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Review of Sophisticated for Thermal Management Systems in Battery Cooling

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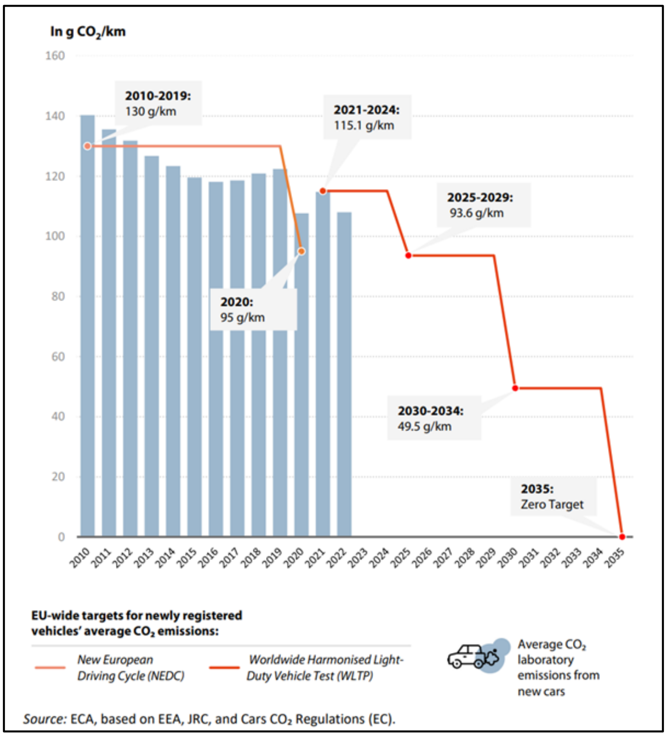
Abstract

The transition to electric vehicles (EVs) is a crucial step towards mitigating climate change and addressing the global energy crisis. The increasing use of lithium-ion batteries in EVs is attributed to their superior power density and efficiency. However, ensuring optimal battery performance and safety necessitates effective thermal management due to the significant heat generated during operation. Current cooling systems face challenges in maintaining the desired temperature range and uniformity. This paper reviews the state-of-the-art techniques in battery thermal management, focusing on phase change material (PCM) cooling and different cooling methods. This study, in accordance with its developments, compares the advantages and limitations of various cooling methods as potential solutions for next-generation EVs. It highlights the potential of method cooling, which, while promising, needs further research to establish its commercial viability and aims to guide future advancements in battery thermal management for next-generation EVs. Under both typical and extreme usage scenarios, direct cooling may enhance the necessary battery performance and serve as an innovative method for managing the temperature of electric vehicle batteries. The primary challenge of this technique lies in its suitability for commercial application. This article is organized to cover the thermal properties of lithium-ion batteries, the main issues associated with lithium-ion battery heat, a discussion of reversible and irreversible heat generation and their effects on battery performance, as well as strategies for preventing and mitigating thermal runaway in battery systems. Finally, it summarizes the key recommendations for future research on battery thermal management.

1. Introduction

Rising energy demands have brought up the problem of fossil fuel depletion, which is already a big challenge on a global scale with fast expanding pollution and climate change. The reduction of carbon dioxide (CO_2) emissions from cars is critical in addressing the broader challenge of climate change. According to the European Court of Auditors 2024, CO_2 emissions from transport account for nearly 23% of EU's total greenhouse gas emission, with passenger cars contributing more than the half, see Fig. 1 [1]. Vehicles powered by internal combustion engines (IC-engines) account for the vast majority of transportation-related fuel consumption and are a major contributor to environmental deterioration. Future environmental protection and IC engine vehicle replacement issues may be best addressed by electric vehicles (EVs) that offer the dual benefits of zero emissions and energy savings [2]. Figure 2 illustrated the future demand of EVs.

While modern cooling techniques for battery thermal management are essential for enhancing performance and longevity, they can also introduce significant complexity and cost to the overall system design. Furthermore, reliance on advanced cooling methods may lead to over-engineering, potentially overshadowing simpler, more efficient solutions that could suffice in less demanding applications.



Source: ECA, based on EEA, JRC, and Cars CO_2 Regulations (EC).

Fig. 1 EU-wide targets for newly registered vehicles average CO_2 emissions [1].

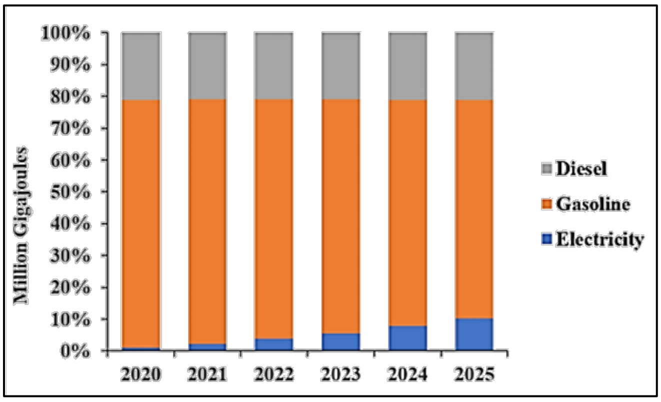


Fig. 2 The proportion of energy demand under the low carbon (LC) scenario [2].

Consequently, the popularity of electric vehicles has been driving growth in the transportation industry around the world in recent years. Due to their many desirable qualities, including a long lifecycle, low self-discharge rate, high power factor, high energy density, and excellent stability, lithium-ion batteries are now the most popular and effective power source for electric vehicles [3]. Electric vehicles use high energy density batteries to match the performance of vehicles with internal combustion engines. Faster and greater charging/discharging circumstances cause such high power-density batteries to generate a lot of heat.

A battery's charging/discharging performance, internal electrochemical processes, dependability, service life, and safety are all impacted by the heat generation, which in turn modifies the operating temperature of the battery.

For electric vehicle (EV) batteries to function efficiently and safely, their maximum temperature should not exceed 20–45 °C, and their temperature uniformity should not exceed 5 °C. The Li-ion battery's performance drops sharply, its lifespan decreases, and it experiences a thermal runaway which can cause a fire or explosion when used outside of the aforementioned range. There is localized deterioration that occurs while operating batteries at variable charging and discharging rates. When the battery module's maximum temperature goes beyond 50 C, the deterioration rate and ageing phenomenon are both expedited [4]. In this paper next sections organized several models.

2. Models of battery colling system

Different battery cooling systems can be categorized as:

2.1. Air cooling systems (ACS)

Use the driving wind owing to the vehicle body to dissipate the heat from the batteries and to cool the batteries. Such a thermal management cooling system is comparatively simple, with lightweight and lower cost. Yet, such a cooling system would work effectively only for the batteries that can be bent for placement on the vehicle floor, since less airflow penetrates into the pack [5].

2.2. Liquid cooling systems (LCS)

Use air or liquid to remove heat from batteries and transfer the heat to a radiator to shed the heat. A cooling system with liquid-cooled batteries has an improved operating performance based on a high heat capacity of the liquid and a high thermal conductivity of a material of the cooling plate to the liquid. Generally, the liquid cooling system can operate better than the air-cooling system when the heat load is raised or the external cooling conditions are stringent [6].

2.3. phase change material (PCM)

Cooling system have been recently actively investigated as an innovative concept to remove the heat from electric vehicle (EV) batteries (see Fig. 3). PCM removes heat through a solid-liquid phase change process (see Fig. 4). It is capable of storing 5 to 14 times more heat compared with the sensible temperature rise of the same material by increasing its temperature. Once the phase transition temperature of the PCM is reached, the substance remains at that temperature until all the PCM is transformed into liquid. Owing to this advantage, PCM can keep the temperature of the cooling system close to the phase change temperature level. Thus, the heat rejection from the PCM-based cooling system occurs at a nearly constant temperature with a variable flow rate on the secondary side, containing the heat in battery cells to a small temperature range. This evens out the hot spots across the battery pack and enables the direct incorporation of battery packs in the cooling circuit. A delta in the low-cc versus large-cc vehicle case for PCM application pays out at 1 h, decreasing to 31.3 min at 6 h charge. Liquid cooling features a higher overall cooling rate and temperature variation compared to PCM cooling, but a longer cool down time. These comparative results assist in a techno-economic assessment of energy demand in the cooling infrastructure. [7]

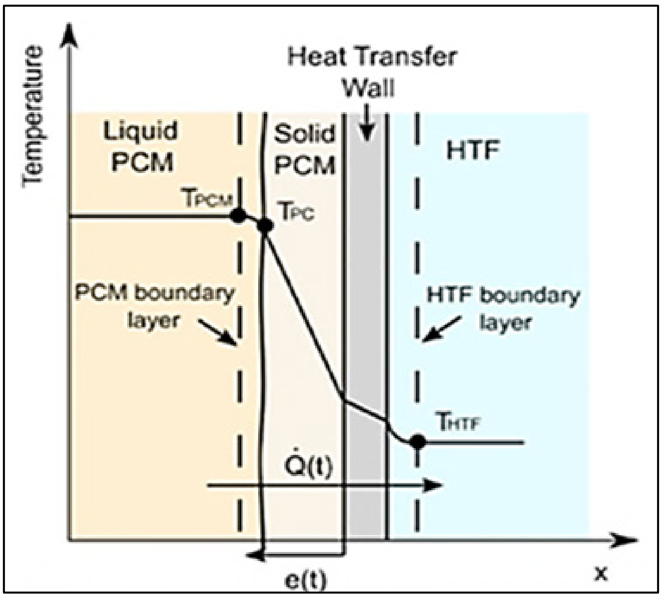


Fig. 3 Temperature profile during PCM solidification [7].

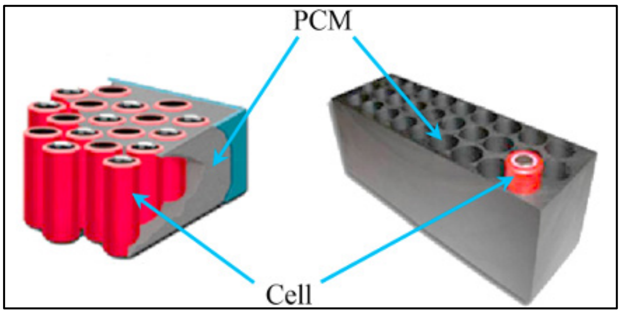


Fig. 4 Phase change material cooling system [8].

2.4. Hybrid colling system

Researchers are developing hybrid thermal management systems (TMS) that use two or three cooling mediums to overcome the limitations of air, liquid, and PCM-based TMS. This method improves system thermal performance. Hybrid cooling with mist is intuitive. This novel method optimizes energy efficiency and heat dissipation, making it a promising solution for many applications. As research advances, these hybrid systems could revolutionize thermal management in electronics and cars. Our research shows that mist cooling requires 5 g/s mass flow and 3% mist concentration to keep the cell surface temperature below 40 °C. Also studied evaporative and convective cooling. Placed liquid channel strips between cells to allow capillary water flow. Recycled the axial airflow over the cells using this method. Recycling allowed air to recover some of its heat extraction capacity, improving temperature uniformity by 56% and cell cooling by 20%. Studied a hybrid thermal management system (TMS) with cold plates at cylindrical cell bases. Air circulation helped recycle air through the cold plate. The fan beneath the cold plates created a fully developed flow field after several fan placement experiments. This strategy increased temperature uniformity by 2.42-fold and lowered maximum temperature by 3.45°C compared to conventional TMS. Researchers optimized a hybrid TMS with air and composite PCMs [8].

The cooling methods can be categorized into three primary types (see Fig. 5) active, passive, and hybrid. These classifications are based on factors such as the cooling medium utilized, energy consumption levels, and the mechanisms of heat transfer involved. Active cooling systems can be categorized into several types, including air, liquid, refrigeration, and immersion cooling. These systems utilize external energy to effectively dissipate heat. The air-cooling method utilizes ambient air or cooled air within the passenger cabin as the heat transfer medium, which is circulated by the fan.

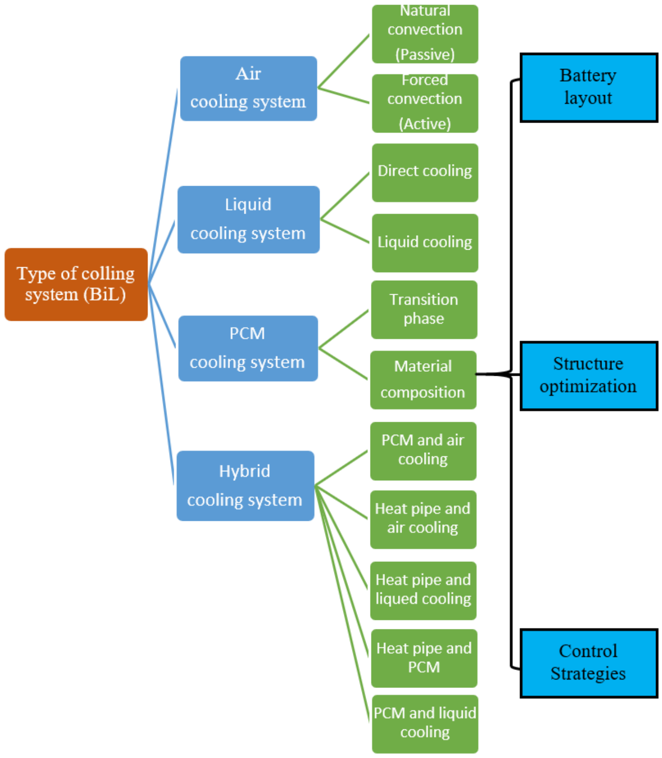


Fig. 5 Classification of LiB cooling systems [9].

Liquid cooling utilizes various types of liquids as coolant that flow within a closed loop to dissipate heat from battery cells. This process employs different configurations of thermal contact elements, where the liquid flow maintains indirect contact with the battery cells. Additionally, immersion cooling is classified as a liquid cooling method that involves direct contact between the dielectric coolant and the battery cells. Refrigerant cooling is designed to utilize the latent heat of a two-phase cooling medium during the cooling process [9].

A number of recent reviews have zeroed in on phase change material cooling as a means of superior thermal management for batteries. Unfortunately, there isn't enough information available in the public domain to provide a thorough evaluation of direct liquid cooling as a means of thermal management for next-generation batteries. It should be mentioned that some reviews discuss the studies on direct liquid cooling for thermal management of batteries, although that is usually only in the context of a subset of the total review.

Direct liquid cooling is not the main topic of these review articles; no specific review has been undertaken that explains. the recent advances in direct liquid cooling for battery thermal management, according to the authors' understanding and the literature research that was conducted. In order to better manage the temperature of electric vehicle batteries, this compiles the most important findings from the last five years' worth of research on advanced cooling technologies, such as direct liquid cooling and phase change material cooling. review by summarizing its review main and offering key features as showed on the Table 1.

3. How the Li-Ion battery handles heat

The overall heat generation of a Li-ion battery is primarily influenced by two factors: reversible heat and irreversible heat. The alteration in entropy leads to reversible heat generation, while polarization causes irreversible heat. The estimation of heat generation can be conducted utilizing Bernardi's equation as outlined [22],

$$Q_{total} = Q_{irreversible} + Q_{reversible} \tag{1}$$

$$Q_{total} = I(u - V_{oc})I\left(T\frac{du}{dt}\right) \tag{2}$$

Investigate the potential for charge transfer at the interface. This term presents the open circuit voltage and operating voltage of battery cells as u and V_{oc}, respectively. The reversible heat involves entropy generation, where *du/dt* represents the entropy coefficient as a function of the temperature and density of the battery cell. The value of *du/dt* can be either negative or positive, influenced by the charging or discharging modes of the battery cell. It approaches zero when the current flow in the battery cell is stopped. The battery cell experiences irreversible heat under high C-rates and reversible heat under low C-rates [23]. The model for accelerated rate or isothermal heat conduction calorimetry is employed to ascertain the irreversible heat via experimental methods.

Where:

I = current (A).

V_{oc} = open circuit voltage (V).

T = cell temperature (K).

Table 1. Review of current temperature management solutions for batteries, with an emphasis on recent developments.

No.	Authors	Review's main focus	Key Features
1	Deng et al. (2018) [10]	The thermal management of batteries is founded on the use of liquid cooling.	Summary of the performance of various coolants, the design of battery packs, and the sort of liquid cooling structures.
2	Chen et al. (2019) [11]	Battery thermal management is founded on the cooling of phase change materials.	Battery cooling research summary works on pure, composite, and hybrid phase change materials
3	Wu et al. (2019) [12]	Thermal management of batteries using heat pipes and liquids.	An overview of the research conducted on direct liquid cooling, indirect liquid cooling, and heat pipe cooling.
4	Akinlabi and Solyali (2020) [13]	Thermal management of batteries utilizing air cooling.	An overview of studies on battery air cooling, both active and passive.
5	Karthik et al. (2020) [14]	Phase change material (PCM) cooling, liquid cooling, and air cooling are the three methods used to manage battery thermals.	to mitigate the propagation of thermal runaway in batteries through the implementation of cooling strategies.
6	Thakur et al. (2020) [15]	Batteries utilize air, liquid, and heat pipe conditioning for thermal management.	Research works on the cooling of batteries through natural and forced air, direct and indirect liquid cooling, and heat pipe cooling are summarized.
7	Tete et al. (2021) [16]	Thermal management of batteries is founded on refrigeration cooling, phase change material, heat conduit, air, and liquid.	Summary of experimental and numerical research conducted on battery thermal management systems for hybrid electric vehicles (EVs) and pure electric vehicles (EVs).
8	Murali et al. (2021) [17]	Thermal control of batteries using passive phase change materials.	Comprehensive review of research on the integration of phase change material with a variety of battery cooling strategies. The research on the cooling of composite phase materials for the battery is also summarized.
9	Jiang et al. (2022) [18]	Air, liquid, heat conduit, phase change material, and combined cooling are all utilized in the thermal management of batteries.	Research summary on battery thermal management under normal and abusive conditions, utilizing a variety of cooling strategies.
10	Hamed et al. (2022) [19]	Batteries utilize phase change material, liquid, and air conditioning for thermal management.	An overview of the research conducted on external cooling strategies for batteries.
11	Roe et al. (2022) [20]	An immersion cooling-based thermal management system for batteries.	An immersion cooling-based thermal management system for batteries.
12	Zhao et al. (2023) [21]	liquid cooling-based thermal management of batteries.	The article summarizes research studies that concentrate on the optimization and design enhancement of liquid cooling systems for batteries.

The potentiometric method is frequently utilized among various implementation techniques to ascertain the entropy coefficient [24]. Nonetheless, this method presents complexities and demands significant time investment; therefore, a multitude of recent studies have been conducted to precisely assess the entropy change. Murashko et al. [25] introduced a model for measuring heat flux to assess the profiles of thermal diffusivity and entropy change concurrently. Damay et al. [26] calculated entropy variation curves utilizing the thermal inversion model grounded in the calorimeter method. Panchal et al. [27] created a Bayesian Regularization approach utilizing a neural network model to forecast the thermal characteristics of the battery across different discharge conditions. Additionally, Panchal et al. [28] conducted predictions and validations of battery temperature distribution using thermographic measurements derived from infrared radiation. Xie et al. [29] introduced an electro-thermal model that forecasts the thermal dynamics of the battery, achieving an error margin of 0.72 °C.

4. Thermal runaway (TR)

Thermal runaway is the phenomenon by which a battery ignites as a result of the rapid transfer of heat from one damaged cell to another. When the temperature of the cell rises by approximately 80°C, the Solid Electrolyte Interface (SEI) layer of the negatively charged anode begins to decompose. The electrolyte undergoes exothermic reactions at temperatures between 100°C and 120°C, resulting in the production of a variety of gases within the cell. As the temperature rises to 120°C to 130°C, the separator melts, resulting in an internal short circuit as the electrodes, anode, and cathode come into contact. Approximately 130°C-150°C is the temperature at which a positively charged cathode commences to react and generate oxygen. The cell is able to ignite and capture fire as a result of the discharge of oxygen and the other chemical reactions. If the heat dissipation is not rapid, the cell becomes thermally unstable and a condition of Thermal Runaway (TR) is attained, which results in the release of igniting gases and the self-sustaining of the fire as the temperature increases from approximately 150°C to 180°C. The heat generated is on the order of 10^7 W/m^3, and thermal runaway can occur in less than 10 seconds. The battery's optimal operational temperature range is 15°C to 35°C, 20°C to 40°C, and 20°C to 50°C [30] (see Fig. 6).

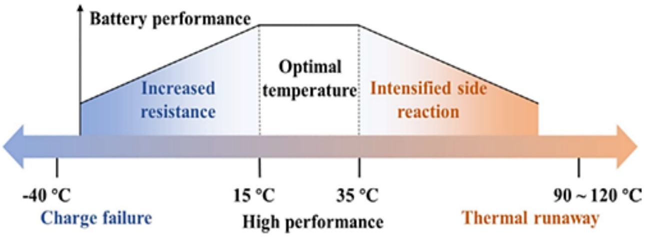


Fig. 6 Relation between battery performance and operating temperature [30].

5. Analysis of thermal runaway

The focus on safety within battery design has notably increased. Under circumstances of improper use, batteries may undergo a phenomenon referred to as thermal runaway. A rise in temperature can trigger this state. In these situations, the excessive generation of heat may damage the battery cell, which could result in fires or even explosions. It is essential to recognize that thermal runaway reactions exhibit significant complexity and vary considerably depending on the materials at play. The mechanisms that initiate thermal runaway encompass mechanical, electrical, and thermal abuse processes [31]. Various strategies can be employed at multiple stages from the selection of materials to the individual cell and the overall system to guarantee the thorough safety of energy storage systems utilizing LiBs. These strategies may be based on various techniques, including chemical, mechanical, electrical, or thermal methods, as long as they achieve any of the following steps focused on reducing failure:

1. Decrease the probability of dangerous conditions arising.
2. Eliminate hazardous conditions after they have appeared.
3. Enhance the thermal stability of the battery cell under hazardous conditions.
4. Reduce the energy released during Thermal Runaway.
5. Identify potential Thermal Runaway and provide early alerts.
6. Manage the risk of spread and limit damage to a small area.

6. The battery thermal management system

The central control unit of a battery pack. Multiple battery cells, arranged in various configurations such as series, parallel, and combinations, compose a battery pack.

LiBs are the most preferred option for commercial purposes due to their superior performance to other battery types.

The efficiency of the battery is contingent upon an electrochemical process that is fundamentally influenced by temperature. The Arrhenius law indicates that the rate of a chemical reaction escalates exponentially as the temperature increases. The research indicated that the hotspot within a battery cell is situated close to the electrode in contrast to the overall battery surface. The uneven distribution of temperature results in non-uniformity, subsequently leading to a decrease in both the life cycle and performance of the cell. The temperature of the battery fluctuates as a result of internal heat produced during both the charging and discharging processes. The internal heat generation within a battery is influenced by ohmic heat, the heat of mixing, enthalpy heating, and the entropy change of the electrochemical reaction. The electrochemical reaction is endothermic during charging, whereas it is exothermic during discharging. The internal generation that occurs during charge-discharge cycles presents a significant challenge in the application of lithium-ion batteries within electric vehicles and hybrid electric vehicles.

Consequently, addressing these disputes is essential, and BTMS is pivotal in determining the lifespan and overall efficacy of the battery pack (see Fig. 7). A number of scholars have committed their efforts to the study of thermal management in batteries for electric vehicles, and their contributions are documented in this article [32].

Several common investigations have employed commercial CFD solvers to address thermal issues in batteries, utilizing straightforward battery models in conjunction with three-dimensional thermal models. The conclusions drawn from these studies indicate that the majority focus primarily on the design of thermal management systems and enhancing cooling performance, often overlooking the electrochemical performance.

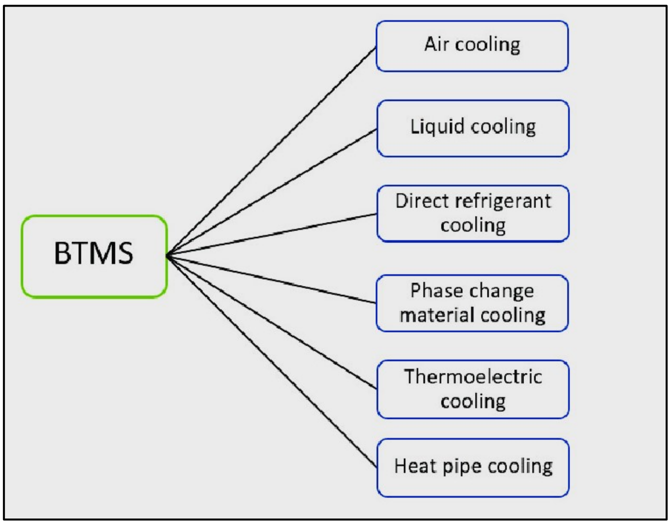


Fig. 7 BTMS controller scheme [32].

The coupled model can effectively address various battery thermal management systems discussed from past study has focused about important ideas from different author, as shown in Table 2, such as air cooling, liquid cooling, phase change materials, heat pipes, and hybrid cooling solutions.

The BTM models typically share the following common assumptions [43]:

1. The material properties of the battery are considered to be unaffected by temperature and state of charge due to their minimal variations.
2. The heat produced within the battery is evenly spread throughout.
3. The rate of charging or discharging remains constant.
4. The radiation heat transfer within the battery is not considered.

7. Thermal model

In their research, the authors utilized calculations derived from equations that excluded thermal radiation from the entire model to streamline the numerical simulation. Furthermore, the momentum equation for the molten phase change material does not apply because there is no fluid motion within the paraffin-graphite compound [44, 45]. Consequently, the governing equation relevant to both the battery cells and the PCM fields is the energy conservation.

$$\rho_i C_{p,i} \frac{\partial T}{\partial t} = \nabla(\lambda_i \nabla T) + q_i \tag{3}$$

Where i is a battery cell or PCM and qi is a heat source. In the battery cell domain, q_i represents the total heat generated by the 1-D electrochemical model. The average battery cell temperature determined by Eq. (1) is employed in the 1-D electrochemical model. In the PCM domain, q_i is 0. The melting point is determined using the equivalent heat capacity. latent heat of PCM into account, with which the apparent heat capacity of the PCM during phase transition is defined as:

Table 2. Important Study focus on BTMs is highlighted.

No.	Author	Study focus
1	Chidambaranathan et al. (2020) [33]	• used multiple cooling methods including AC, LC, PCMs, heat pipes (HPs), and cold plates.
2	Jaguemont et al. (2020) [34]	• This review examines the impact of temperature on LiBs, with a particular focus on safety issues and the variations observed at both high and low temperatures. • This document assesses current BTM systems, forecasts future developments, and provides a comparative analysis of existing and emerging systems, delivering critical insights into their prospective applications within the automotive sector.
3	Kumar et al. (2020) [35]	• This document analyses different types of batteries. Additionally, it assesses and contrasts various cooling techniques for thermal regulation. • An assessment of the efficacy of nanofluids as a BTM approach for LiBs is conducted.
4	Patel et al. (2020) [36]	• A comprehensive investigation of PCM-based BTMS is performed. • A comprehensive analysis of the influence of HPs on batteries cooling is presented. • A comprehensive quantitative evaluation of different BTMS is presented.
5	Liu et al. (2022) [37]	• The comparison of more than 200 high latent heat phase change materials (PCMs) is performed across a temperature range of 0 to 100 degrees Celsius. • A review of phase change materials (PCMs) employed in the thermal management of electronic devices and power batteries is provided.
6	Qin et al. (2021) [38]	• An overview of battery generated heat modelling and field flow was provided. • A new method was employed to classify the optimization is pure forced-air convection, which taking into account recent research on hybrid BTM forced-air convection.
7	Fayaz et al. (2022) [39]	• This review concentrates on the optimization of thermal and structural design parameters of lithium-ion batteries (LiBs) with different battery thermal management (BTM) systems. • This document presents comprehensive analyses of optimization algorithms employed for the enhancement of design parameters, categorized according to various BTM systems to achieve improved results.
8	Zhao et al. (2023) [40]	• This review systematically analyses recent studies focused on design improvements and optimization strategies for LC BTM systems. • The review encompasses multiple methodologies aimed at enhancing design, alongside developments in coolant selection, chilling cooling systems, heat pumps, and hybrid liquid cooling systems.
9	Akinlabi et al. (2023) [41]	• This review systematically analyses recent studies focused on design improvements and optimization strategies for LC BTM systems. • The review encompasses multiple methodologies aimed at enhancing design, alongside developments in coolant selection, chilling cooling systems, heat pumps, and hybrid liquid cooling systems. • Recent studies on AC BTM systems have been systematically categorized in a tabular format. • Advancements in AC BTMS, with a focus on hybrid systems, are detailed. Additionally, various techniques for optimizing parameter configurations are examined and categorized.
10	Ghaeminezhad et al. (2023) [42]	• Identification of optimization algorithms utilized by researchers to enhance BTM system objectives is discussed. • This review provides a new categorization of BTM methods focused on control. Furthermore, different BTM techniques are examined. • A Comparison of various non-feedback and feedback-based BTMS methods is conducted, considering the pros and cons of each method.

$$C_{p,pcm} = C_{eq} + C_L(T) \tag{4}$$

In this context, C_{eq} represents the equivalent heat capacity of the solid-liquid mixture, while $C_L(T)$ denotes the distribution of latent heat during the phase transition interval. In the context of cooling air, the dynamics of fluid flow and heat transfer are dictated by the equations of continuity, momentum conservation, and energy conservation:

$$\frac{\partial \rho_{air}}{\partial t} + \nabla.\left(\rho_{air}\vec{V}\right) = 0 \tag{5}$$

$$\frac{\partial\left(\rho_{air}\vec{V}\right)}{\partial t} + \nabla.\left(\rho_{air}\vec{V}\vec{V}\right) = -\ \Delta p \tag{6}$$

$$\frac{\partial\left(\rho_{air}\, C_{p,air}\, T\right)}{\partial t} + \nabla.\left(\rho_{air}\, C_{p,air}\,\vec{V}T\right) = \nabla.(\lambda_{air}\nabla T) \tag{7}$$

Temperature and heat flux are continuous at the interface of PCM/cell and air/cell, where the energy conservation equation can be expressed as:

$$\lambda_{batt}\frac{\partial T}{\partial n} = \lambda_{pcm}\frac{\partial T}{\partial n} \tag{8}$$

$$\lambda_{batt}\frac{\partial T}{\partial n} = h(T_{batt} - T_{air}) \tag{9}$$

Where:
amb: Ambient.
$C_{p,i}$: Heat capacity (J/kg K).
h: Heat transfer coefficient (W/m^2 K).
q: Total heat generation (J/m^3).
Δp: Maximum change pressure.
v: Thermodynamic factor.
T: Temperature (°C).
λ: Thermal conductivity (W/m K)
ρ: Density (kg/m^3)
∇: Divergence

8. Conclusions

The successful control of thermal conditions and precise forecasting of heat generation in lithium-ion batteries continue to pose considerable challenges in battery technology. These issues significantly influence the safety, performance, and longevity of batteries used in applications like electric vehicles and energy storage systems. This study offers an in-depth examination of different thermal coupled battery models, encompassing straightforward battery models, equivalent circuit models, and physics-based electrochemical models. Furthermore, the discussion has encompassed methods for parameter identification in these models. This review leads to the following general conclusions:

1. Basic battery models are insufficient to capture the intricate dynamic and electrochemical properties of a battery. They are usually integrated with three-dimensional CFD thermal models to facilitate the design, evaluation, optimization, and enhancement of battery thermal management systems. The sensitivity of these studies to the inherent properties of batteries is often limited.
2. ECM, due to its complex structure, provides a more comprehensive representation of battery performance, incorporating various resistive and capacitive components to more accurately reflect the dynamic behavior.
3. Furthermore, a review of a model known as the Four-equation thermal abuse model is also presented. The model classifies thermal runaway reactions into four distinct categories: decomposition reactions of the solid electrolyte interface (SEI), reactions between the negative electrode and the electrolyte, reactions between the positive electrode and the electrolyte, and decomposition reactions of the electrolyte itself. The model fails to consider reactions that involve lithium metal and combustion processes. Nonetheless, the methodology presented here can be readily modified to incorporate such reactions. The essential parameters for thermally coupled battery modeling were determined. This paper provides an overview and example-based explanation of various methodologies used for identifying parameters in battery models, specifically focusing on the techniques commonly employed in the thermal models of batteries. This study identifies several limitations that warrant attention. For instance, thermal models integrated within coupled models have not been thoroughly developed. Furthermore, the analysis did not take into account less frequently utilized battery thermal models

9. Recommendation

The updating comprehensive analysis presented in our article highlights enhanced thermal management efficiency in lithium-ion batteries (LiBs) through various techniques. This improvement is likely due to either a well-designed thermal management system or a careful selection of cooling strategies tailored to the specific case study. During the optimization process, it is essential to identify several key elements. Factors to consider include power consumption, mass flow rate, viscosity, density, heat capacity, heat transfer coefficient, the spacing between the LiBs pack, system maintenance, and overall cost. We recommend conducting further investigations to maximize potential enhancements.

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