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Heat generation mechanisms in batteries of electric and hybrid vehicles: Effects on performance and thermal management solutions

Mecanismos de geração de calor em baterias de veículos elétricos e híbridos: Efeitos no desempenho e soluções de gerenciamento térmico

Mecanismos de generación de calor en baterías de vehículos eléctricos e híbridos: Efectos en el rendimiento y soluciones de gestión térmica

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Abstract
This study investigates the heat-generation mechanisms in lithium-ion batteries used in electric and hybrid vehicles, analyzing their impact on performance and the solutions adopted to control temperature. Based on a literature review, the main thermal management strategies currently applied were examined, including air cooling, liquid cooling, phase-change materials, and heat pipes. The literature indicates that the optimal thermal operating range lies between 25 °C and 40 °C; temperatures above this threshold compromise cell integrity, accelerate aging processes, and significantly increase the risk of thermal runaway, considered the primary safety challenge. The reviewed studies demonstrate that geometric optimizations, material adjustments, and improvements in thermal-management system arrangements contribute to greater temperature uniformity, enhanced heat dissipation, and mitigation of thermal failures. Improving cooling systems is essential and integrating them with intelligent technologies represents a promising solution for the future of electric vehicles.
Keywords: Lithium-ion batteries; Electric vehicles; Hybrid electric vehicles; Heat generation mechanisms; Thermal management.

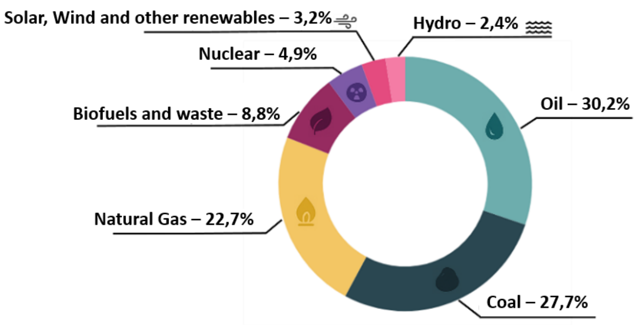
Resumo
Este estudo investiga os mecanismos de geração de calor em baterias de íons de lítio utilizadas em veículos elétricos e híbridos, analisando seus impactos no desempenho e as soluções adotadas para controlar a temperatura. A partir da revisão bibliográfica, foram investigadas as principais estratégias de gerenciamento térmico aplicadas atualmente, incluindo resfriamento a ar, resfriamento líquido, materiais de mudança de fase e tubos de calor. A literatura indica que a faixa ideal de operação térmica situa-se entre 25 °C e 40 °C; valores superiores de temperatura comprometem a integridade das células, aceleram processos de envelhecimento e elevam significativamente o risco de fuga térmica, considerado o principal desafio de segurança. Os estudos revisados demonstram que otimizações geométricas, ajustes nos materiais e melhorias nos arranjos dos sistemas de gerenciamento térmico contribuem para maior uniformidade de temperatura, melhor dissipação de calor e mitigação de falhas térmicas. Melhorar os sistemas de resfriamento é essencial, e integrá-los com tecnologias inteligentes é uma solução promissora para o futuro dos veículos elétricos.
Palavras-chave: Baterias de íons de lítio; Veículos elétricos; Veículos híbridos; Mecanismos de geração de calor; Gerenciamento térmico.

Resumen
Este estudio investiga los mecanismos de generación de calor en baterías de iones de litio utilizadas en vehículos eléctricos e híbridos, analizando sus impactos en el rendimiento y las soluciones adoptadas para controlar la temperatura. A partir de una revisión bibliográfica, se examinaron las principales estrategias de gestión térmica aplicadas actualmente, incluyendo el enfriamiento por aire, el enfriamiento por líquido, los materiales de cambio de fase y los tubos de calor. La literatura indica que el rango óptimo de operación térmica se sitúa entre 25 °C y 40 °C; valores superiores comprometen la integridad de las celdas, aceleran los procesos de envejecimiento y aumentan significativamente el riesgo de fuga térmica, considerado el principal desafío de seguridad. Los estudios revisados demuestran que las optimizaciones geométricas, los ajustes en los materiales y las mejoras en los arreglos de los sistemas de gestión térmica contribuyen a una mayor uniformidad de temperatura, una mejor disipación de calor y la mitigación de fallas térmicas. Mejorar los sistemas de enfriamiento es esencial, e integrarlos con tecnologías inteligentes representa una solución prometedora para el futuro de los vehículos eléctricos.
Palabras clave: Baterías de iones de litio; Vehículos eléctricos; Vehículos eléctricos híbridos; Mecanismos de generación de calor; Gestión térmica.

1. Introduction

Energy is essential to meeting the needs of modern society. Currently, the demand for electricity is growing more rapidly than total energy demand, driven by economic expansion and the electrification of end uses such as cooling, electric vehicles, and data centers. Despite advances in renewable sources, fossil fuels still accounted for approximately 80% of global energy demand in 2023 (IEA, 2025). The combustion of these fuels releases large volumes of carbon dioxide (CO_2), increasing the concentration of greenhouse gases (GHG) and intensifying the environmental impacts of climate change (Edenhofer, 2015). Figure 1 shows the percentage share of different sources in the global energy matrix, highlighting the predominance of fossil fuels.

Figure 1 – Global Energy Matrix 2023.



Source: IEA (2025).

Conventional vehicles not only require large amounts of petroleum-based fuels but also emit pollutants such as suspended particulate matter, hydrocarbons, nitrogen oxides, and sulfur oxides through their exhaust gases, thereby contributing to the worsening of environmental pollution (Lu et al., 2020). This scenario results in significant environmental impacts, including record high temperatures, anomalies in rainfall patterns, melting of polar ice caps, and an increase in respiratory diseases (Drumm et al., 2014).

In response to the energy crisis and environmental challenges, electric vehicles (EVs) have been regarded by several countries and the scientific community as viable alternatives to internal combustion engine vehicles. They have increasingly established themselves as significant forces in the global automotive market, as they align with more sustainable solutions for the transportation sector (Sun et al., 2019). Although many people consider electric vehicles to be a recent innovation, their development began as early as the nineteenth century (Novais, 2016). EVs are characterized by being propelled by at least one electric motor, unlike internal combustion vehicles, in which electric motors play secondary roles, such as powering auxiliary systems (Castro & Ferreira, 2010).

Despite the environmental and technological benefits associated with EVs, several challenges remain. Among these, the development of reliable, efficient, and robust energy storage and charging systems stands out, as these components are fundamental to the feasibility and overall performance of such vehicles (Liang et al., 2023). In this context, the advancement of battery technologies plays a central role. Batteries operate as energy storage devices, converting chemical energy into electrical energy and vice versa, typically through redox reactions (Castro et al., 2013). This technology has revolutionized the electric vehicle market; however, significant progress is still required to enhance performance, reduce costs, and increase production capacity (Zeng et al., 2019).

Among the various types of energy storage devices, lithium-ion batteries receive particular attention due to their environmental compatibility and widespread use in electric vehicles around the world (Deng et al., 2020). This technology stands out as the primary energy source for EVs because of its intrinsic advantages, including high energy density, absence of memory effect, long cycle life, and design versatility (Zhang et al., 2018). However, the storage capacity and durability of lithium-ion batteries are strongly affected by temperature. Numerous studies indicate that increased cell temperature accelerates capacity degradation and reduces battery lifespan (Behi et al., 2020). Additionally, factors such as aging, thermal runaway, high cost, safety concerns, and electronic waste disposal remain critical issues, as these systems involve highly energetic materials and flammable electrolyte solutions. Among these challenges, safety is the foremost concern for any manufacturer (Choudhari et al., 2020).

Therefore, an effective cooling system is essential to maintain energy efficiency, extend battery lifespan, and ensure the safe operation of batteries in electric vehicles. Among the main technologies employed in thermal management are air cooling, liquid cooling, phase-change materials, and heat pipes. Each of these solutions presents specific advantages and limitations, yet all share the primary objective of keeping battery operating temperatures within an optimal range, generally between 25 °C and 40 °C, thereby ensuring performance and prolonging the lifespan of energy storage systems (Pesaran et al., 2001).

Traditionally, vehicles are powered by internal combustion engines, which operate through the combustion of fossil fuels such as gasoline and diesel. In these engines, the combustion of a compressed mixture of air and fuel generates mechanical energy that is transmitted to drive the wheels. However, this combustion process produces significant emissions of pollutants that are released into the environment through the exhaust system, directly contributing to environmental degradation and public health issues (Vaz et al., 2015).

As an alternative to conventional vehicles, electric vehicles have emerged as a more efficient and environmentally sustainable solution. These vehicles stand out for energy savings, reduced pollutant emissions, and mitigation of environmental impacts. The widespread adoption of such vehicles represents a strategic advancement in the transition toward a cleaner energy matrix, while also strengthening energy security and promoting a sustainable model of socioeconomic development (Zhang et al., 2022).

Depending on the primary energy source, EVs can be classified mainly into three categories: battery electric vehicles, hybrid electric vehicles, and plug-in hybrid electric vehicles (Guo et al., 2021). The energy flow in these three types of EVs is presented in Figure 2.

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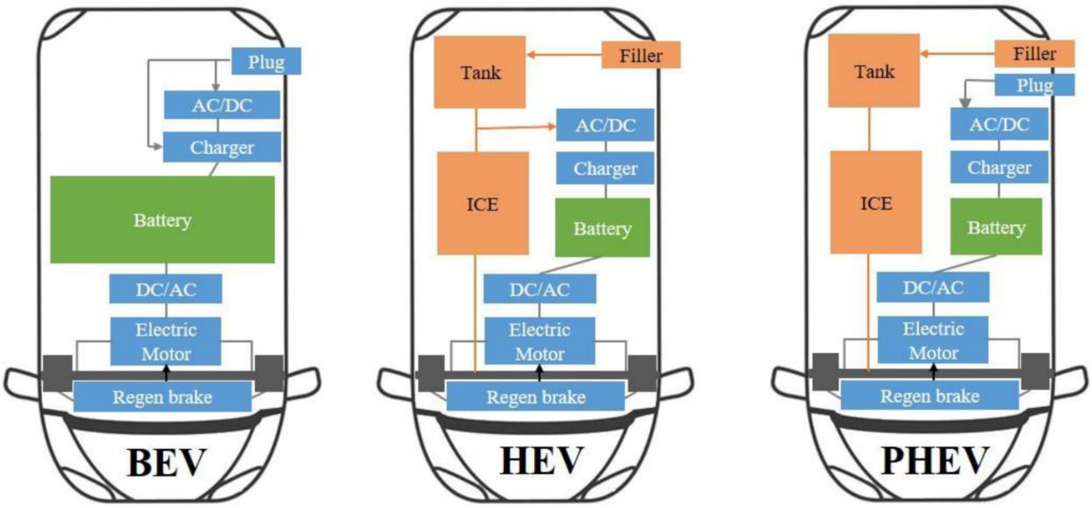
Figure 2 – The schematic representation of the three types of EVs; from left to right: Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV), and Plug-In Hybrid Electric Vehicles (PHEV).



Source: Guo et al. (2021).

Battery Electric Vehicles (BEVs) operate exclusively on electrical energy stored in rechargeable batteries. Recharging is performed through a direct connection to the power grid, with no electricity generation on board. Because they rely solely on batteries as their energy source, BEVs require higher-capacity batteries and greater driving range compared with other types of electric vehicles (Guo et al., 2021).

Hybrid Electric Vehicles (HEVs) represent an intermediate solution between conventional combustion vehicles and fully electric vehicles, combining an internal combustion engine with one or more electric motors for propulsion. This configuration enables more compact sizing components. In general, the greater the degree of hybridization, the larger the electric motor, alternator, and battery tend to be, while the combustion engine is typically downsized. However, HEVs are not designed to be connected to the power grid; that is, they do not have cables or connectors for external charging. Their batteries are recharged internally, primarily by the internal combustion engine and through regenerative braking, a system that converts the kinetic energy generated during braking into electrical energy stored in the battery. As a result, refueling with conventional fuel remains necessary for their operation (Vaz et al., 2015).

Plug-in Hybrid Electric Vehicles (PHEVs) share a configuration similar to that of conventional hybrid vehicles, combining an internal combustion engine with an electric motor. The key distinction lies in the ability of PHEVs to be recharged from an external electrical power source, such as dedicated vehicle chargers. Additionally, recharging can also occur through systems such as regenerative braking. Due to their higher-capacity batteries, these vehicles can operate over longer distances using only electrical energy, contributing to reduced fuel consumption and lower emissions (Guo et al., 2021).

However, it is essential to consider that the environmental benefits provided by electric vehicles are directly dependent on the source of electricity generation. In regions where the energy matrix is composed predominantly of renewable sources, a significant reduction in greenhouse gas emissions associated with the use of electric vehicles can be observed, reaching up to a 40% decrease in total emissions (Andersen et al., 2009).

Despite their advantages, the transition to electric and hybrid vehicles also presents challenges, such as high initial cost, limited charging infrastructure, and issues related to the sustainable disposal of batteries. These factors highlight the need for technological advances and public policies that encourage their adoption and ensure the maximization of both environmental and economic benefits.

Batteries are central components in electric vehicles, responsible for storing and supplying the energy required for traction. Unlike the auxiliary batteries used in internal combustion engine vehicles, EVs rely on high-capacity energy storage systems, which are typically organized into modules (groups of cells) or packs (sets of modules) (Castro & Ferreira, 2010). From an electrochemical perspective, batteries are devices that convert chemical energy into electrical energy through redox reactions. During discharge, oxidation occurs at the anode (negative electrode) and reduction occurs at the cathode (positive electrode), with electrons flowing through an external circuit and generating an electric current (Castro et al., 2013).

In the market, batteries can be classified as primary (non-rechargeable) and secondary (rechargeable). For electric vehicle applications, only secondary batteries are viable, as they offer the ability to undergo multiple charge-discharge cycles and present a lower environmental impact compared with disposable solutions (Silva Neto, 2023).

Among the most relevant battery technologies for the automotive industry are (Castro & Ferreira, 2010):

- **Lead–acid:** high cost and limited-service life, in addition to containing hazardous components (lead and sulfuric acid), which are subject to environmental regulations.
- **Nickel-metal hydride:** high reliability and long service life; however, disadvantages include high cost, mainly due to the elevated nickel content, relatively high weight, less-than-ideal efficiency because a considerable amount of energy is lost as heat, and the inability to undergo full discharge.
- **Lithium-ion (Li-ion):** higher capacity per volume, greater efficiency, and lower metal cost.
- **Sodium-ion:** emerging technologies with the potential to reduce costs and improve safety.

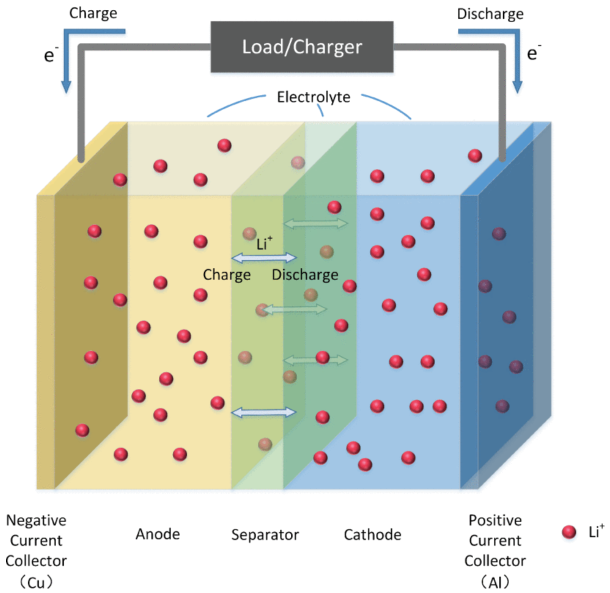
Lithium-ion batteries have become the most promising option for electric vehicles due to their critical advantages, such as high energy density, elevated cell voltage (3.0 - 4.5 V), low self-discharge rate, and good thermal efficiency compared with other chemistries, as well as simple charging requirements and extended cycle life. These characteristics make them the preferred choice for commercial applications (Mohammadi & Saif, 2023).

However, challenges such as thermal degradation, high cost, and the need for advanced management systems still limit their full potential. Research into new battery Technologies, such as sodium-ion systems, among others, seeks to overcome these barriers, offering prospects for improved safety and sustainability in the future.

In summary, lithium-ion batteries currently represent the most mature technology for electric vehicles, yet the continuous development of alternatives and the advancement of thermal management strategies are essential to ensuring large-scale performance, durability, and safety.

The fundamental architecture of a lithium-ion battery comprises five essential elements: anode (negative electrode), cathode (positive electrode), separator, current collectors, and casing, as illustrated in Figure 3. The separator acts as a physical barrier between the electrodes, preventing direct contact while allowing ion transport. The current collectors, positioned externally to the anode and cathode, enable the flow of electrons through conductive tabs that connect the battery to the external circuit, either to supply power to a load or to allow charging (Ismail et al., 2013). Lithium-ion batteries use lithium-containing compounds as cathode materials, such as $LiFePO_4$ (lithium iron phosphate), $LiMn_2O_4$ (lithium manganese oxide), and $Li(NiCoMn)O_2$ (nickel–cobalt–manganese oxide), while the negative electrode is typically composed of carbon (Zhang et al., 2022).

Figure 3 – Structure of the lithium-ion battery.



Source: Zhang et al. (2019).

The operation of lithium-ion batteries is based on the migration of lithium ions between the electrodes during charge and discharge cycles. During discharge, the ions move from the anode to the cathode through the electrolyte, releasing electrical energy. During charging, this movement occurs in the opposite direction, with the ions returning to the anode. These processes involve electrochemical reactions that require time and result in the simultaneous conversion of electrical and thermal energy (Zhang et al., 2022). The reaction dynamics can be exemplified, for instance, by the behavior of the lithium iron phosphate electrode (Padhi et al., 1997).

The positive electrode reaction during the discharge of a lithium-ion battery is expressed as follows:

$$LiFeO_4 \rightarrow Li_{1-x}FePO_4 + xLi^+ + xe^- \quad (1)$$

The negative electrode reaction is given by:

$$6C + xLi^+ + xe^- \rightarrow Li_xC_6 \quad (2)$$

The overall reaction is obtained as follows:

$$Li_xC_6 + Li_{1-x}FePO_4 \rightarrow 6C + LiFeO_4 \quad (3)$$

A detailed understanding of this structure is essential for the development of efficient thermal management systems.

The operation of lithium-ion batteries is associated with heat generation, which occurs primarily through two mechanisms: Joule heating, resulting from internal resistance during electron transfer, and electrochemical reactions, including entropy change (Hémery, 2013). These sources are also commonly referred to as irreversible heat (Q_irreversible) and reversible heat (Q_reversible).

To predict the heat generation rate in batteries, Bernardi et al. (1985) proposed an equation that integrates these factors, as follows:

$$Q = Q_{irreversivel} + Q_{reversivel} = I^2 \times R_{int} - IT \times \frac{dE_{ov}}{dT} \quad (4)$$

Where *I* represents the electric current, *R_int* is the internal resistance, *T* is the temperature, and *dE_OV/dT* corresponds to the entropic coefficient, which depends on both charge density and temperature. This coefficient changes its sign between charge and discharge processes, directly influencing the thermal behavior of the cell (Buidin & Mariasiu, 2021). The first term of the equation indicates that higher electrical currents, typical of high C-rate operation, lead to increased irreversible heat generation due to ohmic losses. Conversely, under low C-rate conditions, the proportion of reversible heat becomes more significant, as entropic contributions play a relatively larger role in the overall thermal balance (Heubner et al., 2015; Nazari & Farhad, 2017).

Several factors influence the amount of heat generated during the operation of lithium-ion batteries, including (Hémery, 2013):

- **C-rate:** the charge and discharge of current directly influences internal heating;
- **State of Charge (SoC):** it is directly related to electrochemical reactions and lithium-ion diffusion. This parameter affects, for example, the internal resistance of the battery;
- **Temperature:** elevated temperatures intensify electrochemical reactions and reduce the internal resistance of the battery;
- **Electrochemistry:** the active materials used in the electrodes significantly impact the amount of heat generated;
- **State of Health (SoH):** as the battery ages, its internal resistance tends to increase, thereby raising thermal dissipation.

Lithium-ion batteries are sensitive to thermal variations and tend to exhibit severe performance degradation when exposed to elevated temperatures, particularly above 40 °C (De Hoog et al., 2018). This behavior is associated with the high reactivity of lithium, an essential and highly flammable element in the composition of these batteries (Ouyang et al., 2019). In vehicles, battery packs are typically composed of numerous cells connected in series or in parallel, which promotes the accumulation of heat generated during charge and discharge cycles. This, in turn, hinders adequate heat dissipation in high-temperature environments (Xiaoqing et al., 2020).

When the heat generated is not efficiently controlled, one or more cells may enter a state of overheating, significantly increasing the risk of incidents such as combustion, explosions, or the release of toxic gases, including carbon monoxide (CO), nitric oxide (NO), sulfur dioxide (SO_2), hydrogen chloride (HCl), and hydrogen (H) [32]. In addition, it is important to consider that battery systems installed in vehicles are subjected to adverse operational conditions, such as continuous vibrations, mechanical shocks, overcharging, short circuits, collisions, and even punctures. These factors increase the likelihood of hazardous events, such as thermal runaway (Zhang et al., 2019).

Another important factor is the impact of temperature on the capacity of lithium-ion batteries. Studies indicate that, under a constant temperature of 55 °C, these batteries can lose up to 70% of their capacity after 500 discharge cycles, while at an operating temperature of 50 °C they lose about 60% of their capacity after 600 cycles (Ramadass et al., 2002). In addition to performance loss, excessive and uncontrolled heat poses a real safety risk to vehicle occupants, making the development of effective thermal management strategies essential to ensure the stable and safe operation of batteries in electric vehicles.

The purpose of a battery thermal management system is to ensure that the battery operates within an ideal average temperature range, with minimal variations in temperature and voltage among cells, modules, and within the pack, as specified by the battery manufacturer (Karimi & Li, 2013). Temperature must be uniformly distributed within the pack, as a thermal gradient can lead to different aging rates among cells, causing distinct charge–discharge behaviors and possibly triggering thermal runaway (Fleckenstein et al., 2011).

To fulfill this function effectively, the thermal system must also meet the vehicle's structural and operational requirements, being reliable, compact, lightweight, easy to maintain, and with low energy consumption and reduced cost (Tran et al., 2014). Currently, battery thermal management systems rely on different cooling methods, which can be generally classified into four main categories:

- Air cooling
- Liquid cooling
- Phase Change Materials (PCMs)
- Heat pipes

The selection of the most appropriate method depends on several factors, such as the operational characteristics of the vehicle, the space available for the system, the required power density, and the environmental conditions to which the system will be exposed.

Air cooling is widely used for heat dissipation in battery packs, taking advantage of the airflow generated by vehicle motion to promote natural convection or create a forced airflow through fans. Natural convection offers benefits such as simplicity, low weight, and low cost, but it has the disadvantage of limited thermal dissipation capability since the airflow cannot be controlled. Forced convection, on the other hand, generated by fans, is more efficient and easier to maintain, making it a more common solution for battery cooling. However, a frequent drawback of this system is the uneven temperature distribution among cells and the low heat capacity of air, which restrict its application in higher C-rate operations. Several researchers worldwide have dedicated efforts to optimizing this process, aiming to improve thermal uniformity while considering internal variations within the cells (Zhang et al., 2022; Peng et al., 2019).

In battery thermal management systems using liquid cooling, the heat generated by the cells is transferred through conduction and convection to a coolant, typically a mixture of water and ethylene glycol, that circulates through cooling channels. Compared to air-based systems, liquid coolants present higher thermal conductivity and superior specific heat capacity, making them more efficient at absorbing and removing heat. This efficiency allows the system to operate with lower flow rates while achieving the same thermal performance, thereby reducing energy consumption and noise levels. However, liquid cooling introduces challenges such as increased system weight and volume, which may compromise the driving range of electric and hybrid vehicles (Koyama et al., 2019). Additionally, because these fluids are electrically conductive, they require rigorous sealing to prevent leaks that could lead to short circuits, component failures, or even fires. As a result, sealing becomes a critical design requirement, increasing manufacturing costs compared to air-cooling systems (Zhao et al., 2021).

In recent years, the use of phase change materials (PCMs) in battery thermal management systems has gained prominence as a promising solution, primarily due to their notable advantages, including compact dimensions, low cost, high energy-storage density, and the potential for energy savings (Lu et al., 2020; Jiang et al., 2020). During the phase change process, PCMs can absorb or release large amounts of latent heat, maintaining the system's temperature nearly constant. This characteristic, combined with minimal temperature and volume variation during the phase transition, significantly contributes to the thermal uniformity of the battery, keeping it operating within safe limits (Lu et al., 2020; Huang et al., 2019; Verma et al., 2019).

The heat pipe is an effective thermal management method for electric vehicle batteries, standing out for its ability to maintain uniformity among the battery cells and being adaptable to operate at different temperatures according to system requirements (Wang et al., 2020). This device operates based on the phase change principle, which grants it high heat-transfer efficiency and low thermal resistance, functioning as a heat exchanger capable of transferring heat from high-temperature regions to lower-temperature ones through phase transitions (Wang et al., 2023; Shailesh et al., 2023). This system features low cost, reduced maintenance, light weight, and long service life, making it a passive cooling solution that has attracted considerable attention for various applications, including electric vehicles (Behi et al., 2017). Its variable structure enables the transport of large heat loads within the battery pack, keeping it within the ideal operational temperature range (Lu et al., 2020; Zhang et al., 2020).

Given the scenario presented and the recognized criticality of thermal management, this study investigates the heat generation mechanisms in lithium-ion batteries used in electric and hybrid vehicles, examining how these phenomena affect system performance, safety, and lifespan. In addition, the efficiency and limitations of the main thermal management solutions currently employed are analyzed.

2. Methodology

This study was conducted through a literature review (Snyder, 2019), characterizing it as qualitative research with an exploratory approach (Pereira et al., 2018) and of specific kind of narrative revision of literature (Rother, 2007). The investigation was based on the analysis of scientific and technical publications available in recognized databases, such as the Journal of Energy Storage, Energies, Journal of Power Sources, Applied Thermal Engineering, among others. The research focused on the mechanisms of heat generation in lithium-ion batteries and on the main thermal management strategies applied to these systems. Articles addressing solutions such as air cooling, liquid cooling, the use of phase change materials, and heat pipes were selected. The identified content was organized into thematic categories, enabling an analysis of the different research areas and methodologies employed in literature.

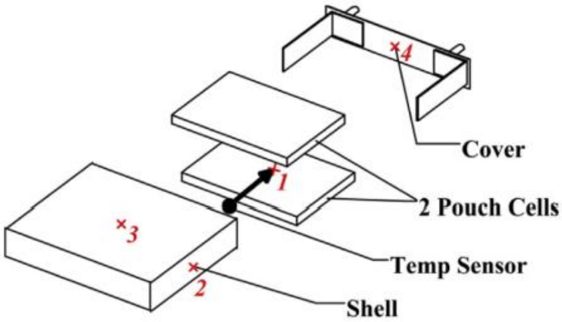
3. Results and Discussion

This section presents and discusses the findings obtained from the review of experimental and numerical studies on the thermal management of lithium-ion batteries. Given the growing demand for greater range, efficiency, and safety, understanding the thermal risks associated with battery operation and the technological solutions employed for temperature control becomes essential. The results are organized into two thematic axes. The first addresses battery behavior under stress conditions, highlighting mechanisms of thermal runaway, failure propagation, and aging effects. The second examines cooling strategies applied to thermal management systems, including air convection, liquid cooling, phase change materials, and heat pipes, evaluated in terms of thermal efficiency, temperature uniformity, and feasibility for electric and hybrid vehicle applications.

3.1 Thermal Runaway Characteristics and Abuse Behavior

Feng et al. (2014) investigated a large-format (25 A) prismatic lithium-ion cell with an NCM (Nickel–Cobalt–Manganese) cathode composition using extended-volume accelerating rate calorimetry (EV-ARC). Figure 4 illustrates the prismatic cell, which is composed of two pouches, as well as a temperature sensor, casing, and lid. The parallel pouches are wrapped in aluminum to enable precise internal measurements using micro-thermocouples, in addition to external sensors distributed around the battery. The study found that the internal temperature of the battery can reach 870 °C during thermal runaway, with an internal temperature difference of up to 520 °C at the critical moment. The internal resistance of the cell progressively increased from 20mΩ to 60mΩ prior to runaway, reaching 370mΩ at the critical point. Moreover, a sharp voltage drop precedes the temperature rise by 15 to 40 seconds, providing a window for early detection of thermal risk. The study highlights the importance of early identification of critical warning signs as an essential tool to mitigate the risk of catastrophic failures.

Figure 4 – Thermocouple positions.



Source: Feng et al. (2014).

Feng et al. (2014) also conducted a study focused on the performance of 25 A NCM cells subjected to high temperatures without reaching the point of thermal runaway, as the test was interrupted in time. Even without structural collapse, a capacity loss of up to 20% was observed after a single heating event at 120 °C. If the temperature exceeded 140 °C, the battery became unusable due to separator collapse. Subsequent analyses using incremental capacity and prognostic modeling indicated that the degradation was caused by an increase in ohmic resistance, loss of lithium inventory (LLI) at the anode, and loss of active material (LAM) at the cathode. Nevertheless, part of the lost capacity could be partially recovered after additional cycles, suggesting the possibility of limited post-event recovery. The results demonstrate that elevated temperatures, even without thermal runaway, accelerate electrochemical degradation and compromise battery lifespan.

Larsson & Mellander (2014) conducted thermal, electrical, and mechanical abuse tests on different types of commercial lithium-ion cells. The results revealed variable responses depending on cell chemistry. Laptop cells with cobalt-based cathodes, when exposed to heat, experienced thermal runaway events accompanied by gas release, fire, and temperatures exceeding 700 °C. In contrast, lithium iron phosphate cells, although more stable, also exhibited thermal runaway in some samples. Under overcharge tests, only one severe incident was recorded, although minor events were frequent. Short-circuit tests produced high current peaks (up to 1000 A), but the resulting temperature rise remained relatively moderate. These findings demonstrate that, although modern lithium-ion batteries are generally safer, they remain susceptible to hazardous failures under severe abuse conditions.

The propagation of thermal failures in multi-cell modules was analyzed by Chen et al. (2019), who demonstrated that, once initiated, thermal runaway tends to spread rapidly, triggering multiple cells simultaneously. In controlled tests, up to 32 batteries ignited at the same time, which drastically increased the mass-loss rate and intensified the fire. Heat flux and impact pressure data confirmed the simultaneous ejection of heat and combustible material from multiple cells, indicating a highly hazardous collective behavior. The study highlights the elevated risk of thermal propagation in multi-cell modules and underscores the importance of physical barriers and containment strategies.

Complementing this analysis, Lamb et al. (2015) compared modules composed of cylindrical cells and pouch cells. They found that modules using cylindrical cells (10S1P) exhibited greater resistance to thermal propagation due to the limited physical contact between cells. In contrast, modules with pouch-type cells, which have a larger contact area, experienced propagated failures within 60–80 seconds after the initial ignition. Thus, both the electrical configuration and the physical compactness between cells directly influence the severity and speed of thermal propagation. The study demonstrates that the cell type and its physical configuration play a critical role in determining thermal propagation behavior, making them essential factors in the design of safer battery modules.

Cui et al. (2022) conducted a large-scale experimental study to investigate the behavior and risks associated with fires in plug-in hybrid electric vehicles (PHEVs) caused by thermal runaway in lithium-ion batteries. Using two new vehicles, the tests showed that after approximately 60 minutes of heat exposure, intermittent releases of white smoke, rich in combustible gases, occurred, leading to gas explosions prior to the appearance of visible flames. The flames spread rapidly, reaching the passenger compartment in less than 10 minutes, with temperatures peaking at 843.6 °C and fire columns up to 3 m high. The results demonstrate the high thermal and explosive hazard potential in PHEVs, highlighting the need for flame-retardant materials and effective fire-protection strategies.

Table 1 presents a summary of the studies addressing thermal runaway characteristics and abuse-related behavior.

Table 1 – Summary of Studies on Thermal Runaway Characteristics and Abuse Behavior.

Author/Year	Study Focus	Methodology	Main Advantages
Feng et al. (2014)	Investigation of a 25A NCM prismatic cell under thermal runaway conditions using EV-ARC	EV-ARC equipped with internal micro-thermocouples and external sensors (two pouches in parallel)	- Precise internal measurements with micro-thermocouples. - Identification of critical temperatures (up to 870 °C). - Discovery of an early detection window (15–40 s) before thermal escalation.
Feng et al. (2014)	Evaluate heating effects in 25A NCM cells without triggering thermal runaway	Controlled heating (up to 120–140 °C), incremental capacity tests and prognostic modeling	- Assessment of thermal performance below the runaway threshold. - Quantification of capacity loss (20% at 120 °C). - Identification of degradation mechanisms (increase in ohmic resistance, LLI and LAM). - - Evidence of partial capacity recovery after additional cycling.
Larsson & Mel-lander (2014)	Evaluate thermal, electrical and mechanical abuse tests in different lithium-ion battery chemistries	Thermal abuse tests, overcharge, short-circuit and mechanical evaluations on small commercial cells	- Comparison between chemistries (NCM, LFP, cobalt). - Demonstration of variability in response. - Evidence of higher stability in LFP, although not completely failure-free. - Records of current peaks (~1000 A) during short-circuit and frequent minor events during overcharge.
Chen et al. (2019)	Compare thermal failure propagation in multicell modules	Controlled propagation tests in modules; measurements of mass loss, heat flux and impact pressure; observation of simultaneous ignition	- Clear evidence of rapid thermal runaway propagation. - Identification of hazardous collective behavior (up to 32 cells igniting simultaneously). - Quantitative measurements (mass loss, heat flux, pressure) confirm the ejection of heat and combustible material.
Lamb et al. (2015)	Comparison between modules with cylindrical and pouch cells	Ignition tests in different layouts; measurement of propagation time; variation of physical compaction and electrical configuration	- Cylindrical cell modules demonstrated greater resistance to propagation. - Showed a direct influence of physical compaction and electrical configuration. - It demonstrated that geometry, physical contact, and packing density influence the severity and speed of propagation.
Cui et al. (2022)	Investigation of fires in HEVs/EVs caused by thermal runaway in lithium-ion batteries (tests on real vehicles)	Destructive tests on two new vehicles exposed to heat; monitoring of smoke, gas explosions, propagation, and temperatures	- Full-scale evaluation on complete vehicles. - Identification of explosive risks occurring before visible flames. - Evidence of rapid propagation toward the passenger compartment.

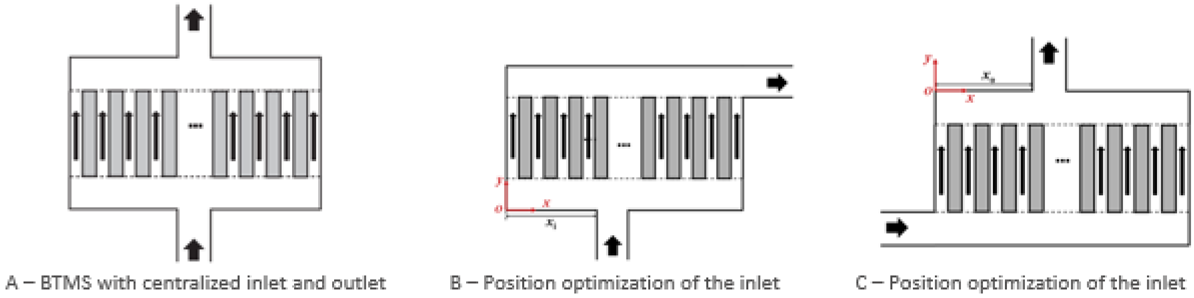
Source: Research data (2025).

3.2 Air Cooling System

In the study by Chen et al. (2019), the objective was to enhance the cooling efficiency of air-based thermal management systems through a redesign of the airflow pattern, with emphasis on the positioning of inlet and outlet regions.

Using Computational Fluid Dynamics (CFD) simulations, the authors demonstrated that these positions significantly influence the system's thermal performance. Figure 5 illustrates the air-cooled battery thermal management system with three inlet–outlet configurations. Figure 5A shows a centralized inlet and outlet arrangement, which provided improved temperature distribution, whereas the optimized outlet design shown in Figure 5C achieved the best performance among the evaluated models, markedly reducing both the maximum temperature and the thermal gradient between the cells. The study reinforces that airflow design is a critical factor for improving cooling efficiency in air-based thermal management systems.

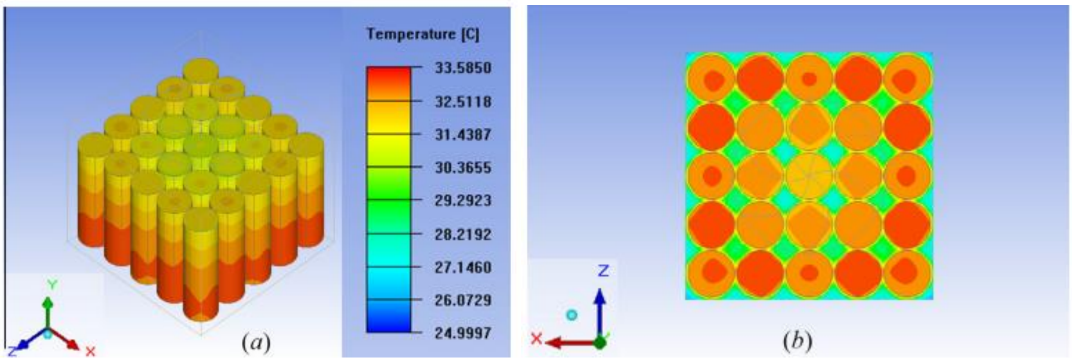
Figure 5 – Schematic of the simulated battery management system.



Source: Chen et al. (2019).

Wang et al. (2014) investigated the thermal performance of lithium-ion battery modules with different cell arrangements and forced-air cooling strategies. Using CFD simulations, the authors found that the position of the fan significantly affects thermal efficiency, with the upper-mounted configuration being the most effective. Among the evaluated arrangements, the cubic design illustrated in Figure 6 exhibited the best thermal performance with favorable cost–benefit characteristics, whereas the hexagonal layout provided superior space utilization. The study also identified an optimal spacing between cells to enhance temperature uniformity, emphasizing the importance of module design and ventilation in air-cooling systems. These results highlight that both cell arrangement and ventilation configuration play essential roles in optimizing the thermal performance of forced-air cooling solutions.

Figure 6 – Temperature distribution of the 5×5 battery module with a fan placed on the top surface of the module: (a) surface temperature and (b) cross-section temperature distribution through the middle of the cells

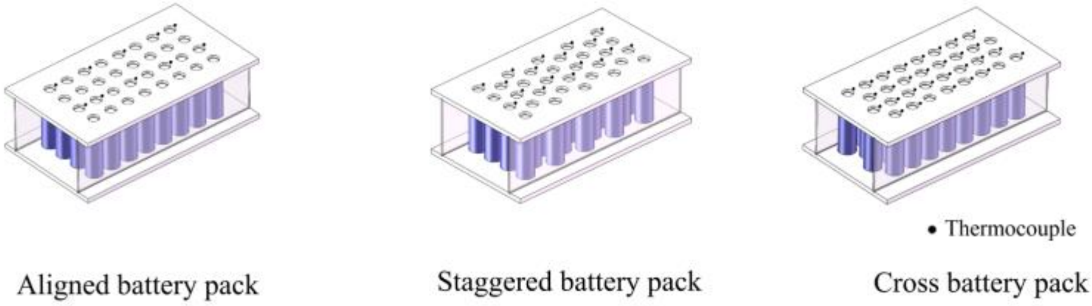


Source: Wang et al. (2014).

Fan et al. (2019) conducted an experimental study with 32 cylindrical lithium-ion cells to evaluate the thermal performance of different battery arrangements (aligned, staggered, and crossed) under air cooling, as illustrated in Figure 7.

The results showed that the aligned configuration provides the best cooling performance and temperature uniformity, in addition to the lowest energy consumption, being up to 23% more efficient than the crossed layout. The authors also observed that the system's energy efficiency decreases as air velocity increases and that the cooling capacity is limited by the discharge rate. The study demonstrates the influence of physical arrangement and operating conditions on the effectiveness of air-cooled battery systems, while also highlighting their limitations under high-demand scenarios. These findings are relevant for the development of more economical and efficient cooling solutions in practical applications.

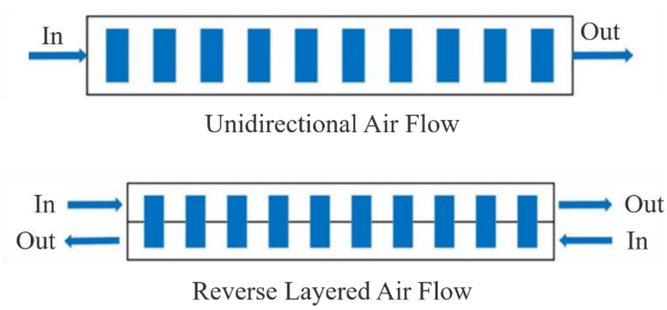
Figure 7 – Battery module in aligned, staggered, and crossed arrangements.



Source: Fan et al. (2019).

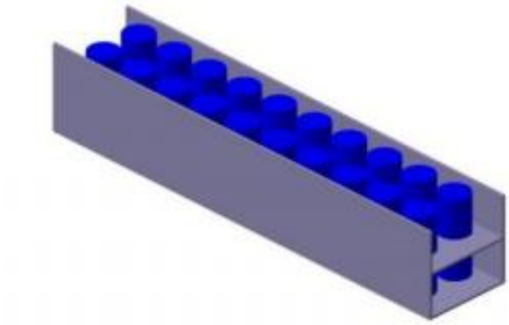
Na et al. (2018) proposed a novel reverse-layer airflow cooling strategy for the thermal management of lithium-ion batteries, aiming to improve temperature uniformity within the battery pack. In this system, air flows in opposite directions through adjacent channels separated by transverse partitions made of diathermic material, enabling heat exchange between the streams, as illustrated in Figures 8 and 9. Compared with conventional unidirectional cooling, the proposed configuration reduced both the maximum temperature and the average temperature difference within the module. With the addition of rectifying grids at the inlet, the maximum temperature was further reduced by 0.5 °C, while the average temperature difference decreased by 0.6 °C (a 54.5% reduction). The study also optimized design parameters such as inter-cell spacing and inlet air velocity, providing practical guidance for the development of more efficient air-cooling systems. The reverse-flow concept with inter-channel heat exchange represents an innovative approach for air-cooled battery thermal management, improving temperature uniformity and offering valuable design parameters for systems used in electric vehicles.

Figure 8 – Airflow diagram.



Source: Na et al. (2018).

Figure 9 – Three-dimensional model of reverse layered air flow.



Source: Na et al. (2018).

Table 2 summarizes the main studies on air-cooling systems applied to the thermal management of lithium-ion batteries.

Table 2 – Summary of studies on air-cooling battery thermal management systems.

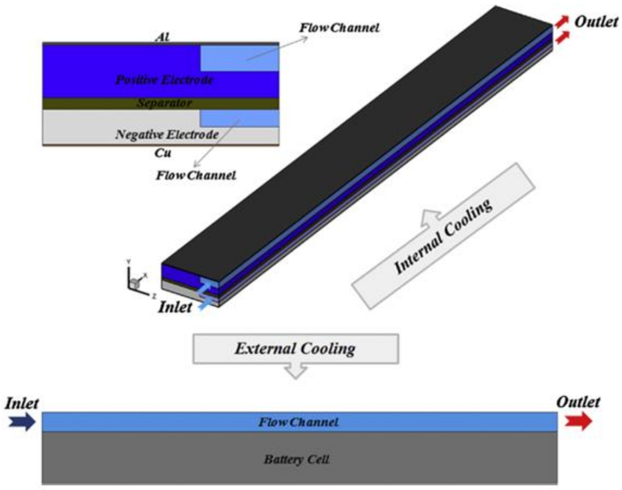
Author/Year	Study Focus	Methodology	Main Advantages
Chen et al. (2019)	Improve the efficiency of air-based thermal management systems by redesigning airflow patterns (inlet/outlet positioning)	CFD simulations comparing different inlet and outlet configurations	- Demonstrates the significant influence of inlet/outlet positioning on thermal performance. - Identifies the configuration with the best temperature distribution (centralized inlet/outlet). - Optimizes the configuration with the most uniform thermal field (Figure 7-C), reducing maximum temperature and thermal gradients.
Wang et al. (2014)	Evaluate the thermal performance of modules with different cell arrangements and forced-air cooling	CFD simulations testing fan placement, module layouts, and inter-cell spacing	- Identifies the most effective fan position (top-mounted). - Shows that cubic configurations offer the best performance-to-cost balance, while hexagonal layouts improve space utilization. - Determines optimal inter-cell spacing for thermal uniformity.
Fan et al. (2019)	Evaluate the thermal performance of physical layouts (aligned, staggered, crossed) in modules of 32 cylindrical cells under forced-air cooling	Experimental testing on 32 cells in different physical arrangements; measurement of temperature uniformity and energy consumption	- Finds that the aligned arrangement provides the best thermal uniformity and lowest energy consumption. - Notes reduced cooling effectiveness at higher airflow velocities, with performance limited by discharge rate.
Na et al. (2018)	Propose a reverse-layer airflow method to improve thermal uniformity in battery modules	Simulations and experiments with reverse-layer flow using diathermal baffles and rectifying grids	- Achieves reduction of maximum temperature and average temperature difference in the module (≈54.5% reduction). - Shows that optimized cell spacing and air inlet velocity provide practical design guidance.

Source: Research data (2025).

3.3 Liquid Cooling System

Mohammadian et al. (2015) compared internal and external cooling methods for prismatic lithium-ion cells using two- and three-dimensional simulations (Figure 10). In the internal cooling configuration, the electrolyte flows through microchannels embedded within the electrodes, whereas in the external method, the coolant (water) circulates through microchannels placed outside the cell. The results indicate that, under the same pumping power, internal cooling is more effective in reducing the maximum temperature and improving thermal uniformity. Moreover, internal cooling enhanced convective heat-transfer efficiency based on the field-synergy principle, demonstrating its potential as an advanced solution for lithium-ion battery thermal management. The study shows that internal microchannel cooling embedded in the electrodes offers significant advantages in terms of thermal efficiency and uniformity, highlighting the importance of technologies that act directly on the internal components of the cell to optimize heat dissipation.

Figure 10 – Internal and external cooling method applying microchannels.

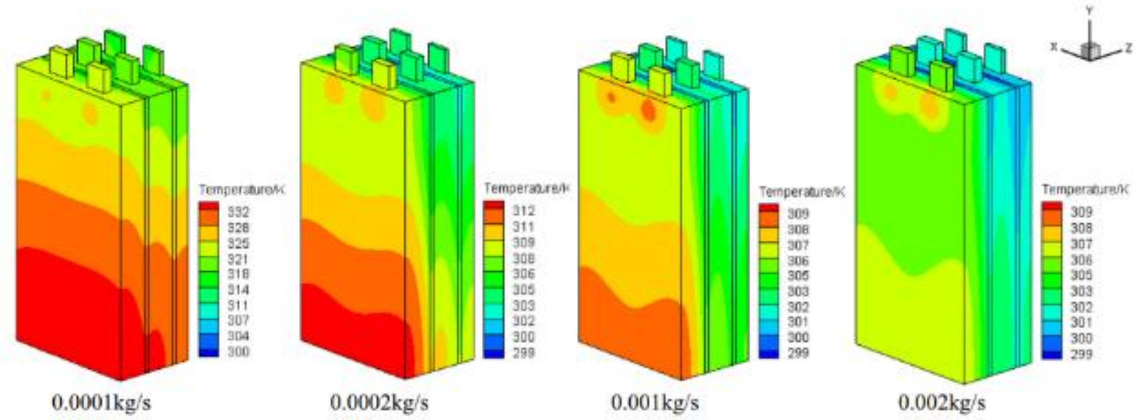


Source: Mohammadian et al. (2015).

Darcovich et al. (2019) conducted a comparison between two liquid–channel cooling plate configurations for battery thermal management in electric vehicles, using numerical simulations combined with electrochemical and thermal models. The first configuration, referred to as the ice plate, is positioned between the battery cells and provides highly uniform cooling, with temperature variations ranging from 304.2 K to 304.6 K. The second configuration, the cold plate, is installed at the bottom of the cells, cooling them only from the lower surface, which results in a less uniform thermal distribution with temperature differences of up to 5 K. The ice plate exhibited superior performance in maintaining thermal uniformity, a crucial factor for preventing localized thermal stress that can accelerate cell degradation. However, the cold plate showed advantages in terms of simplicity and integration cost, in addition to supporting higher coolant flow rates. The study highlighted that although the ice plate provides better thermal performance, the most suitable choice depends on the balance between performance and design complexity for practical applications.

Qian et al. (2016) investigated the thermal performance of a liquid-cooling battery thermal management system based on cold plates with minichannels for lithium-ion cells. Using three-dimensional numerical simulations, the authors analyzed the influence of parameters such as the number of channels, inlet mass flow rate, channel width, and flow direction. The results showed that plates with up to five channels already provide efficient cooling, keeping the maximum temperature below 40 °C for most of the discharge cycle. Increasing the mass flow rate improves thermal performance (Figure 11), although at the cost of higher energy consumption, whereas increasing the channel width reduces pressure drop. The study demonstrates the importance of optimizing cold-plate design parameters, such as the number of channels and coolant flow rate, to ensure efficient cooling while controlling energy consumption and pressure losses.

Figure 11 – Temperature distribution at different inlet mass flow rates.



Source: Qian et al. (2016).

Wang et al. (2018) developed an innovative liquid-cooling strategy for large-capacity lithium iron phosphate ($LiFePO_4$) battery modules by combining thermal silica plates with water circulation. The high thermal conductivity of silica, together with the efficiency of liquid cooling, proved effective in reducing temperature under high-discharge conditions and elevated ambient temperatures. Experimental tests showed that this solution can reduce the maximum module temperature by up to 11.3 °C and limit the temperature difference to 6.1 °C. The best performance was achieved with a flow rate of 4 mL/s, which maintained the maximum temperature at 48.7 °C and kept the thermal gradient within 5 °C, while consuming only 1.37% of the system's total energy. The study demonstrates the potential of hybrid solutions that combine high-conductivity materials, such as silica, with liquid-cooling systems, reinforcing the need for innovative and combined approaches to thermal management in high-capacity battery systems.

Table 3 provides a summary of the main studies on liquid-cooling systems, highlighting the methodologies employed and the key findings reported in each investigation.

Table 3 – Summary of studies on liquid cooling systems.

Author/Year	Study Focus	Methodology	Main Advantages
Mohammadian et al. (2015)	Compare internal vs. external cooling in prismatic cells using microchannels.	2D/3D simulations of internal microchannels (embedded in electrodes) and external microchannels (on the cell surface)	- Internal cooling more effective in reducing peak temperature. - Improved thermal uniformity across the cell regions. - Increased convective heat transfer efficiency.
Darcovich et al. (2019)	Compare two liquid cooling plate configurations (cold plate vs. ice plate) for vehicular applications.	Numerical simulations coupled with electrochemical and thermal models	- Ice plate: better thermal uniformity. - Cold plate: simpler integration and lower cost. - Provides basis for design-performance trade-off decisions.
Qian et al. (2016)	Evaluate performance of cold plates with minichannels and the influence of geometric and flow parameters.	3D parametric simulations (number of channels, mass flow rate, channel width, and flow direction)	- Minichannels provide effective thermal control. - Higher mass flow rate significantly improves cooling performance. - Channel geometry optimizes both pressure drop and heat dissipation.
Wang et al. (2018)	Develop a practical liquid cooling solution for large-capacity $LiFePO_4$ modules (thermal silica + water circulation).	Experimental testing on a module using thermal silica plates with circulating water	- Significant reduction in module temperature. - Improved control of temperature differences between cells. - Low energy demand and practical viability for large-scale modules.

Source: Research data (2025).

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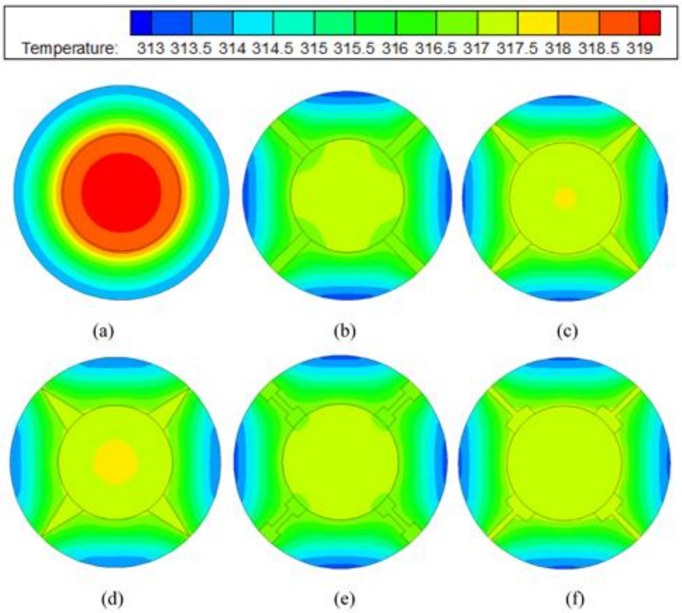
3.4 Phase-Change Material Cooling System

As an alternative to conventional air- or liquid-cooling methods, several studies have investigated the use of phase change materials (PCMs), leveraging their high latent heat during phase transition (Zhang et al., 2019).

Choudhari et al. (2020) conducted a numerical simulation to evaluate the thermal performance of a PCM-based cooling system for battery modules, examining different fin geometries and quantities (rectangular, triangular, trapezoidal, I-shaped, and T-shaped) to enhance heat dissipation (Figure 12). The results indicated that PCMs are effective at low discharge rates, keeping the cell temperature within safe limits. However, under high discharge rates, thermal performance deteriorates due to the low thermal conductivity of the PCM. Among the fin geometries tested, the I-shaped fin demonstrated the highest efficiency, and using four fins provided the best balance between thermal conduction and available PCM volume. An optimized model combining the best fin shape, optimal fin number, and external convection achieved superior performance, reducing battery temperature by up to 6.1 °C and improving thermal efficiency by 9.28% at high discharge rates. These findings show that fin geometry and quantity are critical design parameters governing the effectiveness of PCM-based thermal management systems.

Figure 12 – Temperature contours of PCM module (a) Without Fin (b) Rectangular Fin (c) Trapezoidal Fin (d) Triangular Fin (e) I-shape Fin (f) T-shape Fin.

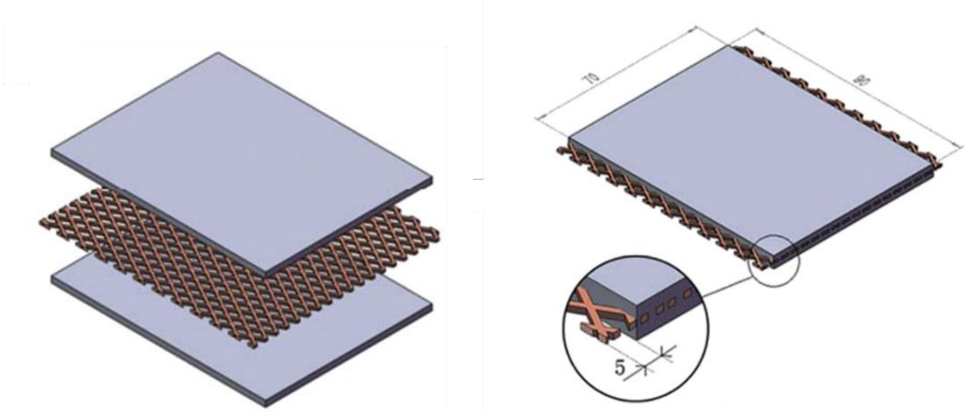


Source: Choudhari et al. (2020).

Bai et al. (2017) numerically analyzed a hybrid thermal management system combining a phase change material (PCM) and a water-cooled cold plate, applied to lithium iron phosphate battery modules. Using a two-dimensional electro-thermal model with a non-uniform internal heat source, the study evaluated parameters such as plate height, inter-cell spacing, coolant flow rate, flow direction, thermal conductivity, and PCM melting point. The results showed that the cold plate positioned near the electrodes effectively removed the heat generated during discharge, while the PCM inserted between the cells improved temperature uniformity. During five continuous charge–discharge cycles, the hybrid system successfully reduced the maximum temperature and maintained thermal balance, preventing thermal runaway and enhancing module safety. The study also concluded that the inlet flow rate strongly influences thermal performance, and that optimizing the PCM melting point and coolant inlet temperature is more impactful than increasing the PCM's thermal conductivity. These findings reinforce that strategically combining technologies such as PCMs and liquid cooling can overcome individual limitations, yielding more effective thermal control and improved battery safety.

Wu et al. (2016) developed a novel battery cooling solution using a composite phase change material consisting of paraffin, expanded graphite, and copper mesh (Figure 13). The goal was to overcome limitations of traditional materials, such as low thermal conductivity, leakage, and limited structural strength. In the composite, paraffin absorbs the generated heat, while expanded graphite prevents leakage and enhances heat transfer. The copper mesh reinforces the structure and further improves thermal dissipation. In practical tests, this composite material reduced the maximum cell temperature from 65.5 °C to 61.6 °C at a 5C discharge rate, in addition to improving temperature uniformity and accelerating cooling during rest periods. The exposed copper fins also enhanced convective heat transfer, making the system more efficient even under demanding conditions. The study demonstrates that combining multiple materials can significantly advance passive battery cooling. The proposed composite highlights the potential of materials engineering to overcome the inherent limitations of conventional PCMs, showing that innovations in material formulation represent a promising pathway to improved cooling performance and enhanced battery safety.

Figure 13 – Model developed using a phase-change material made of paraffin, expanded graphite, and copper mesh.



Source: Wu et al. (2016).

Table 4 provides a summarized overview of studies on phase change material (PCM) cooling systems and their thermal efficiency in battery applications.

Table 4 – Summary of studies on PCM-based cooling systems.

Author/Year	Study Focus	Methodology	Main Advantages
Choudhari et al. (2020)	Evaluate the use of PCM systems with different fin shapes and quantities for heat dissipation in battery modules	Numerical simulations varying fin geometry (I, T, rectangular, triangular, trapezoidal) and number of fins	- Improved thermal storage capability at low discharge rates. - Optimized fin geometry increases thermal conduction efficiency of the PCM. - Enables optimized design (shape + number of fins) for enhanced performance.
Bai et al. (2017)	Investigate a hybrid PCM + liquid cooling plate system for $LiFePO_4$ modules	2D electro-thermal modeling with parametric analysis (plate position, coolant flow rate, PCM melting point, spacing)	- Combines PCM buffering capacity with active liquid cooling, improving thermal uniformity. - Supports continuous operation (cycling) while reducing thermal risk in the module. - Provides practical design guidelines for integrating PCM with liquid cooling circuits.

Wu et al. (2016)	Develop a composite PCM (paraffin + expanded graphite + copper mesh) for passive thermal management	Experimental development of the composite material and discharge testing (5C), evaluating temperature and uniformity	- Increases effective thermal conductivity of the PCM, improving passive heat dissipation. - Enhances thermal uniformity and accelerates cooling during rest periods. - Provides structural robustness and compatibility with heat transfer intensification solutions (fins/airflow).

Source: Research data (2025).

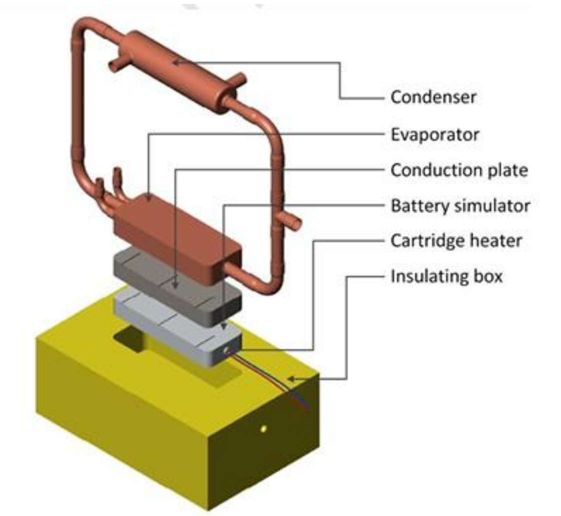
3.5 Heat Pipe Cooling System

Heat pipes are thermal devices that transport energy between two regions through the phase change of a working fluid inside a high thermal conductivity tube, attracting significant interest in research and studies.

Guo et al. (2023) analyzed the performance of thermal management systems using heat pipes in aged batteries, comparing conventional pipes and microtubes. Both systems performed well during the initial cycles but lost efficiency after 1,250 cycles due to increased heat generation caused by battery aging. The microtube system showed superior performance and, after optimizations such as tube orientation, non-equidistant arrangements, and the addition of cold plates, was able to maintain temperature control even after prolonged use, mitigating aging effects and preventing capacity loss. The study highlights that microtube heat pipe systems provide higher thermal efficiency in aged batteries, extending their lifespan. This emphasizes the importance of adaptive solutions to maintain thermal performance even after extended operational cycles.

Putra et al. (2016) experimentally investigated the use of closed-loop heat pipes with flat plates for thermal management of lithium-ion batteries in electric vehicles (Figure 14). The study tested different working fluids (distilled water, alcohol, and acetone) at a 60% fill ratio, simulating heat generation with a heater. The results showed that acetone exhibited the best performance, achieving a thermal resistance of 0.22 W/°C under a heat flux of 1.61 W/cm², maintaining the evaporator temperature around 50 °C, within the battery's ideal operating range. The research underscores the importance of selecting an appropriate working fluid for heat pipe performance, demonstrating that proper selection can optimize thermal dissipation and keep the battery within safe operational conditions.

Figure 14 – Flat plate heat pipe with battery simulator.

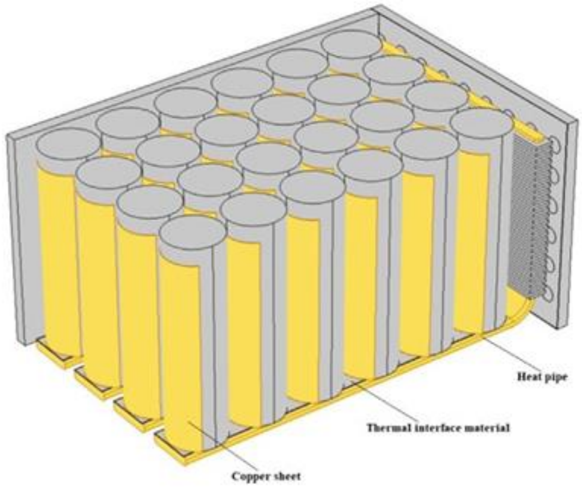


Source: Putra et al. (2016).

Ye et al. (2018) conducted an experimental study to evaluate the efficiency of a cooling system based on heat microtubes applied to lithium-ion batteries under continuous 1C charge and discharge cycles. The tests showed that the use of heat microtubes with fins helped maintain the battery temperature within the ideal operating range (25–40 °C), reducing the temperature rise rate and ensuring greater thermal uniformity between cells, with variations below 5 °C. The system also stood out for being compact, lightweight, easy to manufacture, and effective in both natural and forced cooling. Additionally, it was possible to prevent localized thermal runaway, increasing the stability and safety of the module during operation. The study demonstrated that heat microtube cooling is a promising and practical solution to enhance the thermal performance of batteries in high-power applications.

Behi et al. (2020) proposed a new hybrid thermal management system for electric vehicle batteries, combining air cooling with heat pipes and copper sheets (Figure 15). Using numerical simulations validated with experimental data, the study analyzed different cooling strategies in a module with 24 cylindrical cells, evaluating variables such as cell spacing, air velocity, and ambient temperature. The results indicated that the inclusion of heat pipes and copper sheets was the most efficient, reducing the module's maximum temperature to 37.1 °C and improving thermal uniformity by up to 73.4% compared to natural cooling. Heat pipes alone also performed well, followed by forced air cooling. The study demonstrates that combining these technologies is a promising approach to increase thermal efficiency and battery safety in electric vehicles.

Figure 15 –Battery module with heat pipes and copper plates.



Source: Behi et al. (2020).

Table 5 compiles studies on heat pipe systems, highlighting the positive aspects of the research and their effectiveness in battery thermal management.

Table 5 – Summary of studies on heat pipe–based cooling systems

Author/Year	Study Focus	Methodology	Main Advantages
Guo et al. (2023)	Evaluate the performance of conventional heat pipes vs. micro heat pipes in aged batteries	Simulations and long-cycle testing (>1250 cycles); optimization of pipe orientation and spacing; addition of cold plates	- Micro heat pipes maintain better performance in aged batteries. - Optimized configurations (orientation, non-uniform spacing, cold plates) improve thermal control. - Mitigates aging effects and reduces capacity degradation.

Putra & Nandy et al. (2016)	Test closed-loop flat heat pipe systems with different working fluids for thermal management	Experimental tests using various working fluids (distilled water, alcohol, acetone) and a heater simulating heat generation	- Working fluid selection strongly affects thermal performance. - Enables maintaining evaporator operation within optimal temperature range with the proper fluid. - Practical, low-complexity solution suitable for vehicular battery modules.
Ye et al. (2018)	Evaluate finned micro heat pipes under continuous cycling for maintaining cell temperature	Experimental tests at 1C discharge using finned micro heat pipes; measurement of temperature and inter-cell uniformity	- Finned micro heat pipes maintain cells within the ideal temperature range (≈25–40 °C). - Improve thermal uniformity between cells (variation <5 °C). - Compact, lightweight, and effective under both natural and forced convection; inhibits localized thermal runaway.
Behi et al. (2020)	Propose a hybrid system (air + heat pipes + copper sheets) for cylindrical cell modules	Numerical simulations validated experimentally on a 24-cell module; analysis of spacing, air velocity, and environmental conditions	- Combining air cooling, heat pipes, and copper plates improves thermal efficiency and module safety. - Reduces maximum module temperature and significantly improves uniformity (e.g., Tmax ≈37.1 °C with strong uniformity improvements). - Applicable to real modules and more effective than natural cooling alone.

Source: Research data (2025).

4. Conclusion

This study aimed to analyze the heat generation mechanisms in lithium-ion batteries used in electric and hybrid vehicles, emphasizing their effects on thermal performance, operational safety, and lifespan, as well as exploring the main solutions adopted in battery thermal management systems. The analysis was conducted through a literature review based on various research sources, including experimental and numerical studies that investigate both heat generation mechanisms and thermal containment and dissipation technologies applied under real operating conditions. Some key conclusions from the review can be summarized as follows:

- Heat generation in batteries occurs due to both irreversible effects (Joule heating) and reversible effects (electrochemical reactions with entropic variation), being intensified at high current rates and with system aging.
- The ideal thermal operating range for lithium-ion batteries is between 25 °C and 40 °C. Temperatures above this range accelerate degradation, reduce capacity, and can trigger thermal runaway.
- Thermal runaway represents the greatest risk associated with batteries, potentially causing fires with temperatures exceeding 800 °C, release of flammable gases, and rapid propagation between cells, especially in compact modules with high thermal contact.
- In aged batteries, the reduced thermal performance of traditional cooling systems highlights the need for specific optimizations, such as directional arrangements, cold plates, and adaptive cooling based on the cell’s state of health.
- Air-cooling systems stand out for their simplicity and low cost but exhibit limitations in high thermal load environments. Optimized ventilation strategies, such as reverse flow and specific structural arrangements, significantly improve thermal uniformity and heat dissipation.
- Liquid cooling demonstrates excellent thermal performance, including technologies with cold plates, minichannels, or thermal silica. These solutions maintain lower temperatures even under intense cycling, with minimal energy impact.

- The use of phase change materials (PCMs) has shown promise for passive applications, contributing to thermal uniformity. However, their effectiveness at high discharge rates depends on hybrid solutions, such as metallic fins, thermal conductors, or combined liquid plates.
- Heat pipes, especially micro-scale tubes and flat plates, demonstrated efficient thermal management without significant energy consumption, standing out for their light weight and applicability in space-constrained environments.

As future perspectives, it is recommended to investigate new battery technologies, develop intelligent thermal management systems based on sensors and predictive algorithms, create strategies to extend the lifespan of aged batteries, as well as integrate battery thermal management with other vehicle systems to enhance energy efficiency and reduce costs, in addition to exploring sustainable solutions for the disposal or repurposing of batteries at the end of their life cycle.

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