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REVIEW ARTICLE OPEN ACCESS

A brief survey on heat generation in lithium-ion battery technology

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Abstract. The powertrain in electric vehicles typically comprises various components, including lithium-ion batteries (LIBs), a battery management system, an energy converter, an electric motor, and a mechanical transmission system. Electric vehicles utilize the electrical energy stored in LIBs to efficiently drive the motors efficiently. LIBs find widespread use in portable electronic devices like laptops, mobile phones, and other electronic appliances, with potential applications in the automotive sector. To examine the thermal performance of LIBs across diverse applications and establish accurate thermal models for batteries, it is essential to understand heat generation. Numerous researchers have proposed various methods to determine the heat generation of LIBs through comprehensive experimental laboratory measurements. This study comprehensively explores diverse experimental and modeling techniques used to analyze the thermal behavior and heat generation of LIBs.

Keywords: Renewable energy / lithium-ion batteries / heat generation / thermal behavior

1 Introduction

Global warming is a direct consequence of the accumulation of greenhouse gases. Internal combustion engines contribute significantly to carbon dioxide emissions, prompting worldwide research efforts to substitute green energy sources for automotive propulsion. [1,2]. In recent years, there has been a growing focus from authorities, universities, manufacturers, and the scientific community on the environmental implications of greenhouse gas issues. Simultaneously, there have been notable advancements in energy storage technologies, recognized as pivotal for fostering an eco-friendly and sustainable society, particularly in future energy markets dominated by renewable power generation. Energy storage systems, including rechargeable batteries, have gained increased attention for backup energy supply applications such as renewable grid integration and grid support [3–5].

Various rechargeable batteries are currently available in the market for powering electric vehicles, presenting an environmentally friendly alternative to conventional internal combustion engine vehicles. The widespread adoption of electric vehicles hinges on the advancement of rechargeable battery technologies. Lithium-ion batteries (LIBs) have emerged as a preferred choice due to their outstanding performance characteristics, including high energy density, long lifespan, and low self-discharge [6–8].

The heat generation of LIBs has been a subject of investigation by multiple researchers. Many have endeavored to develop accurate, simplified, and computationally efficient models for LIBs. However, several thermal analyses are based on modeling and are often limited to LIB operation near room temperatures, neglecting the wide range of working temperatures encountered in various applications, such as electric vehicles. Furthermore, there is a lack of comprehensive studies in the literature that systematically explore the impacts of different parameters related to the heat management of LIBs.

Recent advancements in lithium-ion battery (LIB) technology have underscored the critical importance of understanding and managing heat generation to enhance performance, safety, and longevity. This paper now integrates foundational studies with cutting-edge research to present a comprehensive overview of heat generation mechanisms, measurement techniques, and thermal

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management strategies in LIBs. Furthermore, this paper now includes recent advancements focusing on improving thermal management systems, enhancing safety, and optimizing the performance of lithium-ion batteries (LIBs). These advancements mark significant progress towards developing more reliable and efficient LIB applications.

2 Advancements and environmental considerations in lithium-ion battery technologies

The lithium-ion battery (LIB) stands out among all battery categories and cell types due to its exceptional performance and characteristics. The recycling potential and the increasing awareness of the ecological impact of lithium batteries have spurred innovative investigations aimed at enhancing LIB technologies. While ensuring safe operation remains a priority, research efforts are also directed towards cost reduction and minimizing adverse environmental effects [9–11].

The field of lithium-ion battery technology is witnessing rapid advancements. Research efforts in [12] on solid-state batteries, [13] on using AI for battery health diagnostics, and the analysis of patenting trends by [14] reflect the dynamic nature of LIB research. Furthermore, [15] 's discussion on emerging battery technologies and Karuppasamy et al. [16] 's exploration of 3D printed anode materials for sodium-ion batteries highlight the broadening scope of energy storage research.

A considerable number of researchers worldwide are currently engaged in modifying and advancing lithium-ion chemistry to achieve superior performance, considering factors such as cost and other physical parameters. Reference [17,18] has highlighted the volume of research publications focusing on lithium-ion battery (LIB) implementations and technology, particularly in physics and engineering research. The majority of research paper publications were predominantly concentrated in certain Asian countries, including China, South Korea, and Japan. Additionally, these publications indicated a growing significance of LIB in research. Moreover, production facilities for LIBs designed for vehicle use are not uniformly available in all regions of the world in sufficient quantities. This limitation is attributed to the need for effective material supply management, substantial technical contributions, and financial constraints [17,18].

Pang et al. [19] introduced a novel methodology employing a physics-informed neural network (PINN) to precisely predict the heat generation rate (HGR) of Lithium-ion Batteries (LIBs) under varying conditions. This approach integrates a single particle model with thermodynamics (SPMT) to extract essential physical insights regarding battery HGR. The surface concentrations of electrodes are incorporated into bidirectional long short-term memory (BiLSTM) networks, constituting the PINN method that enhances the accuracy of HGR estimation. The key hyperparameters of BiLSTM are optimized using a Bayesian algorithm. The proposed approach demonstrates effective prediction of battery HGR during dynamic stress tests and light vehicle tests, with errors of $0.542\,\mathrm{kW/m^3}$ and $1.428\,\mathrm{kW/m^3}$, respectively, at 25 °C. This highlights the potential of PINN in accurately estimating battery HGR.

Cao et al. [20] presented a method of forced convection calorimetry utilizing the lumped capacitance model for the continuous and noise-free measurement of battery heat generation rates. The validity of the approach is established through calibration with reference samples. Experimental results from battery tests underscore the significant impact of discharge current, ambient temperature, and cycle aging on battery heat generation behavior. Higher discharge currents and lower ambient temperatures (within the range of 20–45 °C) result in increased heat generation rates and faster temperature elevation. The average heat generation rate over the discharge duration shows a quadratic polynomial relationship with discharge current and an inverse quadratic correlation with ambient temperature. The cycling process contributes to an increase in the heat generation rate, reflecting the aging phenomenon of the battery. Moreover, the charge rate during cycling has a notable effect on battery lifespan. Importantly, the two battery cells exhibit distinct heat generation behaviors after cycling with varying currents, even when their health states are similar. This observation suggests that the cycling process and varying cycle rates can exacerbate battery inconsistency.

3 Assessment techniques for heat generation in lithium-ion batteries

Calorimeters can be categorized into four essential groups: isoperibolic, isothermal, adiabatic, and Tian Calvet heat flux. These devices play a crucial role in collecting heat generation data from a battery calorimeter, which is subsequently used to evaluate the performance of lithium-ion batteries (LIBs). Different current rates are employed for charge and discharge cycles to observe LIB heat generation trends and determine LIB efficiency.

Figure 1 illustrates the classification of calorimeters. Battery calorimeters consist of a sizable volume analysis chamber immersed in a bath. Once the calibration of the battery calorimeter is completed, tests can be initiated. Ensuring calibration of the battery calorimeter before each experiment is essential. Typically, this calibration involves applying various electrical currents to a precise resistance positioned within the calorimeter chamber of the battery calorimeter. By utilizing the heat loss, which the battery calorimeter can measure, a model can be simulated to ascertain the temperature distribution of the LIBs. Additionally, the heat capacity of LIBs can be determined through this process.

A classification scheme outlining the heat generation processes within Lithium-ion Batteries (LIBs) is depicted in Figure 1. Understanding the origins of heat generation and thermal effects in LIBs is crucial. Various parameters influence the heat generation of LIBs, with battery temperature being affected by factors such as cooling

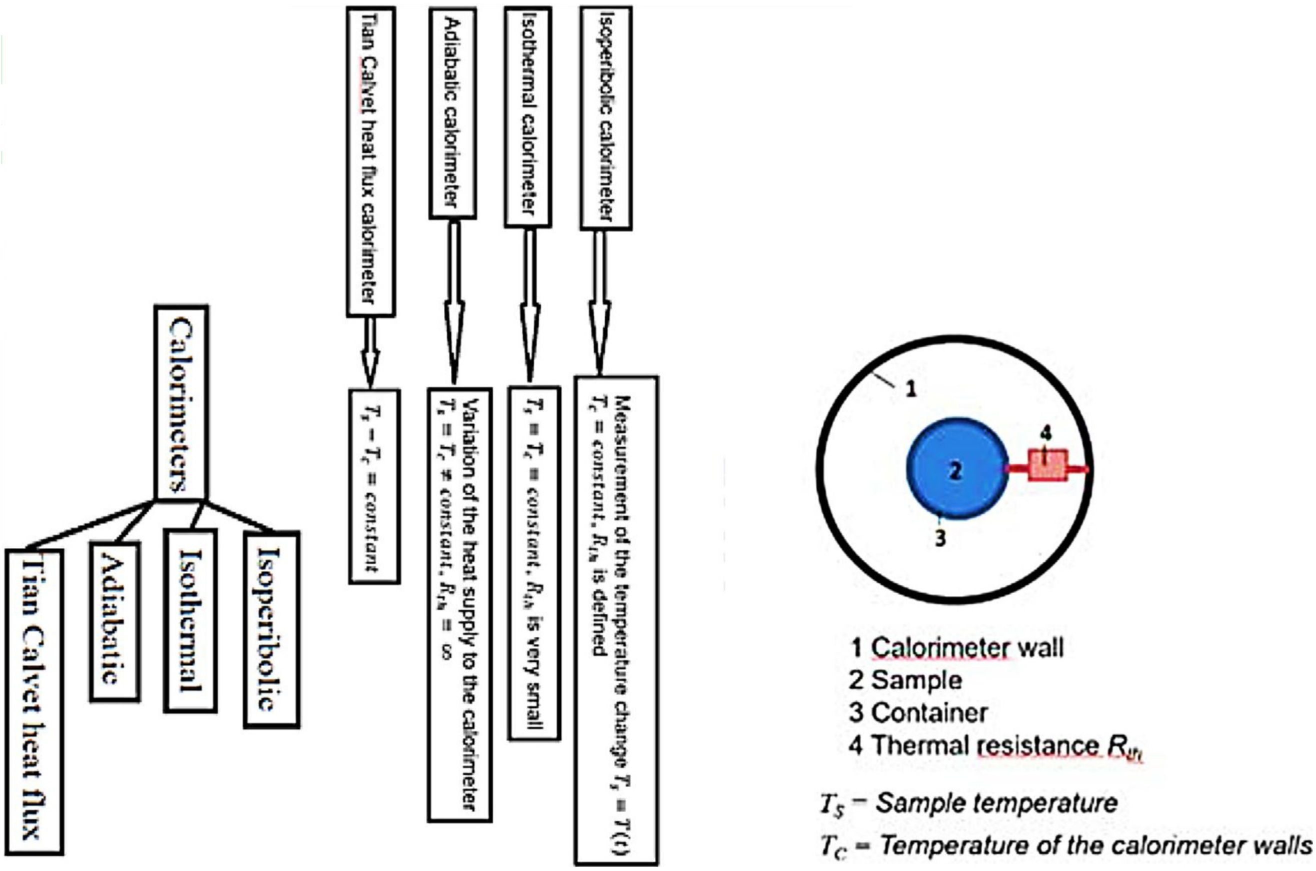
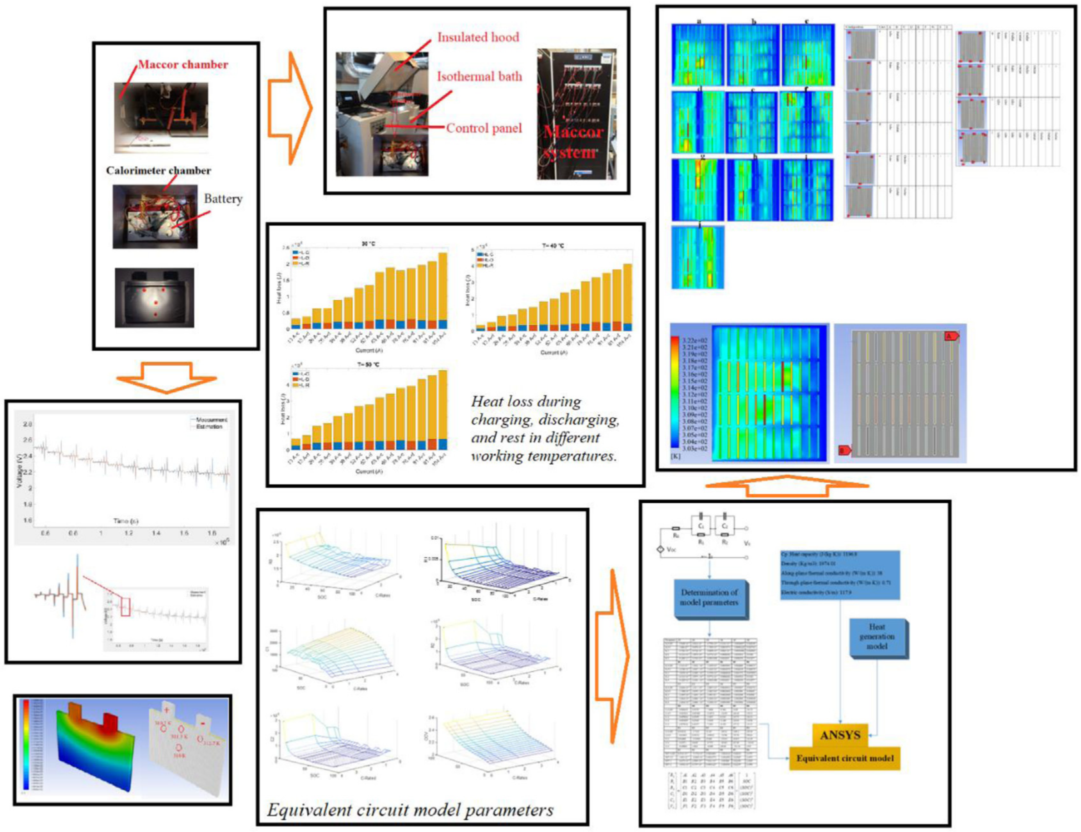


Fig. 1. Classification of calorimeters.

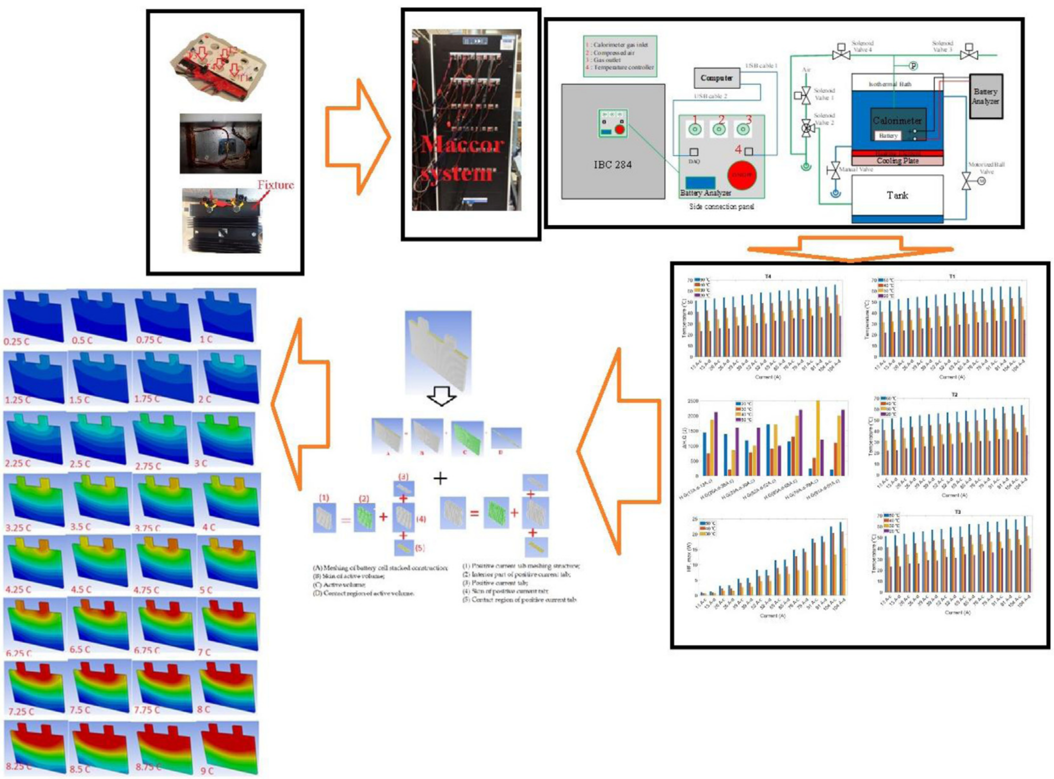
and heating systems in the thermal management system, ambient temperature, battery thermal conductivity, heat generation, and battery heat capacity. Among these factors, some may exert a more significant impact on the LIB temperature.

Table 1 presents various methods employed in the literature for determining the heat generation of lithium-ion batteries, with a notable inclusion of battery calorimetry. Numerous tests were conducted using different calorimeters to gain insights into the thermal behavior of Lithium-ion Batteries (LIBs). These investigations allow for the assessment of LIB features, including heat generation and efficiency, under diverse conditions such as varying current rates, temperatures, and state of charge during different charge and discharge operations. Figure 2 illustrates the application of battery calorimetry in thermal modeling and thermal management of lithium-ion batteries.

The study, conducted by S.J. Drake et al. [21], investigates the heat generation rates of a Li-ion cell under high discharge rates. They rely on temperature and surface heat flux measurements directly from the cell to assess the heat generation rates, providing insights into the concurrent heat accumulation within the cell and the heat lost from it. In contrast to traditional calorimetry-based methods, this approach enables in-situ measurements of heat generation rates, which can be particularly useful for both laboratory and real-world field settings. This study also introduces a novel technique for determining the internal temperature of the cell and verifies the measurements against theoretical models. The second study, conducted by C. Lin et al. [22], focuses on the electrochemical and thermal behaviors of a prismatic 40 Ah C/LiFePO4 battery. Their study highlights the impact of temperature on cell capacity during mixed charge-discharge cycles and explores heat generation and energy efficiency across different charging and discharging current rates. The empirical results reveal significant increases in both charging and discharging capacities within specific temperature ranges, with energy efficiency exceeding 95% at certain current rates and temperatures. The researchers also develop a thermal mathematical model to simulate temperature changes in the battery, incorporating internal resistances and entropy coefficients derived from experiments. Their findings suggest a reduction in heat generation with increasing temperatures. In the third study, conducted by E. Schuster et al. [23], an evaluation of commercial 40 Ah lithium-ion pouch cells with Li(Ni1/3Mn1/3Co1/3)O2 cathodes is conducted. This assessment involves testing under both isoperibolic and adiabatic conditions, covering a range of charging and discharging currents from 5 A to 40 A. Both charging and discharging phases exhibit an overall exothermic behavior, resulting in a temperature rise of 3 K to 11 K over a single half cycle. The researchers determine the effective specific heat capacity and heat transfer coefficient to convert the



(a)



(b)

Fig 2. The application of battery calorimetry in (a) thermal modeling (b) thermal management of lithium-ion batteries.

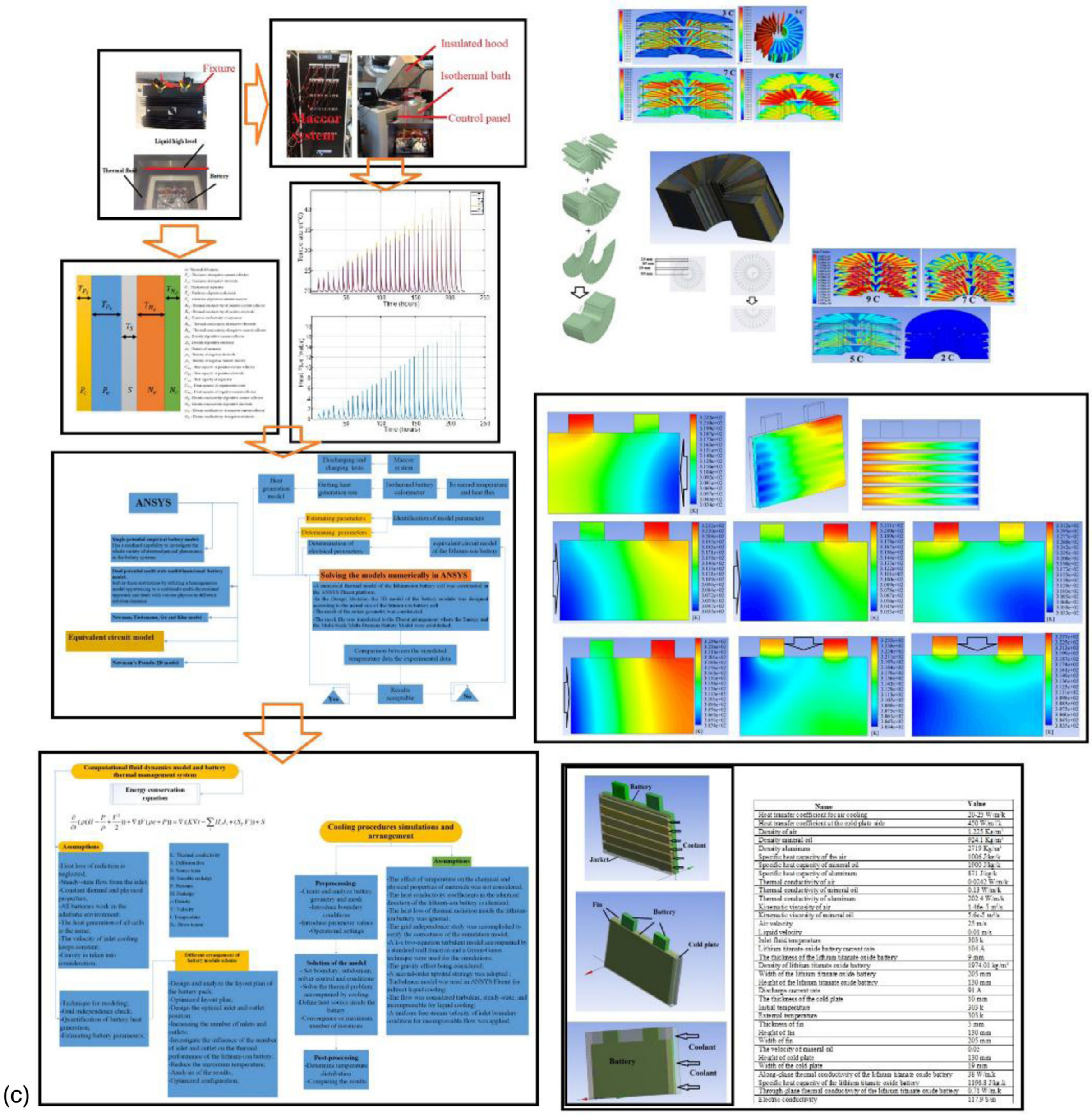


Fig 2. Continued.

recorded temperature fluctuations into heat-related data. Additionally, they compare the experimental results with total heat data calculated from reversible and irreversible heat, which was determined through potentiometric and current interruption methods. There is a strong alignment among all three methods, which indicates the accuracy of the heat generation measurements. In the fourth study, conducted by T. M. Bandhauer et al. [24], experimentally measured reversible and irreversible electrochemical heat generation rates in a commercially available small-scale C/LiFePO4 lithium-ion battery (LIB) designed for high-rate applications. The study tests the battery across a wide range of temperatures (10 °C to 60 °C) and discharge/charge rates (from fractional C/4 to 5C). The heat rate increases with increasing rate and decreasing temperature, and even under demanding conditions (5C and 55 °C), the reversible heat rate remains significant, accounting for 7.4% of the total heat rate. This study also highlights the importance of reversible heat rate in dynamic simulations, especially in charge-depleting hybrid electric vehicle (HEV) applications. The fifth study, conducted by K. Chen et al. [25], concentrates on developing and validating a calorimeter specifically designed for measuring heat generation rates in prismatic batteries. The validation is carried out using a controllable electric heater, and heat generation rates are assessed for a prismatic A123 LiFePO4 battery under various discharge rates and operating temperatures. Interestingly, the presence of heat of mixing emerges as a notable component of total heat generation, becoming significant even at modest discharge rates.

Table 1. Different methods were used in the literature for the heat generation determination of LIBs.

Study	Heat generation measurement method	Battery type	Current rate	Heat generation rate/Total generated heat	Ref
Direct measurements of heat generation	Heat flux sensor	2.6 Ah $LiFePO_4$ cell	9.6C		[21]
Heat generation characteristics	Accelerated rate calorimeter	40 Ah $LiFePO_4$ pouch cel	0.33C, 1C, 2C	23.24 kJ	[22]
Analyzing thermal behaviour	Accelerated rate calorimeter	40 Ah NMC111/graphite pouch cell	0.125, 0.25C, 0.5 C 1C	13.4 kJ	[23]
Temperature-dependent electrochemical heat generation	Open-circuit potential variation with temperature	$C/LiFePO_4$	0.25 C-5C	193.4J	[24]
Analyzing the thermal behaviour	Accelerated rate calorimeter	A123 20 Ah pouch cell	0.25C - 3C	23 W	[25]
Estimating heat generation rate	Accelerated rate calorimeter	large-format 25 Ah lithium-ion battery	1C		[26]
In situ studies	Micro-calorimeter	Li_xMn2O_4 and $Li_xAl_{0.17}Mn_{1.83}O_{3.97}S_{0.03}$ Cathode	0.1C, 0.14C, 0.33C, 1C	0.63 W/L (0.1C-0.2C) 2.65 W/L (0.2C-0.5C) 7.51 W/L (0.5C-1C)	[27]
Experimental study on heat generation behaviour	Thermal bath	18650 Secondary Li-ion batteries	0.1C, 0.5C,1C	11.0 W/L 27.5 W/L 84.5 W/L	[28]
Electrochemical calorimetry : estimation of degradation mechanism	Calvet-type conduction micro-calorimeter	$LiCoO_2$ /Graphite cylindrical Lithium-Ion Cell	0.02C and 0.1C	0.97 W/L (0.1C-0.2C)	[29]
Heat loss measurement under fast charging conditions	Isothermal calorimeter (20 °C)	Lithium Titanate Oxide Batteries	1C,1.5C,2C,2.5C,3C,3.5C ,4C,4.5C, 5C,5.5C,6C,6.5C,7C,7.5C ,8C,8.5C (Charge-discharge)	Charge:82.25J-113.78J Discharge: 124.25J-127.99J	[30]
Study of temperature impacts on thermal behaviour	Isothermal calorimeter (30 °C, 40 °C, 50 °C)	Lithium Titanate Oxide Batteries	1C,2C,3C,4C,5C,6C,6.5C ,7C,8C (Charge-discharge)	50 °C:1020mW-23880 mW 40 °C:702 mW - 20800 mW 30 °C:514 mW -15460 mW	[31]

A double plateau in the battery discharge curve is observed at certain operating temperatures, and the established experimental setup has the potential to characterize heat generation in prismatic batteries of various chemistries. In the sixth study, conducted by J. Zhang et al. [26], different methods for estimating heat generation rates are compared. The study identifies techniques to address challenges associated with estimating heat generation rates for large-format lithium-ion batteries (LIBs), such as using a pouch cell with reduced capacity and employing the first-order inertial system to correct observed delays in surface temperature rise. In the seventh study, conducted by K. Onda et al. [27], the overpotential resistance and entropy change in two compact lithium-ion secondary batteries are investigated. Various methods are used to assess these parameters, including voltage-current characteristics during constant current discharge, intermittent discharge for 60 seconds, and AC impedance measurement. The study compares the calculated temperature increases and total heat generation rates using overpotential resistance and entropy change with the measured data for both batteries during constant current discharge, finding close alignment between them. In the eighth study, conducted by T. M. Bandhauer et al. [28], a comprehensive review of existing literature addressing thermal concerns in Lithium-ion Batteries (LIBs) is conducted. The review integrates findings from both experimental studies and modeling inquiries, identifying areas that demand further investigation, such as more accurate measurements of heat generation and enhanced models for estimating heat generation rates.

Comparing these studies, several emphasize the importance of temperature on LIB performance. S.J. Drake et al. [21] and C. Lin et al. [22] highlight active cooling's impact, while E. Schuster et al. [23] provide insights into both exothermic and endothermic behaviors during charge and discharge. T. M. Bandhauer et al. [24] focus on reversible heat rate in dynamic simulations, while K. Chen et al. [25] show a significant heat of mixing component. J. Zhang et al. [26] explore different methods for estimating heat generation rates, underscoring the need for accurate heat measurement techniques. K. Onda et al. [27] examine overpotential resistance and entropy change, and T. M. Bandhauer et al.'s review [28] addresses a broader spectrum of thermal concerns, emphasizing the need for better heat generation measurement and management. Choudhari et al. [32] studied heat generation in LIB components and temperature control strategies, while Kantharaj et al. [33] highlight advancements in thermal analysis and modeling, focusing on factors influenced by battery capacity, charge/discharge rates, and microstructure. The early works of researchers like Pang et al. [34] introduced a physics-informed neural network approach for estimating the heat generation rate (HGR) of LIBs under various conditions, demonstrating the potential of machine learning models in enhancing predictive accuracy for battery thermal management. Concurrently, Cao et al. [20] utilized forced convection calorimetry to study the impact of discharge current and ambient temperature on LIB heat generation, providing crucial insights into the factors influencing thermal behavior. Recent studies have highlighted the critical nature of controlling triggering energy to prevent catastrophic failures in LIBs. Zhang et al. [35] investigated the propagation of internal thermal runaway, showing the importance of improved safety profiles, especially for high-energy-density applications. Recent research by Zhang et al. [35] into the propagation of internal thermal runaway in LIBs underscores the importance of advanced research in developing batteries with improved safety profiles, addressing one of the most critical aspects of high-energy-density LIB applications.

Addressing the need for innovative thermal management solutions, a study by Sadeh et al. [36] explored a hybrid liquid-cooled battery thermal management system, showcasing its efficiency in heat removal from LIB packages. This aligns with research by Li et al. [37], who developed a novel flexible composite phase change material, offering a promising approach for mitigating thermal risks in LIB applications. In addition, the work by Cai et al. [38] introduces bio-based flexible phase change materials, utilizing lauric acid for better thermal management, emphasizing the development's impact on heat transfer capacity and battery safety. Likewise, the solvent-free method for processing hybrid solid electrolytes explored by Macray [39] presents a safer alternative to conventional electrolytes, significantly contributing to thermal stability in LIBs.

3.1 Comprehensive analysis of factors influencing heat generation in lithium-ion batteries

The thermal performance of lithium-ion batteries (LIBs) is a pivotal aspect of their overall functionality, impacting efficiency, safety, and longevity. Heat generation within LIBs is influenced by a complex interplay of electrochemical, physical, and operational factors. This section delves into the primary parameters affecting heat generation, supported by recent studies and findings.

3.1.1 Electrochemical reactions

At the heart of LIB heat generation are the electrochemical reactions during charging and discharging. Bandhauer et al. [40] provide an in-depth analysis of the thermodynamics and kinetics of these reactions, highlighting how variations in material composition and electrode design can significantly impact heat generation.

3.1.2 Internal resistance

The internal resistance of a battery, encompassing both ohmic resistance and polarization resistance, is a direct contributor to heat production through Joule heating (I^2R losses). Bedürftig [41] discusses the mechanisms behind internal resistance and its implications for battery thermal management.

3.1.3 C-Rate (Charge/Discharge Rate)

The rate of charge or discharge, denoted as C-rate, profoundly influences LIB thermal behavior. Fast charging or high-power applications can exacerbate heat generation, necessitating enhanced cooling strategies. Reference [42] explores the relationship between C-rate and battery temperature, offering strategies to mitigate thermal risks.

3.1.4 State of Charge (SoC) and Depth of Discharge (DoD)

The operational state of charge (SoC) and depth of discharge (DoD) affect the lithium-ion concentration gradients, influencing the internal resistance and heat generation. Authors in [43] demonstrate how SoC and DoD levels impact the thermal stability of LIBs, underscoring the importance of controlled charging practices.

3.1.5 Temperature

The ambient and internal temperatures are crucial in dictating the thermal dynamics of LIBs. Temperature influences the speed of electrochemical reactions, with high temperatures potentially leading to thermal runaway. Researchers in [44] discuss the role of ambient temperature in LIB performance and safety, advocating for advanced thermal management systems.

3.1.6 Ageing and degradation

Battery ageing and degradation mechanisms, such as SEI layer growth and lithium plating, can increase internal resistance over time, leading to heightened heat generation. Wang et al. [45] examine the effects of ageing on LIB thermal behavior, providing insights into the long-term thermal management.

3.1.7 Battery management systems (BMS)

Effective BMS are critical in regulating operational parameters to mitigate excessive heat generation. H. Binsalim and S. Badaam [46] detail how BMS can optimize battery operation, enhance safety, and extend lifespan through intelligent thermal regulation.

3.1.8 Implications for battery design and management

The discussed factors underscore the multifaceted nature of heat generation in LIBs, necessitating a holistic approach to battery design and management. Incorporating advanced materials, optimizing cell architecture, and employing intelligent BMS are key strategies for enhancing thermal performance and ensuring safety. The continuous innovation in materials science and battery technology, alongside sophisticated management algorithms, will play a critical role in addressing the thermal challenges faced by next-generation LIBs.

4 Modeling and simulation studies

Significant contributions to the modeling and simulation of LIBs have been made, underscoring the importance of accurate modeling in predicting key performance parameters under varying operational conditions. Bedürftig's [41] work on equivalent circuit dynamic modeling of lithium-ion cells, along with Pegel et al. [47] 's development of design guidelines to prevent thermal propagation within battery systems, emphasizes the role of advanced simulation tools in enhancing battery safety. The theme of thermal management is further expanded in [48], providing detailed analysis into the heat generation and dissipation dynamics of LIBs. Similarly, Pegel et al. [47] offer invaluable design guidelines aimed at preventing thermal propagation within battery systems, a critical challenge in battery safety and performance.

5 Battery calorimetry

A classification scheme for the heat generation processes inside lithium-ion batteries and classification of heat generation of lithium-ion batteries including classification of battery thermal analysis is demonstrated in Figure 3. Kobayashi et al. [51] investigated the heat generated during a chemical reaction in a lithium-ion cell composed of LiCoO2 and graphite electrodes. They isolated the thermal behavior of each electrode by comparing cells with LiCoO2/Li and graphite/Li configurations. Results indicated that the LiCoO2 electrode produced more reversible heat compared to graphite. These distinct thermal characteristics were attributed to individual electrodes and correlated well with phase changes. Additionally, the degradation of commercially available lithium-ion cells was assessed using calorimetry. It was found that the decrease in active material of graphite was the primary factor contributing to capacity degradation after cycling.

Accurate heat generation data from battery modules is essential for designing proper battery thermal management systems. To address this need, Pesaran et al. [52] developed and tested a custom-made calorimeter designed specifically for large battery modules. This calorimeter can accommodate battery modules measuring up to 21 cm x 39 cm in cross-section and 20 cm in height. It is capable of measuring heat generation rates ranging from 1 W to 100 W while the battery operates within a temperature range of $-30\,°C$ to $+60\,°C$. The instrument can detect heat effects as small as 10 joules with an accuracy of 5%. Additionally, we utilize a state-of-the-art high-power battery cycler to cycle the modules within the calorimeter, enabling comprehensive testing and analysis.

Reversible heat effects (TAS) of half-cell processes were investigated by Sherfey et al. [53] using a twin calorimeter setup comprising a Dewar flask divided by a vertical partition. Each compartment contains the same electrolyte and an electrode, with a hole in the partition allowing electrolytic current passage covered by filter paper. Total heat and irreversible heat effects are measured separately in each compartment, enabling determination of reversible heat. Various half-cell configurations were studied, including copper in acid copper sulfate, silver in acid silver perchlorate, and silver-silver chloride in different chloride solutions. The impact of "transport entropies" on these measurements was examined. Theoretical predictions regarding the equivalence of half-cell entropy data obtained through calorimetry and thermocell studies were not fully realized in the case of the silver-silver perchlorate half-cell.

Chemical and physical processes typically involve heat effects, which can provide valuable insights into process mechanisms and are crucial for safe process scaling.

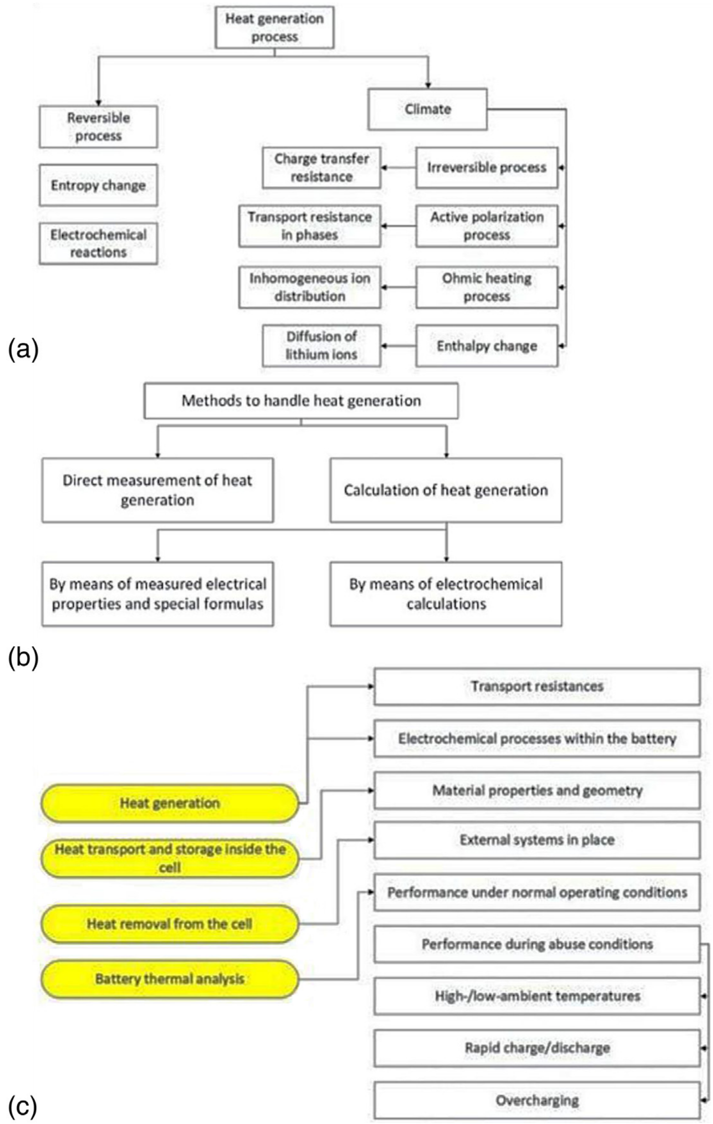


Fig. 3. (a): A classification scheme for the heat generation processes inside lithium-ion batteries [49], (b): Classification of heat generation of lithium-ion batteries [50], (c): Classification of battery thermal analysis [50].

Karlsen et al. [54] focused on one specific laboratory equipment for measuring heat effects: the isothermal reaction calorimeter. The review surveys available calorimeter equipment, categorizing isothermal reaction calorimeters based on their measurement principles. In addition, discussed various techniques for analyzing calorimeter data numerically. The review argues that modern filtering methods and careful mathematical modeling can significantly enhance the determination of physical and chemical parameters from calorimeter experiments.

6 Conclusions

This review collects various studies on the origin and management of heat generation in lithium-ion batteries (LIBs). It identifies factors such as internal resistance, electrochemical reactions, side reactions, and external factors like overcharging and high temperatures as contributors to heat generation. Strategies to mitigate heat include thermal management, cell design optimization, battery management systems, and research into advanced materials. This section highlights the importance of managing heat for the safety, efficiency, and longevity of LIBs. The review outlines specific research efforts and findings related to heat generation in LIBs, covering topics such as the impact of temperature on battery performance, the development of advanced calorimeters for accurate heat measurement, and studies investigating heat generation rates in various battery designs and operating conditions. Each study aims to enhance the understanding and management of heat generation, ultimately contributing to safer and more efficient LIBs.

Lithium-ion batteries (LIBs) are complex systems characterized by interconnected electrochemical and thermal processes that result in elevated temperatures.

These batteries are gaining significant attention in industries such as automotive, electronics, and aerospace. However, challenges related to battery thermal management, safety concerns, costs, and suboptimal performance in low temperatures hinder their widespread adoption in commercial vehicle applications. Heat generation within the lithium-ion cells poses limitations on performance, safety, and dependability, necessitating a thorough examination of its impact on various battery components and the formulation of optimal strategies to address these issues.

Despite the favorable attributes of LIBs for use in fully electric and hybrid electric vehicles, challenges related to safety, cost considerations, and suboptimal performance in low temperatures have impeded their widespread deployment. These challenges are closely tied to the realm of battery thermal management. Understanding the speed at which heat is produced within a Li-ion cell is crucial for ensuring the safety and efficacy of individual cells and broader Li-ion systems. The overall performance, lifespan of the cell's cycles, and the safety of the system are contingent on the distribution of temperature within the cell, which depends on the rate of heat generation and dissipation.

While various theoretical models exist to predict heat generation rates, practical measurements at elevated C-rates are lacking in the literature. LIBs inherently face thermal constraints, including capacity deterioration and thermal runaway. Therefore, understanding the heat generation during regular operation is crucial. A well-designed thermal management system requires a comprehensive understanding of the thermal characteristics exhibited by power batteries. Accurate quantitative information regarding the thermal dynamics of LIBs during charging and discharging is essential for developing effective thermal management systems and enhancing battery safety.

Given the lack of detailed experimental and numerical information in existing literature about the thermal behavior and heat generation of LIBs, various studies were gathered to analyze their thermal behavior through heat generation measurements under different working conditions. The results of these investigations can be utilized to improve the design of LIBs. It is evident that LIB heat generation is influenced by factors such as the initial and final state of charge, chemistry, construction, charge or discharge rate, and battery temperature. The literature review indicates a scarcity of studies on the influence of configurational parameters using battery calorimeters with computational fluid dynamics. Most previous studies used comparatively small charge and discharge rates and complicated designs, highlighting the need for well-designed thermal management systems, especially during ultra-fast charging and discharging.

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Data availability statement

In this section, please provide, if your study reports data, details regarding where data supporting reported results can be found. If legally and ethically possible, authors should indicate whether or not their manuscript has associated data and where positive (and appropriate), if the data has been deposited in a data repository [whose location should be disclosed here]. Alternatively, authors could write: This article has no associated data generated and/or analyzed / Data associated with this article cannot be disclosed due to legal/ethical/other reason.

Author contribution statement

We expect that all authors will have reviewed, discussed, and agreed to their individual contributions ahead of this time. Contributions will be published before the references section, and they should accurately reflect contributions to the work. The following statements should be used "Conceptualization, X.X. and Y.Y.; Methodology, X.X.; Software, X.X.; Validation, X.X., Y.Y. and Z.Z.; Formal Analysis, X.X.; Investigation, X.X.; Resources, X.X.; Data Curation, X.X.; Writing – Original Draft Preparation, X.X.; Writing – Review & Editing, X.X.; Visualization, X.X.; Supervision, X.X.; Project Administration, X.X.; Funding Acquisition, Y.Y.".

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