently, when the current reaches zero, and the resting period begins, heat loss during rest occurs. This heat loss starts immediately after charge or discharge cycles when there is no current flowing and continues until the battery reaches its operating temperature. This phenomenon is crucial to consider in battery thermal management and plays a role in determining the overall efficiency and performance of lithium-ion batteries during operation.

The experiments were conducted using an isothermal battery calorimeter (IBC), which is designed to maintain a constant temperature and can operate within a temperature range of −30 °C to 60 °C. The IBC consists of various components, including a tank, cooling plate, heating element, and an isothermal bath. Fluid flow is controlled using four solenoid valves, one manual valve, and a motorized ball valve. The calorimeter is capable of measuring the heat generated by different types of batteries, with power levels ranging from 100 mW to 50 W. For the experiments, the IBC was connected to the Maccor automated test system using four cables. The IBC has maximum current, power, and voltage ratings of 250 A, 50 W, and 50 V, respectively. To measure the surface temperature of the battery and track its distribution over time, contact thermocouples were used. The IBC was able to measure these parameters simultaneously. However, it is important to note that the IBC has limited cooling and heating rates due to its high thermal inertia. At the middle of the temperature range, a maximum rate of five K/h could be achieved, while rates of around one to two K/h were possible near the temperature extremes. The stability of the isothermal bath and the accuracy of enthalpy measurements for the IBC are reported to be 0.01 °C and 2%, respectively. The heat flux area was determined using a linear baseline method, as the IBC operates under isothermal conditions. Linear measurements were found to be suitable for all experiments, and baseline stability and noise levels were recorded at 30 and 5 mW, respectively.

In the research conducted by [21,22], a novel method that combines thermal and electrochemical modeling was introduced to predict the simultaneous thermal and electrochemical behaviors of lithium-ion batteries. The approach involved linking the thermal and electrochemical models to achieve accurate predictions. Using first principles and the volume-averaging procedure, the researchers established a generic thermal energy equation model for different lithium-ion battery configurations.

Table 1. Experimental method for thermal analysis of lithium-ion batteries.

Battery	Description	Reference
Lithium-ion batteries	Investigation of lithium-ion battery's self-discharge	Aurbach D et al. [23]
Lithium-ion batteries	Investigation of lithium-ion battery's self-discharge for one month at 25 °C	Johnson BA et al. [24]
$LiFePO_4$	Investigation of the positive electrode material of $LiFePO_4$ in thermal stability issue	Joachin H et al. [25]
Lithium-ion batteries	This paper presents a general path to thermal runaway in lithium-ion batteries.	Amiruddin S et al. [26]
Lithium-ion batteries	Experimental study of thermal runaway inside a 1.35 Ah cylindrical Sony battery with a $LiCoO_2$ positive electrode	Al Hallaj S et al. [27]
Lithium-ion batteries	Experimental investigation of thermal runaway	Roth EP et al. [28]
lead-acid battery packs	Study of the effect of the charge algorithm, ambient temperature, and module connection methods for parallel strings on the performance and cycle life of these laboratory packs	Dickinson BE et al. [29]
Lithium-ion batteries	Investigation of specific properties of lithium-ion batteries essential for automotive applications, especially cell balancing	Kuhn BT et al. [30]
Lithium-ion batteries	A review of the primary charge equalization schemes for lithium-ion batteries	Moore SW et al. [31]
Lithium-ion batteries	Experimental balancing method for lithium-ion batteries	Kasnatscheew J et al. [32]
Lithium-ion batteries	Measuring the heat effects of electrochemical processes to find areas where such measurements might prove helpful, such as determining reaction heat	Sherfey JM et al. [33]
Lithium-ion batteries	Experimental determination of the effective heat capacity of the cell and calorimeter constant	Al Hallaj S et al. [34]
Lithium-ion batteries	Experimental determination of the effective heat capacity of the cell and calorimeter constant	Hong JS et al. [35]
LFP cell and ternary ($Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$, NCM)Lithium-ion cell	- Determination of thermal parameters of prismatic lithium-ion battery cells was accomplished; - The specific heat capacity and thermal conductivity of lithium-ion battery cells increase linearly, accompanied by rising temperature.	Lei Sheng et al. [36]

Figure 1 depicts the heat-generation model for lithium-ion batteries. The thermal modeling of a lithium-ion battery was successfully performed, revealing that the area near the negative tab of the battery cell experienced the highest temperature during the discharging process. Moreover, an uneven temperature distribution was observed, indicating potential areas for concern. At higher current rates, it took longer for the battery to reach thermal equilibrium, highlighting the importance of considering different operating conditions in thermal analysis. The research also indicated that the electrical conductivity of the active material in the negative electrode was notably higher than that of the positive electrode, leading to differences in current flow near the tabs of both electrodes. The non-homogeneity of the battery surface was identified as a significant concern, which calls for modifications to address this undesirable thermal behavior. The study suggests potential improvements, such as modifying physical and material properties and enhancing the thermal management system, to achieve better thermal performance and overall safety of lithium-ion batteries. This research represents a significant advancement in understanding and predicting the thermal behavior of lithium-ion batteries, contributing to the development of more efficient and reliable battery systems. The integration of thermal and electrochemical modeling provides valuable insights for optimizing battery design and thermal management, ultimately improving the performance and safety of lithium-ion batteries in various applications.

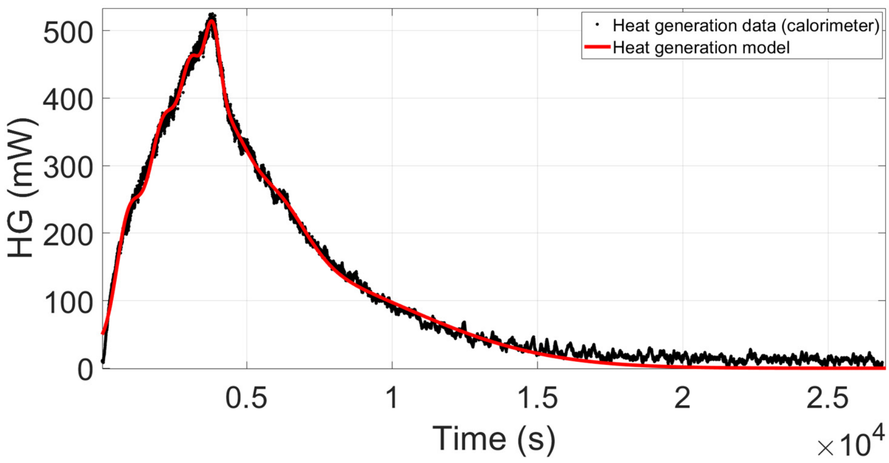


Figure 1. Lithium-ion battery heat-generation (HG) model [21].

In their research, Aurbach et al. [23] focused on enhancing Li-ion batteries through diverse research and development (R&D) approaches. The study specifically emphasized novel methods to assess the aging processes of Li-ion battery electrodes and to create innovative electrode materials. The researchers successfully utilized standard LiPF6 solutions with organosilicon additives at elevated temperatures, even in 5 V systems, showcasing the potential for improved battery performance under such conditions. They also explored the measurement of self-discharge current in lithiated graphite electrodes during cycling to gain insights into the intricate aging mechanisms that impact battery performance over time. Additionally, the article presented various techniques for synthesizing nanomaterials, including carbonaceous materials, tin-based compounds, and transition metal oxides. These methods included soft reactions in the liquid phase and high-temperature reactions under autogenic pressure, microwave radiation, and sonochemistry. By leveraging these techniques, the researchers aimed to enhance the performance and stability of electrode materials, thus contributing to the advancement of Li-ion batteries. On the other hand, Johnson et al. [24] conducted a study to evaluate the physical design, performance, and characteristics of lithium-ion batteries available from different companies in the market. The research involved analyzing cells from various manufacturers, including Sony, Matsushita, A&T, Moli, and Sanyo, totaling 85 cells. Throughout their analysis, the researchers found that the cells generally met the manufacturers' specifications. The study explored design differences through various methods, including gas chromatography–mass spectrometry (GC-MS) analysis of electrolytes, differential scanning calorimetry (DSC) analysis of separators, activation of positive temperature coefficient (PTC), and a comparison of basic physical parameters. The findings revealed important distinctions among the different cells from various manufacturers. For instance, A&T and Matsushita cells exhibited strong performance at high discharge rates, while Sony cells demonstrated excellent cycle-lifetime performance, and self-discharge effects were minimal. Overall, these research efforts contributed valuable insights into advancing Li-ion battery technology. Aurbach et al.'s work highlighted the importance of understanding electrode aging and developing innovative materials, while Johnson et al.'s study provided a comprehensive assessment of commercially available lithium-ion batteries, shedding light on performance variations among different manufacturers' cells. Such knowledge is essential for driving advancements in battery technology and improving battery performance and reliability in various applications.

In their research, Joachin et al. [25] focused on the carbon-coated $LiFePO_4$ material used as a cathode in Li-ion batteries, with particular attention to its electrochemical and thermal performance. The study revealed that the carbon-coated $LiFePO_4$ electrode exhibited a reversible capacity of over 90% of its theoretical capacity when subjected to cycling between 2.5 and 4.0 V. This indicates that the material has good cycling stability and retains its capacity even at high power levels. The carbon coating was found to enhance electronic conductivity, contributing to the improved cycling performance of the electrode. The researchers also employed electrochemical impedance spectroscopy to determine the diffusion coefficient of the material, providing valuable insights into its transport properties. Regarding thermal properties, the study investigated heat generation during charge and discharge using an isothermal microcalorimeter. Comparisons with other commonly used lithium metal oxide cathodes with layered structures were made, showing that $LiFePO_4$ is safer in terms of thermal behavior. Thermal studies conducted using a differential scanning calorimeter and an accelerating rate calorimeter validated this safety aspect, highlighting the advantages of using $LiFePO_4$ as a cathode material for lithium-ion batteries. On the other hand, Al Hallaj et al. [27] developed a one-dimensional thermal mathematical model with lumped parameters to simulate temperature profiles in lithium-ion cells, specifically using Sony US18650 cells. The model demonstrated good agreement with temperature measurements for various discharge rates, with only slight deviations observed at one discharge rate. The researchers extended the model's application to simulate temperature profiles in larger cylindrical lithium-ion cells (10 and 100 Ah). They found that cooling rate significantly influenced cell temperature, with notable temperature gradients observed at higher cooling rates (Biot number below 0.1). This indicates the importance of effective cooling strategies in large battery systems. Furthermore, the study tested commercial lithium-ion cells with different open-circuit potentials to determine onset-of-thermal-runaway (OTR) temperatures. They observed OTR temperatures of 104 °C, 109 °C, and 144 °C for cells with open circuit voltages of 4.06, 3.0, and 2.8 V, respectively. Additionally, internal short circuits occurred near the separator material's melting point for all tested open-circuit voltages, emphasizing the significance of separator material selection for thermal safety. Both research efforts contribute valuable insights into the electrochemical and thermal performance of lithium-ion batteries and highlight the importance of electrode material choice and thermal management for enhancing battery safety and reliability.

Roth et al. [28] conducted a study using differential scanning calorimetry (DSC) to investigate thermal interactions between different binder materials and representative anode carbons in lithium-ion cells. The research explored various binder materials, including vinylidene fluoride (VDF) homo- or copolymers and fluorinated and non-fluorinated binders. They found that the exothermic reactions in the anode were influenced by the state of charge and the presence of an electrolyte. The magnitude of these reactions increased with higher carbon surface area but showed similar reaction enthalpies for all binder materials and levels used in the study. This research provided valuable insights into the thermal behavior of different binder materials in lithium-ion cells and contributed to the understanding of binder material selection for improved battery performance. Kuhn BT et al. [30] conducted a study focusing on the essential properties of lithium-ion batteries, with particular relevance to automotive applications. The research involved long-term laboratory tests to thoroughly analyze and characterize these batteries. The primary areas of investigation included state-of-charge measurement and characterization, input-output charge efficiency, and the role of charge equalization. The study found that open-circuit voltage serves as a reliable indicator for state-of-charge measurement. Additionally, Li-ion technology was identified to have high input–output energy storage efficiency, making it particularly advantageous for hybrid vehicles. The importance of charge equalization in Li-ion applications was emphasized, with the need for active equalization to ensure safe operation and maximize battery lifespan. The study also highlighted the variability in commercial charge equalization devices among manufacturers. Overall, this research provided valuable insights into the performance characteristics of lithium-ion batteries in automotive applications and underscored the significance of charge equalization for battery safety and longevity. Moore SW et al. [31] focused on battery balancing in lithium-based batteries compared to traditional lead–acid batteries. Unlike lead–acid battery packs that can be balanced through controlled overcharging, lithium-based batteries require alternative methods, as they cannot be balanced through overcharging. The paper explored various cell-balancing methodologies specifically designed for lithium-based batteries. Active cell balancing methods involve transferring charge from high cells to low cells to achieve a more balanced charge distribution. In contrast, dissipative techniques identify high cells and dissipate excess energy through a resistive element until their charges align with the low cells. The paper thoroughly discussed the underlying theories behind these charge-balancing techniques and provided a comprehensive analysis of their advantages and disadvantages. The primary objective of the research was to offer valuable insights into cell balancing for lithium-based batteries and present different available approaches to optimize battery performance. This information is essential for ensuring the efficient and safe operation of lithium-ion batteries in various applications.

Kasnatscheew et al. [32] conducted a study on balancing active materials in lithium-ion batteries to enhance safety and cycle life. The researchers aimed to find the optimal trade-off between maximizing specific energy and minimizing the risk of lithium plating. To achieve this, they adjusted the state of charge (SOC) through active mass ratios and charge cutoff voltage. By using specific charge capacity, they were able to indirectly predict electrode potentials, enabling better investigation and control. The study revealed that specific capacity losses were primarily influenced by the negative electrode's BET surface area, providing valuable insights for optimizing performance and safety in lithium-ion batteries. This research contributes to understanding the relationship between specific energy and lithium plating risk, which is crucial for developing safer and more efficient lithium-ion battery systems. Lei Sheng et al. [36] conducted a study to characterize the thermal parameters of lithium-ion batteries with the goal of accurately predicting the temperature distribution in battery cell modules. They proposed a novel method based on quasi-steady-state heat-transfer analysis, allowing for the simultaneous determination of the batteries' thermal conductivity and specific heat. In the experimental test, prismatic lithium iron phosphate cells and pouch cells with different electrode materials were utilized. The researchers applied a constant heat flux to the cell surface and estimated the heat loss by analyzing the temperature drop curve. This approach facilitated achieving quasi-steady-state heat transfer, enabling the determination of cell thermal parameters. The study findings indicated that the thermal parameters of the cells increased linearly with the operating temperature. Additionally, the operating temperature had a more substantial impact on the cell's specific heat compared to its thermal conductivity. On the other hand, the state of charge had a minimal effect on these two parameters. Overall, the developed method presents an effective and practical approach to simultaneously determine the thermal conductivity and specific heat of lithium-ion battery cells. This research provided valuable insights into the thermal behavior of lithium-ion batteries, which is critical for designing efficient thermal management strategies and ensuring battery safety and performance.

Ping et al. [37] addressed the flammability concerns associated with organic phase change materials (PCMs) commonly used for thermal management in lithium-ion batteries. To mitigate these concerns, the study introduces an encapsulated inorganic PCM

(EIPCM) synthesized through nano-encapsulation. The core material, $Na_2HPO_4 \cdot 12H_2O$, is encapsulated within a matrix of silica. The EIPCM exhibits a melting temperature of 51 °C and a latent heat of 111.69 kJ/kg. Experimental tests conducted on battery modules reveal that the implementation of EIPCM results in a substantial 23.7% reduction in peak battery temperature (from 86.6 °C to 66.1 °C) at a discharge rate of 3C, while simultaneously maintaining a minimal temperature difference. Furthermore, EIPCM demonstrates the ability to delay thermal runaway by 495 seconds and significantly lower the peak surface temperature by 194 °C. This characteristic offers nonflammable suppression of thermal runaway and an enhanced level of battery safety. The study concludes by suggesting promising practical applications of EIPCM in the realms of batteries and energy storage.

Liang et al. [38] aimed to enhance the performance of lithium-ion batteries in electric vehicles (EVs) during cold conditions by introducing an innovative battery thermal management system (BTMS) utilizing a unique bent flat micro heat pipe array (FMHPA). The bent FMHPAs serve as efficient thermal bridges, facilitating independent preheating and cooling operations while optimizing spatial efficiency. Experimental results highlight the impressive thermal conductivity of the Z-shaped bending FMHPA, measured at 15,741 Wm-1K−1, resulting in a temperature rise rate of approximately 1 °C/min across a temperature range of −20 °C to 0 °C. The temperature differences within both cell and module levels remain within 5 °C. Additionally, the introduction of a 20 mm insulation shell enhances the temperature rise rate and difference at the module level, yet has minimal impact on the active cooling performance at higher ambient temperatures.

The disadvantages of utilizing the experimental approach in the realm of thermal analysis for lithium-ion batteries encompass the following aspects:

1. High Cost and Resource Intensity: The execution of experimental thermal analysis necessitates specialized equipment, materials, and proficient personnel, which can incur substantial expenses for establishment and maintenance. This entails procuring thermal imaging cameras, calorimeters, and other measurement instruments as well as conducting trials within controlled environments;
2. Time-Consuming Nature: The undertaking of experimental thermal analysis can consume significant time, particularly when investigating diverse battery configurations, materials, and operational circumstances. The preparatory stages, actual experimentation, and subsequent analysis may lead to delays in acquiring findings and insights;
3. Limited Adaptability: Experimental setups are frequently tailored to specific conditions, posing challenges in exploring a broad spectrum of scenarios and parameters. Such constraints can impede the exploration of intricate interactions influencing thermal behavior in real-world applications;
4. Intrusive Character: Numerous experimental techniques involve modifying the battery's surroundings or structure, potentially affecting its performance. For instance, embedding sensors or thermocouples within the battery could disrupt its thermal attributes and influence the outcomes;
5. Environmental and Safety Considerations: Certain experimental methodologies, like abuse testing or simulations of thermal runaway, carry inherent safety hazards and environmental implications. These assessments might involve deliberately inducing battery malfunctions, which could lead to perilous situations or contribute to waste generation;
6. Real-Time Monitoring Challenges: Continual real-time monitoring of thermal performance during battery operation proves arduous with experimental methods. This constraint hampers researchers from capturing dynamic and momentary effects transpiring during swift alterations in operating conditions;
7. Scale and Reproducibility Complexities: Upscaling experiments to mirror real-world circumstances can be intricate and might not entirely emulate the actual conduct of lithium-ion batteries within larger systems. Replicating experimental

outcomes across diverse laboratories can also be demanding due to variations in equipment and protocols;

8. Data Complexity: Experimental thermal analysis generates copious volumes of data that necessitate meticulous analysis and interpretation. Extracting meaningful insights from intricate experimental data can be labor-intensive and may mandate sophisticated data analysis techniques;
9. Limited Holistic Insights: Experimental methodologies may not furnish an all-encompassing comprehension of the fundamental physical and chemical mechanisms accountable for thermal behavior. Frequently, they supply surface-level observations without disclosing the molecular-level interactions;
10. Equipment Inherent Constraints: The precision and resolution of experimental apparatus can introduce uncertainties and limitations into the amassed data, affecting the precision of thermal analysis outcomes.

To summarize, while experimental approaches hold value in studying thermal attributes of lithium-ion batteries, they entail drawbacks encompassing cost, time, adaptability, intrusiveness, safety, reproducibility, and data interpretation. Integrating experimental findings with computational modeling and simulation can help surmount some of these limitations and offer a more comprehensive insight into thermal characteristics within lithium-ion batteries.

3. Numerical Method for Thermal Analysis of Lithium-Ion Batteries

Numerical methods for thermal analysis of lithium-ion batteries are crucial for predicting battery behavior and assessing its performance under various conditions. These models encompass nominal electrothermal modeling, considering aging and mechanical stress, as well as thermal runaway modeling. Numerical simulations play a significant role in understanding the intricate relationship between electrochemical reactions and transport processes, which directly affect the battery's temperature. Temperature has a significant impact on battery performance, lifespan, and safety. Hence, thermal management techniques are essential to address thermal challenges in lithium-ion batteries. These challenges include battery capacity and power degradation, the risk of thermal runaway, cell imbalances within battery packs, and the influence of low temperatures on battery performance. Understanding how temperature affects these phenomena is crucial for developing effective thermal management strategies. Heat generation in batteries is a critical aspect that needs to be understood for effective thermal management. Various studies have critically assessed research in this field, identifying knowledge gaps and prerequisites for thermal management systems in lithium-ion batteries, particularly in hybrid electric vehicles (HEVs) and electric vehicles (EVs). The comparison of estimated battery surface temperatures from numerical models with experimental data is essential for model validation. To achieve optimal performance in thermal management, different studies have investigated temperature distribution in various thermal management systems, such as air and liquid cooling. Efficient heat-transfer capabilities are crucial for lithium-ion battery thermal management systems.

Figure 2 presents a systematic approach for designing a thermal modeling system for lithium-ion batteries. The use of numerical methods for thermal analysis offers valuable insights into the thermal behavior of lithium-ion batteries, contributing to the development of safer, more efficient, and reliable battery systems for various applications. A three-dimensional model was developed in ANSYS, based on the battery cell's construction and geometry and enabling detailed analysis of the battery's structure. The figure illustrates the components of the positive and negative current tabs responsible for facilitating current flow through the battery cell. The model consists of five distinct parts, each playing a specific role in the analysis. Geometrical meshing of the lithium titanate oxide battery cell's structure is shown in another figure, providing a detailed representation of the cell's internal configuration. To accurately represent the battery's behavior, a 2-RC-quivalent circuit model was used. The parameters of this model were determined through different loading profiles involving various charge and discharge cycles at different C-rates. The model was solved within ANSYS using the multi-scale multi-dimensional (MSMD) battery module, which integrates key design parameters of the battery cell, such as physical attributes, materials, and dimensions, into the realm of computational fluid dynamics and heat transfer. Importantly, the battery model can simulate both a single battery cell and an entire battery pack, enabling investigation into their electrochemical and thermal behaviors. During the solution phase of the model, unsteady-state problems and interdependent thermal effects over time were addressed through numerical techniques, considering the dynamic heat generation within the battery cell. The quantity of heat generated within the lithium-ion battery cell, which is influenced by temperature and current rate, was quantified using IBC measurements and used as input for the thermal model. By employing this systematic approach and integrating numerical simulations with experimental data, a more comprehensive understanding of the thermal behavior of lithium-ion batteries can be achieved, leading to improved battery design, performance, and safety.

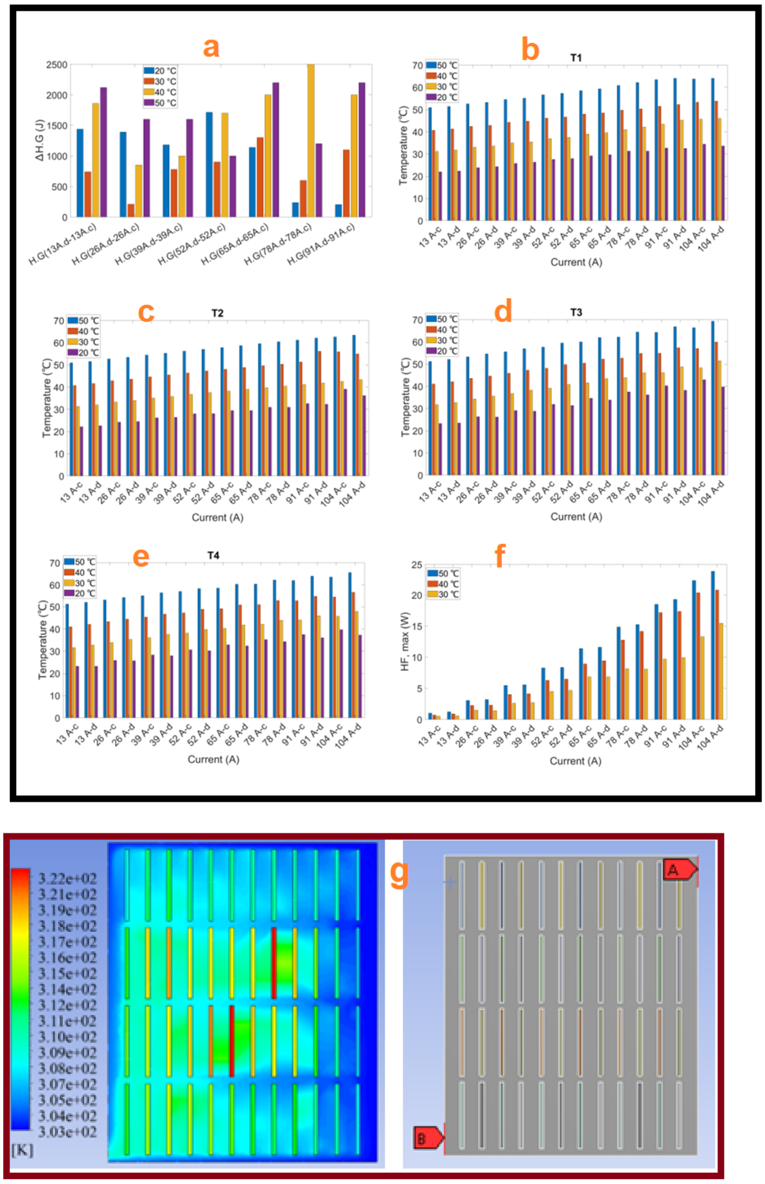


Figure 2. (**a**) Difference between charge and discharge heat losses [21], (**b**–**e**) the battery surface temperature at different working temperatures and position [22], (**f**) maximum of heat flux at different current rates and temperatures [39], and (**g**) temperature profile inside the battery pack during air cooling [40], A: input, B = output.

Table 2 provides a comprehensive overview of numerical methods used for thermal analysis of lithium-ion batteries. These methods are valuable for accurately predicting temperature distribution and addressing temperature inhomogeneities within the battery cell. The findings from these simulations can aid in the design of efficient thermal management systems to optimize battery performance and ensure safety. One notable study by Verbrugge et al. [41] focused on analyzing the current and temperature distributions in large-scale battery modules using three-dimensional simulations. The research emphasizes the nonlinear relationship between power output and system temperature, with temperature significantly influencing electrochemical reaction rates and ionic conductivity. The study also provided a practical approach to estimate physicochemical parameters crucial for their model, addressing potential data limitations and enhancing simulation accuracy. Overall, the numerical methods presented in Table 2 offer valuable insights into the thermal behavior of lithium-ion batteries, paving the way for more effective thermal management strategies and improved battery performance and safety.

Table 2. Numerical method for thermal analysis of lithium-ion batteries.

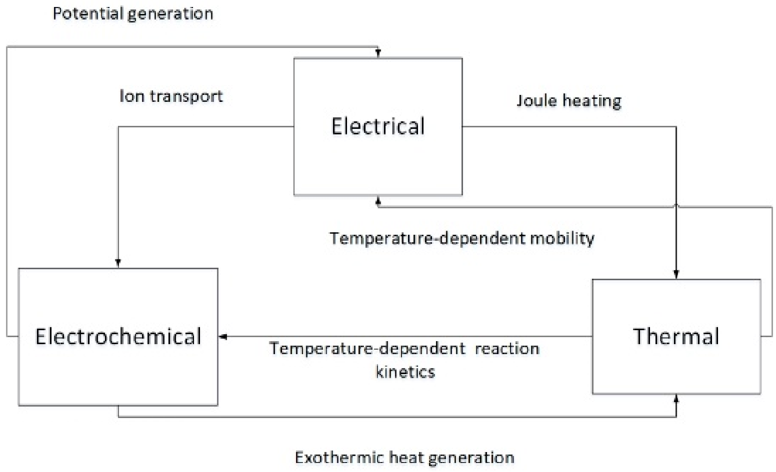
Battery	Description	Reference
Lithium-polymer battery module	Numerical investigation of the effect of battery design on the onset of thermal runaway	Verbrugge MW et al. [41]
Lithium-ion batteries	- Study of the temperature distribution inside a prismatic lithium-ion battery; - Simulation of thermal runaway event due to a localized hot spot.	Chen Y et al. [42]
Lithium-ion batteries	Design of both lumped and three-dimensional thermal models for the simulation of various side reactions inside the battery under abusive conditions	Kim GH, Pesaran et al. [43]
Lithium-ion batteries	Presentation of a thermal-electrochemical coupled approach for modelling Li-ion batteries to predict battery electrochemical and thermal behaviors	Gu WB et al. [44]
Lithium-ion batteries	- Design of an optimization framework for battery economic-conscious charging; - Costs of both electrical energy waste and battery aging were directly considered; - Contradictory objectives, along with immeasurable states and constraints, were optimized; - Charging strategies towards time, energy, and economic management were obtained; - Effects of three sensitive elements were comparatively studied via the Pareto frontier.	Liu K et al. [45]
Lithium-ion batteries	Accurate estimation of battery degradation cost using deep reinforcement learning method	Cao J et al. [46]

The studies conducted by Chen et al. [42] and Kim et al. [43] provided valuable insights into the thermal behavior and safety considerations of lithium-ion batteries. Chen et al. [42] employed a mathematical model to conduct thermal analysis during charge/discharge cycles and thermal runaway events. The research focused on understanding the thermal behavior of room temperature batteries and the potential for significant temperature increases that could lead to thermal runaway. The study investigated the impact of various battery design parameters and operating conditions on temperature rise and profiles during normal battery operation. Additionally, the likelihood of thermal runaway occurring under abusive or extreme conditions was evaluated. The findings contribute to enhancing our understanding of thermal management and safety in lithium-ion batteries, enabling the development of effective strategies to improve battery safety. Kim et al. [43] conducted a study specifically focused on the thermal abuse behavior of large-format Li-ion batteries designed for automotive applications. The research used a three-dimensional modeling approach to simulate oven tests and analyze local hot spots and their propagation within the cell. The results showed that the three-dimensional model predicted thermal runaway occurrence at different times compared to the lumped one-dimensional model. The study emphasized the importance of considering three-dimensional effects and cell size when assessing the risk of thermal runaway. Understanding these thermal behaviors is crucial for designing safe and reliable large-format Li-ion batteries for automotive applications. In conclusion, the findings from these studies contributed significantly to the field of lithium-ion battery thermal analysis, helping to enhance safety considerations and develop effective thermal management strategies for practical applications.

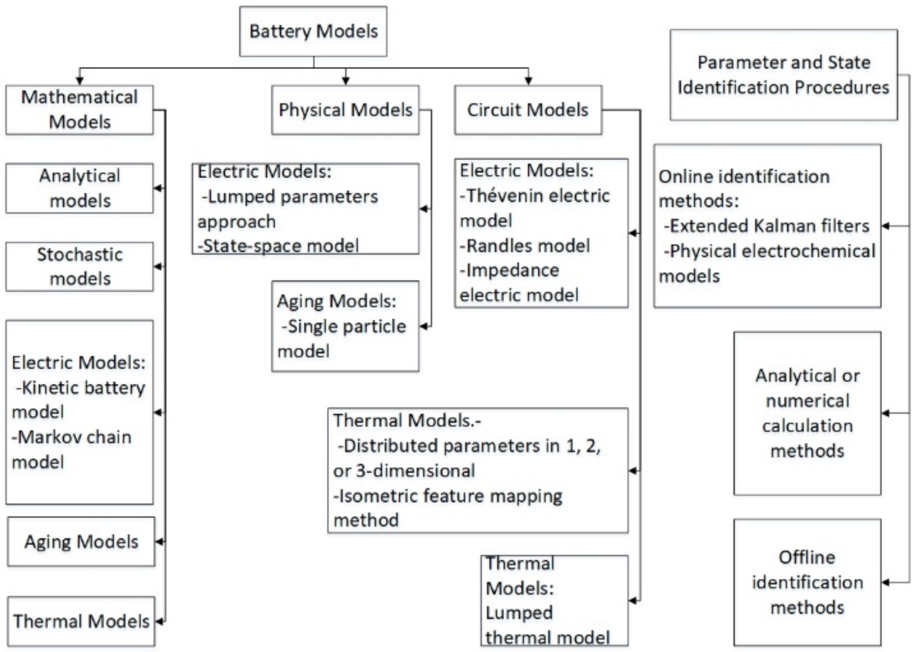
The studies conducted by Gu et al. [44], Liu et al. [45], and Cao et al. [46] focused on different aspects of battery modeling and optimization for improved performance and economic charging. Gu et al. [44] proposed a thermal-electrochemical-coupled modeling approach to predict the electrochemical and thermal behaviors of batteries. By considering heat-generation and temperature-dependent properties, their model allows for the analysis of average cell temperature and temperature distribution. The coupling of the thermal energy equation with a multiphase micro-macroscopic electrochemical model enables simultaneous analysis of both aspects. The study demonstrated the importance of thermal-electrochemical coupling, emphasizing its significance in optimizing battery design and performance under various charging conditions. Liu et al. [45] addressed technical challenges in battery economic charging for energy management by proposing a constrained multi-objective optimization framework. Their approach incorporated a coupled electrothermal-aging model for a lithium-ion battery, considering electrical, thermal, and aging characteristics. The framework included an economic indicator that considers charging costs related to battery aging and energy loss. The conflicting objectives of charging time and battery average temperature were also considered, along with hard constraints related to state of charge (SOC), charging current, terminal voltage, and temperature. The proposed approach provided a systematic and efficient way to optimize battery economic charging, taking into account economic and user-oriented objectives while respecting battery operation constraints. Cao et al. [46] addressed the challenge of accurately estimating battery degradation costs in the energy arbitrage market using a model-free deep reinforcement learning (DRL) approach. Their method combined a DRL technique with an accurate battery degradation model to optimize battery energy arbitrage. By formulating the control problem as a Markov decision process (MDP), sequential decisions in battery charging/discharging strategies were made. The proposed approach used a noisy network-based DRL technique to learn an optimized control policy, and a hybrid model with CNN and LSTM was employed to predict electricity prices for the next day. The study demonstrated the effectiveness and advantages of the proposed framework in optimizing battery energy arbitrage in the presence of uncertain electricity prices. Overall, these studies contributed valuable insights into battery modeling and optimization, addressing key challenges and providing solutions for improved battery performance and cost-effective charging strategies.

4. Thermal Modelling of Lithium-Ion Batteries

The thermal modeling of lithium-ion batteries involves considering various parameters and factors that influence their temperature behavior and performance. Some of the key parameters that are typically included in thermal models are heat capacity, density, along-plane and through-plane thermal conductivity, electric conductivity, and equivalent circuit model parameters. These parameters collectively determine how heat is generated, distributed, and dissipated within the battery during charging and discharging processes. Heat generation is a significant factor in thermal modeling, as it acts as a volumetric heat source within the battery. This heat generation can vary based on the operating conditions and the rate of charge or discharge. Temperature gradients also play a crucial role in influencing the rate of electrochemical reactions within the battery. Higher temperature gradients can lead to increased reaction rates, affecting the overall battery performance. Different regions within a lithium-ion battery may experience varying temperature gradients and current rates, especially in high-demand applications like electric vehicles that require high discharge rates. The interplay between thermal, electrochemical, and electrical processes within the battery is depicted in Figure 3a, illustrating the coupled nature of these phenomena and how they influence each other. To develop accurate lithium-ion battery models, parameter identification is crucial. Various methods, as shown in Figure 3b, are employed to determine and validate the model parameters. These methods help in understanding battery performance, optimizing battery design for specific applications, and developing efficient lithium-ion battery systems for energy applications. Overall, thermal modeling of lithium-ion batteries is a complex and critical aspect of battery research and development, enabling the study of their dynamic behavior and ensuring their suitability for various applications.



(**a**)



(**b**)

Figure 3. (**a**) Scheme for coupled thermal, electrochemical, and electrical processes interacting in a lithium-ion battery [47]; (**b**) parameter identification methods and models of lithium-ion batteries [48].

The intricate connections and interactions among thermal, electrochemical, and electrical mechanisms within a battery play a pivotal role in comprehending its overall effectiveness, safety, and efficiency. Batteries, being intricate electrochemical contrivances, transform chemical energy into electrical energy. The following parts describe the interconnections of these mechanisms:

1. Electrochemical Mechanisms: These operations encompass the movement of ions between the battery's positive and negative electrodes during charging and discharging cycles. Discharge triggers chemical reactions at both electrodes, liberating energy in the form of electrons. Charging reverses these reactions, storing energy within the battery. These electrochemical mechanisms ascertain the battery's capacity, voltage, and overall energy storage potential;
2. Electrical Mechanisms: Electrical mechanisms pertain to the electron movement through the external circuit during discharge and charging. As the battery discharges, electrons flow from the negative electrode (anode) through the external circuit to the positive electrode (cathode), energizing the connected device. During charging, electron flow is reversed, moving from cathode to anode. This electron flow engenders an electric current, forming the foundation for the battery's power delivery capability;
3. Thermal Mechanisms: Thermal mechanisms emanate from the electrochemical and electrical processes, giving rise to heat generation and dissipation within the battery. During charge and discharge cycles, resistive losses within battery components and internal resistance induce heat production. Efficient heat management impacts the battery's efficacy. Excessive heat can precipitate thermal runaway, compromising performance and safety.

The interplay among these mechanisms yields several implications:

1. Efficiency: Optimal electrochemical reactions lead to efficient charge and discharge cycles, curtailing energy losses as heat. Inefficiencies in electrochemical processes can curtail battery performance;
2. Heat Regulation: Thermal processes are pivotal for safe battery operation. Effective heat management is imperative to avert overheating and thermal runaway, which could trigger battery damage, fires, or explosions;
3. Capacity and Cycle Life: Interplay between electrochemical and electrical mechanisms influences battery capacity (charge retention) and cycle life (number of charge-discharge cycles before capacity decline). Effective electrochemical reactions and judicious electrical utilization bolster prolonged cycle life;
4. Voltage and Power Output: Electrochemical mechanisms determine battery voltage, influencing power output and compatibility with connected devices. The speed of electrochemical reactions can influence the battery's capacity to provide high power on demand.

In summation, the intricate interplay of thermal, electrochemical, and electrical processes within batteries is multifaceted and interconnected. Comprehending and optimizing these mechanisms is indispensable for designing batteries that exhibit heightened performance, safety, efficiency, and durability.

Empirical electrothermal modeling of lithium-ion batteries has made significant progress and is categorized into different approaches, as shown in Figure 4a. Developing accurate thermal models for lithium-ion batteries is crucial for their successful integration into various applications and understanding their behavior under real-world operating conditions. By integrating heat-generation and electrical models, dynamic thermal models can be created, enabling the analysis of data obtained from battery experiments. Figure 4b illustrates the classification of thermal and electrochemical modeling approaches for lithium-ion batteries. Creating thermal models that accurately represent the behavior of lithium-ion batteries is essential for research and development purposes as well as for activities related to system integration, thermal management, and designing battery packs. The development of models for both thermal and electrochemical behavior contributes to a deeper understanding of how lithium-ion batteries behave thermally under different operating conditions. One critical concern in the thermal modeling of lithium-ion batteries is the non-uniform temperature distributions within battery cells. To address this issue, various methods can be employed to achieve and demonstrate 3D thermal analysis, considering the spatial variations of temperature within the battery cell. Overall, the progress made in empirical electrothermal modeling and the classification of modeling approaches for lithium-ion batteries have enhanced our capability to study and optimize their thermal behavior in real-world applications. These advancements contribute to improving battery performance, safety, and efficiency in various practical settings, enabling researchers and engineers to design better thermal management systems and enhance the overall performance of lithium-ion batteries for diverse applications.

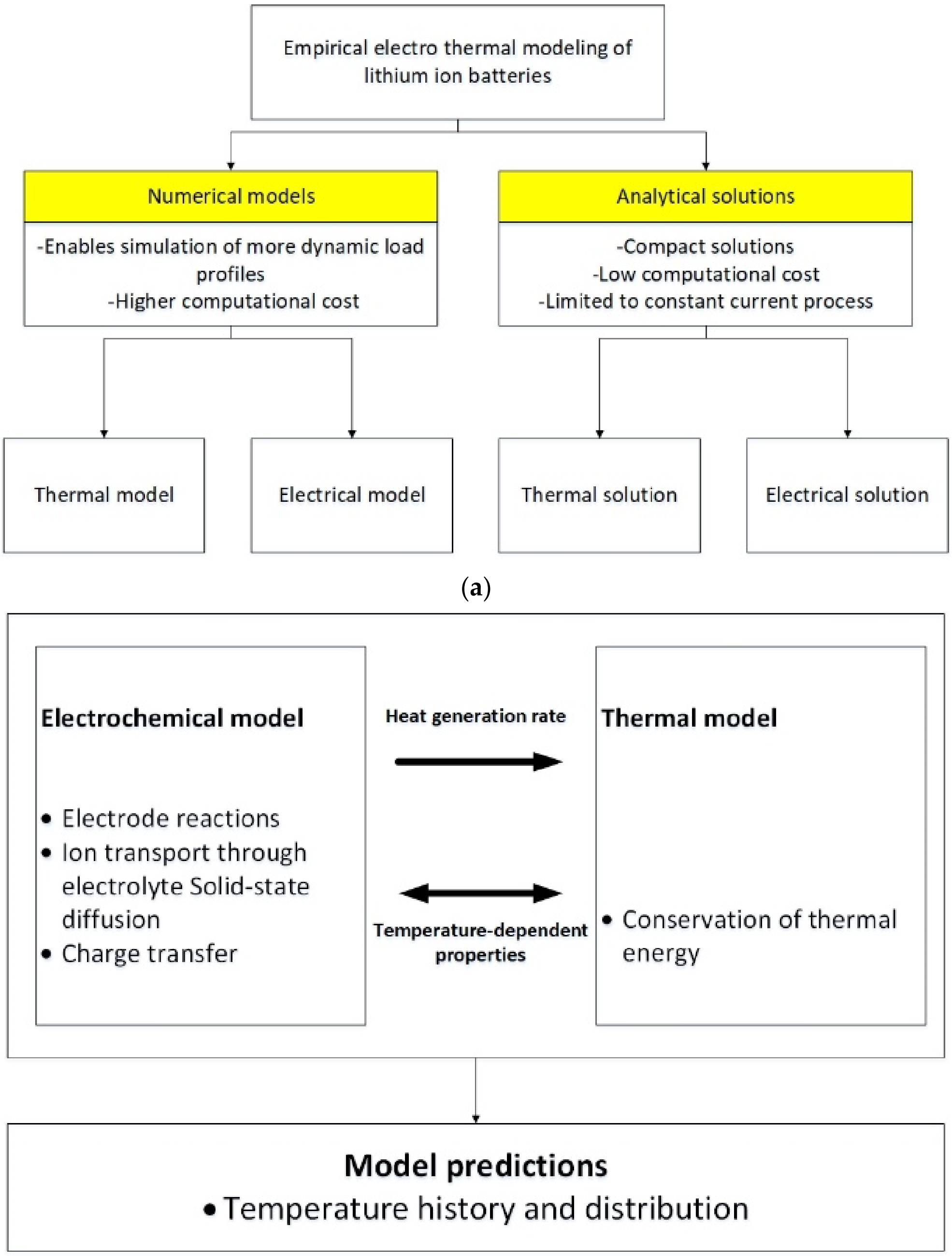


Figure 4. (**a**) Empirical electrothermal modeling of lithium-ion batteries [49]; (**b**) thermal-electrochemical modeling method [44].

Table 3 provides a comprehensive overview of the current state of thermal analysis in the context of lithium-ion batteries. The literature review encompasses various studies that focused on the thermal modeling of these batteries. Three-dimensional models were developed to match the specific configurations and geometries of the batteries under investigation. Different techniques were employed to simulate and model the thermal behavior of lithium-ion batteries, and the results from these simulations were compared to laboratory measurements. The proposed models demonstrated their capability to predict the thermal behavior of lithium-ion batteries. Notably, temperature variations were observed on the surface of the batteries, especially at higher current rates, leading to significant heat loss due to increased temperature gradients. In general, the electrical conductivity of the negative electrode was found to be higher than that of the positive electrode, resulting in lower temperatures near the current collecting tab of the positive electrode compared to the negative electrode. Several studies combined numerical simulations with experimental data from the laboratory, thus laying the foundation for future thermal investigations of lithium-ion battery cells. These integrated studies contribute to the advancement of thermal-based modeling for lithium-ion batteries, providing valuable insights into the non-uniform temperature distribution within the battery cells. By modeling and simulating heat loss and the thermal behavior of lithium-ion batteries, these studies effectively describe temperature gradients at various current rates. The investigated models successfully capture and illustrate the observable heterogeneity of temperature distribution on the surface of lithium-ion batteries at different current rates. This knowledge is vital for enhancing the thermal management and overall performance of lithium-ion batteries in various applications. Improved thermal modeling and understanding of temperature distribution will lead to better battery designs, improved safety, and increased efficiency in diverse practical settings, including electric vehicles, portable devices, and energy storage systems.

Temperature has a significant impact on the performance and operation of LIBs, and precise temperature measurement is crucial for effective battery management. Wang et al. [7] utilized artificial neural networks (ANNs) to forecast temperature fluctuations in lithium-ion batteries within a metal foam thermal management setup. The study evaluated three different ANN architectures: back propagation neural network (BP-NN), radial basis functions neural network (RBF-NN), and Elman neural networks (Elman-NN), aiming to compare their predictive capabilities. The Elman-NN model demonstrated superior adaptability, generalization, and a shorter training time, establishing it as the optimal choice for predicting temperature changes in the thermal management system, particularly when coupled with forced air cooling for lithium-ion batteries. The accuracy of the neural network thermal model was verified through separate performance tests, generating anticipated temperature data and comparison graphs for various scenarios.

The study conducted by Emre Gümüssu et al. [50] represented a significant advancement in the field of thermal analysis for lithium-ion batteries. They developed a comprehensive three-dimensional computational fluid dynamics (CFD) model to analyze the thermal behavior of lithium-ion batteries under natural convection. The model takes into account the complete flow field around the battery and conduction inside the battery, using the heat-generation model proposed by Bernardi et al. (1985). One notable feature of this model is its thermally fully predictive nature, meaning that it only requires the electrical performance parameters of the battery to calculate its temperature during discharge. This simplifies the modeling process, making it more efficient and practical for real-world applications. The researchers conducted a detailed investigation into the effects of variations in macro-scale thermo-physical properties and the entropic term of the heat-generation model. Their findings revealed that the specific heat of the battery is a critical property that significantly influences the simulation results, while the thermal conductivity has a relatively minor impact. A particularly interesting observation from their study was that the experimental data could be successfully predicted without considering the entropic term in the heat-generation calculation. This suggests that the model's accuracy in predicting battery surface temperatures is already quite high, and further improvements may not necessarily require accounting for the entropic term. The model's performance was validated by comparing the predicted battery surface temperatures with experimental data for various discharge rates and usage histories. The discrepancy between the predicted and experimental temperatures was found to be less than 3 °C, indicating a high level of accuracy and reliability in the model's predictions. Overall, the developed CFD model provides valuable insights into the factors affecting battery temperature and can be utilized to aid in the design and optimization of battery cooling systems. By ensuring safe and efficient battery operation, this research significantly contributes to the advancement of thermal management in lithium-ion batteries and facilitates the development of more reliable and efficient battery systems for various applications.

Table 3. Thermal modelling of lithium-ion batteries.

Method	Battery	Description	Reference
A thermally fully predictive three-dimensional computational fluid dynamic model	Panasonic NCR18650B type	- Investigation of entropic terms and the macro-scale thermos-physical properties was accomplished; - The lithium-ion battery's usage history and discharge rate were comprehensively investigated.	Emre Gümüssu et al. [50]
Three-dimensional thermal modelling	A lithium-ion battery	- The model was derived from multi-physics and calorimetric measurements; - The model was proposed to indicate the cooling mechanism within the lithium-ion battery pack.	Mohammad Rezwan Khan et al. [51]
A lumped thermal model	Lithium-ion battery cell ($LiFePO_4$)	- The principal thermal phenomena in the lithium-ion battery cell and the outer part of the casing were presented.	Nicolas Damay et al. [52]
Physics-based electrochemical-thermal modelling	$(Ni_{0.6}Mn_{0.2}Co_{0.2})O_2$/Carbon	- Considering the effects of lithium plating/stripping; - To explore the degradation mechanism and behaviors of NMC/carbon cells.	Xinchen Zhao et al. [53]
One-dimensional thermal-electrochemical model	A lithium-ion battery	- The model was able to reveal the effects of temperature, reaction kinetics, and diffusivity on solid electrolyte interphase layer growth and cell capacity fade.	Lin Liu et al. [54]
Three-dimensional coupled electrochemical, thermal modelling	Commercially available Li-NCA/C 18650 cells.	- Investigation of a simple temperature estimation algorithm; - Introduction of a novel lithium-ion battery pack configuration for compact liquid cooling.	Suman Basu et al. [55]
Electrochemical-thermal modelling	155 Ah $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ (NMC523)/graphite	- Investigation of a parallel technique; - Design optimal parameters for large-format lithium-ion batteries; - Determination of the effect of lithium-ion electron-transfer behavior and transport inertia.	Min Hou et al. [56]
Adaptive thermal modelling	7.5 Ah $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	- Investigation of a generic model and independent of the lithium-ion battery design and cell chemistry; - Considering the state-of-charge- and heat-generation-dependent entropy contributions.	M. Shadman Rad et al. [57]

Table 3. *Cont.*

Method	Battery	Description	Reference
Equivalent thermal model	Li/SO_2 Li/$SOCl_2$	The performance degradation of lithium-ion batteries is characterized by the loss of available energy or power	Walter van Schalkwijk et al. [58]
Thermal and electrochemical model for lithium-ion batteries aging	Lithium-ion battery	Examination of underlying aging mechanisms	Arora P et al. [59]
Thermal and electrochemical model	Lithium-ion battery	Examination of underlying aging mechanisms	Aurbach D et al. [60]
Model for lithium-ion batteries aging	Lithium-ion battery	Examination of underlying aging mechanisms	M. Broussely et al. [61]
Thermal and electrochemical model	Lithium-ion battery	Examination of underlying aging mechanisms	Vetter J et al. [62]
Thermal and electrochemical model for lithium-ion batteries aging	Lithium-ion battery	Degradation of the batteries was investigated by cycling the battery repeatedly at a constant rate while the battery is maintained at high temperatures.	Ramadass PH et al. [63]
Dynamic thermal model	Lithium-ion batteries	State-of-charge estimation at different temperatures	Ramadass PH et al. [64]
Model for lithium-ion batteries aging	18650 cell	Constant rate while the battery is maintained at high temperatures	Ehrlich GM [65]
Thermal and electrochemical model	C-$LiFePO_4$/graphite Li-ion cells	Degradation of the batteries was investigated by cycling the battery repeatedly.	Amine K et al. [66]
Thermal and electrochemical model	C/$LiCoO_2$ cylindrical	The results show that the capacity fade increased as the maximum cell voltage increased.	Takei K et al. [67]
Equivalent thermal model		- Investigation of the capacity fading characteristics of a lithium-ion battery was accomplished; - Estimation of the internal temperature of a lithium-ion battery was accomplished.	Liu Xintian et al. [68]
An electrochemical-thermal coupling model	Graphite/ $Li[Ni_{1/3}Co_{1/3}Mn_{1/3}]O_2$	- An investigation of heat transfer and capacity fade in a prismatic lithium-ion; - The battery was accomplished.	Guiwen Jiang et al. [69]
Thermal and electrochemical model for lithium-ion batteries aging	Graphite/$LiFePO_4$ battery	- Sensitivity investigation of a multi-physics model was accomplished; - Determination of the essential parameters for voltage and temperature simulation was accomplished.	C. Edouard et al. [70]
Equivalent circuit model	800 mAh Sony commercial Li-ion polymer battery	- Investigation of thermal and state-of-charge effects was accomplished.	Jamie Gomez et al. [71]
Temperature-dependent material properties model	$LiCoO_2$	- Determination of the thermal conductivity of prismatic hard-case cell was accomplished; - Determination of the overall and averaged thermal properties of the electrode stack of lithium-ion cells was accomplished; - A bottom-up method was studied.	Daniel Werner et al. [72]

Table 3. *Cont.*

Method	Battery	Description	Reference
A two-dimensional electrochemical-thermal-coupled model	$LiFePO_4$	- Investigation of the asymmetrical electrochemical and thermal distribution was accomplished; - Investigation of thermal analysis and Li+ transport characteristics in a lithium-ion battery was accomplished.	Zhoujian An et al. [73]
Electrothermal impedance spectroscopy	Cathode: $LiMO_2$ (M-metal) Anode: $Li_4Ti_5O_{12}$	- A cost-efficient approach was employed; - Thermal parameters of lithium-ion batteries were determined; - Investigation of prospects, the state of knowledge, and the measurement methodology was accomplished.	Maciej Swierczyn-ski et al. [74]
Electro-thermal-coupled model	Commercial 18650 battery: Anode: graphite Cathode:$LiNi_xCo_yAlzO_2$ (NCA)	- Determination of thermal parameters was accomplished; - A diminished wide-temperature-range method was used; - Online estimation of thermal parameters was accomplished.	Haijun Ruan et al. [75]
Inverse heat-transfer formulation	Anode, graphite, cathode: $LiNiO_2$ + $LiCoO_2$ + Li_2MnO_2	- A simultaneous approximation of thermal parameters was employed; - Big-format laminated lithium-ion batteries were used.	Jianbo Zhang et al. [76]
Physical grounding of mechanistic models	Lithium-ion battery	Diagnosis of different thermodynamic degradation modes using a machine learning approach	Mayilvahanan KS et al. [77]

The work by Mohammad Rezwan Khan et al. [51] presented a three-dimensional multi-physics-based thermal model of a battery pack, combining heat transfer (HT), and computational fluid dynamics (CFD) to analyze its cooling mechanism. The model uses experimental data to represent heat generation inside the battery cells as a lumped value. By considering time-dependent and steady-state scenarios, the model accurately captures temperature gradients across the pack's surfaces and the temperature evolution over time. This detailed spatio-temporal thermal behavior information is crucial for understanding the thermal characteristics of battery packs, optimizing their design, and ensuring efficient cooling and safe operation. Nicolas Damay et al. [52] proposed a thermal modeling approach for a large prismatic Li-ion battery and experimentally validated its accuracy. The lumped model considers various factors such as heat capacity, internal thermal resistance, and interfacial thermal resistance between the battery cell and its cooling system. The authors combined analytical calculations based on physical and geometrical properties with experimental identification to determine model parameters. The experimental measurements and model predictions were found to be in good agreement, with an accuracy of 1 °C. This validation demonstrated the model's capability to accurately represent the thermal behavior of the large prismatic Li-ion battery, making it valuable for assessing the thermal performance of similar battery systems, optimizing cooling strategies, and ensuring safe and efficient battery operation. Xinchen Zhao et al. [53] investigated the electrochemical performance of lithium-ion batteries at low temperatures, focusing on the effects during charging and discharging. The study highlighted the phenomenon of lithium stripping during discharging, which leads to decreased battery performance. To understand the degradation mechanisms, they developed a physics-based electrochemical-thermal model that considers lithium plating and stripping effects. The model accurately predicted battery degradation during cycling and revealed that lithium plating starts at the interface between the composite anode and separator, accelerated by lower temperatures and higher charging current rates. The model also accounted for various degradation effects, such as loss of recyclable lithium ions, anode active material, plated lithium growth, secondary solid electrolyte interphase (SEI), and electrolyte solvent consumption. The model's capacity estimation accuracy is about 3% for capacity fade below 30%. This research provided valuable insights into mitigating degradation and enhancing battery performance and lifespan under low-temperature conditions. Overall, these studies contributed significantly to the field of thermal modeling and analysis of lithium-ion batteries, aiding in the development of more reliable, efficient, and safe battery systems for a wide range of applications.

Lin Liu et al. [54] developed a one-dimensional thermal-electrochemical model to investigate the effects of the solid electrolyte interphase (SEI) layer's growth on the performance degradation of lithium-ion batteries. The SEI layer is known to increase internal resistance and cause capacity loss over time. The model considered diffusivity, reaction kinetics, and temperature to incorporate the growth mechanism of the SEI layer. It revealed that the growth can be either kinetics-limited or diffusion-limited, depending on the layer's thickness. Thicker layers experienced slower growth due to increased diffusion resistance. The model also showed that the SEI layer grows faster during charging than discharging due to temperature changes during cycling. Understanding the dynamics of SEI layer growth can guide monitoring strategies and help mitigate its formation and growth, leading to improved performance and lifespan of lithium-ion batteries. Suman Basu et al. [55] proposed an efficient and compact liquid coolant-based thermal management system for an 18,650 battery pack. They developed a coupled three-dimensional electrochemical thermal model to evaluate the thermal performance of the battery pack. The model considered the electrochemical processes inside the battery cells and heat-generation and -dissipation mechanisms. By simulating different operating conditions such as coolant flow rate and discharge current, the model assessed their impact on the temperature of the battery pack. Contact resistance was identified as the most influential factor affecting the thermal performance of the battery pack, emphasizing the importance of ensuring good thermal contact between the battery cells and the cooling system. Based on the numerical solution, the researchers devised a novel temperature correlation that allows predicting the temperatures of all individual cells in the pack by measuring the temperature of just one cell. Experimental validation confirmed the validity of this correlation. The use of such temperature correlations can reduce complexity and sensor requirements in large Li-ion battery packs, especially in electric vehicles. By accurately predicting temperatures with a single measurement, the overall system becomes more cost-effective and simpler to implement. This study significantly contributed to the development of efficient and economical thermal management systems for Li-ion battery packs, enhancing their performance, safety, and overall usability in various applications, including electric vehicles.

Min Hou et al. [56] developed an electrochemical-thermal model specifically tailored for large-format lithium-ion batteries (LIBs) considering their non-homogeneous microstructure caused by materials and fabrication processes. They used a simplified parallel method and combined the Maxwell–Cattaneo–Vernotte theory with Marcus–Hus–Chidsey kinetics to analyze lithium-ion transport and electron transfer within 3D electrodes. To validate the model, temperature distribution measurements were conducted on a 155 Ah prismatic-type Li-ion battery during charge and discharge processes at various current densities using built-in temperature sensors. The simulation results demonstrated that the developed model had a maximum error of only 1.7 °C at 1.0 C discharge and 3.9 °C at 2.0 C discharge, indicating its effectiveness in accurately predicting temperature changes. The study revealed that the hottest region inside the battery was near the positive connector, emphasizing the importance of considering temperature gradients in the design of large-format LIBs. Additionally, the research identified that the internal currents of these large-format batteries were unstable during constant current discharge, with some areas experiencing local internal currents up to 6.0 C and even negative currents. This observation suggests a significant change in the local redox direction within the battery, which can be attributed to the nonuniform distribution of reactant concentration and temperature. In conclusion, the researchers highlighted that their approach provides a valuable tool for the LIB industry, offering fast and accurate diagnosis and facilitating the design of optimal parameters for large-format LIB batteries. By accounting for the non-homogeneous microstructure and considering complex electrochemical and thermal behaviors, this model contributes to enhancing the performance, safety, and overall efficiency of large-format LIBs. Such advances are crucial for the further development and widespread adoption of large-format lithium-ion batteries in various applications.

M. Shadman Rad et al. [57] focused on developing a highly accurate thermal model for rechargeable batteries, particularly in high-power applications like electric vehicles, where detailed information about battery materials and cell design is often unavailable. Their model considered temperature- and current-dependent overpotential heat-generation and state-of-charge-dependent entropy contributions to accurately predict the thermal behavior of Li-ion batteries under various operating conditions. To validate the model, the researchers conducted experimental investigations on high-power rechargeable Li-ion batteries with a capacity of 7.5 Ah. The experimental results were used to verify the accuracy of the model, which demonstrated that the state-of-charge-dependent entropy is a significant heat source and plays a crucial role in accurately predicting the thermal behavior of Li-ion batteries. To enhance the accuracy of their model, the researchers introduced an adaptive approach to determine the entropy values and incorporated a temperature-dependent equation for heat transfer to the environment. The simulations based on this model and the experimental measurements showed good agreement in all cases. The parameters obtained from the heat-generation and heat-transfer processes can be applied in the thermal design of advanced battery packs, making this methodology highly practical for real-world applications. Additionally, the proposed approach is applicable to different cell chemistries and battery designs, making it a generic and versatile solution. By conducting simple measurements of cell potential, current, and temperature during a limited number of charge/discharge cycles, the parameters for the adaptive model can be determined. Overall, this research provided a valuable and robust thermal modeling approach for rechargeable batteries, particularly in high-power applications like electric vehicles, where accurate thermal management is crucial for achieving optimal battery performance and safety. This advancement contributes to the development of more efficient and reliable battery systems for various applications, including electric vehicles.

Arora P et al. [59] conducted a study focusing on the capacity loss or fade observed in lithium-ion batteries during cycling. This reduction in capacity is caused by various mechanisms, primarily related to unwanted side reactions occurring during overcharge or over-discharge. These reactions lead to electrolyte decomposition, passive film formation, active material dissolution, and other related phenomena. However, the existing mathematical models for lithium-ion batteries found in the literature do not account for these capacity-loss mechanisms, which makes them inadequate for accurately predicting battery performance during cycling and under abuse conditions. To address this limitation, the article emphasizes the importance of including these capacity-loss mechanisms in advanced lithium-ion battery models. The researchers conducted a comprehensive review of the current literature on capacity-fade mechanisms to gain insights into the factors contributing to capacity loss in lithium-ion batteries. They highlighted the need for additional information and data to enhance these models and make them more accurate in predicting battery behavior. By incorporating these capacity-loss mechanisms into the models, researchers can gain a deeper understanding of battery performance during cycling and improve their ability to predict battery behavior under various conditions. This research is essential for advancing the development of more accurate and reliable models for lithium-ion batteries, enabling better battery design and management strategies to mitigate capacity fade and prolong battery life. Overall, the study contributed to the ongoing efforts to enhance the understanding of capacity-fade mechanisms in lithium-ion batteries and provided valuable insights for the development of more comprehensive and accurate battery models. By considering these mechanisms, researchers can work towards improving battery performance, extending battery lifespan, and optimizing battery management strategies for various applications.

The comprehensive review by Aurbach et al. [60] focused on the interactions between cathode materials and electrolyte solutions in lithium-ion batteries. The study examined various cathode materials and used multiple techniques, such as spectroscopy and electron microscopy, along with electrochemical methods to investigate these interactions. One significant observation from the study was the potential dissolution of transition metal ions from cathode materials, leading to changes in active mass and hindered electrode kinetics due to surface film formation. The stability of cathode materials is influenced by factors such as temperature and the presence of acidic species, particularly in water-contaminated $LiPF_6$ solutions. Certain cathode materials, such as $LiMn_{1.5}Ni_{0.5}O_4$ and $LiMn_{0.5}Ni_{0.5}O_2$, demonstrated high stability in common electrolyte solutions due to their unique surface chemistry with Ni ions in the lattice. Understanding these interactions is vital for enhancing lithium-ion battery design and performance, leading to more reliable and efficient energy storage systems. M. Broussely et al. [61] discussed aging mechanisms in Li-ion batteries during rest or cycling based on long-term storage or cycling data. The stability of the solid electrolyte interface (SEI) at the negative electrode/electrolyte interface was highlighted as crucial for cell performance. Proper material selection and additives can ensure SEI stability, preventing the excessive growth that leads to capacity loss and reduced power capability. Vinylen carbonate was highlighted as an effective additive. At elevated temperatures and high state of charge (SOC), side reactions occur at the positive electrode interface, causing an increase in cell impedance and potential gas evolution. Careful battery system design with appropriate materials and electrolytes can extend the service life of Li-ion batteries. Vetter J et al. [62] conducted a comprehensive review and evaluation of aging mechanisms in lithium-ion batteries, likely covering capacity fade, calendar aging, and performance degradation over time. The study explored factors such as active material chemistry, electrolyte decomposition, and passivation layer formation on electrodes. By shedding light on the challenges faced by lithium-ion batteries during their operational lifespan, this research aimed to develop strategies for enhancing battery performance and extending their lifetime. The findings from this study are crucial for advancing practical applications, particularly in electric vehicles and stationary energy storage systems, as we transition to cleaner and more sustainable energy sources.

The study conducted by Ramadass PH et al. [63,64] focused on capacity fade in Sony 18650 Li-ion cells and its relationship with temperature. The researchers cycled the cells at different temperatures and observed varying degrees of capacity loss over cycles. Cells cycled at higher temperatures experienced significantly higher capacity fade, with the cell at 55 °C suffering a 70% decrease after 490 cycles. Impedance measurements revealed an overall increase in cell resistance with more cycling and higher temperatures. The researchers attributed the increased capacity fade at higher temperatures to repeated film formation on the anode's surface, leading to accelerated lithium loss and an increase in negative electrode resistance with each cycle. This study highlighted the critical role of temperature in capacity fade and underscored the importance of understanding the thermal behavior of lithium-ion batteries to optimize their performance and extend their lifespan. Amine K et al. [66] investigated the storage and cycling performance of prismatic Li-ion cells with specific electrode materials and electrolytes at high temperatures. They observed capacity loss and increased impedance during high-temperature cycling. The study revealed that the use of a specific electrolyte salt ($LiB(C_2O_4)_2$) significantly improved cycling stability, mitigating capacity fade and interfacial film formation. Understanding the effects of electrode materials and electrolyte compositions on battery performance at high temperatures is crucial for developing more reliable and efficient lithium-ion batteries. Takei K et al. [67] developed testing methods for estimating the lifespan of lithium-ion batteries over a short period. They focused on a commercially available cell with a $LiCoO_2$/hard carbon cell system. The researchers found that degradation reactions in the battery occurred primarily above 4 V, leading them to divide the operating voltage range for testing purposes. Accelerated aging tests involving stress factors such as high charge and discharge rates and high-temperature thermal stress were conducted to investigate the effects on battery performance. These accelerated aging tests provided significant acceleration coefficients, especially with high charge rates and high-temperature stress. Understanding the degradation mechanisms and how different stress factors influence battery performance can aid in the development of more robust and reliable lithium-ion batteries for various applications. The findings from this study contributed to improving battery testing and design to enhance the overall reliability and efficiency of lithium-ion batteries.

The study by Liu Xintian et al. [68] introduced the ETM–Arrhenius model, which estimates the internal temperature of a Li-ion battery by observing the surface and ambient temperatures. This model allows precise predictions of capacity-fading patterns over the battery's lifespan by establishing a correlation between battery capacity fading and internal temperature. The researchers conducted a lifecycle test on a Li-ion battery under various temperatures and demonstrated the accurate predictive abilities of the ETM–Arrhenius model. Integrating this model into state-of-charge (SOC)-estimation algorithms like EFK and UKF significantly enhances the accuracy of SOC estimation. Guiwen Jiang et al. [69] addressed the problem of uneven heat distribution in large-format Li-ion batteries, which can cause degradation and negatively affect the battery's electrochemical reactions. They developed a one-dimensional (1D) electrochemical-three-dimensional (3D) thermal coupling model to study heat transfer in a prismatic Li-ion battery when cooling different external surfaces. The study highlighted that cooling the small side surfaces of the prismatic battery leads to a more even temperature distribution compared to cooling the larger front surfaces. The researchers also investigated the impact of operating temperature on capacity fade during cycling and found that higher operating temperatures accelerate parasitic lithium/solvent-reduction reactions, leading to a higher rate of capacity fade. C. Edouard et al. [70] developed a simplified model that effectively combines electrochemical and thermal aspects to provide accurate predictions of the physicochemical and aging behavior of Li-ion batteries. They conducted a sensitivity analysis on all the physical parameters within the model to understand their influence on the model's output and identified specific conditions where certain parameters had the most significant impact. The researchers implemented a step-wise identification method to minimize the influence of parameter values during their identification, resulting in improved alignment of the simulated cell voltage with experimental data. Jamie Gomez et al. [71] introduced an equivalent circuit model (EMC) for a high-power Li-ion battery that takes into account the influence of both temperature and state of charge (SOC) on battery performance. The EMC was constructed using a non-linear least-squares fitting procedure involving thirteen parameters to analyze the Li-ion cell. The developed model provided correlations for the observed impedance behavior concerning temperature and SOC effects, making it suitable for process control algorithms and demonstrating a strong statistical agreement between the correlation model and the actual experimental values.

The study by Daniel Werner et al. [72] presented a bottom-up approach to calculating the thermal properties of the jelly roll or electrode stack within Li-ion cells, specifically applied to a prismatic hard-case cell. The model takes into consideration temperature-dependent material properties and various geometric properties to determine anisotropic unit cell properties for homogenized three-dimensional thermal models. The researchers also proposed a non-destructive measurement technique for assessing the thermal conductivity of prismatic hard-case cell geometries, which serves as a validation method for the proposed model. Zhoujian An et al. [73] developed a 3D electrochemical-thermal-coupled model for a 30 Ah ternary cathode LIB to analyze the internal electrochemical processes and thermal characteristics that affect the performance of large-size lithium-ion batteries. The model combines a 3D layered electrochemical model with a 3D thermal model and was validated against experimental data. The researchers investigated the internal electrochemical processes and thermal characteristics at different discharge rates and ambient temperatures. They found that high discharge rates and low temperatures lead to reduced discharge capacity and voltage due to increased polarization and transport resistance. The 3D layered model also revealed the distribution of current density and total heat-generation rate within the unit cell, showing that the proportion of heat generation in different components changes with the discharge rate. The study further explored the influence of battery thickness and heat-transfer coefficient, showing that thicker batteries and larger heat-transfer coefficients lead to higher temperature gradients and heat inhomogeneities during the electrochemical processes. The findings provided valuable insights for optimizing electrode and structural designs, improving battery thermal management systems, and enhancing battery safety.

The development of accurate thermal models and effective thermal management systems for lithium-ion batteries is essential to ensure their performance, safety, and longevity. Researchers have made significant advancements in estimating key thermal parameters using novel in situ experimental techniques. Haijun Ruan et al. [75] developed an online estimation method that directly estimates thermal parameters through carefully designed experiments. Instead of relying on values from the literature or empirical sources, this approach provides accurate predictions of heat generation using a reduced electro-thermal-coupled model. The researchers proposed a combined experimental/computational approach to simultaneously estimate the specific heat capacity and thermal resistance. This method significantly reduces the identification time and exhibits good robustness under different temperatures, cooling conditions, and battery chemistries. It offers a promising way to accurately model battery thermal behavior, evaluate thermal safety in real time, and design advanced thermal management systems for electric vehicles. Jianbo Zhang et al. [76] introduced a method for in situ determination of multiple thermal parameters in large-format laminated lithium-ion batteries. The approach involves heating one battery surface and measuring temperature responses at multiple locations on the opposite surface. The thermal system is modeled using a two-dimensional axially symmetric thermal conduction equation, considering various thermal parameters such as thermal capacity and anisotropic thermal conductivities. Optimization techniques are employed to adjust the thermal parameters until the simulated temperature responses match the experimental data. The proposed method's validation showed good agreement with measured specific heat capacity, making it suitable for accurately estimating thermal parameters in various objects with anisotropic internal materials and outer packaging made of different materials. This method contributes to providing accurate inputs for battery thermal models and enhancing thermal management strategies. Overall, these innovative in situ experimental techniques for estimating thermal parameters provide valuable tools for developing accurate thermal models and optimizing thermal management systems for lithium-ion batteries, contributing to their overall performance, safety, and reliability.

The research conducted by Mayilvahanan KS et al. [77] represented a novel approach that combines the strengths of mechanistic models and machine learning techniques to gain a deeper understanding of degradation in Li-ion batteries and predict their lifetime. Mechanistic models provide valuable insights into the physical processes involved in battery degradation, allowing researchers to understand the underlying mechanisms that lead to capacity fade and reduced performance over time. On the other hand, machine learning models offer powerful data-driven analysis, enabling state estimation and lifetime prediction based on large datasets. In this study, the researchers utilized published synthetic low-rate-charge curves generated by a mechanistic model to analyze different thermodynamic degradation modes in three common types of Li-ion battery cells: LFP, NMC, and NCA. They then developed a step-by-step procedure to create interpretable machine learning models. This involved dataset splitting, featurization (extracting relevant features from the data), and model fitting for both regression and classification tasks. To accurately estimate degradation modes, the authors used random forest regressors trained on features extracted from incremental capacity analysis of the low-rate-charge curves. The resulting machine learning models achieved a root mean squared error of 5%, indicating their effectiveness in degradation estimation. Additionally, the research focused on feature importance analysis, which provided insights into the key factors driving battery degradation. By understanding which features have the most significant impact on degradation, researchers can gain valuable insights into the underlying processes and develop strategies to mitigate degradation and improve battery performance. The results obtained from the machine learning models were compared with expert-defined features to validate their findings. This comparison further confirmed the accuracy and usefulness of the approach. Overall, by combining the physical grounding of mechanistic models with the data-driven capabilities of machine learning, this research offered a comprehensive and powerful approach to understanding and predicting degradation in Li-ion batteries. The proposed methodology not only provides valuable insights into feature importance but also contributes to the development of interpretable machine learning models for degradation analysis in battery systems. These findings have significant implications for optimizing battery design, predicting battery lifetime, and enhancing the performance and reliability of Li-ion batteries in various applications.

5. Importance of Charge Equalization to the Performance Characteristics of Lithium-Ion Batteries in Automotive Applications and to Battery Safety and Lifespan

The importance of charge equalization for the performance characteristics of lithium-ion batteries in automotive applications and for battery safety and lifespan cannot be overstated. Charge equalization, also known as cell balancing, is a critical aspect of managing lithium-ion batteries in electric vehicles (EVs) and plays a vital role in enhancing battery efficiency, safety, and overall durability. The following points outline the significance of cell equalization in these aspects:

1. Enhancing Battery Efficiency: In electric vehicle battery packs, multiple individual cells are connected in series and parallel configurations. However, due to manufacturing variations, different cell capacities, temperature fluctuations, and usage patterns, cells may experience varying charging and discharging rates. This imbalance in the state of charge (SoC) among cells can lead to a decrease in the overall pack capacity and energy utilization. Cell equalization addresses this issue by ensuring that all cells reach a similar SoC, optimizing the usable capacity of the battery pack and maintaining consistent performance;
2. Ensuring Battery Safety: Safety is of utmost importance in battery design. Imbalanced cells can lead to overcharging or over-discharging of certain cells, resulting in reduced safety margins, thermal runaway, and potentially hazardous events such as cell venting, fires, or explosions. Cell equalization prevents overcharging by capping the SoC of fully charged cells while increasing the SoC of cells with lower levels. This approach minimizes the risk of cell damage and thermal runaway, thereby enhancing the overall safety of the battery;
3. Prolonging Battery Lifespan: Cell equalization significantly contributes to extending the longevity of lithium-ion batteries in automotive settings. Cells experiencing continuous overcharging or over-discharging due to imbalance can deteriorate more rapidly, leading to capacity loss and reduced cycle life. By maintaining uniform SoC levels across all cells, cell equalization ensures that cells experience comparable stress levels during charge and discharge cycles. This even distribution of stress helps mitigate premature aging, allowing the battery pack to retain its capacity and energy storage capabilities over an extended period;
4. Optimizing Energy Efficiency: Balanced cells contribute to improved energy efficiency as they operate at similar voltage levels during both charging and discharging. This uniform voltage operation ensures that energy is utilized efficiently and consistently throughout the entire battery pack, thereby optimizing the overall energy output of the system.

In conclusion, cell equalization is pivotal in optimizing the efficiency, safety, and lifespan of lithium-ion batteries used in automotive applications. By maintaining consistent SoC levels among individual cells, cell equalization enhances overall battery efficiency, prevents hazardous conditions, and mitigates premature deterioration. This technology stands as a fundamental element within advanced battery management systems in electric vehicles, playing a crucial role in ensuring the reliable and sustainable operation of EVs over the long term.

6. The Evaluation, Potential, and Future Prospects of Experimental Methods, Numerical Analysis, and Thermal Modeling of Lithium-Ion Batteries

The evaluation, potential, and future prospects of experimental methods, numerical analysis, and thermal modeling of lithium-ion batteries play a vital role in advancing battery technology and enhancing the performance, safety, and durability of these energy storage devices. The following points delve into each of these components:

1. Experimental Techniques: Experimental methods involve conducting physical tests and measurements on lithium-ion batteries to comprehend their behavior, performance, and limitations. These methods encompass the following:
    - Cycling Experiments: Subjecting batteries to charge and discharge cycles to evaluate capacity decline and performance deterioration over time;
    - Electrochemical Investigation: Exploring battery electrochemistry using methods like cyclic voltammetry and impedance spectroscopy to analyze kinetics, charge-transfer, and degradation mechanisms;
    - Aging Studies: Performing accelerated aging tests to simulate extended battery usage and uncover degradation mechanisms;
    - Material Analysis: Examining battery materials at the microscopic and nanoscale to grasp their structure, composition, and interactions;
    - Thermal Assessment: Monitoring temperature fluctuations during battery operation to assess strategies for thermal management.
2. Numerical Analysis: Numerical analysis entails utilizing computational models and simulations to predict battery behavior and performance. This approach provides insights into intricate processes that are challenging to observe experimentally:
    - Electrochemical Modeling: Simulating electrochemical reactions, ion transport, and diffusion within battery electrodes and electrolytes;
    - Thermal Simulations: Forecasting temperature distributions and thermal behavior to optimize battery cooling and heating strategies;
    - Multi-Physics Simulations: Integrating electrochemical, thermal, and mechanical models to capture interactions between different aspects of battery operation.
3. Thermal Modeling: Thermal modeling specifically concentrates on comprehending and controlling the heat generated during battery operation. Excessive heat can pose safety hazards and degrade battery performance. Key aspects encompass the following:
    - Heat Generation: Modeling the heat produced during charging, discharging, and internal chemical reactions;
    - Prediction of Thermal Runaway: Developing models to anticipate conditions that might lead to thermal runaway, a hazardous and self-propagating overheating phenomenon;
    - Thermal Management Approaches: Designing effective cooling and heating systems to maintain optimal operating temperatures and mitigate thermal risks;
    - Electrothermal Linkage: Integrating thermal and electrochemical models to consider the interplay between temperature and electrochemical behavior.
4. Potential and Future Outlook: The potential impact and future prospects of these approaches are substantial:
    - Improved Battery Performance: A deeper understanding of battery behavior through experimental and numerical analysis can result in enhanced battery designs and improved performance;

- Prolonged Battery Lifespan: Identifying degradation mechanisms and formulating mitigation strategies can extend battery longevity and reduce the need for frequent replacements;
- Enhanced Safety of Battery Designs: Accurate thermal modeling and management can avert overheating, diminish safety hazards, and aid in designing safer battery systems;
- Optimal Energy Storage: Advanced modeling and analysis can contribute to optimizing energy storage systems for diverse applications, ranging from electric vehicles to integrating renewable energy;
- Innovative Materials: Insights derived from these methods can propel the development of novel materials and technologies for next-generation lithium-ion batteries and potentially even beyond Li-ion technologies.

In the future, these approaches are likely to undergo further refinement and integration, potentially leading to more efficient, safer, and longer-lasting lithium-ion batteries. Additionally, emerging technologies like solid-state batteries and advanced manufacturing techniques may also leverage these evaluation methods and modeling techniques to expedite their development and commercialization. The continuous progress and convergence of experimental and computational methods will undoubtedly drive significant advancements in the field of lithium-ion battery technology, paving the way for a more sustainable and electrified future.

7. The Contribution of Thermal Behavior Modeling of Lithium-Ion Batteries

The modeling of thermal behavior in lithium-ion batteries has made significant contributions across various fields, including battery technology, electric vehicles, renewable energy systems, and consumer electronics. By creating mathematical and computational models to understand the impact of temperature on battery functionality, safety, and lifespan, thermal behavior modeling has led to several notable achievements:

1. Improving Battery Safety: Precise modeling of battery thermal behavior enables the development of effective cooling systems, thermal management strategies, and safety mechanisms to prevent and mitigate thermal runaway incidents, ensuring safer battery operation;
2. Enhancing Battery Design: Thermal modeling allows for optimizing electrode materials, cell geometries, and packaging, ensuring efficient heat dissipation and uniform temperature distribution within battery cells. This optimization results in improved battery efficiency and extended lifespan;
3. Forecasting Battery Performance: Temperature significantly influences battery capacity, power output, and efficiency. Thermal models help researchers predict how temperature variations affect battery performance, guiding battery design and operation under different conditions;
4. Development of Battery Management Systems (BMS): Accurate thermal modeling is crucial for advanced battery management systems, which regulate parameters like temperature to ensure secure and optimal battery operation, leading to improved battery performance and safety;
5. Integration in Electric Vehicles (EVs): Efficient thermal management is essential for optimal battery performance, range, and longevity in EVs. Thermal modeling aids in designing thermal systems that cool or heat battery packs as needed, enhancing overall EV performance and safety;
6. Integration with Renewable Energy: Thermal modeling helps design energy storage systems that can withstand temperature fluctuations, ensuring high efficiency and stability when integrating renewable energy sources like solar and wind;
7. Consumer Electronics and Wearable Devices: Thermal modeling contributes to the creation of consumer electronics with enhanced battery life and safety. It manages heat generation during resource-intensive tasks, preventing overheating and improving user experience;

8. Accelerating Research and Development: Thermal models provide insights into complex thermal phenomena within battery cells, allowing researchers to explore various scenarios and design modifications virtually, reducing costs and expediting innovation.

In conclusion, the contribution of thermal behavior modeling in lithium-ion batteries is significant in advancing battery technology and energy storage systems across various industries. It elevates safety, performance, and overall efficiency, ensuring the continued progress and integration of lithium-ion batteries in diverse applications.

8. Algorithm Design of the Thermal Models of Lithium-Ion Batteries

Developing thermal models for lithium-ion batteries involves creating mathematical or computational representations of the battery's thermal performance in different operating conditions. Here is an overview of the algorithm design for crafting thermal models for lithium-ion batteries:

1. Data Collection and Characterization: Gather relevant data about the battery's thermal properties, including specific heat capacity, thermal conductivity, and heat-generation rates at various charging and discharging rates. These data can be obtained from experiments or the existing literature;
2. Thermal Equivalent Circuit Model: Create a thermal-equivalent circuit model that reflects the pathways of heat flow within the battery. Divide the battery into thermal resistors and capacitors, representing the different thermal behaviors of components like the core, electrodes, and casing;
3. Formulation of Differential Equations: Develop a set of interconnected ordinary differential equations (ODEs) that describe the heat-transfer dynamics within the battery. These equations should account for heat generation from electrochemical reactions, heat conduction through different components, and convective heat transfer;
4. Establishment of Boundary Conditions: Specify appropriate boundary conditions for the model, including external temperature, convective heat-transfer coefficients, and initial temperature distribution;
5. Numerical Solution: Implement numerical techniques to solve the ODEs. Methods such as finite differences, finite elements, or other suitable approaches can discretize and solve the equations over time and space;
6. Parameter Estimation: Identify model parameters by aligning the simulated temperature responses with experimental data. Techniques like least-squares optimization can help find the most fitting parameters;
7. Validation and Calibration: Validate the thermal model by comparing its predictions with independent experimental data. Adjust the model's parameters as needed to improve accuracy;
8. Accounting for Operating Conditions and Scenarios: Extend the model to cover various operating conditions, such as different charging and discharging rates, ambient temperatures, and cooling strategies (e.g., active or passive cooling);
9. Sensitivity Analysis: Conduct sensitivity analysis to identify the most impactful model parameters on the battery's thermal behavior. This insight helps prioritize accurate parameter determination;
10. Integration with Battery Management System (BMS): Integrate the thermal model with the battery management system to enable real-time temperature prediction and control. The BMS can use the model's forecasts to adapt charging and discharging rates, preventing overheating and thermal degradation;
11. Balancing Model Complexity and Accuracy: Strike a balance between model intricacy and precision based on the application and available computational resources. A more detailed model may offer better accuracy but require greater computational power;
12. Continuous Enhancement: Continuously refine and enhance the thermal model as additional experimental data become available, or new insights into the battery's behavior emerge.

Creating an accurate thermal model for lithium-ion batteries can be a complex and iterative process. Collaboration with experts in battery chemistry, materials science, and thermal engineering is essential to ensure the model's reliability and practicality in real-world scenarios.

9. Conclusions and Discussion

The current research focus on lithium-ion batteries goes beyond increasing energy density and also includes enhancing power density to meet the rising power demands of emerging applications. As lithium-ion batteries are now capable of handling higher charging and discharging power, ensuring their safety and implementing effective thermal management for the entire battery system has become crucial. Temperature significantly impacts the short-term and long-term performance of lithium-ion batteries. Thermal modeling of battery cells and packs has gained importance in addressing these challenges. Equivalent thermal circuit models have been widely adopted due to their relatively accurate results and low computational burden, but parameterizing these models can be expensive.

The comprehensive review of experimental and simulation-based thermal characterization and analysis of lithium-ion batteries (LIBs) presented in this study highlights the critical importance of understanding the heat effects in these electrochemical systems. As the demand for high-performance LIBs continues to grow across various applications, from portable electronics to electric vehicles and renewable energy storage, it becomes essential to quantitatively comprehend the thermal behavior of these batteries. Accurate thermal modeling and effective thermal management are crucial for optimizing battery performance, enhancing safety, and extending the overall lifespan of LIBs. The review underscores that temperature is a key factor affecting the performance and safety of lithium-ion batteries. Both low and high temperatures have detrimental effects on battery operation. At low temperatures, the ionic conductivity is reduced, leading to higher charge-transfer resistance and decreased battery capacity. Furthermore, cold temperatures can induce lithium plating on the anode, causing irreversible capacity loss and potential safety hazards. On the other hand, high temperatures accelerate aging processes within the battery, degrading the electrochemical components and shortening the battery's lifespan. Maintaining the operating temperature within the optimal range is, therefore, paramount for achieving the best performance and safety of lithium-ion batteries. This can be achieved through effective thermal management strategies, which involve the use of cooling systems, thermal interface materials, and temperature regulation algorithms. By maintaining a uniform temperature distribution across the battery pack, thermal management techniques can mitigate temperature fluctuations among individual cells, enabling more efficient electrical balancing schemes and extending the overall battery life. Furthermore, thermal management strategies play a crucial role in preventing thermal runaway events, which are potentially catastrophic for large-scale battery systems. Thermal runaway occurs when a localized temperature increase triggers exothermic reactions within the battery, leading to further heat generation and an uncontrollable chain reaction. Effective thermal management, along with advanced safety features and protective devices, can prevent thermal runaway and enhance the overall safety of lithium-ion batteries. While existing thermal modeling approaches have shown promise, there is still room for improvement, especially in predicting battery behavior under various operating conditions. Comprehensive, fully coupled electrochemical-thermal models offer valuable insights into the intricate interplay between electrochemical reactions and heat generation in lithium-ion batteries. However, parameterizing these models can be challenging due to the complexity and scarcity of detailed experimental data. As such, researchers are exploring novel experimental techniques, such as electrothermal impedance spectroscopy and in situ determination of thermal parameters, to provide more accurate inputs for thermal modeling. In conclusion, the comprehensive understanding of the thermal behavior of lithium-ion batteries is vital for optimizing their performance, enhancing safety, and extending their lifespan in various applications. By integrating experimental and simulation-based approaches, along with advanced thermal management techniques, researchers and engineers can unlock the full potential of lithium-ion batteries and accelerate their widespread adoption in the transition towards a more sustainable and electrified future. Continued research in thermal modeling, advanced thermal management systems, and safety features will be instrumental in shaping the next generation of high-performance and reliable lithium-ion batteries.

The review highlights the significance of thermal management strategies in mitigating performance degradation and safety risks related to temperature in lithium-ion batteries. Various thermal models, such as the electrochemical-thermal-coupled model and equivalent thermal circuit models, have been proposed and developed to accurately predict temperature changes and heat generation within batteries. These models offer valuable insights into internal electrochemical processes and thermal characteristics, contributing to battery optimization and safe operation. Furthermore, this article discusses the importance of integrating mechanistic models with machine learning techniques for understanding degradation in lithium-ion batteries and predicting their lifetime. The combination of physical grounding with data-driven analysis allows researchers to gain a deeper understanding of degradation modes and key factors influencing battery performance. In situ determination and estimation of thermal parameters are also explored as novel methodologies, enabling real-time evaluation and precise inputs for thermal models. Additionally, the application of electrothermal impedance spectroscopy for non-destructive thermal characterization is highlighted as a promising method for battery thermal analysis. The review underscores the need to stay informed about the latest advancements in thermal modeling and management for lithium-ion batteries. It advocates for prioritizing safety, performance, and sustainability in battery technologies; supporting policy initiatives; and exploring alternative energy storage solutions. Diversifying investment portfolios and collaborating with research institutions are seen as essential steps to foster innovation and accelerate the transition to cleaner energy sources. By adhering to these recommendations, stakeholders can make informed decisions and actively contribute to the growth and optimization of lithium-ion battery technologies. Ultimately, this approach can lead to safer, more efficient, and environmentally friendly energy storage solutions.

For the audience and stakeholders interested in lithium-ion batteries and their applications, here are some key recommendations:

1. Stay Informed: Given the rapid advancements in lithium-ion battery technology and its widespread applications, it is essential for the audience and stakeholders to stay informed about the latest research, developments, and market trends. Regularly following reputable scientific journals, industry reports, and updates from leading battery manufacturers will provide valuable insights into the state of the technology and potential opportunities;
2. Emphasize Safety and Performance: As lithium-ion batteries are increasingly used in critical applications such as electric vehicles and grid storage systems, safety and performance should be top priorities. Stakeholders should prioritize investing in and supporting technologies and companies that prioritize safety features, thermal management systems, and continuous improvements in battery performance and reliability;
3. Explore Sustainable Alternatives: While lithium-ion batteries have shown remarkable progress, exploring sustainable alternatives and complementary technologies is crucial for a well-rounded energy storage ecosystem. Stakeholders should consider investing in research and development of other energy storage technologies, such as solid-state batteries, flow batteries, and emerging post-lithium technologies, to diversify their investment portfolios and address specific use cases;
4. Support Policy and Regulatory Initiatives: Policy and regulatory decisions play a significant role in shaping the future of energy storage technologies. Stakeholders should engage with policymakers to advocate for favorable policies, incentives, and standards that encourage the adoption of safe and sustainable battery technologies;
5. Collaborate with Research Institutions: Engaging with universities, research institutions, and battery experts can provide valuable insights and potential collaboration

opportunities for stakeholders. Supporting research and development initiatives can accelerate the pace of innovation and lead to breakthroughs in battery technology;

6. Monitor Market Trends: Understanding market trends and demands is crucial for investors and stakeholders. Stay informed about the evolving needs of industries such as electric vehicles, renewable energy, and portable electronics to identify potential investment opportunities and business partnerships;
7. Consider Environmental and Social Impact: ESG (environmental, social, and governance) factors are increasingly becoming a focus for investors and stakeholders. Companies that prioritize sustainable practices, recycling and end-of-life management, and fair labor practices should be given preference;
8. Invest in Energy Storage Infrastructure: Supporting the development and deployment of energy storage infrastructure, such as charging stations for electric vehicles and grid-scale storage facilities, will play a vital role in promoting the adoption of lithium-ion batteries and facilitating the transition to cleaner energy sources;
9. Promote Education and Outreach: Increasing awareness and education about lithium-ion batteries and their impact on various industries can foster a better understanding of the technology's potential and challenges. Educational programs, workshops, and public outreach initiatives can create informed stakeholders who can make well-informed decisions;
10. Diversify Investment Portfolios: For stakeholders interested in investing in the energy storage sector, it is advisable to diversify their investment portfolios to spread risk across different technologies and companies. Investing in a mix of established players and promising startups can provide a balanced approach to harnessing the potential of lithium-ion batteries and other emerging energy storage solutions.

By adopting these recommendations, the audience and stakeholders can position themselves to make informed decisions, support sustainable technologies, and contribute to the growth and advancement of the lithium-ion battery industry.

Author Contributions: S.S.M. proposed the idea of the paper; S.S.M. wrote the paper; C.Z. provided suggestions on the content and structure of the paper; C.Z. and M.M. has been reviewing the draft manuscripts. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Helmholtz Association and contributes to the research performed at CELEST (Center of Electrochemical Energy Storage Ulm-Karlsruhe), in the programme Materials and Technologies for the Energy Transition (MTET) under grant number FE.5341.0118.0012, and we want to express our gratitude for the funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bandhauer, T.M.; Garimella, S.; Fuller, T.F. A critical review of thermal issues in lithium-ion batteries. *J. Electrochem. Soc.* **2011**, *158*, R1. [CrossRef]
2. Hoelle, S.; Dengler, F.; Zimmermann, S.; Hinrichsen, O. 3D Thermal Simulation of Lithium-Ion Battery Thermal Runaway in Autoclave Calorimetry: Development and Comparison of Modeling Approaches. *J. Electrochem. Soc.* **2023**, *170*, 010509. [CrossRef]
3. Zhu, G.; Kong, C.; Wang, J.V.; Kang, J.; Yang, G.; Wang, Q. A fractional-order model of lithium-ion battery considering polarization in electrolyte and thermal effect. *Electrochim. Acta* **2023**, *438*, 141461. [CrossRef]
4. Luo, M.; Lin, X.; Feng, J.; Ling, Z.; Zhang, Z.; Fang, X. Fast self-preheating system and energy conversion model for lithium-ion batteries under low-temperature conditions. *J. Power Sources* **2023**, *565*, 232897. [CrossRef]
5. Rabissi, C.; Sordi, G.; Innocenti, A.; Casalegno, A. Fast and reliable calibration of thermal-physical model of lithium-ion battery: A sensitivity-based method. *J. Energy Storage* **2023**, *59*, 106435. [CrossRef]
6. Wu, L.; Liu, K.; Liu, J.; Pang, H. Evaluating the heat generation characteristics of cylindrical lithium-ion battery considering the discharge rates and N/P ratio. *J. Energy Storage* **2023**, *64*, 107182. [CrossRef]
7. Wang, Y.; Chen, X.; Li, C.; Yu, Y.; Zhou, G.; Wang, C.; Zhao, W. Temperature prediction of lithium-ion battery based on artificial neural network model. *Appl. Therm. Eng.* **2023**, *228*, 120482. [CrossRef]
8. Cui, X. Online temperature distribution estimation of lithium-ion battery considering non-uniform heat generation characteristics under boundary cooling. *Appl. Therm. Eng.* **2023**, *225*, 120206. [CrossRef]

9. Zhai, J.; Jia, Z.; Lei, Z. Thermal Model and Experimental Verification of Lithium-Ion Battery Based on Heat Generation Rate. *J. Energy Eng.* **2023**, *149*, 04022059. [CrossRef]
10. Khaboshan, H.N.; Jaliliantabar, F.; Abdullah, A.A.; Panchal, S. Improving the cooling performance of cylindrical lithium-ion battery using three passive methods in a battery thermal management system. *Appl. Therm. Eng.* **2023**, *227*, 120320. [CrossRef]
11. Ma, S.; Jiang, M.; Tao, P.; Song, C.; Wu, J.; Wang, J.; Deng, T.; Shang, W. Temperature effect and thermal impact in lithium-ion batteries: A review. *Prog. Nat. Sci. Mater. Int.* **2018**, *28*, 653–666. [CrossRef]
12. Feng, X.; Ren, D.; He, X.; Ouyang, M. Mitigating thermal runaway of lithium-ion batteries. *Joule* **2020**, *4*, 743–770. [CrossRef]
13. Zhang, X.; Li, Z.; Luo, L.; Fan, Y.; Du, Z. A review on thermal management of lithium-ion batteries for electric vehicles. *Energy* **2022**, *238*, 121652. [CrossRef]
14. Liao, Z.; Zhang, S.; Li, K.; Zhang, G.; Habetler, T.G. A survey of methods for monitoring and detecting thermal runaway of lithium-ion batteries. *J. Power Sources* **2019**, *436*, 226879. [CrossRef]
15. Patel, J.R.; Rathod, M.K. Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries. *J. Power Sources* **2020**, *480*, 228820. [CrossRef]
16. Li, D.; Wang, L.; Duan, C.; Li, Q.; Wang, K. Temperature prediction of lithium-ion batteries based on electrochemical impedance spectrum: A review. *Int. J. Energy Res.* **2022**, *46*, 10372–10388. [CrossRef]
17. Kobayashi, Y.; Miyashiro, H.; Kumai, K.; Takei, K.; Iwahori, T.; Uchida, I. Precise Electrochemical Calorimetry of $LiCoO_2$/Graphite Lithium-Ion Cell. *J. Electrochem. Soc.* **2002**, *149*, A978. [CrossRef]
18. Pesaran, A.A.; Russell, D.J.; Crawford, J.W.; Rehn, R.; Lewis, E.A. Unique calorimeter-cycler for evaluating high-power battery modules. In Proceedings of the Thirteenth Annual Battery Conference on Applications and Advances, Long Beach, CA, USA, 13–16 January 1998; pp. 127–131.
19. Kong, D.; Lv, H.; Ping, P.; Wang, G. A review of early warning methods of thermal runaway of lithium ion batteries. *J. Energy Storage* **2023**, *64*, 107073. [CrossRef]
20. Karlsen, L.G.; Villadsen, J. Isothermal reaction calorimeters-I. A literature review. *Chem. Eng. Sci.* **1987**, *42*, 1153–1164. [CrossRef]
21. Madani, S.S.; Schaltz, E.; Knudsen Kær, S. Heat Loss Measurement of Lithium Titanate Oxide Batteries under Fast Charging Conditions by Employing Isothermal Calorimeter. *Batteries* **2018**, *4*, 59. [CrossRef]
22. Madani, S.S.; Schaltz, E.; Kær, S.K. Study of temperature impacts on a lithium-ion battery thermal behaviour by employing isothermal calorimeter. *ECS Trans.* **2018**, *87*, 295–305. [CrossRef]
23. Aurbach, D. A review on new solutions, new measurements procedures and new materials for rechargeable Li batteries. *J. Power Sources* **2005**, *146*, 71–78. [CrossRef]
24. Johnson, B.A.; White, R.E. Characterization of commercially available lithium-ion batteries. *J. Power Sources* **1998**, *70*, 48–54. [CrossRef]
25. Joachin, H.; Kaun, T.D.; Zaghib, K.; Prakash, J. Electrochemical and thermal studies of carbon-coated $LiFePO_4$ cathode. *J. Electrochem. Soc.* **2009**, *156*, A401. [CrossRef]
26. Amiruddin, S.; Li, B.; Sun, Y.K.; Prakash, J. Electrochemical Characterization of Cathode Material (Li [Ni0.8Co0.1Mn0.1]O_2 as Core and Li [Ni0.5-0.5xCoxMn0.5-0.5x]O_2 as shell) for Lithium-Ion Batteries. In Proceedings of the 211th ECS Meeting, Chicago, IL, USA, 6–11 May 2007; IOP Publishing: Bristol, UK, 2007; p. 240.
27. Al Hallaj, S.; Maleki, H.; Hong, J.S.; Selman, J.R. Thermal modeling and design considerations of lithium-ion batteries. *J. Power Sources* **1999**, *83*, 1–8. [CrossRef]
28. Roth, E.P.; Doughty, D.H.; Franklin, J. DSC investigation of exothermic reactions occurring at elevated temperatures in lithium-ion anodes containing PVDF-based binders. *J. Power Sources* **2004**, *134*, 222–234. [CrossRef]
29. Dickinson, B.E.; Swan, D.H. EV battery pack life: Pack degradation and solutions. *SAE Trans.* **1995**, *104*, 2792–2801.
30. Kuhn, B.T.; Pitel, G.E.; Krein, P.T. Electrical properties and equalization of lithium-ion cells in automotive applications. In Proceedings of the 2005 IEEE Vehicle Power and Propulsion Conference, Chicago, IL, USA, 7–9 September 2005; IEEE: Piscataway, NJ, USA, 2005; p. 5.
31. Moore, S.W.; Schneider, P.J. A review of cell equalization methods for lithium ion and lithium polymer battery systems. *SAE Publ.* **2001**, 2001010959.
32. Kasnatscheew, J.; Placke, T.; Streipert, B.; Rothermel, S.; Wagner, R.; Meister, P.; Laskovic, I.C.; Winter, M. A tutorial into practical capacity and mass balancing of lithium ion batteries. *J. Electrochem. Soc.* **2017**, *164*, A2479. [CrossRef]
33. Sherfey, J.M.; Brenner, A. Electrochemical calorimetry. *J. Electrochem. Soc.* **1958**, *105*, 665. [CrossRef]
34. Al Hallaj, S.; Prakash, J.; Selman, J.R. Characterization of commercial Li-ion batteries using electrochemical–calorimetric measurements. *J. Power Sources* **2000**, *87*, 186–194. [CrossRef]
35. Hong, J.S.; Maleki, H.; Al Hallaj, S.; Redey, L.; Selman, J.R. Electrochemical-calorimetric studies of lithium-ion cells. *J. Electrochem. Soc.* **1998**, *145*, 1489. [CrossRef]
36. Sheng, L.; Su, L.; Zhang, H. Experimental determination on thermal parameters of prismatic lithium ion battery cells. *Int. J. Heat Mass Transf.* **2019**, *139*, 231–239. [CrossRef]
37. Ping, P.; Dai, X.; Kong, D.; Zhang, Y.; Zhao, H.; Gao, X.; Gao, W. Experimental study on nano-encapsulated inorganic phase change material for lithium-ion battery thermal management and thermal runaway suppression. *Chem. Eng. J.* **2023**, *463*, 142401. [CrossRef]

38. Liang, L.; Zhao, Y.; Diao, Y.; Ren, R.; Zhu, T.; Li, Y. Experimental investigation of preheating performance of lithium-ion battery modules in electric vehicles enhanced by bending flat micro heat pipe array. *Appl. Energy* **2023**, *337*, 120896. [CrossRef]
39. Madani, S.S.; Schaltz, E.; Knudsen Kær, S. Investigation of the effect of state of charge and C rates on the heat loss and efficiency of a lithium ion battery. *ECS Trans.* **2018**, *87*, 51. [CrossRef]
40. Madani, S.S.; Schaltz, E.; Knudsen Kær, S. Simulation of thermal behaviour of a lithium titanate oxide battery. *Energies* **2019**, *12*, 679. [CrossRef]
41. Verbrugge, M.W. Three-dimensionai temperature and current distribution in a battery module. *AIChE J.* **1995**, *41*, 1550–1562. [CrossRef]
42. Chen, Y.; Evans, J.W. Thermal analysis of lithium-ion batteries. *J. Electrochem. Soc.* **1996**, *143*, 2708. [CrossRef]
43. Kim, G.H.; Pesaran, A.; Spotnitz, R. A three-dimensional thermal abuse model for lithium-ion cells. *J. Power Sources* **2007**, *170*, 476–489. [CrossRef]
44. Gu, W.B.; Wang, C.Y. Thermal-electrochemical modeling of battery systems. *J. Electrochem. Soc.* **2000**, *147*, 2910. [CrossRef]
45. Liu, K.; Hu, X.; Yang, Z.; Xie, Y.; Feng, S. Lithium-ion battery charging management considering economic costs of electrical energy loss and battery degradation. *Energy Convers. Manag.* **2019**, *195*, 167–179. [CrossRef]
46. Cao, J.; Harrold, D.; Fan, Z.; Morstyn, T.; Healey, D.; Li, K. Deep reinforcement learning-based energy storage arbitrage with accurate lithium-ion battery degradation model. *IEEE Trans. Smart Grid* **2020**, *11*, 4513–4521. [CrossRef]
47. Shah, K.; Vishwakarma, V.; Jain, A. Measurement of multiscale thermal transport phenomena in Li-ion cells: A review. *J. Electrochem. Energy Convers. Storage* **2016**, *13*, 030801. [CrossRef]
48. Barcellona, S.; Piegari, L. Lithium Ion battery models and parameter identification techniques. *Energies* **2017**, *10*, 2007. [CrossRef]
49. Pour, M.Y. Electrothermal Modeling of Lithium-Ion Batteries. Ph.D. Thesis, Bahonar University, Kerman, Iran, 2015.
50. Gümüşsu, E.; Ekici, Ö.; Köksal, M. 3-D CFD modeling and experimental testing of thermal behavior of a Li-Ion battery. *Appl. Therm. Eng.* **2017**, *120*, 484–495. [CrossRef]
51. Khan, M.R.; Kaer, S.K. Three Dimensional Thermal Modeling of Li-Ion Battery Pack Based on Multiphysics and Calorimetric Measurement. In Proceedings of the 2016 IEEE Vehicle Power and Propulsion Conference (VPPC), Hangzhou, China, 17–20 October 2016.
52. Damay, N.; Forgez, C.; Bichat, M.P.; Friedrich, G.; Ospina, A. Thermal modeling and experimental validation of a large prismatic Li-ion battery. In Proceedings of the IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10–13 November 2013; pp. 4694–4699.
53. Zhao, X.; Yin, Y.; Hu, Y.; Choe, S.Y. Electrochemical-thermal modeling of lithium plating/stripping of $Li(Ni_{0.6}Mn_{0.2}Co_{0.2})O_2$/Carbon lithium-ion batteries at subzero ambient temperatures. *J. Power Sources* **2019**, *418*, 61–73. [CrossRef]
54. Liu, L.; Park, J.; Lin, X.; Sastry, A.M.; Lu, W. A thermal-electrochemical model that gives spatial-dependent growth of solid electrolyte interphase in a Li-ion battery. *J. Power Sources* **2014**, *268*, 482–490. [CrossRef]
55. Basu, S.; Hariharan, K.S.; Kolake, S.M.; Song, T.; Sohn, D.K.; Yeo, T. Coupled electrochemical thermal modelling of a novel Li-ion battery pack thermal management system. *Appl. Energy* **2016**, *181*, 1–13. [CrossRef]
56. Hou, M.; Hu, Y.; Zhang, J.; Cao, H.; Wang, Z. Development of electrochemical-thermal modelling for large-format Li-ion battery. *Electrochim. Acta* **2020**, *347*, 136280. [CrossRef]
57. Rad, M.S.; Danilov, D.L.; Baghalha, M.; Kazemeini, M.; Notten, P.H.L. Adaptive thermal modeling of Li-ion batteries. *Electrochim. Acta* **2013**, *102*, 183–195.
58. Scrosati, W.A. *Advances in Lithium-Ion Batteries*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2002.
59. Arora, P.; White, R.E.; Doyle, M. Capacity fade mechanisms and side reactions in lithium-ion batteries. *J. Electrochem. Soc.* **1998**, *145*, 3647. [CrossRef]
60. Aurbach, D.; Markovsky, B.; Salitra, G.; Markevich, E.; Talyossef, Y.; Koltypin, M.; Nazar, L.; Ellis, B.; Kovacheva, D. Review on electrode–electrolyte solution interactions, related to cathode materials for Li-ion batteries. *J. Power Sources* **2007**, *165*, 491–499. [CrossRef]
61. Broussely, M.; Biensan, P.; Bonhomme, F.; Blanchard, P.; Herreyre, S.; Nechev, K.; Staniewicz, R.J. Main Aging Mechanisms in Li Ion Batteries. *J. Power Sources* **2005**, *146*, 90. [CrossRef]
62. Vetter, J.; Novák, P.; Wagner, M.R.; Veit, C.; Möller, K.C.; Besenhard, J.O.; Winter, M.; Wohlfahrt-Mehrens, M.; Vogler, C.; Hammouche, A. Ageing mechanisms in lithium-ion batteries. *J. Power Sources* **2005**, *147*, 269–281. [CrossRef]
63. Ramadass, P.H.; Haran, B.; White, R.; Popov, B.N. Capacity fade of Sony 18650 cells cycled at elevated temperatures: Part I. Cycling performance. *J. Power Sources* **2002**, *112*, 606–613. [CrossRef]
64. Zheng, X.; Zhang, Z. State of charge estimation at different temperatures based on dynamic thermal model for lithium-ion batteries. *J. Energy Storage* **2022**, *48*, 104011. [CrossRef]
65. Ehrlich, G.M. *Handbook of Batteries*; McGraw-Hill: New York, NY, USA, 2001.
66. Amine, K.; Liu, J.; Belharouak, I. High-temperature storage and cycling of C-$LiFePO_4$/graphite Li-ion cells. *Electrochem. Commun.* **2005**, *7*, 669–673. [CrossRef]
67. Takei, K.; Kumai, K.; Kobayashi, Y.; Miyashiro, H.; Terada, N.; Iwahori, T.; Tanaka, T. Cycle life estimation of lithium secondary battery by extrapolation method and accelerated aging test. *J. Power Sources* **2001**, *97*, 697–701. [CrossRef]

68. Liu, X.; Zeng, G.; He, Y.; Dong, B.; Xu, X. Research on the capacity fading characteristics of a Li-ion battery based on an equivalent thermal model. In Proceedings of the 2015 International Conference on Intelligent Computing and Internet of Things ICIT, Harbin, China, 17–18 January 2015; pp. 145–150.
69. Jiang, G.; Zhuang, L.; Hu, Q.; Liu, Z.; Huang, J. An investigation of heat transfer and capacity fade in a prismatic Li-ion battery based on an electrochemical-thermal coupling model. *Appl. Therm. Eng.* **2020**, *171*, 115080. [CrossRef]
70. Edouard, C.; Petit, M.; Forgez, C.; Bernard, J.; Revel, R. Parameter sensitivity analysis of a simplified electrochemical and thermal model for Li-ion batteries aging. *J. Power Sources* **2016**, *325*, 482–494. [CrossRef]
71. Gomez, J.; Nelson, R.; Kalu, E.E.; Weatherspoon, M.H.; Zheng, J.P. Equivalent circuit model parameters of a high-power Li-ion battery: Thermal and state of charge effects. *J. Power Sources* **2011**, *196*, 4826–4831. [CrossRef]
72. Werner, D.; Loges, A.; Becker, D.J.; Wetzel, T. Thermal conductivity of Li-ion batteries and their electrode configurations—A novel combination of modelling and experimental approach. *J. Power Sources* **2017**, *364*, 72–83. [CrossRef]
73. An, Z.; Jia, L.; Wei, L.; Yang, C. International Journal of Heat and Mass Transfer Numerical modeling and analysis of thermal behavior and Li + transport characteristic in lithium-ion battery. *Int. J. Heat Mass Transf.* **2018**, *127*, 1351–1366. [CrossRef]
74. Swierczynski, M.; Stroe, D.I.; Stanciu, T.; Kær, S.K. Electrothermal impedance spectroscopy as a cost efficient method for determining thermal parameters of lithium ion batteries: Prospects, measurement methods and the state of knowledge. *J. Clean. Prod.* **2017**, *155*, 63–71. [CrossRef]
75. Ruan, H.; Jiang, J.; Sun, B.; Gao, W.; Wang, L.; Zhang, W. Online estimation of thermal parameters based on a reduced wide-temperature-range electrothermal coupled model for lithium-ion batteries. *J. Power Sources* **2018**, *396*, 715–724. [CrossRef]
76. Zhang, J.; Wu, B.; Li, Z.; Huang, J. Simultaneous estimation of thermal parameters for large-format laminated lithium-ion batteries. *J. Power Sources* **2014**, *259*, 106–116. [CrossRef]
77. Mayilvahanan, K.S.; Takeuchi, K.J.; Takeuchi, E.S.; Marschilok, A.C.; West, A.C. Supervised Learning of Synthetic Big Data for Li-Ion Battery Degradation Diagnosis. *Batter. Supercaps.* **2022**, *5*, e202100166. [CrossRef]