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# Battery Thermal Management System: A Review on Recent Progress, Challenges and Limitations

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**Abstract.** In electric vehicles (EVs), wearable electronics, and large-scale energy storage installations, Battery Thermal Management Systems (BTMS) are crucial to battery performance, efficiency, and lifespan. This comprehensive analysis covers the latest BTMS advances and provides an overview of current methods and technologies. Recent developments in passive and active thermal management are covered in the following sections. The simplicity and efficiency of passive solutions like phase change materials and thermal insulators are highlighted. Operational systems, such as liquid cooling, air cooling, and sophisticated refrigeration, are precise and adaptable. BTMS still faces several obstacles despite advances. Non-uniform battery pack temperature distribution, thermal runaway hazards, and BTMS integration in tight locations are discussed. The review also highlights material limits, energy consumption trade-offs, and scalability issues in present techniques. This review provides a comprehensive history of BTMS, identifying knowledge and technological gaps and suggesting battery technology research and development for academics, industry veterans, and newcomers.

## 1 Introduction

This article reviews various thermal management solutions for batteries used in electric vehicle batteries as well as the fundamentals, attributes, and thermal concerns relating to lithium-ion batteries [1]. In recent times, rechargeable Li-ion (lithium-ion) batteries have gained significant recognition as the most effective means of storing power. These batteries possess several advantageous characteristics, including high specific power, lightweight composition, recyclability, low self-discharge rate, long cycle life, and high energy density. In comparison to other rechargeable battery options such as nickel-metal hydride (Ni-MH), nickel-cadmium (Ni-Cd) batteries and lead acid and, Li-ion batteries exhibit superior performance in these aspects [2-4]. In the past few years, lithium-ion battery (LIB) technologies have come a long way. Now, because they have such high energy and power densities, LIBs are the best choice for running electric vehicles [5]. These Li-ion batteries' functionality, shelf life, and safety are all significantly affected by ambient temperature [6]. Almost all cell materials used in Li-ion batteries suffer a decrease in performance and

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stability in the anomalous temperature range. Batteries are affected by their surroundings, and they give off heat as a byproduct of the chemical reactions that occur when being charged and discharged, therefore temperature fluctuations are commonplace [7]. To properly maintain battery temperature, a BTMS must be in place to keep batteries within an acceptable range of temperatures and reduce the gap between internal cell temperatures [8]. There is no consensus on what temperature range is best for LIB operation; the literature reports temperatures between 25 and 40 degrees Celsius [9], 20 and 40 degrees Celsius [10], and 15 and 35 degrees Celsius [11-13]. Elevated temperatures can give rise to a phenomenon commonly referred to as thermal runaway, which has the potential to culminate in the catastrophic malfunction of the system through fire or explosion [14]. This emphasizes the importance of BTMSs, which maintain battery temperature within an ideal range and ensure temperature uniformity among battery packs to prevent thermal runaway [15]. Low-temperature effects and high-temperature effects are the two main types of temperature-related phenomena [16-18]. Low-temperatures mostly have an effect on countries with high latitudes, like Greenland, Russia and Canada [19, 20]. During the winter months, the average low temperatures in these areas typically fall well below 0 degrees Celsius. Pure electric vehicles, hybrid electric vehicles, and plug-in hybrid electric vehicles (PHEVs) that operate in these conditions will have their performance and longevity negatively impacted by the extremely high temperatures [6]. LIBs can exhibit sluggish chemical-reaction behavior and charge-transfer speed at these low ambient temperatures [21], this is a factor in the drastic drop in electrolyte ionic conductivity [22] and diffusion of lithium ions between electrodes [23]. This reduction may result in a decline in power and energy efficiency, as well as a decrease in performance. Power and energy efficiency may drop, and performance may suffer as a result. There are still certain safety concerns, despite the fact that the lithium-ion battery sector is well on its way to maturity. When a battery is subjected to abuses like short circuiting, overheating, overcharging, and over discharging, internal temperatures rise quickly, increasing the risk of catastrophic failures including deflagration and explosion [15], [24-26]. As a result, the implementation of a battery thermal management system, also known as a BTMS, is of the utmost significance.

The battery, which undergoes a number of charging and discharging cycles in the open air over the course of its lifespan, is the most crucial component of EVs. Lithium-ion batteries performance is intricately linked to temperature, thereby necessitating a comprehensive comprehension of the mechanisms underlying heat generation within the battery [27]. Newman and Thomas (2003) claim that Lithium-ion cells generate heat by a combination of chemical reaction, relaxation of a concentration gradient, resistive dissipation, and entropy [28].

Studies like this have found that charging and discharging Li-ion batteries generate three different types of heat. The electrochemical reaction polarization generates activation irreversible heat, ohmic losses cause joule heating, and charge and discharge induce change in entropy that causes reversible reaction heat. If the battery experiences rapid heating throughout the processes of charging or discharging, it can be inferred that the battery's internal temperature has grown owing build-up of heat. This increase in temperature has the potential to impact the battery's lifespan, safety, and overall performance. Battery capacity declines as a result of the battery's active material transitioning into an inactive phase, while battery power declines as a result of an increase in impedance [29]. The low temperature makes the electrode material not spread easily, which restricts the intercalation reaction [1]. When constructing and optimizing BTMS, it is imperative to take into account not only the prevention of rising temperatures too high, while also reducing temperature disparities. Feng et al. (2018) conducted a comprehensive examination of the precise thermal runaway mechanism shown by Li-ion batteries [30]. There are a few different ways to prevent bad effects at low temperatures, including the preheating method, the heating plate method, and the air conditioning (AC) heating method [31–33]. ZHIGUO (2015) studied the effects of low temperatures on how well a high-capacity Li-ion battery with 35Ah of juice performs. Based on their findings, in order to significantly boost the battery's performance at low temperatures, they devised a wide line metal film heating approach [34]. These thermal concerns with lithium-ion batteries can be avoided with a battery thermal management system that keeps the battery within an optimal temperature uniformity and temperature range [5].

This review study is prompted by the increasing advancements in technology related to transportation electrification. Li-ion batteries face thermal runaway because of increased temperatures. This paper will cover thermal runaway and its many features. The assessment will also cover thermal runaway prevention and mitigation measures, crucial to battery thermal management system design for electric vehicles.

## 2 Classification of Battery Cooling System

The primary role of the Battery Thermal Management System (BTMS) is to ensure the maintenance of an ideal operational temperature range and the uniform distribution of temperature across the battery cell, module, and pack, particularly when subjected to high rates of charge and discharge, as well as adverse environmental conditions [35]. PESARAN (2001) claims that, a BTMS's four most important features are cooling (which removes heat from the battery), heating (which raises the battery's temperature when it's too low), insulation (which prevents the battery's temperature from fluctuating too drastically), and ventilation (which removes potentially hazardous gases) [8]. Except for when an EV is first used in a very cold climate, the temperature increase caused by most critical is the battery's ability to generate heat, and hence in this article, we examine the battery's cooling system in detail [5]. Different types of battery cooling systems are based on the type of medium they use. These include air cooling, liquid cooling, two-phase cooling, heat pipe cooling, and PCM cooling [36]. Power consumption is another factor to consider; passive cooling utilizes nothing but the air around it, whereas active cooling requires an external power source [37]. The effect that operating temperatures have on the capacity of the battery is presented in Table 1.

**Table 1.** Effect of operating temperatures on battery capacity

| **Reference** | **Voltage range (%)** | **Battery cathode/anode** | **Number of cycle** | **Capacity fade (%)** | **Cycle rate** | **Temperature (°C)** |
|---|---|---|---|---|---|---|
| Ehrlich [37] | 4.2 – 2.5 | $C/LiCoO_2$<br>0<br>$C/LiMnO_4$ | 500 | 9<br>13<br>28<br>51 | C/1 | 21<br>45<br>21<br>45 |
| Ramadass [38] | 2.01 -4.2 | $C/LiCoO_2$ | 150<br>500<br>800 | 6.09<br>9.4<br>22.5<br>70.56<br>30.63<br>36.21 | C/1.8 - C/9- 1C | 25<br>55<br>25<br>55<br>25<br>45 |
| Shim [39] | <4.1<br><100%> | $C/LiNi0.8Co0.14Al0.05O_2$ | 140 | 4<br>65 | C/2 | 25<br>60 |
| Amine [40] | 2.7–3.8 | $MCMB/LiFePO_4$ | 100 | 55<br>72 | C/3 | 37<br>55 |
| Liu [41] | <90><br><50> | $C/LiFePO_4$ | 2628<br>757<br>1376 | 7.5<br>20.1<br>22.1 | – | 15<br>60<br>45 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Jaguemont [42] | <60><br><60–40> | LiFeMnPO$_4$ | 170<br>12 | 7<br>20.8 | 1C | 25<br>-20 |
| Zheng [43] | <70><br><100> | LiFePO$_4$/MCMB | 100<br>100<br>40<br>20 | 12.77<br>2.97<br>30.69<br>29.33 | 1/3C<br>1/10<br>1/2<br>1C | -10 |

## 2.1 Air Cooling System

Air is commonly employed as a cooling medium in BTMS, mostly owing to its lightweight composition and cost-effectiveness in terms of both initial implementation and ongoing upkeep. The restricted utilization of air-cooled BTMS in contemporary electric vehicles (EVs) can be attributed to their limited ability for dissipating heat from the batteries. This limitation arises from the relatively air-cooled BTMS have a low thermal conductivity and heat capacity [44]. The battery configuration, as well as the location of the ventilation system's intake and outlet, must be carefully engineered to improve its efficiency and effectiveness. To investigate the many possible configurations for cylindrical batteries within a pack, Yang [45] used a thermal model created on a computer. The research team led by Fan [46] came at the same conclusion. Cylindrical batteries had a comprehensive parametric study performed by Zhao [47] to better understand the effects of ambient temperature, ventilation kinds, inflow velocities, and distances between adjacent batteries. The findings led the researchers to the conclusion that the movement of air within neighbouring battery rows is less efficient when the wind direction is changed compared to when the airflow was unidirectional. It is important to note that the movement of air within neighbouring battery rows is not the same as the airflow that is produced by reciprocating airflow systems (as shown in Figure 1).

The enhancement of cooling capabilities is contingent upon the inclusion of air flow as a crucial factor. However, Tong [48] conducted research that revealed an adverse consequence of raising parasitic load, which counteracts any potential benefits derived from augmenting air flow. The outlet and inlet flow duct geometries determine the cooling channel flow rate uniformity, which affects battery pack pressure drop, thermal distribution and cell temperature [49]. In order to achieve a more uniform and lowered temperature distribution across the battery, the air-cooling system of the prismatic Lithium-ion battery makes use of a pin-fin heat transfer mechanism, as shown in Figure 2 [50].

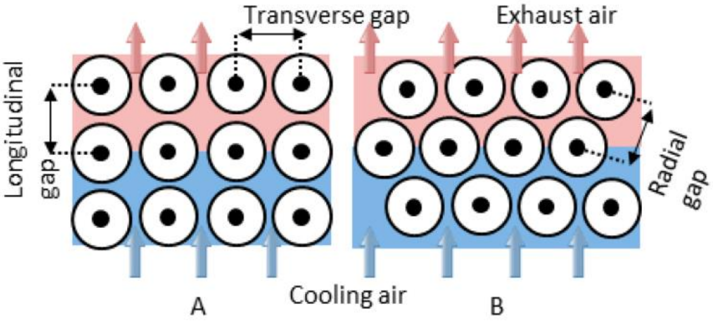

**Fig. 1.** Arrangement of (A) cell aligned, and (B) staggered [45]

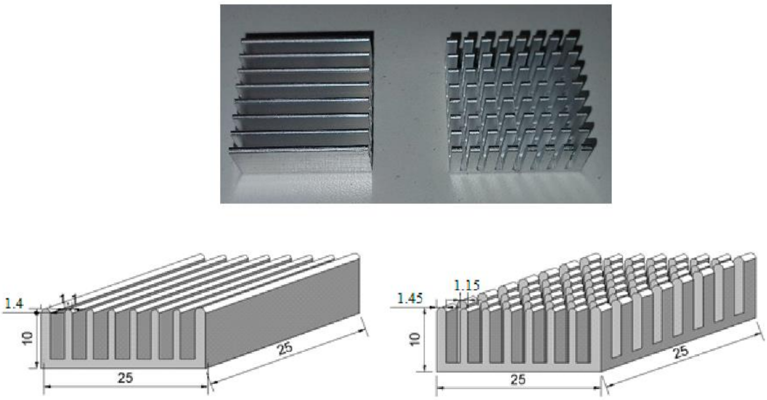

**Fig. 2.** Battery Pin-fin heating plate [50]

But the problem using time valves integrated into the BTMS, reciprocating airflow is an active system [52, 55]. This makes the system more complicated, which makes it less reliable and more expensive [51].

The optimal size of the inlet plenum was then determined through a parametric study, and effect repercussions of increasing the Reynolds number, thermal efficiency was investigated. The calculations show that the sweet spot for the Reynolds number is 7,440 [53]. The period also saw the development of other passive methods, such as jet inlets and vortex generators. The results of installing these inside battery improvement ventilation on the battery's leeward side were quite encouraging [54]. To create a vortex, jet inlets and generators are used the temperature gradient was narrowed to less than 5 degrees Celsius [55].

## 2.2 Liquid Cooling System

Both heat capacity and thermal conductivity are higher in liquids than in air. Direct or indirect liquid BTMS cooling methods exist. To effectively maintain temperature, direct BTMS places an electrically insulating liquid in direct contact with the batteries [56-58]. However, since liquids are denser than air, they have a larger pushing strength. Furthermore, there is a substantial possibility of liquid leakage, particularly in large battery packs. The indirect BTMS, which uses cold plates to keep the fluids in place, was developed as a solution to these issues. After that, the batteries are topped with these cold plates [59]. At the moment, the use of cold plates is appropriate for prismatic and pouch batteries due to the fact that it readily conforms that these batteries have a rectangular shape [59-60]. Zhao also analyzed cold plates for cylinder batteries [47]. However, because cylindrical cold plates are so difficult to manufacture, the structure's complexity increased dramatically. Tesla's initial line of defense against this issue was the liquid cooling pipeline which ran along a side of batteries. A novel tablet battery design has been recently introduced batteries with very huge cylinders, with enhanced heat dissipation and reduced resistance characteristics. This enables the batteries to be directly affixed to the aluminium structure without necessitating the creation of distinct modules. The placement of cold plates has been modified to facilitate heat extraction from the batteries, with the plates being positioned both at the top and bottom. Aluminium cubes of varying lengths are used for each battery, Rao and his colleagues [61] created a liquid-cooled BTMS that is designed to work with cylindrical batteries.

The tubes carrying the liquid were embedded in the aluminium blocks that made up the battery bank. When compared to a block of length-uniform aluminium enhanced temperature consistency by 6% for every 1 mm in length, 14% for every 2 mm, and 28% for every 3 mm.

For cylindrical batteries, Zhao [62] created a number of liquid cooling designs. Two of them demonstrated a noticeable improvement in batteries and the battery pack temperature uniformity. A numerical analysis contrasted parallel and cross flow plates. After multi-objective optimization, cross flow plate reduced heat resistance by 20.23%, power needs by 39.44%, and pressure drop by 39.44%. The production of eddies in the shunt channel increases flow channel mixing and cooling. The scientists found that a flowrate of 48 millilitres/second per cold plate is necessary to maintain temperature homogeneity within 5 ◦C [63].

Nano-fluids have been used in order to improve the working fluids' thermal characteristics alongside traditional fluids for liquid cooling, thanks to the efforts of researchers. The authors additionally indicated that in order for the system to operate efficiently, it is necessary to take into account specific measures. The placement of a wired connection within a nano-fluid environment presents a vulnerability to potential harm, necessitating the implementation of protective measures such as the use of mini-channels. The aggregation of nanoparticles leads to the formation of clusters, resulting in a notable decline in the nano-fluid's thermal efficiency. Both the nano-fluid's and the container's boiling points should be considered during the design phase. Keeping the channel's geometry fixed, we investigate how changing operating conditions affect the battery or working fluid's temperature. Panchal (2017) conducted an experimental and numerical investigation of velocity distributions and a temperature of liquid coolants in a cooling plates mini-channel under varying discharge rates and coolant temperatures [59]. Since the maximum and average temperatures of liquid at 30 °C lie within the 25-40 °C range that batteries generally run at, this temperature was found to be the most effective for cooling battery packs in the parametric analysis. Rao (2017) created a BTMS reliant on liquid cooling by affixing an aluminium block to a cylindrical Li-ion battery in such a way that cooling water could circulate freely through it, as opposed to a usual method of attaching a battery cell with a cooling plate in the shape of a prism [61].

## 2.3 Direct Refrigerant Two-Phase Cooling System

This BTMS includes a two-phase, direct-refrigerant cooling system [64]. Secondary liquid cooling systems with several circuits can benefit from this technique by integrating battery cooling into the already-existing vapor compression cycle. To accomplish this, as seen in Figure 3, an extra evaporator was built within the battery pack. By connecting the evaporator's refrigerant circuit to the existing vapor compression cycle, it can function in parallel with the AC evaporator.

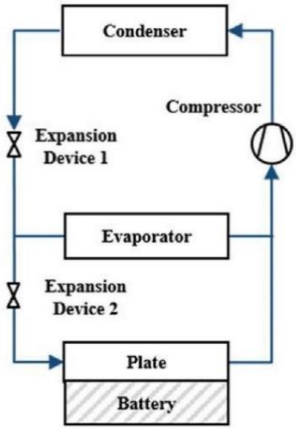

**Fig. 3.** Two Phase Cooling of Direct Refrigerant

A secondary heat exchanger is thermally linked to the cells via fins with excellent thermal conductivity [65]. The primary difference between this method and the more common liquid glycol coolant used in fin-cooled secondary battery systems is the use of refrigerants. Additionally, the system has a built-in expansion mechanism. This part senses the heat load on the battery and regulates the flow of refrigerant to the auxiliary evaporator. The liquid coolant loop and chiller of the secondary liquid cooling system could be removed to reduce mass and size. This system has the ability to conserve both weight and space as a result of its elimination of the liquid coolant loop and chiller that are components of liquid-based secondary cooling system. The battery's thermal management can also make use of the constant temperature on the refrigerant side during evaporation. So, you can get a very even temperature spread across the battery by making sure the whole cooling surface is the same temperature. At a low flow rate, you can also keep the battery at the right temperature. Cabin air conditioning (A/C) and BTM have different load characteristics, having two evaporators sharing a refrigerant circuit can cause complications. The thermal comfort of passengers may be compromised in the case of a collision due to the prioritization of refrigerant usage for the body temperature management (BTM) system, which is primarily implemented for safety purposes [66]. The correct refrigerant flow control method is crucial. Because the compressor must run regardless of cabin AC, this method can use a lot of power. Finally, without a heat pump system, battery heating is problematic without auxiliary heaters. Direct refrigerant two-phase cooling systems for BTMS have only been tested a handful of times. How the battery reacted to high temperatures during the New European Drive Cycle (NEDC) in 2012 was studied by Krüger, who used R134a and R1234yf in a direct refrigerant cooling system [67]. According to research, both refrigerants kept the battery's Tmax below 40 °C throughout NEDC, however the R1234yf cycle causes a 2 K reduction in battery temperature. During the NEDC, the R134a cycle required 60 kJ of energy for battery cooling, which is roughly 40% less than the R1234yf cycle required. Prior to the Li-ion battery's thermal runaway becoming uncontrollable, Kritzer (2014) looked into the possibility of using the air conditioning system's CO2 refrigerants to meet emergency cooling requirements [68]. They used an extra tube circuit to route refrigerant from electrical current to the battery, overcharging a standard 4-amp-hour battery to 85% SOC at a charge rate of 5C before cooling it with a burst of amplify for 20 seconds CO2 (50 gram). After the CO2 pulse ended, the surface temperature of the cell climbed again from its low point at -49 degrees Celsius. Until simpler, better heat transfer, and cheaper technologies are developed, it is expected that further research will be conducted on electric vehicles' battery-powered climate control systems.

## 2.4 Heat Pipe Cooling System

Heat-pipes have found extensive application in many commercial and industrial settings as a means of effectively regulating temperatures within acceptable thresholds. Their demonstrated heat conductivity efficiency is the main reason. These materials are known as ‘thermal superconductors’ due to their 91× higher thermal conductivity than copper rods of the same size [69–71]. It can also keep the evaporator's surface at a uniformly stable temperature. In addition, this device's geometry is flexible enough to accommodate spaces of varying dimensions. These advantageous characteristics make heat pipe an attractive option for the refrigeration of HEV or EV batteries.

## 2.5 Phase Change Material (PCM) Cooling System

A phase change material is a substance that absorbs or emits heat by transforming from one state to another at a specific temperature [72, 73]. Phase change processes can take in or give off a lot of heat with no net energy loss, making this useful in many industries, including energy and civil engineering [74–76]. Increases in battery energy density and capacity have made significant strides in recent years. As a result, BTMS has installed a reliable cooling system that makes use of numerous liquid-cooled channel systems. One disadvantage of such a system is that it increases the overall system complexity and the amount of electricity required to run the compressor. One way to lessen the consequences of these limitations is the PCM cooling system [77]. A PCM is often a solid block of material that has been machined or moulded to allow for the insertion of cells, as seen in Figure 4.

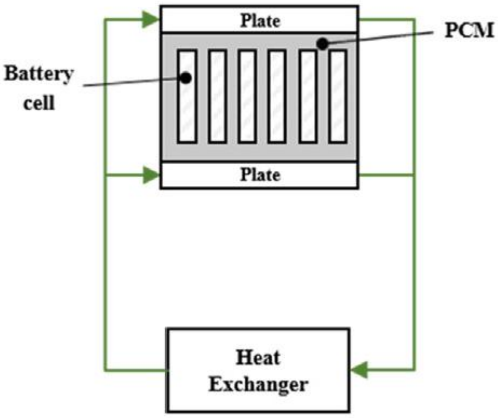

**Fig. 4.** Phase Change Material Cooling System

Additionally, the PCM has two plates on its bottom and top or left and right sides for heat dissipation. When charged or discharged, the battery cells generate heat, which is transported to the permeable cellular matrix, which is in intimate touch with cells because of temperature-based conduction. Sensible heat absorption occurs first in PCM, and then as latent heat in increasing amounts, all the way up to the melting point in the last stage of the phase transition at a fixed temperature. This means it can take the high temperatures generated by the battery without overheating or experiencing large temperature variations [78]. But if only phase change material is used as BTMS, it can't work all the time if the PCM melts fully because of hot weather or the battery keeps charging and discharging [79]. Therefore, supplementary cooling devices that vent the PCM's heat to the atmosphere are crucial. LV's (2016) original design for venting PCM heat to the air was limited in its ability to do so by the use of low fins and the use of extended graphite, paraffin, and low-density polyethylene [80]. A brief review of the various strategies for preventing thermal runaway is presented in Table 2.

**Table 2.** Brief overview of methods for avoiding thermal runaway.

| Cooling Method | Study Type | Major Finding | Battery Shape | Reference |
|---|---|---|---|---|
| Air | Numerical | When comparing staggered and aligned battery placement, the former is preferable. | Cylindrical | [45], [46] |
| Air | Numerical | Reciprocating airflow allows for temperature uniformity of −4 °C. | Cylindrical | [52], [81] |
| Air | Numerical & Experimental | Putting air tubes around each battery ensures a consistent temperature within a tolerance of 3 degrees Celsius. | Cylindrical | [82] |
| Air | Numerical & Experimental | When the inlet is at the top and the exhaust is at the bottom, the cooling effect is maximized. | Cylindrical | [83]–[86] |

| | | | | |
|---|---|---|---|---|
| Air | Experimental & Numerical | Maximum cooling efficiency is attained by the cells' cuboid shape. | Cylindrical | [83] |
| Air | Numerical & Experimental | Injecting jet inlets and vortex generators into the unidirectional airflow keeps the space's temperature under 5 °C. | Cylindrical | [54], [55] |
| Liquid | Numerical | Increased battery contact area produces 0.7 °C temperature uniformity. | Cylindrical | [62] |
| Liquid | Numerical | Avoiding clustering, shielding wires, and taking into account the nano-fluid's boiling point are all necessary for their utilization. | Cylindrical | [87] |
| Liquid | Numerical | Perfected "fork" cold plate design. Temperature homogeneity below 5 °C requires 48 mL/s. | Prismatic | [63] |
| Liquid | Numerical | A changing aluminum block with a 3 mm linear gradients achieves temperature homogeneity below 5 °C. | Cylindrical | [61] |
| Liquid | Numerical | The cooling and temperature homogeneity are enhanced when the liquid is mixed utilizing Tesla valves. | Prismatic | [88] |
| PCM | Numerical | It's not a good idea to utilize refrigerators to cool down the superheated state. | Cylinder | [89] |
| PCM | Experimental | This new paraffin-coated graphene nickel foam-based phase change material (PCM) has a thermal conductivity that is 23 times higher than that of pure paraffin. | Cylinder | [90] |
| PCM | Numerical | Propane, ammonia, R134a, and hydrogen are used in a novel liquid PCM method. Optimal operating temperatures call for a wide range of pressure, temperature, and liquid volume configurations. | Cylindrical & Prismatic | [91]–[94] |
| PCM | Experimental | Ideal EG concentration in paraffin-based composite PCM is 7%. | Cylindrical | [17] |
| Hybrid (Air & Liquid) | Numerical | Each battery had a fluid jacket, and passive air-cooling maintained 1.3 °C temperature uniformity. | Cylindrical | [95] |
| Hybrid (Air & Liquid) | Experimental | Water evaporation, convective air movement, and conductive heat transfer are all utilized in a novel approach. | Cylindrical | [44], [96] |
| Hybrid (Liquid & PCM) | Experimental | PCM thickness of 0.65 mm and liquid flowrate of 54 mL/min create 1 °C temperature uniformity. | Prismatic | [97] |
| Hybrid (Mist Cooling) | Numerical | To keep the temperature below 40 degrees Celsius, a mist with a 3% humidity and a mass flow rate of 5 g/s are needed. | Cylindrical | [98] |

# 3 Challenges and Limitations

## 3.1 Challenges

There are several challenges that need to be addressed when it comes to BTMS. These challenges are depicted in detail in figure 5.

**Fig. 5.** Challenges associated with BTMS

Maintaining an even temperature distribution is a significant challenge for BTMS. It is challenging to keep the cell temperature stable for any battery system. This becomes more complex with larger battery packs in EVs and energy storage. Each cell in large arrays has distinct heat profiles, leading to temperature disparities affecting performance and safety.

It is crucial to prevent thermal runaway. A battery cell's self-sustaining, exothermic process can cause catastrophic failures if left unchecked. Early diagnosis and prevention of thermal runaway are vital due to its seriousness. Without proper protection, a thermal runaway in a single cell can potentially eradicate an entire battery system.

As technology advances, batteries become smaller and more powerful. While advantageous, this trend complicates assimilation. Integrating an efficient BTMS into these compact and high-capacity batteries is challenging. Integrating the battery without compromising its form or function is complex.

Material compatibility is essential for heat management in batteries. These compounds may interact with battery components, reducing efficiency or posing safety risks. Finding materials that handle heat and work with battery chemistry is complicated.

The operation of batteries is dynamic, and BTMSs must adapt to many internal and external factors. A BTMS that can adjust to external factors like ambient temperatures is needed. Internally, battery charging and discharging rates add complexity. The BTMS must be resilient and adaptable to maintain appropriate thermal conditions in both scenarios.

Due to its high cost, the efficiency-cost dilemma arises when implementing modern BTMS solutions with advanced features and materials. Manufacturers and consumers must balance the performance benefits of these modern systems against their costs. Finding a balance between cost and efficient heat control is difficult in the field.

## 3.2 Limitations

There are several limitations that need to be addressed when it comes to BTMS. These limitations are depicted in detail in figure 6.

**Fig. 6.** Limitations associated with BTMS

Energy management is vital to Battery Thermal Management System development and use. When active, BTMS consumes more energy as it utilizes liquid coolants or fans for cooling purposes. This may seem minor, but it always uses the energy reserves the system is designed to maximize. Regulating the battery's temperature using active management strategies reduces its net energy production and creates an efficiency problem. Maximizing temperature regulation with little energy loss is difficult.

When integrating BTMS components, carefully considering the design and structure is important. This will guarantee a successful integration process and seamless component operation. Post-integration, the battery system is more extensive and heavier. Mobile applications have substantial obstacles, yet stationary applications may not. Even the smallest amount of weight can make a significant difference when it comes to electric cars, drones, and portable electronics. BTMS components can increase weight and volume, affecting mobility, energy efficiency, and design aesthetics.

With BTMS integration, maintenance is another consideration. Systems with moving parts or liquid coolants require frequent maintenance, including check ups, replacements, repairs, and monitoring. If maintenance needs are not promptly addressed, commercial applications and end-users may suffer longer downtimes, higher expenses, and shorter system lifespan.

Any technology that wants to change the market needs scalability. Scaling a BTMS system can be a difficult task. A system built for a smaller battery module may fail with larger packs or arrays. This goes beyond adding components and cooling. Heat distribution, energy management, and efficiency throughout a broader range are critical. While BTMSs may perform well in lab settings, their real-world scalability is an issue.

BTMS is also full of innovation, introducing new solutions quickly. However, rapid technical developments often exceed long-term testing. Several modern BTMS methods, while promising on paper and under controlled conditions, have yet to be tested in real life. Their long-term reliability under changing conditions has yet to be discovered. This presents issues for manufacturers and consumers who must assess the longevity and reliability of their investments.

The environmental impact of BTMS is crucial. The global focus on sustainability and eco-friendly technologies requires that any new system, including BTMS, be assessed for its ecological impact. Some coolants are environmentally harmful despite being thermally efficient. They may not biodegrade or emit toxic pollutants. Some BTMS materials may be challenging to recycle or dispose of. Combining efficient thermal management with environmental care becomes essential as we move toward a greener future.

# 4 Conclusion

The Li-ion battery is considered a promising battery technology for electric vehicle (EV) applications due to the advantageous properties of lithium, such as its has a strong negative potential despite its modest atomic weight. Lithium-based batteries offer electric vehicles (EVs) superior performance attributes regarding both distal reach and rate of acceleration. In addition to possessing a high-specific energy, lithium-ion batteries exhibit exceptional potential for extended lifespan. Furthermore, the typical configuration and elevated voltage of the Li-ion battery render it a highly promising and cost-effective energy storage solution. Air cooling technology is frequently employed in numerous applications of Li-ion batteries due to its cost-effectiveness, ease of maintenance, straightforward construction, and minimal parasitic energy resulting from the low viscosity of air. Nevertheless, the effectiveness of air-based BTMS is contingent upon their application in small-scale battery packs and mild environmental temperatures. However, these systems encounter challenges when confronted with high-power outputs and harsh ambient temperatures, leading to potential failures. Liquid cooling systems have the potential to exhibit superior cooling performance compared to cabin air cooling systems due to their utilization of a liquid medium possessing a higher heat capacity in contrast to air. Nevertheless, this system exhibits certain drawbacks including heightened intricacy, elevated cost, and increased weight as a result of the incorporation of heat exchangers and circuitry. When compared to single-phase heat exchange systems like those used to compared secondary liquid loop cooling systems, the improved effectiveness of cooling at low flow rates achieved by the Direct refrigerant two-phase cooling system uses refrigerant heat exchange. Furthermore, the system has the capability to enhance simplicity and decrease mass by obviating the necessity for fluidic circuits and supplementary heat exchangers. The heat pipe cooling system exhibits enhanced heat transfer efficiency compared to conventional phase change materials (PCM) owing to its superior thermal conductivity. However, in order to address the limited space where the heat pipe makes contact with the battery, it is necessary to integrate a cooling plate into the system. The phase change mechanism employed by PCM cooling systems enables efficient absorption of substantial battery heat without significant energy expenditure, maintaining a consistent temperature. However, the low thermal conductivity of presents difficulties for this system of phase change material (PCM), the persistent heat load on the battery following the repeated melting and solidifying cycles, PCM phase transition completion, PCM leakage, volume variations, and lack of internal homogeneity. Due to differences in battery type, capacity, and operating circumstances, it was concluded after a thorough evaluation of numerous BTMS that a direct comparison between each system was not viable. However, a study was done to weigh the benefits and downsides of each strategy. Thus, to improve the performance of the BTMS, an adequate BTMS must be chosen for the intended use of the EV, and multiple systems may be used to compensate for any limitations. The thermal load of electrical vehicle batteries is predicted to rise in the future due to the higher energy density of EV batteries. This means that the BTMS will eventually combine heat pipe technologies, thermoelectric systems, and direct two-phase refrigerant cooling with phase change material (PCM).

# References

[1] M. Yacoub Al Shdaifat, R. Zulkifli, K. Sopian, and A. Adel Salih, “Basics, properties, and thermal issues of EV battery and battery thermal management systems: Comprehensive review,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 237, no. 2–3. SAGE Publications Ltd, pp. 295–311, Feb. 01, 2023. doi: 10.1177/09544070221079195.

[2] 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," in *2015 17th UKSim-AMSS International Conference on Modelling and Simulation (UKSim)*, 2015, pp. 444–450. doi: 10.1109/UKSim.2015.69.

[3] M. Lowe, S. Tokuoka, T. Trigg, and G. Gereffi, "Lithium-ion Batteries for Electric Vehicles: Contributing CGGC researcher: Ansam Abayechi," 2010. [Online]. Available: http://www.edf.org/home.cfm

[4] J.-M. Tarascon and M. Armand, "Issues and challenges facing rechargeable lithium batteries," in *Materials for Sustainable Energy*, Co-Published with Macmillan Publishers Ltd, UK, 2010, pp. 171–179. doi: doi:10.1142/9789814317665_0024.

[5] J. Kim, J. Oh, and H. Lee, "Review on battery thermal management system for electric vehicles," *Appl Therm Eng*, vol. 149, pp. 192–212, 2019, doi: https://doi.org/10.1016/j.applthermaleng.2018.12.020.

[6] T. M. Bandhauer, S. Garimella, and T. F. Fuller, "A Critical Review of Thermal Issues in Lithium-Ion Batteries," *J Electrochem Soc*, vol. 158, no. 3, p. R1, 2011, doi: 10.1149/1.3515880.

[7] K. Smith and C. Y. Wang, "Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles," *J Power Sources*, vol. 160, no. 1, pp. 662–673, Sep. 2006, doi: 10.1016/j.jpowsour.2006.01.038.

[8] A. Pesaran, "Battery Thermal Management in EVs and HEVs: Issues and Solutions," *Battery Man*, vol. 43, Jan. 2001.

[9] A. Pesaran, "Battery Thermal Models for Hybrid Vehicle Simulations," *J Power Sources*, vol. 110, pp. 377–382, Aug. 2002, doi: 10.1016/S0378-7753(02)00200-8.

[10] Z. Jiang, H. B. Li, Z. Qu, and J.-F. Zhang, "Recent progress in lithium-ion battery thermal management for a wide range of temperature and abuse conditions," *Int J Hydrogen Energy*, vol. 47, Jan. 2022, doi: 10.1016/j.ijhydene.2022.01.008.

[11] A. K. Thakur *et al.*, "A state of art review and future viewpoint on advance cooling techniques for Lithium–ion battery system of electric vehicles," *J Energy Storage*, vol. 32, p. 101771, 2020, doi: https://doi.org/10.1016/j.est.2020.101771.

[12] A. Gupta et al., "A comparative study of the impact on combustion and emission characteristics of nanoparticle-based fuel additives in the internal combustion engine," Energy Sci. Eng., Dec. 2023, doi: 10.1002/ese3.1614.

[13] M. Keyser, G.-H. Kim, J. Neubauer, A. Pesaran, S. Santhanagopalan, and K. Smith, *Design and Analysis of Large Lithium-Ion Battery Systems*. Artech, 2014. [Online]. Available: http://ieeexplore.ieee.org/document/9100518

[14] Q. Wang, P. Ping, X. Zhao, C. Guanquan, J. Sun, and C. Chen, "ChemInform Abstract: Thermal Runaway Caused Fire and Explosion of Lithium Ion Battery," *J Power Sources*, vol. 208, pp. 210–224, Jun. 2012, doi: 10.1016/j.jpowsour.2012.02.038.

[15] P. Liu, Y. Li, B. Mao, M. Chen, Z. Huang, and Q. Wang, "Experimental study on thermal runaway and fire behaviors of large format lithium iron phosphate battery," *Appl Therm Eng*, vol. 192, p. 116949, Apr. 2021, doi: 10.1016/j.applthermaleng.2021.116949.

[16] S. Ambade et al., "Experimental investigation of microstructural, mechanical and corrosion properties of 316L and 202 austenitic stainless steel joints using cold metal transfer welding," J. Mater. Res. Technol., vol. 27, pp. 5881–5888, Nov. 2023, doi: 10.1016/j.jmrt.2023.11.091.

[17] F. He, X. Li, G. Zhang, G. Zhong, and J. He, "Experimental investigation of thermal management system for lithium ion batteries module with coupling effect by heat sheets and phase change materials," *Int J Energy Res*, vol. 42, no. 10, pp. 3279–3288, Aug. 2018, doi: https://doi.org/10.1002/er.4081.

[18] D. Finegan *et al.*, “Characterising thermal runaway within lithium-ion cells by inducing and monitoring internal short circuits,” *Energy Environ. Sci.*, vol. 10, pp. 1377–1388, Apr. 2017, doi: 10.1039/C7EE00385D.

[19] 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, 2016, doi: https://doi.org/10.1016/j.apenergy.2015.11.034.

[20] S. Panchal *et al.*, “Cycling degradation testing and analysis of a LiFePO4 battery at actual conditions,” *Int J Energy Res*, vol. 41, no. 15, pp. 2565–2575, Dec. 2017, doi: https://doi.org/10.1002/er.3837.

[21] Y. Ji, Y. Zhang, and C.-Y. Wang, “Li-Ion Cell Operation at Low Temperatures,” *J Electrochem Soc*, vol. 160, pp. A636–A649, Jan. 2013, doi: 10.1149/2.047304jes.

[22] K. S. Reddy, H. Vemanaboina, B. V. V. Naidu, B. Yelamasetti, P. Bridjesh, and S. D. Shelare, “Minimizing distortion in multi-pass GTAW welding of SS316L structures: a Taguchi approach,” Int. J. Interact. Des. Manuf., Sep. 2023, doi: 10.1007/s12008-023-01512-4.

[23] R. Bugga, M. Smart, J. Whitacre, and W. West, *Lithium Ion Batteries for Space Applications*. 2007. doi: 10.1109/AERO.2007.352728.

[24] R. Zalosh, P. Gandhi, and A. Barowy, “Lithium-ion energy storage battery explosion incidents,” *J Loss Prev Process Ind*, vol. 72, p. 104560, 2021, doi: https://doi.org/10.1016/j.jlp.2021.104560.

[25] Y.-W. Wang, “Evaluate the deflagration potential for commercial cylinder Li-ion cells under adiabatic confinement testing,” *J Therm Anal Calorim*, vol. 143, Jan. 2020, doi: 10.1007/s10973-020-09282-x.

[26] S. Yalçin, S. Panchal, and M. Herdem, “A Cnn-Abc Model for Estimation and Optimization of Heat Generation Rate and Voltage Distributions of Lithium-Ion Batteries for Electric Vehicles,” *Int J Heat Mass Transf*, vol. 199, p. 123486, Dec. 2022, doi: 10.1016/j.ijheatmasstransfer.2022.123486.

[27] S. Al Hallaj, H. Maleki, J. S. Hong, and J. R. Selman, “Thermal modeling and design considerations of lithium-ion batteries,” *J Power Sources*, vol. 83, no. 1, pp. 1–8, 1999, doi: https://doi.org/10.1016/S0378-7753(99)00178-0.

[28] K. Thomas and J. Newman, “Thermal Modeling of Porous Insertion Electrodes,” *J. Electrochem. Soc.*, vol. 150, pp. A176–A192, Feb. 2003, doi: 10.1149/1.1531194.

[29] S. D. Shelare, R. Kumar, and P. B. Khope, “Flywheel Energy Application in Commercial and Agricultural Field: A Typical Review,” in Lecture Notes in Mechanical Engineering, Springer, 2021, pp. 177–186. doi: 10.1007/978-981-16-1079-0_19.

[30] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, and X. He, “Thermal runaway mechanism of lithium ion battery for electric vehicles: A review,” *Energy Storage Mater*, vol. 10, pp. 246–267, 2018, doi: https://doi.org/10.1016/j.ensm.2017.05.013.

[31] T. A. Stuart and A. Hande, “HEV battery heating using AC currents,” *J Power Sources*, vol. 129, no. 2, pp. 368–378, 2004, doi: https://doi.org/10.1016/j.jpowsour.2003.10.014.

[32] C. Alaoui and Z. M. Salameh, “A Novel Thermal Management for Electric and Hybrid Vehicles,” *Vehicular Technology, IEEE Transactions on*, vol. 54, pp. 468–476, Apr. 2005, doi: 10.1109/TVT.2004.842444.

[33] J. Li, P. Wu, and H. Tian, *Researches on heating low-temperature lithium-ion power battery in electric vehicles*. 2014. doi: 10.1109/ITEC-AP.2014.6941276.

[34] Z. Lei, C. Zhang, J. Li, G. Fan, and Z. Lin, “Preheating method of lithium-ion batteries in an electric vehicle,” *Journal of Modern Power Systems and Clean Energy*, vol. 3, Jun. 2015, doi: 10.1007/s40565-015-0115-1.

[35] D. Adair, K. Ismailov, and Z. Bakenov, *Thermal Management of Li-ion Battery Packs*. 2014.
[36] 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, Dec. 2011. doi: 10.1016/j.rser.2011.07.096.
[37] R. Sabbah, R. Kizilel, J. R. Selman, and S. Al-Hallaj, “Active (air-cooled) vs. passive (phase change material) thermal management of high power lithium-ion packs: Limitation of temperature rise and uniformity of temperature distribution,” *J Power Sources*, vol. 182, no. 2, pp. 630–638, 2008, doi: https://doi.org/10.1016/j.jpowsour.2008.03.082.
[38] P. Ramadass, B. Haran, R. White, and B. Popov, “Capacity fade of Sony 18650 cells cycled at elevated temperatures:: Part I. Cycling performance,” *J Power Sources*, vol. 112, Nov. 2002, doi: 10.1016/S0378-7753(02)00474-3.
[39] J. Shim, R. Kostecki, T. Richardson, X. Song, and K. A. Striebel, “Electrochemical analysis for cycle performance and capacity fading of a lithium-ion battery cycled at elevated temperature,” *J Power Sources*, vol. 112, no. 1, pp. 222–230, 2002, doi: https://doi.org/10.1016/S0378-7753(02)00363-4.
[40] K. Amine, J. Liu, and I. Belharouak, “High-temperature storage and cycling of C-LiFePO 4/graphite Li-ion cells,” *Electrochemistry Communications - ELECTROCHEM COMMUN*, vol. 7, pp. 669–673, Jul. 2005, doi: 10.1016/j.elecom.2005.04.018.
[41] P. Liu *et al.*, “Aging Mechanisms of LiFePO[sub 4] Batteries Deduced by Electrochemical and Structural Analyses,” *J Electrochem Soc*, vol. 157, no. 4, p. A499, 2010, doi: 10.1149/1.3294790.
[42] J. Jaguemont, L. Boulon, P. Venet, Y. Dubé, and A. Sari, “Lithium-Ion Battery Aging Experiments at Subzero Temperatures and Model Development for Capacity Fade Estimation,” *IEEE Trans Veh Technol*, vol. 65, no. 6, pp. 4328–4343, 2016, doi: 10.1109/TVT.2015.2473841.
[43] Y. Zheng *et al.*, “Influence of charge rate on the cycling degradation of LiFePO4/mesocarbon microbead batteries under low temperature,” *Ionics (Kiel)*, vol. 23, Aug. 2017, doi: 10.1007/s11581-017-2032-y.
[44] Y. Wei and M. Agelin-Chaab, “Development and experimental analysis of a hybrid cooling concept for electric vehicle battery packs,” *J Energy Storage*, vol. 25, p. 100906, 2019, doi: https://doi.org/10.1016/j.est.2019.100906.
[45] A. A. A. Hakeem and D. Solyali, “Empirical Thermal Performance Investigation of a Compact Lithium Ion Battery Module under Forced Convection Cooling,” Applied Sciences, vol. 10, no. 11. 2020. doi: 10.3390/app10113732.
[46] Y. Fan, Y. Bao, C. Ling, Y. Chu, X. Tan, and S. Yang, “Experimental study on the thermal management performance of air cooling for high energy density cylindrical lithium-ion batteries,” *Appl Therm Eng*, vol. 155, pp. 96–109, 2019, doi: https://doi.org/10.1016/j.applthermaleng.2019.03.157.
[47] J. Zhao, Z. Rao, H. Yutao, X. Liu, and Y. Li, “Thermal management of cylindrical power battery module for extending the life of new energy electric vehicles,” *Appl Therm Eng*, vol. 85, Jun. 2015, doi: 10.1016/j.applthermaleng.2015.04.012.
[48] W. Tong, K. Somasundaram, E. Birgersson, A. Mujumdar, and C. Yap, “Thermo-electrochemical model for forced convection air cooling of a lithium-ion battery module,” *Appl Therm Eng*, vol. 99, Jan. 2016, doi: 10.1016/j.applthermaleng.2016.01.050.
[49] H. Sun and R. Dixon, “Development of cooling strategy for an air cooled lithium-ion battery pack,” *J Power Sources*, vol. 272, pp. 404–414, Dec. 2014, doi: 10.1016/j.jpowsour.2014.08.107.

[50] O. Ozbalci, A. Dogan, and M. Asilturk, “Heat Transfer Performance of Plate Fin and Pin Fin Heat Sinks Using Al2O3/H2O Nanofluid in Electronic Cooling,” Processes, vol. 10, no. 8. 2022. doi: 10.3390/pr10081644.

[51] W. Tong, K. Somasundaram, E. Birgersson, A. Mujumdar, and C. Yap, “Thermo-electrochemical model for forced convection air cooling of a lithium-ion battery module,” *Appl Therm Eng*, vol. 99, Jan. 2016, doi: 10.1016/j.applthermaleng.2016.01.050.

[52] R. Mahamud and C. Park, “Reciprocating air flow for Li-ion battery thermal management to improve temperature uniformity,” *Lancet*, vol. 196, pp. 5685–5696, Jul. 2011, doi: 10.1016/j.jpowsour.2011.02.076.

[53] S. Shahid and M. Agelin-Chaab, “Experimental and numerical studies on air cooling and temperature uniformity in a battery pack,” *Int J Energy Res*, vol. 42, Feb. 2018, doi: 10.1002/er.4018.

[54] S. Shahid and M. Agelin-Chaab, “Analysis of Cooling Effectiveness and Temperature Uniformity in a Battery Pack for Cylindrical Batteries,” *Energies (Basel)*, Aug. 2017, doi: 10.3390/en10081157.

[55] S. Shahid and M. Agelin-Chaab, “Application of Jets and Vortex Generators to Improve Air-Cooling and Temperature Uniformity in a Simple Battery Pack,” *J Therm Sci Eng Appl*, vol. 11, Sep. 2018, doi: 10.1115/1.4041493.

[56] S. Park and D. Jung, “Battery cell arrangement and heat transfer fluid effects on the parasitic power consumption and the cell temperature distribution in a hybrid electric vehicle,” *J Power Sources*, vol. 227, pp. 191–198, 2013, doi: https://doi.org/10.1016/j.jpowsour.2012.11.039.

[57] M. Patil, J.-H. Seo, and M.-Y. Lee, “A novel dielectric fluid immersion cooling technology for Li-ion battery thermal management,” *Energy Convers Manag*, vol. 229, p. 113715, Feb. 2021, doi: 10.1016/j.enconman.2020.113715.

[58] P. Dubey, G. Pulugundla, and A. Srouji, “Direct Comparison of Immersion and Cold-Plate Based Cooling for Automotive Li-Ion Battery Modules,” *Energies (Basel)*, vol. 14, p. 1259, Feb. 2021, doi: 10.3390/en14051259.

[59] S. Panchal, R. Khasow, I. Dincer, M. Agelin-Chaab, R. Fraser, and M. Fowler, “Thermal design and simulation of mini-channel cold plate for water cooled large sized prismatic lithium-ion battery,” *Appl Therm Eng*, vol. 122, pp. 80–90, 2017, doi: https://doi.org/10.1016/j.applthermaleng.2017.05.010.

[60] S. Panchal, S. Mathewson, R. Fraser, R. Culham, and M. Fowler, “Thermal Management of Lithium-Ion Pouch Cell with Indirect Liquid Cooling using Dual Cold Plates Approach,” *SAE International Journal of Alternative Powertrains*, vol. 4, May 2015, doi: 10.4271/2015-01-1184.

[61] Z. Rao, Z. Qian, Y. Kuang, and Y. Li, “Thermal performance of liquid cooling based thermal management system for cylindrical lithium-ion battery module with variable contact surface,” *Appl Therm Eng*, vol. 123, pp. 1514–1522, Aug. 2017, doi: 10.1016/j.applthermaleng.2017.06.059.

[62] C. Zhao and F. Jiang, “Minimization of Thermal Non-uniformity in Lithium-ion Battery Pack Cooled by Channeled Liquid Flow,” *Int J Heat Mass Transf*, vol. 129, pp. 660–670, Oct. 2018, doi: 10.1016/j.ijheatmasstransfer.2018.10.017.

[63] Q. Li, H. Shi, G. Xie, Z. Xie, and H. Liu, “Parametric study and optimization on novel fork-type mini-channel network cooling plates for a Li-ion battery module under high discharge current rates,” *Int J Energy Res*, vol. 45, Jun. 2021, doi: 10.1002/er.6933.

[64] D.-I. Florian Schoewel and D.-I. Elmar Hockgeiger, “THE HIGH VOLTAGE BATTERIES OF THE BMW i3 AND BMW i8. AABC 2014, FEBRUARY 3TH-7TH, ATLANTA.”

[65] "Sheet 1 of 27 Patent Application Publication," 2014.
[66] S. Waghmare, N. Mungle, C. Tembhurkar, S. Shelare, and N. Pathare, "Design and analysis of power screw for manhole cover lifter," Int. J. Recent Technol. Eng., vol. 8, no. 2, 2019, doi: 10.35940/ijrte.B2628.078219.
[67] I. Krüger and G. Schmitz, *Energy Consumption Of Battery Cooling In Hybrid Electric Vehicles*. 2012.
[68] P. Kritzer, H. Döring, and B. Emmermacher, "Improved Safety for Automotive Lithium Batteries: An Innovative Approach to include an Emergency Cooling Element," *Advances in Chemical Engineering and Science*, vol. 04, pp. 197–207, Jan. 2014, doi: 10.4236/aces.2014.42023.
[69] A. Faghri and C. Harley, "Transient lumped heat pipe analyses," *Heat Recovery Systems and CHP*, vol. 14, no. 4, pp. 351–363, 1994, doi: https://doi.org/10.1016/0890-4332(94)90039-6.
[70] X. Yang, Y. Y. Yan, and D. Mullen, "Recent developments of lightweight, high performance heat pipes," *Appl Therm Eng*, vol. s 33–34, pp. 1–14, Feb. 2012, doi: 10.1016/j.applthermaleng.2011.09.006.
[71] C.-C. Ting and C.-C. Chen, "Analyzing the Heat Transfer Property of Heat Pipe Influenced by Integrated Cooling Apparatus," *Chinese Journal of Engineering*, vol. 2014, pp. 1–10, Mar. 2014, doi: 10.1155/2014/409074.
[72] Y. Li, F. Qi, H. Guo, Z. Guo, G. Xu, and J. Liu, "Numerical investigation of thermal runaway propagation in a Li-ion battery module using the heat pipe cooling system," *Numeri Heat Transf A Appl*, vol. 75, pp. 183–199, Feb. 2019, doi: 10.1080/10407782.2019.1580956.
[73] J. Liang, Y. H. Gan, and Y. Li, "Investigation on the thermal performance of a battery thermal management system using heat pipe under different ambient temperatures," *Energy Convers Manag*, vol. 155, pp. 1–9, Jan. 2018, doi: 10.1016/j.enconman.2017.10.063.
[74] R. Baetens, B. P. Jelle, and A. Gustavsen, "Phase change materials for building applications: A state-of-the-art review," *Energy Build*, vol. 42, no. 9, pp. 1361–1368, 2010, doi: https://doi.org/10.1016/j.enbuild.2010.03.026.
[75] I. Elefsiniotis, T. Becker, and U. Schmid, "Thermoelectric Energy Harvesting Using Phase Change Materials (PCMs) in High Temperature Environments in Aircraft," *J Electron Mater*, vol. 43, pp. 1809–1814, Jun. 2013, doi: 10.1007/s11664-013-2880-9.
[76] F. Kuznik *et al.*, "A review on phase change materials integrated in building walls A review on phase change materials inte-grated in building walls. Renewable and Sustainable Energy Reviews A review on Phase Change Materials Integrated in Building Walls," vol. 15, no. 1, pp. 379–391, 2011, doi: 10.1016/j.rser.2010.08.019ï.
[77] A. Sharma, V. V Tyagi, C. R. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 2, pp. 318–345, 2009, doi: https://doi.org/10.1016/j.rser.2007.10.005.
[78] S. Wilke, B. Schweitzer, S. Khateeb, and S. Al-Hallaj, "Preventing thermal runaway propagation in lithium ion battery packs using a phase change composite material: An experimental study," *J Power Sources*, vol. 340, pp. 51–59, 2017, doi: https://doi.org/10.1016/j.jpowsour.2016.11.018.
[79] Z. Ling, F. Wang, X. Fang, X. Gao, and Z. Zhang, "A hybrid thermal management system for lithium ion batteries combining phase change materials with forced-air cooling," *Appl Energy*, vol. 148, pp. 403–409, Jun. 2015, doi: 10.1016/j.apenergy.2015.03.080.
[80] Y. Lv, X. Yang, X. Li, G. Zhang, Z. Wang, and C. Yang, "Experimental study on a novel battery thermal management technology based on low density polyethylene-

enhanced composite phase change materials coupled with low fins," *Appl Energy*, vol. 178, pp. 376–382, Sep. 2016, doi: 10.1016/j.apenergy.2016.06.058.

[81] Y. Liu, C. Ouyang, Q. Jiang, and B. Liang, "Design and parametric optimization of thermal management of lithium-ion battery module with reciprocating air-flow," *J Cent South Univ*, vol. 22, pp. 3970–3976, Oct. 2015, doi: 10.1007/s11771-015-2941-8.

[82] H. Zhou, F. Zhou, L. Xu, and J. Kong, "Thermal performance of cylindrical Lithium-ion battery thermal management system based on air distribution pipe," *Int J Heat Mass Transf*, vol. 131, pp. 984–998, Mar. 2019, doi: 10.1016/j.ijheatmasstransfer.2018.11.116.

[83] T. Wang, K. Tseng, J. Zhao, and Z. Wei, "Thermal investigation of lithium-ion battery module with different cell arrangement structures and forced air-cooling strategies," *Appl Energy*, vol. 134, pp. 229–238, Dec. 2014, doi: 10.1016/j.apenergy.2014.08.013.

[84] B. Saw Lip Huat, Y. Ye, M. Yew, W. T. Chong, M. K. Yew, and T. Ng, "Computational fluid dynamics simulation on open cell aluminium foams for Li-ion battery cooling system," *Appl Energy*, vol. 204, Apr. 2017, doi: 10.1016/j.apenergy.2017.04.022.

[85] T. Wang, K. J. Tseng, and J. Zhao, "Development of efficient air-cooling strategies for lithium-ion battery module based on empirical heat source model," *Appl Therm Eng*, vol. 90, pp. 521–529, 2015, doi: https://doi.org/10.1016/j.applthermaleng.2015.07.033.

[86] S. Shahid and M. Agelin-Chaab, "Development and Analysis of a Technique to Improve Air-Cooling and Temperature Uniformity in a Battery Pack for Cylindrical Batteries," *Thermal Science and Engineering Progress*, vol. 5, Mar. 2018, doi: 10.1016/j.tsep.2018.01.003.

[87] A. M. Sefidan, A. Sojoudi, and S. Saha, "Nanofluid-based cooling of cylindrical lithium-ion battery packs employing forced air flow," *International Journal of Thermal Sciences*, vol. 117, pp. 44–58, Jul. 2017, doi: 10.1016/j.ijthermalsci.2017.03.006.

[88] K. Monika, C. Chakraborty, S. Roy, R. Sujith, and S. P. Datta, "A numerical analysis on multi-stage Tesla valve based cold plate for cooling of pouch type Li-ion batteries," *Int J Heat Mass Transf*, vol. 177, p. 121560, 2021, doi: https://doi.org/10.1016/j.ijheatmasstransfer.2021.121560.

[89] R. Jilte and R. Kumar, "Numerical investigation on cooling performance of Li-ion battery thermal management system at high galvanostatic discharge," *Engineering Science and Technology, an International Journal*, vol. 21, Aug. 2018, doi: 10.1016/j.jestch.2018.07.015.

[90] A. Hussain, I. H. Abidi, C. Y. Tso, K. C. Chan, Z. Luo, and C. Y. H. Chao, "Thermal management of lithium ion batteries using graphene coated nickel foam saturated with phase change materials," *International Journal of Thermal Sciences*, vol. 124, pp. 23–35, 2018, [Online]. Available: https://api.semanticscholar.org/CorpusID:125599272

[91] M. Al-Zareer, I. Dincer, and M. Rosen, "Novel thermal management system using boiling cooling for high-powered lithium-ion battery packs for hybrid electric vehicles," *J Power Sources*, vol. 363, pp. 291–303, Sep. 2017, doi: 10.1016/j.jpowsour.2017.07.067.

[92] M. Al-Zareer, I. Dincer, and M. Rosen, "A Novel Phase Change Based Cooling System for Prismatic Lithium Ion Batteries," *International Journal of Refrigeration*, vol. 86, Dec. 2017, doi: 10.1016/j.ijrefrig.2017.12.005.

[93] M. Al-Zareer, I. Dincer, and M. Rosen, "Electrochemical Modeling and performance evaluation of a new ammonia-based battery thermal management system for electric

and hybrid electric vehicles," *Electrochim Acta*, vol. 247, Jun. 2017, doi: 10.1016/j.electacta.2017.06.162.

[94] M. Al-Zareer, I. Dincer, and M. Rosen, "Performance assessment of a new hydrogen cooled prismatic battery pack arrangement for hydrogen hybrid electric vehicles," *Energy Convers Manag*, vol. 173, pp. 303–319, Oct. 2018, doi: 10.1016/j.enconman.2018.07.072.

[95] S. Shahid and M. Agelin-Chaab, "Development of hybrid thermal management techniques for battery packs," *Appl Therm Eng*, vol. 186, p. 116542, 2021, doi: https://doi.org/10.1016/j.applthermaleng.2020.116542.

[96] Y. Wei and M. Agelin-Chaab, "Experimental investigation of a novel hybrid cooling method for lithium-ion batteries," *Appl Therm Eng*, vol. 136, pp. 375–387, 2018, doi: https://doi.org/10.1016/j.applthermaleng.2018.03.024.

[97] S. Chen, A. Garg, L. Gao, and Xuezhe, "An experimental investigation for a hybrid phase change material-liquid cooling strategy to achieve high-temperature uniformity of Li-ion battery module under fast charging," *Int J Energy Res*, Dec. 2020.

[98] L. Huat Saw *et al.*, "Novel thermal management system using mist cooling for Lithium-ion battery packs."