J. Electrical Systems 20-10s (2024): 5079-5096

[1]Sunil Magan More,

Dr. Brajesh Mohan Gupta

A Review of Battery Thermal Management System for Electric Vehicles

Abstract: - Electric vehicles (EVs), which use lithium-ion batteries as stable energy sources, provide a feasible solution to future energy concerns. However, the performance of these batteries is affected by their operating temperatures, necessitates the use of an effective thermal management system. High temperatures can create thermal runaways, which can lead to explosions and short circuits, among other safety issues. The development of contrast lithium dendrites complicates operating concerns. This study addresses prospective technical advances that may enhance thermal management of electric vehicles (EVs) using lithium-ion batteries. The authors also examined the effectiveness of several theoretical and actual battery heat-management approaches for hybrid and electric vehicles. This study provides clear instructions for selecting an innovative cooling technology for battery thermal management for the next cohort of electric vehicles.

Keywords: Electric Vehicles, Battery Thermal Management System (BTMS), Lithium-ion Battery, State of health (SOH), Global Energy Crisis, State of charge (SOC).

INTRODUCTION

Harmful emissions from internal combustion (IC) engines have dramatically degraded air quality, affecting human health and welfare and contributing to global warming [1]. Electric vehicles (EVs) represent a possible answer to global energy depletion. However, current limits, such as a lack of dependability for long-distance driving and a battery unit's relatively short lifespan, impede EV adoption. These challenges must be addressed for EVs to become more viable and accepted [2]. Electric cars are commonly used for lithium-ion batteries, [3]. but heat management challenges affect their performance, health, and safety. High temperatures reduce lithium inventory, leading to capacity deterioration, low temperatures, on the other hand, cause capacity and power loss by decreasing the active anode material [4]. Both extremes accelerate battery degradation. Additionally, high temperatures can cause irreversible wreckage to battery components or the car, potentially causing swelling, explosion or fire [5].

Electric car (EV) batteries depend on the Battery Management System to ensure their performance and safety. It involves state estimation, battery modelling, and charging methods. Accurate modelling is crucial for understanding ways and managing factors like SOH, SOC, and temperature. A well-designed charging strategy is needed for safety and efficiency, balancing the trade-off between charging speed and energy loss. Slow charging affects EV availability, while fast charging can raise the temperature and cause energy loss [6]. Wide temperature fluctuations further accelerate battery ageing and may induce overheating or supercooling, ultimately shortening the battery's service life [7].

Electric vehicles (EVs) use a variety of heat management approaches to manage the temperature of their battery systems. These include liquid cooling, PCM-based cooling, air cooling, and thermoelectric cooling [8]. Each Battery BTMS has unique Benefits and drawbacks in terms of cost and efficiency. Air-cooled systems are cost-effective but may struggle with heat dissipation in hot conditions, while liquid cooling is highly efficient despite potentially higher implementation costs. Phase Change Material-based cooling utilizes the heat of transformation to effectively manage thermal conditions within battery units, offering potential improvements in thermal management. However, PCMs have low heat conductivity, necessitating the incorporation of thermally

[1] Research Scholar, Electrical and Electronics Engineering,
Sri Satya Sai University of Technology and Medical Sciences Sehore, Bhopal (MP), Pin-466001, India.
sunilmmore2009@gmail.com
Professor, Electrical and Electronics Engineering,
Sri Satya Sai University of Technology and Medical Sciences Sehore, Bhopal (MP), Pin-466001, India.
brajesh.mg@gmail.com

conductive components [9]. Thermoelectric-based systems, which use the Peltier effect for thermal transmission, allow precise temperature adjustment, albeit at a higher implementation cost follow.

A. Battery Management System (BMS)

The BMS monitors battery operating parameters to improve longevity and safety. Furthermore, it gives accurate estimates of the SOH and SOC for energy management elements in smart grids and Electric Vehicles. For such objectives to be met, the BMS includes a variety of capabilities for managing and monitoring battery operating conditions at several levels, including cell, module, and pack. As a result, the BMS emerges as a critical component for assuring the safe, dependable, and efficient operation of batteries in smart grids and EVs.

A BMS's tasks include data collecting, charging optimization, state of charge computation and display, also management of temperature, safety, energy, backup battery, and diagnostics. The Battery Management System (BMS) comprises several components, including a battery control unit (BCU), primary and auxiliary chargers, a thermal management system, a state of charge meter, battery warning mechanisms, a module sensing device (MSD), and a safety module, among others.

B. Electrical Vehicles (EV)

The automobile industry is shifting towards zero-emission cars due to environmental concerns and global warming, prompting the transportation sector to seek alternative technological disruption. To keep global temperature rise below 2 ◦C, the transportation industry must reduce carbon emissions [10]. Electric vehicles (EVs) are a promising approach for reducing oil-dependent emissions from road transportation [11]. EV technology in the automotive sector can meet global emission limits. Electric vehicles (EVs) provide environmental sustainability, economic advancement, and emission-free transportation.

VARIOUS TYPES OF BATTERIES

1. Lead-acid Battery

Gaston Planté created the Lead Acid (LA) battery in 1859, and it has since become the most extensively used rechargeable battery worldwide, notably in the automobile sector. Camille Alphonse Faure expanded its production capabilities and methods in 1881 [12]. Lead-acid batteries are built with lead-based electrodes and grids, with lead oxide acting as the active component in the electrochemical charge and discharge processes. This covers both the electrolyte and the positive and negative electrodes [13].

2. Nickel-based Battery

Since the production of the first Ni-MH battery in Japan in 1990, It’s been significantly employed for multiple purposes, such as portable gadgets and hybrid electric vehicles. The Ni-MH battery is made up of nylon separator sheets, a nickel hydroxide positive electrode, a metal hydride negative electrode, and an electrolyte consisting of a concentrated KOH solution. Despite the emergence of Lithium-ion-based batteries, which provide higher energy density, less memory effect, and lower self-discharge, nickel–metal hydride batteries are still popular due to their environmental friendliness, lower cost, and improved thermal stability. However, Ni-MH batteries have limitations, including as low specific energy, rapid self-discharge rates, and heat production during fast charging and high-load discharge, which impair their safety, performance, and lifetime. Modifications that minimize self-discharge can also lower specific energy [5].

3. Lithium-ion Battery

The 1990s saw the development and introduction of rechargeable lithium-ion batteries, and they have considerable weight benefits over conventional battery types. Lithium-ion batteries, known for their superior quality in the electrochemical sector, are currently among the most commonly utilized in electric cars [14]. Their high specific energy allows them to go nearly three times farther than lead-acid-based batteries [15]. Lithium-ion-based batteries are highly valued in the automobile sector for their extended cycle life, high energy capacity, and efficiency. As technological advancements continue, these batteries are projected to play a more essential role in the industry and everyday life [16].

CHARACTERISTICS OF LI-ION BATTERY

Li-ion battery cells are made up of four main parts: the cathode, separator, anode, and electrolyte. A channelled structure supports an aluminium current collector on the lithium metal oxide cathode. The anode is generally composed of lithiated graphite in a multilayer structure atop a copper collector. Lithium ions are liberated past the anode and into the electrolyte during discharge, passing through a porous plastic separator before depositing in the atomic-sized pores of the lithium metal oxide cathode. Simultaneously, the anode releases electrons, generating an electrical current that powers an external load. While charging, from the cathode to the anode, the separator permits the passage of lithium ions. This reversible electrochemical mechanism enables lithium-ion batteries to be recharged.

A lithium-ion battery can be built in two ways using metal containers with cylindrical or prismatic geometry or using laminate films known as lithium-ion polymer batteries. Figure 1 (a) shows a cylindrical design with layers rolled and encased in metal containers with electrolytes. Figure 1 (b) depicts a stacked configuration with layers wrapped, heat-sealed in laminate film with the aluminium-based plastic toolbar.

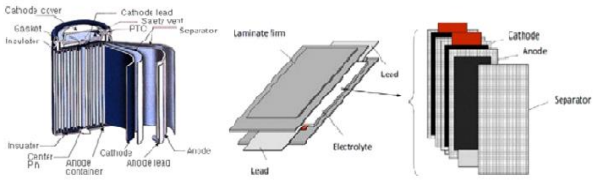

Fig. 1. Designs of lithium-ion batteries [17].

To prevent electrolyte leakage, a gel or polymer is often employed in this packaging. As demonstrated in Fig. 2, for electric vehicle (EV) energy sources, Lithium-ion batteries should be integrated into modules and subsequently integrated into battery packs. These packs entail cells being interconnected in a parallel sequence configuration to meet certain energy and power demands [17].

Fig. 2. Module, pack, and cell of lithium-ion batteries [17].

REASONS FOR BATTERY HEATING

A lithium-ion battery is an electric power source that undergoes a variety of electrochemical processes while being charged and discharged. In the case of large-scale battery packs, the accumulation of heat created by these activities can raise the total temperature of the pack, hastening electrochemical reactions. This phenomenon has the potential to dramatically reduce battery longevity while compromising charging efficiency and safety. Mechanical misuse, overcharging, and short circuits in high temperatures can all damage the battery [18].

At lower surrounding temperatures, the battery's lithium-ion diffusion capacity may diminish [19]. Additionally, a battery pack's modules and cells react differently to variations in ambient temperature, which can lead to capacity loss, changing states of charge between nearby cells, and electrochemical imbalances over time [20]. Consequently, choosing a BTMS is vital for maximizing performance of the battery by sustaining an optimal temperature range [21][22].

BATTERY THERMAL MANAGEMENT SYSTEM (BTMS)

During battery charging and battery discharging, a Li-ion battery generates electricity through a sequence of electrochemical responses. The heat created during these processes can accumulate in big battery units, raising the overall temperature. This temperature increase speeds up the electrochemical reactions, lowering battery life and jeopardizing charging capabilities and safety. Mechanical misuse, overcharging, and short circuits at severe temperatures can all damage the battery [18]. Battery performance decreases at low temperatures due to electrochemical imbalances, charging and discharging rates, and state of charge disparities. A battery thermal management system is essential to guarantee an appropriate temperature range.

Interior adjustments to the systems are possible, including electrode material selection, electrode thickness adjustment, and property optimization such as thermal conductivity and thermal diffusivity [23]. Chan et al. [24] used silicon in the role of an anode substantial in lithium-ion batteries because of its rich charge capacity and less discharge potential. Sheu et al. [25] studied the outcome of lithium cobalt oxide atom size in the Li/LiCoO2 rechargeable battery system, demonstrating a considerable influence on cyclic stability. Wenquan Lu et al. [26] said that reaching 70% utilization of total energy in lithium-ion batteries necessitates a cathode thickness of at least 130mm. Furthermore, Wenquan Lu et al. [27] accomplished a thorough examination, displaying the fluctuation of battery capacity and weight about thickness. Jinli Yang et al. [28] investigated three carbon support structures for LiFePO4 cathodes: acetylene black, carbon nanotubes, and graphene. Their findings highlighted the dependence of LiFePO4's electrochemical performance and particle size on the carbon support used, highlighting graphene as a suitable possibility for LiFePO4 support.

External Battery Thermal Management Systems (BTMS) may cool battery cells via mediums like water or air. External BTMS is divided into two distinct categories, active and passive, based on the usage of external power sources. Active BTMS is the use of additional electricity to run fans or pumps, which includes liquid and air-based systems. In contrast, passive battery thermal management systems depend on explicit structures linked to the batteries to boost heat exchange from the battery to the external surroundings. This category contains both heat pipe and PCM [29]. An exterior BTMS should be small, inexpensive in cost, need minimum maintenance, be compatible with automobiles, and be very reliable [30].

Generally, BTMSs are classified into [31]:

1) air cooling.
2) liquid cooling.
3) phase change materials (PCM).
4) thermoelectric
5) heat pipe for cooling.
6) combinations.

VARIOUS METHODS OF BATTERY COOLING

A. Air Cooling

A few benefits of the cooling system include its price, simplicity, and convenience of installation. Both the Toyota Prius 2001 and the Honda Insight 2000, which contain several NiMH battery cells and air conditioning schemes, have their battery system's thermal behaviour examined by Kelly et al. [32] and Zolot et al. [33], [34]. They discovered that these systems were successful for their intended purposes. However, Chen and Evans [35] observed a considerable rise in battery temperature associated with high discharge rates when reaching a specific threshold for battery module thickness. This was owing to the polymers' limited thermal conductivity, which rendered air cooling ineffective for cooling the battery core. Pesaran et al. [36] proposed that air cooling may only be appropriate for parallel electric vehicles that are hybrid (HEVs). In contrast, electric vehicles (EVs) and series HEVs require more efficient heat transfer mediums to accommodate larger thermal loads. Mahamud and Park discuss temperature discrepancies in battery units [37].

B. Liquid Cooling

A liquid-based thermal management system may be set up in two ways: by immersing the modules directly in a dielectric fluid or by enclosing them in a liquid-cooled plate [38]. In a simple experiment including the first approach [39], 48 Panasonic CGR18650E lithium-ion battery cells were assembled in a triangle module and immersed in water during discharge. When compared to air cooling, water cooling dissipates heat more efficiently due to its high conductivity. However, its requirement for a sealed system to prevent leakage, along with increased weight and complexity, makes it costly and uncommon. Alternatively, heat pipes, known for efficient thermal conductivity, can replace water. These pipes circulate liquid through an evaporator and condenser, transferring heat efficiently through a cyclical process.

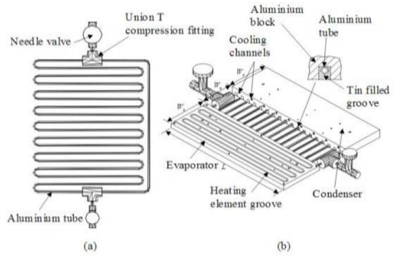

Fig. 3. The PHP cooling system in a closed loop [40].

The PHP cooling system in a closed loop is shown in Figure 3 [40], illustrating the use of PHP in thermal control. Additionally, an integrated hybrid system for cooling with airflow and heat pipes was proposed [41]. The experimental findings demonstrated that this system successfully dissipates heat, keeping each cell's temperature below 50°C even while producing 50W of heat.

C. Phase Change Material (PCM)

PCMs are chemicals that store and release heat energy when a phase changes, such as from a solid to a liquid and back again [42]. hey help maintain stable temperatures, making them useful for thermal management systems. PCMs are categorized into gas-liquid, solid-gas, solid-solid, and solid-liquid types. Gas-liquid and solid-gas transitions are challenging due to high latent energy needs. Solid-solid PCMs are rare due to high transition temperatures. Solid-to-liquid PCMs are preferred for their high heat storage and minimal volume change during phase transition [43].

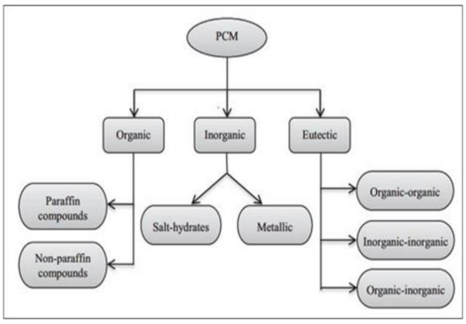

Fig. 4. Classification of solid-to-liquid transition PCMs [44]

PCM-based BTMS does not require any extra components and may efficiently lower the highest temperature and temperature variations between cells in a battery unit, but its applicability is restricted by mass. Common PCMs are paraffin, wax, and composite materials. [45]. Solid-to-liquid PCMs can be categorised as organic, eutectic and inorganic. Hydrocarbon chains, including paraffin, make up organic PCMs. Inorganic PCMs are salt hydrates containing metallic elements, like di-sodium hydrogen phosphate dodecahydrate. Eutectic PCMs combine organic and inorganic materials, such as copper foam with paraffin wax [46].

Mengyao Lu et al. [47] presented a system with paraffin wax as a Phase Change Material based on BTMS. This technology produced more consistent temperature distributions than traditional cooling by natural or forced air convection systems. Javani et al. [48] investigated BTMS using PCM topologies by differing the amount of thickness of PCM layers around battery cells, finding a link between higher thickness and lower maximum temperatures, but smaller layers improved temperature uniformity. Duan et al. [49] investigated PCM design modifications, testing the efficacy of PCM cylinders and jackets around cells for heat regulation, and both were successful. Ziye Ling et al. [50] inspected the influence of PCM phase transition temperatures, concluding that PCMs with extreme temperatures—either too high or too low—were useless. They recommended, from 40 degrees Celsius to 45 degrees celsius is the optimal phase change temperature for PCMs varies.

The application of metal mesh and PCM in BTMS to a pure BTMS was inspected by Amine Lazrak et al. [51]. The discoveries demonstrated that, in contrast to the clean PCM-based system, the combined PCM-based

BTMS lessened the battery's maximum temperature by an additional 10°C. Gholamreza Karimi et al. [52] studied three nanoparticles—Ag, Cu, and $Fe3O4$—as thermal conductivity enhancers. Their findings showed that silver (Ag) particles had the best thermal performance

D. Thermoelectric

A thermoelectric cooler, utilizing the Peltier effect, offers a potential solution for regulating battery thermal conditions in electric vehicles. It comprises P-type and N-type semiconductors attached to ceramic layers with high thermal conductivity. Current flow induces cooling or heating effects according to the course of the current flow between the semiconductor types, facilitating thermal regulation. When placed next to the battery module, the thermoelectric cooler effectively transfers the heat created from the battery to the other side of the thermoelectric cooler [53].

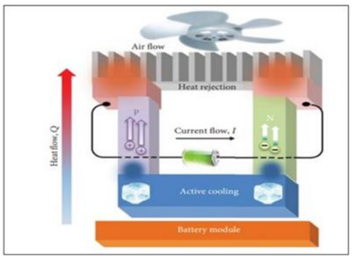

Fig. 5. Classification of solid-to-liquid transition PCMs [44].

Xinxi Li [53] developed a BTMS System that used thermoelectric cooling in conjunction with forced convection and tested its performance against forced convection cooling and natural convection cooling. The outcomes display that thermoelectric cooling is the optimum way to not only lower the maximum battery temperature but also reduce power consumption. Lyu et al. [54] developed a composite BTMS that included liquid cooling, air cooling, and thermoelectric cooling, resulting in a considerable drop in the surface temperature of the battery from 55 degree celsius to 43 degree celsius. Chakib Alaoui [55] created a solid-state BTMS with thermoelectric cooling and successfully tested it in an electric car using the US06 cycle, displaying good performance. Changsheng Qiu et al. [56] developed a BTMS using a thermoelectric cooler with changing cross-sections and optimized its geometric structure. The coefficient of performance improved by 21.59%, and cooling capacity increased by 35.73%, as compared to a system with a constant cross-section. Yong Liu et al. [57] used thermoelectric cooling for battery thermal management, proving its adaptability in cooling and heating batteries under very low ambient temperatures in winter. While research on thermoelectric-based BTMS has progressed, more study is needed for future developments [58].

E. Heat Pipe for Cooling

Figure 6 depicts a heat pipe, which functions as a sealed container holding a vacuum and a working fluid to facilitate heat transmission during the transition from liquid to vapour. It has three main sections: evaporating, condensing, and adiabatic. When in touch using the battery element and the evaporator takes heat from it, causing the working fluid to evaporate. This produces a pressure gradient, which is driven by the high vapour pressure and lower molecular density of the vapour and directs the vaporized fluid towards the condenser. Here, the vapour emits heat into the surrounding environment before condensing back into liquid form. Capillary forces then transport return the liquid to the evaporator, thereby continuing the cycle [59][58].

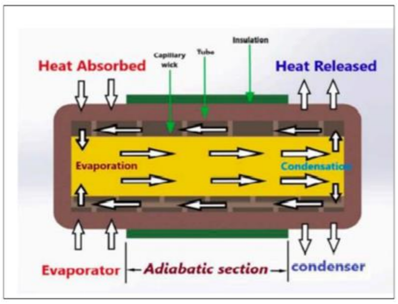

Fig. 6. Working of a heat pipe [8].

Thermal management systems for batteries using heat pipes are a new passive cooling technology that is noted for its low cost, excellent thermal conductivity, lightweight design, and long lifespan [60]. Heat is automatically transmitted from battery cells to cooler sources via the heat pipe's intrinsic evaporation and condensation processes [61]. Thanh-Ha Tran et al. [62] investigated heat pipe's impact of positioning on BTMS efficacy and concluded that vertical placement produced superior results. Similarly, Rui Zhao et al. [63] explored several cooling systems that comprise heat pipes in many configurations, including standalone models, heat pipes integrated with wet cooling, and heat pipes coupled with fans. Their findings underlined the efficiency of the combination of heat pipes and wet cooling as the most suitable cooling method. Zhonghao Rao et al. [64] created a flat-shaped copper heat pipe and tested its performance under various heat generation rates and positions. An oscillating heat pipe-based system was also created by Zhonghao Rao et al. [65] and investigated both horizontal and vertical positions. They discovered that the highest temperature differential between cells was 7°C in the vertical arrangement and 10°C in the horizontal layout.

F. Combinations

Researchers have explored combining multiple cooling methods to enhance overall performance, improving heat pipe systems or combining air or liquid cooling systems with PCM systems. It exhibits rich heat absorption capabilities but low thermal conductive capacity, thus combining them with other cooling technologies improves heat transmission efficiency. For example, Kizilel et al. [66] investigated a PCM-graphite matrix cooling system on an 18650 cell module (4S5P) under thermal runaway circumstances. This technique efficiently avoided thermal runaway propagation from a defective cell to neighbouring cells. Heat pipes, which efficiently transmit heat, supplement air or liquid cooling systems since they require prompt heat dissipation. Rao et al. [64] created a BTMS based on heat pipes for a big-scale prismatic LiFePO4 battery unit, adding a basin for water to cool the area where condensation forms. This approach provided effective thermal control. Similarly, Burban et al. [67] investigated an open-loop pulsing heat pipe (PHP) system for HEV electronic thermal management, taking into account variables such as pipe inclination, air velocity, temperature, and operating fluid.

Moreover, Weng et al. [68] used PCM and heat pipes to upsurge the flow rate of heat and achieve thermal homogeneity while lowering the energy usage of air conditioning fans. This hybrid technique demonstrates the potential for integrating several BTMS technologies to improve cooling performance and energy efficiency.

TABLE I. COMPARISON OF VARIOUS METHODS OF BATTERY COOLING

Cooling Method	Description	Advantages	Disadvantages	Suitable Applications
Air Cooling [30] [31] [32] [33] [35]	Uses air to dissipate heat from battery cells.	Simple, easy to install, and affordable.	Limited effectiveness for high thermal loads; less effective for thicker battery modules.	Parallel hybrid electric vehicles (HEVs).
Liquid Cooling [36] [37] [38] [39]	Utilizes liquid to remove heat, either by immersion or liquid-cooled plates.	Higher heat dissipation efficiency compared to air cooling.	Expensive, increased weight, complexity, and risk of liquid leakage.	Electric vehicles (EVs) and series HEVs require efficient heat transfer.
Phase Change Materials (PCM) [40] [41] [42] [43] [44] [45] [46] [47] [48] [49] [50]	Uses materials that absorb and release heat during phase transitions.	Effective temperature control, with no additional components needed, reduces temperature differences.	Limited by mass; organic, inorganic, and eutectic types have varying performance and applications.	Maintaining consistent temperature distribution in battery units; applicable for reducing temperature peaks.
Thermoelectric Cooling [51] [52] [53] [54] [55] [56]	Based on the Peltier effect; involves P-type and N-type semiconductors to manage heat.	Precise temperature control, compact design.	Lower efficiency, high power consumption, and cost.	Situations requiring precise thermal management, potentially as a supplementary cooling method.

Heat Pipe Cooling [57] [56] [58] [59] [60] [61] [62] [63]	Employs sealed containers with a working fluid to transfer heat via phase changes.	High thermal conductivity, lightweight, cost-effective, long lifespan.	Effectiveness depends on proper positioning and design.	Diverse applications, particularly where passive cooling is preferred; can be combined with other methods.
Combinations [64] [62] [65] [66]	Integrates two or more cooling methods to enhance overall performance.	Improved heat transfer and thermal management, increased efficiency.	Complexity and potential cost increase; require careful design and optimization.	High-performance applications, including large-scale battery systems, require robust thermal management.

TABLE II. OVERVIEW OF WORK PERFORMED ON BTMS

BTMS System	**Battery Type**	**Ambient Temp. in ◦C**	**T_{max} in ◦C**	**ΔT_{max} in ◦C**	**References**	**Year**
Air-cooling	LiFePO4 square battery	27	45	4	Xiongbin Peng et al [69]	2019
Air-cooling (Forced)	Lithium-ion battery	22	28	< 5	R. D. Jilte et al. [70]	2018
Liquid Cooling	Li-ion battery	25	49.8	3	Jingren Gou et al. [71]	2019
Liquid cooling plate	Li-ion soft-pack battery	25.15	34.6	0.35	Siqi Chen et al [72]	2019
PCM Cooling (Carbon fibres+Paraffin)	cylindrical battery simulator	25	52.5	1.1	Fereshteh Samimi et al [73]	2016
Heat Pipe	pouch Li-ion cell	23-24	< 32	< 2	Shuoqi Wang et al. [74]	2019
Combinations (Air + PCM cooling)	Cylindrical Li-ion battery module	27	37.68, 41	< 5	Ravindra D. Jilte et al [75]	2019

SOFTWARE TOOL FOR MODELING BTMS

Building a BTMS requires complete research to investigate the removal of heat efficacy, economic feasibility, and dependability. Alongside traditional experimental methods, unconventional assessment tools are employed to refine BTMS designs. Numerical simulation, notably cost-effective, accelerates BTMS design and improvement by creating predictive models. Constructing a battery thermal model begins with understanding electrochemical processes and selecting appropriate governing equations. This physics-based model simulates internal heat generation and temperature distribution during battery operation.

Before building a MATLAB model, a logic framework needs to be created to provide an overarching foundation for BTMS simulation. This enabled the next modelling procedures and assured the possibility of future tweaks, additions, and upgrades.

Initial inputs and thermal cycle settings involved defining physical parameters like thermal capacity and mass for the battery unit. When PCM is near the battery cell, they are treated as one unit. Heat transfer flows affecting battery temperature include internal heat generation, dependent on driving behaviour and vehicle parameters, and external heat dissipation from different thermal cycles. The parameters were acquired from the battery unit and testing circumstances for computation, leading to the construction of the necessary battery thermal model.

Control strategy development involves using characteristic parameters like battery and ambient temperatures to select the appropriate thermal cycle. Typically, multiple thermal cycles exist in battery thermal models. Based on the selected operation state, components such as the pump adjust their operating state. Sub-states may be introduced under the main operation state for improved performance. Simplification and decoupling are essential to avoid endless loops and speed up simulations. Simplified or approximate methods can resolve these loops. Decoupling is also useful, for instance, the activated thermal cycle consumes electricity, adding load and heat, which complicates the model. Initially decoupling the thermal and electro-thermal models and later integrating them when both are stable can prevent programming issues.

Data processing and output entailed capturing only useful parameters that indicated model outputs. Raw data was transformed into performance metrics for standard evaluation, and visuals were created to aid visual comprehension. Newman's electrochemistry model is a very renowned simplex battery thermal model, with implementations in software systems like ANSYS and COMSOL. Despite its extensive use, Newman's model treats a heterogeneous electrode structure as a slab, failing to represent the electrode's porous structural implications [76][77]. Many thermal models like cylindrical [78], prismatic [78][79] and pouch type [80][81] have been created and are still being refined by researchers to better represent the thermal Li-ion battery phenomenon in the present time.

Three approaches are used to compute the thermal flow of data within the battery thermal management system, finite element analysis (FEM), computational fluid dynamics (CFD), and the battery thermal model [82]. CFD is crucial for developing Battery Thermal Management Systems (BTMS) because it takes spatial heat production changes across cells and three-dimensional coolant flow into account for Lithium-ion battery packs. It simulates the conjugate mode of heat transport, an important process in BTMS. Research demonstrates a strong correlation between modelling and experimental data, with numerous studies utilizing numerical modelling to assess Li-ion batteries and propose effective heat management strategies. These investigations employ diverse mesh types, solvers, and modelling approaches to simulate heat transfer and fluid dynamics within the battery pack

VARIOUS LOADING CONDITIONS ON BATTERY

a) Fast Charging:

To achieve quick charging capabilities, one must first understand the impacts of temperature on batteries and then develop temperature-independent thermal management solutions [83]. The dangers of lithium plating pose a considerable barrier during fast charging, especially at lower temperature ranges, lithium plating on the anode may occur while charging li-ion-based batteries at freezing temperatures, resulting in increased Solid Electrolyte Interphase (SEI) production and rapid degradation. Temperature-dependent variables impact lithium plating kinetics, such are reduced reactions at graphite surfaces and lower electrolyte ionic conductivity, as evidenced by the Arrhenius ratio. As a result, the majority of contemporary electric vehicles (EVs) do not enable fast charging in cold temperatures unless extra preheating techniques are used [84][83][85].

The rate of charge and discharge for batteries is determined by C-rates, which measure the current used. Battery capacity is naturally specified at 1C, which indicates a completely charged battery of 100 Ah can distribute 100A per hour. The discharge duration varies with the C-rate: at 1.5C, the battery provides 150A for 40 minutes, and at 0.66C, it provides 66A for over 90 minutes. Simulation studies show without lithium plating, a lithium-ion battery can charge at 25 degrees Celsius at a rate of 4C. But at 10-degree Celsius and 0-degree Celsius, the charge degree drops to 1.5C and 0.66C, respectively, raising the possibility of plating [86].

Rapid charging efficiency is significantly impeded by low ambient temperatures, as there are restrictions on charging speeds to guarantee vehicle safety and performance. At a lower temperature range, the possibility for plating with lithium during charging grows considerably, resulting in reduced battery capacity [86][87]. The electrical power transfer of the rapid charger with an efficacy of 50 Kwatt exemplifies this difficulty, with efficiency declining from 93% at 25°C to 39% at -25°C when Battery Management Systems (BMSs) seek lower power levels in colder circumstances [88].

b) Slow Charging:

During sluggish charging procedures, ambient temperature has a less apparent impact. Evidence from research in various environmental conditions, in a 2013 Ford Focus using an AC Level 2 charger is reported in [89]. The charger consistently consumes an average power of 6.6 kW during the initial three hours across all temperature levels, typical of Level 2 charging in the United States. Subsequently, slight variations occur, with charging power gradually decreasing as the session progresses. EV drivers opting for slow charging over several hours experience minimal changes in the charging structure, as the electric energy is substantially lower than quick charging rates, which most EV batteries can accommodate.

Another empirical study done in France [90] sought the amount of energy needed to use a slow charger to reheat the batteries and cabin. The tests were taken at a battery warmed to 5 °C, and the Electric Vehicle interior heated to 20°C despite the outside temperature being 10°C. The 3.6-kW onboard charger provided an electric grid to both the batteries and the HVAC systems for warming up. It takes around 45 minutes to complete these chores. These statistics imply that regions with low temperatures and large EV adoption rates may have more weekday morning peaks.

c) Temperature Conditions:

Lithium-ion batteries (LIBs) lose performance at temperatures less than zero degrees Celsius [84][91]. In 2001, Nagasubramanian observed a significant decline in Panasonic 18650 power and energy density of batteries from over 800 W/L and 100 Wh/L at 25°C to less than 10 W/L and approximately 5 Wh/L at -40°C [92]. Another study found that SOC decreased as soon as the working temperature decreased from 25 degrees celsius to -15 degrees celsius of a LIB by about 23% [93]. The state of capacity (SOC) is defined as the proportion of the total available capacity to the present residual capacity [94]. Several factors can contribute to performance loss at low temperatures because of the complex material system used in LIBs. Initially, low temperatures have an impact on the characteristics of electrolytes. The electrolyte's viscosity rises with decreasing temperature, lowering its ionic conductivity. Due to the increased impedance in the direction of chemical ion flow, this causes a rise in internal resistance. To counteract this impact, researchers investigated electrolytes with lower freezing points and other electrolyte additions [95][96][97][98][99].

High temperatures have a more complicated effect on lithium-ion batteries (LIBs) than low temperatures do. Internal heat production occurs during LIB operation, and understanding this process is critical for limiting high-temperature consequences. In the normal temperature range, heat increasing in lithium-ion batteries is primarily caused by the transfer of charge and chemical responses that occur while battery charging and draining [100][101]. Heat is generated either through reversible chemical responses that occur while battery charging and draining processes, such as entropic heat, or irreversible ones [102][103].

The heat produced in the reversible process is caused by an increase in entropy during electrochemical reactions [104]. Irreversible heat-generating mechanisms include active polarization, ohmic heating, and heating caused by ion mixing and enthalpy change [105][106][107]. Polarisation occurs due to a voltage difference between the open circuit and working potentials, enhancing charge transfer resistance at the electrode-electrolyte known as (Solid Electrolyte Interface - SEI). Heat is generated as lithium ions exceed the barrier for intercalation and deintercalation [108]. Because of their resistance, the electrode and electrolyte both experience ohmic heating, which impedes charge transmission [109]. During LIB operation, ion distribution becomes heterogeneous, resulting in ion mixing and heat production [110]. The enthalpy shift produced by phase transitions in cathodes, mostly as a result of lithium-ion diffusion, is an additional irreversible mechanism that produces heat [111].

d) Battery Age and Degradation:

A battery is deemed useless and should be changed when its capacity fades to 20% [112]. The anode, separator, electrolyte, and cathode are the four basic components of a battery cell. These components are linked and susceptible to ageing. [4], with the ageing of one component affecting the others and leading to overall cell ageing. Consequently, cell ageing contributes to the ageing of the entire battery container, which is composed of multiple cells.

The ageing mechanisms are based on chemical or mechanical deterioration [113]. One key ageing factor is the creation of a protective layer at the electrode/electrolyte interface as a result of anode-electrolyte interactions [114]. This layer termed the SEI (Solid Electrolyte Interface), is formed predominantly throughout the initial charges [115][116]. Halting additional electrolyte decrease and negative electrode corrosion is the main purpose of the SEI layer. But, when the SEI continues to expand, it penetrates the electrode's pores, resulting in a loss of active electrode area, increased internal resistance, and consequent power and capacity fading. Though much thinner than on the anode, SEI formation happens on the cathode side.

Another well-known deterioration mechanism in lithium-ion batteries is lithium plating, which happens at low temperatures [117] or rapid charging rates [118]. Either from the electrode's surface quickly transferring lithium ions or the gradual dispersion of the graphite with lithium ions or electrolyte results in the electrode being coated with metallic lithium plating [84]. Furthermore, the dendritic development of metallic lithium can result in internal short circuits and battery failure by getting to the positive electrode by ripping the separator [119]. SEI generation and lithium plating are both responsible for the lack of cyclable lithium. The performance of batteries and ageing is significantly impacted by temperature, especially at low (subzero) and high temperatures, which increase deterioration rates [119]. To maintain optimal working conditions, the Battery Management System (BMS) must manage battery temperature. As a result, many heating methods are used, including internal and exterior heating for fuel cells [120] and batteries [121][122].

DISCUSSION

According to the evaluation, it is clear that all BTMS has unique strengths and weaknesses, making them suitable for a broad spectrum of battery units. Air cooling, aided by natural airflow, emerges as the easiest and most economical way of cooling battery units. However, its poor thermal capacity and heat transmission coefficients make it ineffective in many Electric Vehicle (EV) applications. As a result, it is best suited for EVs with modest charging and discharging rates, smaller designs, and operating in favourable ambient temperature ranges. Whereas, heat pipes provide passive operation and higher cooling efficiency than air-cooled systems. Nonetheless, their popularity in EV applications is impeded by huge space requirements, a lack of temperature regulation, and the need for extra cooling in the condenser portion. To overcome the volumetric limits imposed by the condenser portion, adjusting its angle can help reduce space utilisation.

PCM-based BTMS Systems offer potential due to their high latent heat capacity, which allows them to store and maintain heat at appropriate temperatures for extended periods without requiring active cooling components. However, drawbacks include slow solidification after melting, susceptibility to leakage when liquid, and limited usability within specific temperature ranges, restricting their response to rapid temperature fluctuations within the battery unit. Electric vehicles (EVs) with larger battery modules for distant travel and quick recharge necessitate dynamic cooling systems to effectively dissipate significant heat while optimizing energy efficiency. Forced convection air cooling, for example, with the J-Type cooling channel design, regulates airflow velocity to efficiently remove heat from the battery unit despite varying thermal loads, enhancing overall cooling performance.

However, fan-cooled air BTMS systems suffer from drawbacks like uneven cooling distribution and reduced efficacy due to low air Film coefficient and heat capacity. To address these limitations, strategies involving thermal conductivity enhancers like porous aluminium foam and strategically placed heat sinks within the battery unit are proposed. Despite advancements, liquid-cooled BTMS remains the favoured choice for most EVs owing to liquids' superior heat transfer properties. However, existing research on cooling methods, including those utilizing Phase Change Materials (PCM), often overlooks broader Electric Vehicle (EV) design considerations. Such studies primarily focus on enhancing battery units without assessing potential impacts on other EV components, such as increased weight or volume. Further research on the holistic effects of BTMS improvements on overall EV performance is warranted.

CONCLUSION

In conclusion, this study delves into recent breakthroughs in BTMS technology, assessing the pros and cons of each type. Five primary BTMS systems liquid-cooled, PCM-based, air-cooled, and combinational and heat pipe-cooled are utilized in the electric vehicle (EV) sector. While air-cooled systems offer energy efficiency and cost-effectiveness, they may fall short in adequately cooling batteries with substantial thermal requirements, making them better suited for EVs with shorter ranges and lower thermal loads. In contrast, liquid-cooled BTMS surpasses air-cooled counterparts due to superior heat transfer capabilities, making them ideal for EVs with larger battery packs designed for extended travel distances and high thermal loads. PCM-based systems, while capable of passively absorbing significant heat, face challenges due to low thermal conductivity and limited operating temperature ranges, although enhancements like thermally conductive materials and heat sinks can improve performance. Hybrid BTMS, combining various system strengths, offers versatility but requires careful consideration of trade-offs between complexity and cost.

Developing an efficient BTMS demands thorough research integrating standard experimental methods with innovative assessment tools like numerical modeling. Essential steps include understanding electrochemical processes, establishing a logical framework before MATLAB model creation, and formulating control strategies based on characteristic parameters. Simplification and decoupling are crucial for expediting simulations, while data processing transforms raw inputs into actionable insights for informed decision-making in BTMS design and refinement.

REFERENCES

[1] A. K. Agarwal and N. N. Mustafi, "Real-world automotive emissions: Monitoring methodologies, and control measures," Renewable and Sustainable Energy Reviews, vol. 137. Pergamon, p. 110624, Mar. 01, 2021. doi: 10.1016/j.rser.2020.110624.

[2] G. Krishna, "Understanding and identifying barriers to electric vehicle adoption through thematic analysis," Transp. Res. Interdiscip. Perspect., vol. 10, no. April, p. 100364, 2021, doi: 10.1016/j.trip.2021.100364.

[3] A. Mahmoudzadeh Andwari, A. Pesiridis, S. Rajoo, R. Martinez-Botas, and V. Esfahanian, "A review of Battery Electric Vehicle technology and readiness levels," Renew. Sustain. Energy Rev., vol. 78, pp. 414–430, Oct. 2017, doi: 10.1016/J.RSER.2017.03.138.

[4] C. R. Birkl, M. R. Roberts, E. McTurk, P. G. Bruce, and D. A. Howey, "Degradation diagnostics for lithium ion cells," J. Power Sources, vol. 341, pp. 373–386, Feb. 2017, doi: 10.1016/J.JPOWSOUR.2016.12.011.

[5] K. Ogura and M. L. Kolhe, "Battery technologies for electric vehicles," Electr. Veh. Prospect. Challenges, pp. 139–167, Jan. 2017, doi: 10.1016/B978-0-12-803021-9.00004-5.

[6] Z. Rao and S. Wang, "A review of power battery thermal energy management," Renewable and Sustainable Energy Reviews, vol. 15, no. 9. pp. 4554–4571, 2011. doi: 10.1016/j.rser.2011.07.096.

[7] B. Park, C. H. Lee, C. Xia, and C. Jung, "Characterization of gel polymer electrolyte for suppressing deterioration of cathode electrodes of Li ion batteries on high-rate cycling at elevated temperature," Electrochim. Acta, vol. 188, pp. 78–84, Jan. 2016, doi: 10.1016/J.ELECTACTA.2015.11.102.

[8] M. Shahjalal et al., "A review of thermal management for Li-ion batteries: Prospects, challenges, and issues," J. Energy Storage, vol. 39, p. 102518, Jul. 2021, doi: 10.1016/J.EST.2021.102518.

[9] J. Weng, D. Ouyang, X. Yang, M. Chen, G. Zhang, and J. Wang, "Optimization of the internal fin in a phase-change-material module for battery thermal management," Appl. Therm. Eng., vol. 167, p. 114698, Feb. 2020, doi: 10.1016/J.APPLTHERMALENG.2019.114698.

[10] G. Santos, "Road transport and CO2 emissions: What are the challenges?," Transp. Policy, vol. 59, pp. 71–74, Oct. 2017, doi: 10.1016/J.TRANPOL.2017.06.007.

[11] Z. Rezvani, J. Jansson, and J. Bodin, "Advances in consumer electric vehicle adoption research: A review and research agenda," Transp. Res. Part D Transp. Environ., vol. 34, pp. 122–136, Jan. 2015, doi: 10.1016/J.TRD.2014.10.010.

[12] B. Balagopal, C. S. Huang, and M. Y. Chow, "Effect of calendar aging on li ion battery degradation and SOH," Proc. IECON 2017 - 43rd Annu. Conf. IEEE Ind. Electron. Soc., vol. 2017-January, pp. 7647–7652, Dec. 2017, doi: 10.1109/IECON.2017.8217340.

[13] S. M. A. S. Bukhari, J. Maqsood, M. Q. Baig, S. Ashraf, and T. A. Khan, "Comparison of Characteristics-Lead Acid, Nickel Based, Lead Crystal and Lithium Based Batteries," Proc. - UKSim-AMSS 17th Int. Conf. Comput. Model. Simulation, UKSim 2015, pp. 444–450, Sep. 2016, doi: 10.1109/UKSIM.2015.69.

[14] J. Song, E. Sahadeo, M. Noked, and S. B. Lee, "Mapping the Challenges of Magnesium Battery," J. Phys. Chem. Lett., vol. 7, no. 9, pp. 1736–1749, May 2016, doi: 10.1021/ACS.JPCLETT.6B00384/ASSET/IMAGES/MEDIUM/JZ-2016-003844_0009.GIF.

[15] J. Larminie and J. Lowry, "Electric Vehicle Technology Explained," in John Wiley & Sons, 2012.

[16] N. Nitta, F. Wu, J. T. Lee, and G. Yushin, "Li-ion battery materials: present and future," Mater. Today, vol. 18, no. 5, pp. 252–264, Jun. 2015, doi: 10.1016/J.MATTOD.2014.10.040.

[17] M. Lowe, S. Tokuoka, T. Trigg, and G. Gereffi, "Lithium-ion Batteries for Electric Vehicles: Contributing CGGC researcher: Ansam Abayechi," US Value Chain. Contrib. CGGC Res., pp. 14–15, 2010.

[18] Z. An, L. Jia, Y. Ding, C. Dang, and X. Li, "A review on lithium-ion power battery thermal management technologies and thermal safety," J. Therm. Sci. 2017 265, vol. 26, no. 5, pp. 391–412, Sep. 2017, doi: 10.1007/S11630-017-0955-2.

[19] Y. Huo and Z. Rao, "Investigation of phase change material based battery thermal management at cold temperature using lattice Boltzmann method," Energy Convers. Manag., vol. 133, pp. 204–215, Feb. 2017, doi: 10.1016/J.ENCONMAN.2016.12.009.

[20] N. Yang, X. Zhang, B. Shang, and G. Li, "Unbalanced discharging and aging due to temperature differences among the cells in a lithium-ion battery pack with parallel combination," J. Power Sources, vol. 306, pp. 733–741, Feb. 2016, doi: 10.1016/J.JPOWSOUR.2015.12.079.

[21] A. A. Pesaran, "Battery thermal models for hybrid vehicle simulations," J. Power Sources, vol. 110, no. 2, pp. 377–382, Aug. 2002, doi: 10.1016/S0378-7753(02)00200-8.

[22] S. Arora, "Selection of thermal management system for modular battery packs of electric vehicles: A review of existing and emerging technologies," J. Power Sources, vol. 400, pp. 621–640, Oct. 2018, doi: 10.1016/J.JPOWSOUR.2018.08.020.

[23] L. Yang, F. Zhou, L. Sun, and S. Wang, "Thermal management of lithium-ion batteries with nanofluids and nano-phase change materials: a review," J. Power Sources, vol. 539, p. 231605, Aug. 2022, doi: 10.1016/J.JPOWSOUR.2022.231605.

[24] C. K. Chan et al., "High-performance lithium battery anodes using silicon nanowires," Nat. Nanotechnol. 2008 31, vol. 3, no. 1, pp. 31–35, Dec. 2007, doi: 10.1038/nnano.2007.411.

[25] S. P. Sheu, C. Y. Yao, J. M. Chen, and Y. C. Chiou, "Influence of the LiCoO2 particle size on the performance of lithium-ion batteries," J. Power Sources, vol. 68, no. 2, pp. 533–535, Oct. 1997, doi: 10.1016/S0378-7753(97)02623-2.

[26] W. Lu, A. Jansen, D. Dees, P. Nelson, N. R. Veselka, and G. Henriksen, "High-energy electrode investigation for plug-in hybrid electric vehicles," J. Power Sources, vol. 196, no. 3, pp. 1537–1540, Feb. 2011, doi: 10.1016/J.JPOWSOUR.2010.08.117.

[27] X. Gao, W. Lu, and J. Xu, "Unlocking multiphysics design guidelines on Si/C composite nanostructures for high-energy-density and robust lithium-ion battery anode," Nano Energy, vol. 81, p. 105591, Mar. 2021, doi: 10.1016/J.NANOEN.2020.105591.

[28] J. Yang et al., "3D porous LiFePO4/graphene hybrid cathodes with enhanced performance for Li-ion batteries," J. Power Sources, vol. 208, pp. 340–344, Jun. 2012, doi: 10.1016/J.JPOWSOUR.2012.02.032.

[29] H. Park, "A design of air flow configuration for cooling lithium ion battery in hybrid electric vehicles," J. Power Sources, vol. 239, pp. 30–36, Oct. 2013, doi: 10.1016/J.JPOWSOUR.2013.03.102.

[30] A. Pesaran, "Battery Thermal Management in EVs and HEVs : Issues and Solutions," Adv. Automot. Batter. Conf., p. 10, 2001.

[31] Q. Wang, B. Jiang, B. Li, and Y. Yan, "A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles," Renew. Sustain. Energy Rev., vol. 64, pp. 106–128, Oct. 2016, doi: 10.1016/J.RSER.2016.05.033.

[32] K. J. Kelly, M. Mihalic, and M. Zolot, "Battery usage and thermal performance of the Toyota Prius and Honda Insight during chassis dynamometer testing," in Proceedings of the Annual Battery Conference on Applications and Advances, Nov. 2002, pp. 247–252. doi: 10.1109/BCAA.2002.986408.

[33] M. D. Zolot, K. Kelly, A. Pesaran, M. Keyser, M. Mihalic, and A. Hieronymus, "Thermal evaluation of the honda insight battery pack," in Proceedings of the Intersociety Energy Conversion Engineering Conference, Jun. 2001, pp. 923–928.

[34] M. Zolot, A. A. Pesaran, and M. Mihalic, "Thermal Evaluation of Toyota Prius Battery Pack," SAE Tech. Pap., Jun. 2002, doi: 10.4271/2002-01-1962.

[35] Y. Chen and J. W. Evans, "Heat Transfer Phenomena in Lithium/Polymer-Electrolyte Batteries for Electric Vehicle Application," J. Electrochem. Soc., vol. 140, no. 7, pp. 1833–1838, Jul. 1993, doi: 10.1149/1.2220724/XML.

[36] A. A. Pesaran, S. Burch, and M. Keyser, "An Approach for Designing Thermal Management Systems for Electric and Hybrid Vehicle Battery Packs Preprint," Fourth Veh. Therm. Manag. Syst. Conf. Exhib. 24-27, no. January, pp. 1–18, Jan. 1999.

[37] R. Mahamud and C. Park, "Reciprocating air flow for Li-ion battery thermal management to improve temperature uniformity," J. Power Sources, vol. 196, no. 13, pp. 5685–5696, Jul. 2011, doi: 10.1016/J.JPOWSOUR.2011.02.076.

[38] Z. Rao, Q. Wang, and C. Huang, "Investigation of the thermal performance of phase change material/mini-channel coupled battery thermal management system," Appl. Energy, vol. 164, pp. 659–669, Feb. 2016, doi: 10.1016/J.APENERGY.2015.12.021.

[39] D. R. Pendergast, E. P. Demauro, M. Fletcher, E. Stimson, and J. C. Mollendorf, "A rechargeable lithium-ion battery module for underwater use," J. Power Sources, vol. 196, no. 2, pp. 793–800, Jan. 2011, doi: 10.1016/J.JPOWSOUR.2010.06.071.

[40] S. K. Mohammadian and Y. Zhang, "Thermal management optimization of an air-cooled Li-ion battery module using pin-fin heat sinks for hybrid electric vehicles," J. Power Sources, vol. 273, pp. 431–439, Jan. 2015, doi: 10.1016/J.JPOWSOUR.2014.09.110.

[41] S. Al Hallaj and J. R. Selman, "A Novel Thermal Management System for Electric Vehicle Batteries Using Phase-Change Material," J. Electrochem. Soc., vol. 147, no. 9, p. 3231, Sep. 2000, doi: 10.1149/1.1393888/XML.

[42] A. H. Alami et al., "Potential applications of phase change materials for batteries' thermal management systems in electric vehicles," J. Energy Storage, vol. 54, p. 105204, Oct. 2022, doi: 10.1016/J.EST.2022.105204.

[43] H. Chen et al., "Advance and prospect of power battery thermal management based on phase change and boiling heat transfer," J. Energy Storage, vol. 53, p. 105254, Sep. 2022, doi: 10.1016/J.EST.2022.105254.

[44] A. Mitra, R. Kumar, D. K. Singh, and Z. Said, "Advances in the improvement of thermal-conductivity of phase change material-based lithium-ion battery thermal management systems: An updated review," J. Energy Storage, vol. 53, p. 105195, Sep. 2022, doi: 10.1016/J.EST.2022.105195.

[45] A. R. Bais, D. G. Subhedhar, N. C. Joshi, and S. Panchal, "Numerical investigation on thermal management system for lithium ion battery using phase change material," Mater. Today Proc., vol. 66, pp. 1726–1733, Jan. 2022, doi: 10.1016/J.MATPR.2022.05.269.

[46] P. Zare, N. Perera, J. Lahr, and R. Hasan, "Solid-liquid phase change materials for the battery thermal management systems in electric vehicles and hybrid electric vehicles – A systematic review," J. Energy Storage, vol. 52, p. 105026, Aug. 2022, doi: 10.1016/J.EST.2022.105026.

[47] M. Lu, X. Zhang, J. Ji, X. Xu, and Y. Zhang, "Research progress on power battery cooling technology for electric vehicles," J. Energy Storage, vol. 27, p. 101155, Feb. 2020, doi: 10.1016/J.EST.2019.101155.

[48] N. Javani, I. Dincer, G. F. Naterer, and B. S. Yilbas, "Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles," Int. J. Heat Mass Transf., vol. 72, pp. 690–703, May 2014, doi: 10.1016/J.IJHEATMASSTRANSFER.2013.12.076.

[49] X. Duan and G. F. Naterer, "Heat transfer in phase change materials for thermal management of electric vehicle battery modules," Int. J. Heat Mass Transf., vol. 53, no. 23–24, pp. 5176–5182, Nov. 2010, doi: 10.1016/J.IJHEATMASSTRANSFER.2010.07.044.

[50] Z. Ling et al., "Experimental and numerical investigation of the application of phase change materials in a simulative power batteries thermal management system," Appl. Energy, vol. 121, pp. 104–113, May 2014, doi: 10.1016/J.APENERGY.2014.01.075.

[51] A. Lazrak, J. F. Fourmigué, and J. F. Robin, "An innovative practical battery thermal management system based on phase change materials: Numerical and experimental investigations," Appl. Therm. Eng., vol. 128, pp. 20–32, Jan. 2018, doi: 10.1016/J.APPLTHERMALENG.2017.08.172.

[52] G. Karimi, M. Azizi, and A. Babapoor, "Experimental study of a cylindrical lithium ion battery thermal management using phase change material composites," J. Energy Storage, vol. 8, pp. 168–174, Nov. 2016, doi: 10.1016/J.EST.2016.08.005.

[53] X. Li et al., "Experimental Investigation on a Thermoelectric Cooler for Thermal Management of a Lithium-Ion Battery Module," Int. J. Photoenergy, vol. 2019, 2019, doi: 10.1155/2019/3725364.

[54] Y. Lyu, A. R. M. Siddique, S. H. Majid, M. Biglarbegian, S. A. Gadsden, and S. Mahmud, "Electric vehicle battery thermal management system with thermoelectric cooling," Energy Reports, vol. 5, pp. 822–827, Nov. 2019, doi: 10.1016/J.EGYR.2019.06.016.

[55] [55] C. Alaoui, "Solid-state thermal management for lithium-ion EV batteries," IEEE Trans. Veh. Technol., vol. 62, no. 1, pp. 98–107, 2013, doi: 10.1109/TVT.2012.2214246.

[56] C. Qiu and W. Shi, "Comprehensive modeling for optimized design of a thermoelectric cooler with non-constant cross-section: Theoretical considerations," Appl. Therm. Eng., vol. 176, p. 115384, Jul. 2020, doi: 10.1016/J.APPLTHERMALENG.2020.115384.

[57] Y. Liu, S. Yang, B. Guo, and C. Deng, "Numerical Analysis and Design of Thermal Management System for Lithium Ion Battery Pack Using Thermoelectric Coolers," https://doi.org/10.1155/2014/852712, vol. 2014, Jan. 2014, doi: 10.1155/2014/852712.

[58] J. R. Patel and M. K. Rathod, "Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries," J. Power Sources, vol. 480, p. 228820, Dec. 2020, doi: 10.1016/J.JPOWSOUR.2020.228820.

[59] Z. Liang, R. Wang, A. H. Malt, M. Souri, M. N. Esfahani, and M. Jabbari, "Systematic evaluation of a flat-heat-pipe-based thermal management: Cell-to-cell variations and battery ageing," Appl. Therm. Eng., vol. 192, p. 116934, Jun. 2021, doi: 10.1016/J.APPLTHERMALENG.2021.116934.

[60] S. Babu Sanker and R. Baby, "Phase change material based thermal management of lithium ion batteries: A review on thermal performance of various thermal conductivity enhancers," J. Energy Storage, vol. 50, p. 104606, Jun. 2022, doi: 10.1016/J.EST.2022.104606.

[61] H. Mbulu, Y. Laoonual, and S. Wongwises, "Experimental study on the thermal performance of a battery thermal management system using heat pipes," Case Stud. Therm. Eng., vol. 26, p. 101029, Aug. 2021, doi: 10.1016/J.CSITE.2021.101029.

[62] T. H. Tran, S. Harmand, and B. Sahut, "Experimental investigation on heat pipe cooling for Hybrid Electric Vehicle and Electric Vehicle lithium-ion battery," J. Power Sources, vol. 265, pp. 262–272, Nov. 2014, doi: 10.1016/J.JPOWSOUR.2014.04.130.

[63] R. Zhao, J. Gu, and J. Liu, "An experimental study of heat pipe thermal management system with wet cooling method for lithium ion batteries," J. Power Sources, vol. 273, pp. 1089–1097, Jan. 2015, doi: 10.1016/J.JPOWSOUR.2014.10.007.

[64] Z. Rao, S. Wang, M. Wu, Z. Lin, and F. Li, "Experimental investigation on thermal management of electric vehicle battery with heat pipe," Energy Convers. Manag., vol. 65, pp. 92–97, Jan. 2013, doi: 10.1016/J.ENCONMAN.2012.08.014.

[65] Z. Rao, Y. Huo, and X. Liu, "Experimental study of an OHP-cooled thermal management system for electric vehicle power battery," Exp. Therm. Fluid Sci., vol. 57, pp. 20–26, Sep. 2014, doi: 10.1016/J.EXPTHERMFLUSCI.2014.03.017.

[66] R. Kizilel, R. Sabbah, J. R. Selman, and S. Al-Hallaj, "An alternative cooling system to enhance the safety of Li-ion battery packs," J. Power Sources, vol. 194, no. 2, pp. 1105–1112, Dec. 2009, doi: 10.1016/J.JPOWSOUR.2009.06.074.

[67] G. Burban, V. Ayel, A. Alexandre, P. Lagonotte, Y. Bertin, and C. Romestant, "Experimental investigation of a pulsating heat pipe for hybrid vehicle applications," Appl. Therm. Eng., vol. 50, no. 1, pp. 94–103, Jan. 2013, doi: 10.1016/J.APPLTHERMALENG.2012.05.037.

[68] Y. C. Weng, H. P. Cho, C. C. Chang, and S. L. Chen, "Heat pipe with PCM for electronic cooling," Appl. Energy, vol. 88, no. 5, pp. 1825–1833, May 2011, doi: 10.1016/J.APENERGY.2010.12.004.

[69] X. Peng, C. Ma, A. Garg, N. Bao, and X. Liao, "Thermal performance investigation of an air-cooled lithium-ion battery pack considering the inconsistency of battery cells," Appl. Therm. Eng., vol. 153, pp. 596–603, May 2019, doi: 10.1016/J.APPLTHERMALENG.2019.03.042.

[70] R. D. Jilte and R. Kumar, "Numerical investigation on cooling performance of Li-ion battery thermal management system at high galvanostatic discharge," Eng. Sci. Technol. an Int. J., vol. 21, no. 5, pp. 957–969, Oct. 2018, doi: 10.1016/J.JESTCH.2018.07.015.

[71] J. Gou and W. Liu, "Feasibility study on a novel 3D vapor chamber used for Li-ion battery thermal management system of electric vehicle," Appl. Therm. Eng., vol. 152, pp. 362–369, Apr. 2019, doi: 10.1016/J.APPLTHERMALENG.2019.02.034.

[72] S. Chen, X. Peng, N. Bao, and A. Garg, "A comprehensive analysis and optimization process for an integrated liquid cooling plate for a prismatic lithium-ion battery module," Appl. Therm. Eng., vol. 156, pp. 324–339, Jun. 2019, doi: 10.1016/J.APPLTHERMALENG.2019.04.089.

[73] F. Samimi, A. Babapoor, M. Azizi, and G. Karimi, "Thermal management analysis of a Li-ion battery cell using phase change material loaded with carbon fibers," Energy, vol. 96, pp. 355–371, Feb. 2016, doi: 10.1016/J.ENERGY.2015.12.064.

[74] S. Wang, L. Lu, D. Ren, X. Feng, S. Gao, and M. Ouyang, "Experimental investigation on the feasibility of heat pipe-based thermal management system to prevent thermal runaway propagation," J. Electrochem. Energy Convers. Storage, vol. 16, no. 3, Aug. 2019, doi: 10.1115/1.4042555/368271.

[75] R. D. Jilte, R. Kumar, M. H. Ahmadi, and L. Chen, "Battery thermal management system employing phase change material with cell-to-cell air cooling," Appl. Therm. Eng., vol. 161, p. 114199, Oct. 2019, doi: 10.1016/J.APPLTHERMALENG.2019.114199.

[76] J. Bockris O'M. and S. U. M. Khan, "Quantum electrochemistry," Springer Sci. Bus. Media, vol. (I-XIX+518, 1979, doi: 10.1201/9780429022937-43.

[77] J. Newman and N. P. Balsara, "Electrochemical Systems," in John Wiley & Sons, 2021.

[78] Y. Inui, Y. Kobayashi, Y. Watanabe, Y. Watase, and Y. Kitamura, "Simulation of temperature distribution in cylindrical and prismatic lithium ion secondary batteries," Energy Convers. Manag., vol. 48, no. 7, pp. 2103–2109, Jul. 2007, doi: 10.1016/J.ENCONMAN.2006.12.012.

[79] M. Xu, Z. Zhang, X. Wang, L. Jia, and L. Yang, "A pseudo three-dimensional electrochemical–thermal model of a prismatic LiFePO4 battery during discharge process," Energy, vol. 80, pp. 303–317, Feb. 2015, doi: 10.1016/J.ENERGY.2014.11.073.

[80] A. Samba et al., "Development of an Advanced Two-Dimensional Thermal Model for Large size Lithium-ion Pouch Cells," Electrochim. Acta, vol. 117, pp. 246–254, Jan. 2014, doi: 10.1016/J.ELECTACTA.2013.11.113.

[81] S. Goutam et al., "Three-dimensional electro-thermal model of li-ion pouch cell: Analysis and comparison of cell design factors and model assumptions," Appl. Therm. Eng., vol. 126, pp. 796–808, Nov. 2017, doi: 10.1016/J.APPLTHERMALENG.2017.07.206.

[82] Z. Liu, Y. Wang, J. Zhang, and Z. Liu, "Shortcut computation for the thermal management of a large air-cooled battery pack," Appl. Therm. Eng., vol. 66, no. 1–2, pp. 445–452, May 2014, doi: 10.1016/J.APPLTHERMALENG.2014.02.040.

[83] Y. Liu, Y. Zhu, and Y. Cui, "Challenges and opportunities towards fast-charging battery materials," Nat. Energy 2019 47, vol. 4, no. 7, pp. 540–550, Jun. 2019, doi: 10.1038/s41560-019-0405-3.

[84] J. Jaguemont, L. Boulon, and Y. Dubé, "A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures," Appl. Energy, vol. 164, pp. 99–114, Feb. 2016, doi: 10.1016/J.APENERGY.2015.11.034.

[85] Z. Li, J. Huang, B. Yann Liaw, V. Metzler, and J. Zhang, "A review of lithium deposition in lithium-ion and lithium metal secondary batteries," J. Power Sources, vol. 254, pp. 168–182, May 2014, doi: 10.1016/J.JPOWSOUR.2013.12.099.

[86] X. G. Yang, G. Zhang, S. Ge, and C. Y. Wang, "Fast charging of lithium-ion batteries at all temperatures," Proc. Natl. Acad. Sci. U. S. A., vol. 115, no. 28, pp. 7266–7271, Jul. 2018, doi: 10.1073/PNAS.1807115115/SUPPL_FILE/PNAS.1807115115.SAPP.PDF.

[87] A. Tomaszewska et al., "Lithium-ion battery fast charging: A review," eTransportation, vol. 1, p. 100011, Aug. 2019, doi: 10.1016/J.ETRAN.2019.100011.

[88] G. Trentadue, A. Lucas, M. Otura, K. Pliakostathis, M. Zanni, and H. Scholz, "Evaluation of Fast Charging Efficiency under Extreme Temperatures," Energies 2018, Vol. 11, Page 1937, vol. 11, no. 8, p. 1937, Jul. 2018, doi: 10.3390/EN11081937.

[89] M. Senol, I. Safak Bayram, Y. NADERI, and S. Galloway, "Electric Vehicles under Low Temperatures: A Review on Battery Performance, Charging Needs, and Power Grid Impacts," IEEE Access, 2023, doi: 10.1109/ACCESS.2023.3268615.

[90] D. Ramsey, A. Bouscayrol, and L. Boulon, "Energy Consumption of a Battery Electric Vehicle in Winter Considering Preheating: Tradeoff between Improved Performance and Total Energy Consumption," IEEE Veh. Technol. Mag., vol. 17, no. 3, pp. 104–112, Sep. 2022, doi: 10.1109/MVT.2022.3158043.

[91] T. R. Jow, S. A. Delp, J. L. Allen, J.-P. Jones, and M. C. Smart, " Factors Limiting Li + Charge Transfer Kinetics in Li-Ion Batteries ," J. Electrochem. Soc., vol. 165, no. 2, pp. A361–A367, Jan. 2018, doi: 10.1149/2.1221802JES/XML.

[92] G. Nagasubramanian, "Electrical characteristics of 18650 Li-ion cells at low temperatures," J. Appl. Electrochem., vol. 31, no. 1, pp. 99–104, 2001, doi: 10.1023/A:1004113825283/METRICS.

[93] A. M. Aris and B. Shabani, "An Experimental Study of a Lithium Ion Cell Operation at Low Temperature Conditions," Energy Procedia, vol. 110, pp. 128–135, Mar. 2017, doi: 10.1016/J.EGYPRO.2017.03.117.

[94] K. Liu, K. Li, Q. Peng, and C. Zhang, "A brief review on key technologies in the battery management system of electric vehicles," Front. Mech. Eng., vol. 14, no. 1, pp. 47–64, 2019, doi: 10.1007/s11465-018-0516-8.

[95] R. Bugga, M. Smart, J. Whitacre, and W. West, "Lithium ion batteries for space applications," IEEE Aerosp. Conf. Proc., 2007, doi: 10.1109/AERO.2007.352728.

[96] H. Wang, H. Zhang, Y. Cheng, K. Feng, X. Li, and H. Zhang, "All-NASICON LVP-LTP aqueous lithium ion battery with excellentstability and low-temperature performance," Electrochim. Acta, vol. 278, pp. 279–289, Jul. 2018, doi: 10.1016/J.ELECTACTA.2018.05.047.

[97] Q. Li et al., "Wide-Temperature Electrolytes for Lithium-Ion Batteries," ACS Appl. Mater. Interfaces, vol. 9, no. 22, pp. 18826–18835, Jun. 2017, doi: 10.1021/ACSAMI.7B04099/SUPPL_FILE/AM7B04099_SI_001.PDF.

[98] S. C. Kinoshita et al., "Effects of cyclic carbonates as additives to γ-butyrolactone electrolytes for rechargeable lithium cells," J. Power Sources, vol. 183, no. 2, pp. 755–760, Sep. 2008, doi: 10.1016/J.JPOWSOUR.2008.05.035.

[99] B. Yang, H. Zhang, L. Yu, W. Z. Fan, and D. Huang, "Lithium difluorophosphate as an additive to improve the low temperature performance of LiNi0.5Co0.2Mn0.3O2/graphite cells," Electrochim. Acta, vol. 221, pp. 107–114, Dec. 2016, doi: 10.1016/J.ELECTACTA.2016.10.037.

[100] M. Xiao and S. Y. Choe, "Theoretical and experimental analysis of heat generations of a pouch type LiMn2O4/carbon high power Li-polymer battery," J. Power Sources, vol. 241, pp. 46–55, Nov. 2013, doi: 10.1016/J.JPOWSOUR.2013.04.062.

[101] X. Zhang, "Thermal analysis of a cylindrical lithium-ion battery," Electrochim. Acta, vol. 56, no. 3, pp. 1246–1255, Jan. 2011, doi: 10.1016/J.ELECTACTA.2010.10.054.

[102] D. Bernardi, E. Pawlikowski, and J. Newman, "GENERAL ENERGY BALANCE FOR BATTERY SYSTEMS.," Electrochem. Soc. Ext. Abstr., vol. 84–2, no. 1, pp. 164–165, Jan. 1984, doi: 10.1149/1.2113792/XML.

[103] H. Yang and J. Prakash, "Determination of the Reversible and Irreversible Heats of a LiNi[sub 0.8]Co[sub 0.15]Al[sub 0.05]O[sub 2]/Natural Graphite Cell Using Electrochemical-Calorimetric Technique," J. Electrochem. Soc., vol. 151, no. 8, p. A1222, Jul. 2004, doi: 10.1149/1.1765771/XML.

[104] M. Balasundaram, V. Ramar, C. Yap, L. Lu, A. A. O. Tay, and B. Palani, "Heat loss distribution: Impedance and thermal loss analyses in LiFePO4/graphite 18650 electrochemical cell," J. Power Sources, vol. 328, pp. 413–421, Oct. 2016, doi: 10.1016/J.JPOWSOUR.2016.08.045.

[105] A. Nazari and S. Farhad, "Heat generation in lithium-ion batteries with different nominal capacities and chemistries," Appl. Therm. Eng., vol. 125, pp. 1501–1517, Oct. 2017, doi: 10.1016/J.APPLTHERMALENG.2017.07.126.

[106] Y. Lai et al., "Insight into heat generation of lithium ion batteries based on the electrochemical-thermal model at high discharge rates," Int. J. Hydrogen Energy, vol. 40, no. 38, pp. 13039–13049, Oct. 2015, doi: 10.1016/J.IJHYDENE.2015.07.079.

[107] S. Du et al., "An investigation of irreversible heat generation in lithium ion batteries based on a thermo-electrochemical coupling method," Appl. Therm. Eng., vol. 121, pp. 501–510, Jul. 2017, doi: 10.1016/J.APPLTHERMALENG.2017.04.077.

[108] A. Nyman, T. G. Zavalis, R. Elger, M. Behm, and G. Lindbergh, "Analysis of the Polarization in a Li-Ion Battery Cell by Numerical Simulations," J. Electrochem. Soc., vol. 157, no. 11, p. A1236, Sep. 2010, doi: 10.1149/1.3486161/XML.

[109] X. G. Yang, G. Zhang, and C. Y. Wang, "Computational design and refinement of self-heating lithium ion batteries," J. Power Sources, vol. 328, pp. 203–211, Oct. 2016, doi: 10.1016/J.JPOWSOUR.2016.08.028.

[110] B. Yan, C. Lim, L. Yin, and L. Zhu, "Simulation of heat generation in a reconstructed LiCoO2 cathode during galvanostatic discharge," Electrochim. Acta, vol. 100, pp. 171–179, Jun. 2013, doi: 10.1016/J.ELECTACTA.2013.03.132.

[111] J. Esmaeili and H. Jannesari, "Developing heat source term including heat generation at rest condition for Lithium-ion battery pack by up scaling information from cell scale," Energy Convers. Manag., vol. 139, pp. 194–205, May 2017, doi: 10.1016/J.ENCONMAN.2017.02.052.

[112] M. Woody, M. Arbabzadeh, G. M. Lewis, G. A. Keoleian, and A. Stefanopoulou, "Strategies to limit degradation and maximize Li-ion battery service lifetime - Critical review and guidance for stakeholders," J. Energy Storage, vol. 28, p. 101231, Apr. 2020, doi: 10.1016/J.EST.2020.101231.

[113] M. M. Kabir and D. E. Demirocak, "Degradation mechanisms in Li-ion batteries: a state-of-the-art review," Int. J. Energy Res., vol. 41, no. 14, pp. 1963–1986, Nov. 2017, doi: 10.1002/ER.3762.

[114] M. Broussely et al., "Main aging mechanisms in Li ion batteries," J. Power Sources, vol. 146, no. 1–2, pp. 90–96, Aug. 2005, doi: 10.1016/J.JPOWSOUR.2005.03.172.

[115] H. Zheng et al., "Correlation between lithium deposition on graphite electrode and the capacity loss for LiFePO4/graphite cells," Electrochim. Acta, vol. 173, pp. 323–330, Aug. 2015, doi: 10.1016/J.ELECTACTA.2015.05.039.

[116] J. Vetter et al., "Ageing mechanisms in lithium-ion batteries," J. Power Sources, vol. 147, no. 1–2, pp. 269–281, Sep. 2005, doi: 10.1016/J.JPOWSOUR.2005.01.006.

[117] T. Waldmann, M. Wilka, M. Kasper, M. Fleischhammer, and M. Wohlfahrt-Mehrens, "Temperature dependent ageing mechanisms in Lithium-ion batteries – A Post-Mortem study," J. Power Sources, vol. 262, pp. 129–135, Sep. 2014, doi: 10.1016/J.JPOWSOUR.2014.03.112.

[118] M. Petzl, M. Kasper, and M. A. Danzer, "Lithium plating in a commercial lithium-ion battery – A low-temperature aging study," J. Power Sources, vol. 275, pp. 799–807, Feb. 2015, doi: 10.1016/J.JPOWSOUR.2014.11.065.

[119] C. Vidal, O. Gross, R. Gu, P. Kollmeyer, and A. Emadi, "XEV Li-Ion Battery Low-Temperature Effects-Review," IEEE Trans. Veh. Technol., vol. 68, no. 5, pp. 4560–4572, May 2019, doi: 10.1109/TVT.2019.2906487.

[120] A. A. Amamou, S. Kelouwani, L. Boulon, and K. Agbossou, "A Comprehensive Review of Solutions and Strategies for Cold Start of Automotive Proton Exchange Membrane Fuel Cells," IEEE Access, vol. 4, pp. 4989–5002, 2016, doi: 10.1109/ACCESS.2016.2597058.

[121] X. Hu, Y. Zheng, D. A. Howey, H. Perez, A. Foley, and M. Pecht, "Battery warm-up methodologies at subzero temperatures for automotive applications: Recent advances and perspectives," Prog. Energy Combust. Sci., vol. 77, p. 100806, Mar. 2020, doi: 10.1016/J.PECS.2019.100806

[122] X. Peng, S. Chen, A. Garg, N. Bao, and B. Panda, "A review of the estimation and heating methods for lithium-ion batteries pack at the cold environment," Energy Sci. Eng., vol. 7, no. 3, pp. 645–662, Jun. 2019, doi:10.1002/ESE3.279.