IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.53
Volume 5, Issue 1, January 2025

A Comprehensive Review of Thermal Management Solutions for EV Battery Systems

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Abstract: *Avoiding and minimizing carbon emissions and air pollution is one of the main obstacles to the automotive industry's technological advancement. Additionally, in response to the European Union's promotion of limiting the use of conventional fuel-powered vehicles, such as diesel and gasoline vehicles, the automotive industry has increased research and field applications of electric vehicles. Furthermore, in reaction to the European Union's push to limit the use of traditional fuel-powered vehicles, such as gasoline and diesel vehicles, the automotive industry has increased research and field applications of electric vehicles. Compared to internal combustion engines, the batteries used in electric vehicles today have a significantly longer cycle life, are more environmentally friendly, have a longer driving range, and require less time to charge. Depending on the various techniques used to cool the phase change materials, the multi-physical battery thermal management systems are classified into three categories: air-cooled systems, liquid-cooled systems, and heat-pipe-cooled systems.*

Keywords: Thermal Management Systems, Battery Thermal Control, Active Cooling, Passive Cooling

I. INTRODUCTION

Most nations get all of their transportation needs from fossil fuels. But the careless and unplanned use of fossil fuels is putting nations' fossil fuel reserves in jeopardy and creating severe environmental and economic issues. Furthermore, it is undeniable that the use of fossil fuels bears the majority of the blame for the state of the world, as the effects of climate change and global warming become more apparent by the day. A much-needed tactical shift in the domains of conventional transportation and energy has prompted the development of vehicles based on harmful rather than renewable technologies, given the dire state of the energy and environmental conditions. EV vehicles can reduce greenhouse gas emissions and pollution. The European Union suggested in 2011 that sales of conventional fuels be prohibited. The demand for high-density power batteries increased along with the rapid growth of electric vehicles [1, 2]. Since lithium ion batteries have a low self-discharge rate and a high power and energy density when compared to other battery types, they are preferred in new electric vehicles. The wide variety of electrode materials and electrolyte combinations found in commercial batteries makes it difficult to identify a single mechanism that jeopardizes the performance and safety of Li-ion batteries. Electric vehicles (EVs) are growing in popularity due to their excellent energy efficiency and environmental friendliness. Battery management systems (BMSs) are devices that regulate batteries to make sure they run as reliably and optimally as possible. BMSs have worked on three fundamental projects. For both electric and hybrid vehicles (HEVs and EVs), these variables are directly impacted by the cost, longevity, and efficiency of batteries[2].The temperature of the battery affects charge acceptance during energy recovery from regenerative braking, energy availability (for acceleration and start-up), and availability of discharge power. These impact the vehicle's driving experience and fuel economy. The lifespan of the battery is also impacted by temperature. Therefore, the best temperature range to select is the one that maximizes battery performance and longevity. Because different battery types have different electrochemistry, their ideal operating temperature ranges vary as well. The recommended temperature range for battery operation, as recommended by the battery manufacturer, is typically substantially lower than the vehicle's specified operating range[2]. These days, computation, data monitoring, and protection are the three main responsibilities of BMSs. These tasks are executed with the assistance of several algorithms. Data monitoring algorithms keep an eye on the voltage, current, and temperature of the battery. The BMS computation algorithm computes various characteristics such as battery health, battery charge rate, maximum and

DOI: 10.48175/IJARSCT-22929

minimum voltage, number of cycles, operating duration, and maximum and minimum charge/discharge current by examining the instantaneous values in the monitored data. On the BMS's protection side, the values derived from the first two algorithms are employed[2].

1.1 The thermal management system for Battery

Thus, the automotive industry is moving toward Hybrid electric vehicles (HEVs) and Electric vehicles(EVs) that can run on alternative fuels due to concerns about the environment, power shortages, and global warming. EVs and HEVs are considered the greenest alternatives that could replace traditional ICE vehicles. The battery is a crucial part of electric vehicles (EVs), which repeats Within that, there is a charge-discharge cycle in the external environment. Thus the performance of Lithium Ion batteries is correlated with temperature and the quantity of heat generated within the battery.

The procedure necessitates knowledge of how the battery's current flows as well as how the rate of electrochemical reaction varies with temperature and time. y. Thomas and Newman (2003) state that reversible entropy is the mechanism by which Li-ion cells produce heat [2, 3]. During charging and discharging, Li-ion batteries produce three different types of heat. Activation heat is an irreversible heat produced by the polarization of an electrochemical reaction. According to the aforementioned studies, Li-ion batteries typically produce three different types of heat during charge and discharge: reversible reaction heat from entropy changes, activation irreversible heat from the electrochemical reaction polarization, and joule heating that results in ohmic losses. Because the active material inside the battery transitions into an inactive phase, the battery's capacity decreases. When the temperature rises or falls, the battery's capacity reduces as the number cycle repeats. There are two different kinds of cooling systems, and these are:

1.2 Air cooling

Utilizing the convection principle, air cooling dissipates heat away from the battery. There are two types of air cooling systems: Active cooling systems and Passive cooling systems. In passive cooling, the air is drawn directly from the atmosphere, whereas in an active cooling system, an evaporator and air conditioning system are used. The heating and cooling processes are provided by these two systems. Ultimately, a newly configured air-cooled evaporator for the original VCC is employed in situations where cooling the cabin and batteries might be necessary. Connected battery cells offer enough energy and power. Vibrations, temperature, and pressure are taken into account for this application. The batteries' performance is impacted by storage and operating temperature. Whether charging or discharging, the batteries warm up.

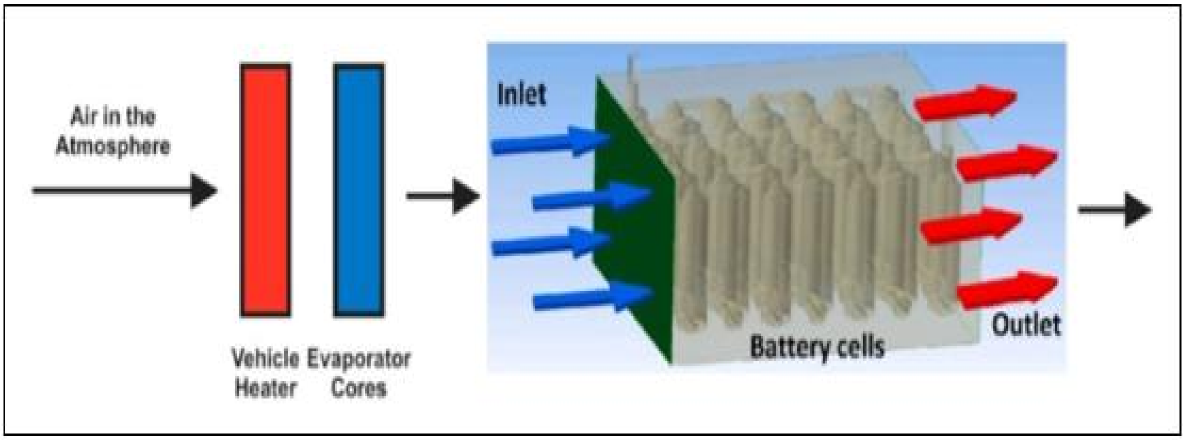

Figure 1 Schematic diagram of Air cooling[2]

So, the battery pack's cooling system is necessary. The battery pack offers the benefit of maximizing its area and providing additional power to meet the demands of operating conditions for electric vehicles. Battery life will increase with the use of an air cooling system. The performance, longevity, and cost of EVs and HEVs are impacted by the air cooling system. To improve the performance of the vehicles, the factors influencing the battery pack should be taken into account and optimized. The battery pack design, the airflow's inlet and outlet, and the preference for materials with higher thermal conductivity are the factors that need to be taken into account in order to improve the air cooling system.[2]

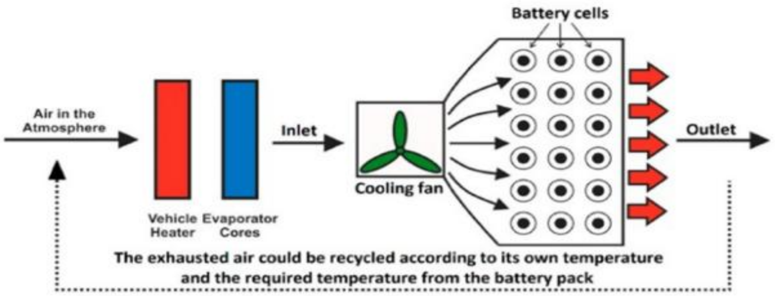

Figure 2 Schematic diagram of air cooling system[2]

1.4 Liquid cooling system

Via direct or indirect contact with the battery, a liquid cooling system lowers the temperature and maintains consistent heat dissipation in the battery pack. There are refrigerant fluids used in this cooling system. Dielectric fluids that come into direct contact with battery modules and indirect fluids that come into indirect contact with battery modules are the two categories into which they are divided. Due to direct contact with the battery module in these two types, direct liquid cooling can achieve higher thermal efficiency than indirect liquid cooling. The liquid cooling system has a higher specific heat capacity and thermal conductivity when compared to other cooling systems. [3]The most effective cooling method for an EV battery pack is liquid cooling.

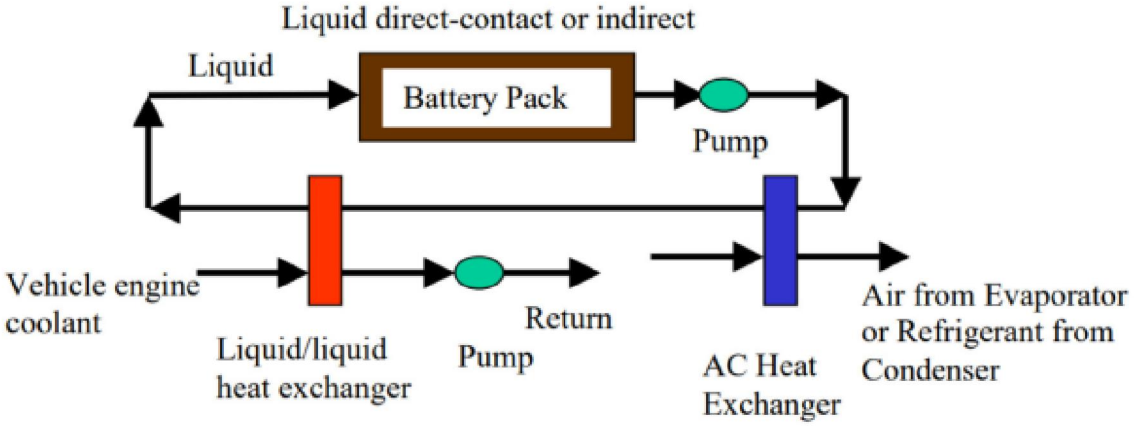

Figure 3. Active cooling- and heating-liquid circulation[2]

1.5 Hybrid cooling system

Hybrid BTMSs can be made by combining two or more basic BTMSs. There are advantages and disadvantages to each of the various BTMSs. The advantages of these systems are combined in hybrid BTMSs. It achieves increased thermal effectiveness [2]. As a result, it produces heat with greater efficiency and performance. Hybrid BTMSs, however, might have some volume, weight, and energy. problems relating to consumption. The hybrid BTMSs, which have certain issues with weight, volume, and energy usage. Heat buildup brought on by inadequate air cooling through natural convection causes issues with PCMs' thermal management system. A battery pack with a PCM-equipped thermal management system is continuously operated at 1.5C and 2C discharge rates for the purposes of this investigation. The battery pack's temperature surpasses its maximum operating range of 60°C after two cycles. They suggested integrating the air-forced convection system with the PCM system to address this issue. The maximum battery pack temperature of the hybrid system was kept at 50°C throughout the testing process by employing this hybrid system experimentation. Experiments show that the thermophysical properties have an impact on the battery pack's maximum temperature rise and temperature uniformity[2,3].

Table 1: Types of Hybrid System [9]

Type	Hybrid BTMS			
1	Heat pipe+air/liquid active cooling	Heat Pipe Heat Pipe	Air Liquid	
2	PCM+Heat Pipe passive cooling	PCM PCM PCM	Heat pipe Heat pipe Heat pipe	 Air Liquid
3	PCM+air/liquid active cooling	PCM PCM	Air Liquid	
4	Others+thermoelectric cooling	Thermoelectric cooling Thermoelectric cooling	Air PCM	Liquid
5	Liquid+air cooling active cooling	Liquid	Air	

II. MODELS FOR BATTERY THERMAL MANAGEMENT SYSTEM

2.1 Theoretically modelling approach

The thermal modelling of a Li-ion battery is carried out using mathematical expressions and descriptions based on the specific thermal circumstances in order to predict the system's performance. Based on the boundary constraints of the working environment, formulations for energy, electrochemical, heat generation, and transfer are generated. It is critical to assess the thermal characteristics of a Li-ion battery using methods such as computational fluid dynamics (CFD). Three categories—thermal runaway models, battery temperature distribution models, and numerical studies of BTM—are used in this section to classify the well-known theoretical works on battery temperature distribution models (BTMS). Jeon (2014) estimated the temperature dispersion inside the cylindrical 18,650 battery cells using a transient thermo-electric model[3]. The results indicated that, although this difference decreased as C-rates increased, the battery's temperature increased more during the discharge cycle than it did during the charging cycle. Thermal behaviour was found to be influenced by applied current and entropy change. A 2D thermal model of a pouch-shaped cell was created by Samba et al. (2014) using CFD. The objective was to use thermal properties and heat generation under different environmental conditions to predict the temperature distribution throughout the battery's surface[3]. Baba et al. (2014) presented a model for understanding the localized heat generation resulting from an electrochemical reaction across the electrode plane.

2.2 Numerical models for BTMS

Panchal et al. (2018) studied the temperature changes of a battery's primary surface under different discharge and charge scenarios and developed a thermal model using a neural network technique. This study shows that battery surface temperature distributions increase with higher discharge rates. Using this neural network, the thermal performance of Li-ion batteries for air cooling was also predicted (Panchal et al., 2016a).[4] Mini-channel cold plates (Panchal et al., 2016b) and water cooling (Panchal et al., 2017).The findings demonstrated that increasing discharge rates increased heat fluxes. According to Saw et al. (2017), an uneven cooling will result in a substantial temperature change, which will shorten the life of the battery pack. A number of aluminium foams that are used to increase thermal conductivity were modelled using CFD simulation in relation to other numerical parameters and the Nusselt number. The results show that the lowest flow resistances and the best thermal performance are achieved by Al foam with high porosityand low PPI.[4,3]

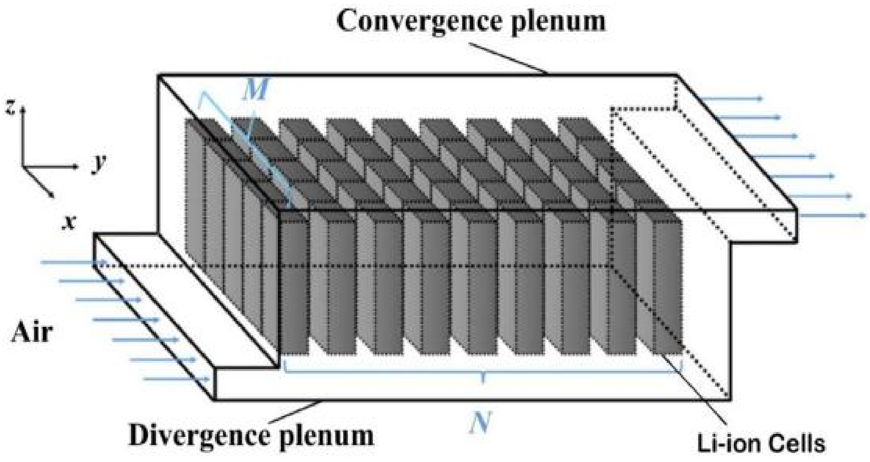

Figure 4 Schematic of the three-dimensional parallel air-cooled BTMS [11]

III. HEAT CAPACITY AND HEAT GENERATION

The kind of batteries, how it is charged or discharged, temperature, and other variables all affect how much heat a battery pack produces. NREL used specialized equipment to conduct tests and measure the amount of heat produced by different batteries under different conditions. The results show that at temperatures above 40°C, NiMH batteries generate more heat than VRLA or Li-Ion batteries. Conversely, NiMH batteries are generally less energy-efficient but produce less heat at the same current at room temperature. The increase in internal resistance, heat generation tends to increase as temperatures drop. Furthermore, faster discharge rates result in the generation of more heat. The discharge process of Li-Ion batteries, for example, can occasionally be endothermic, which means the battery absorbs heat, especially at higher temperatures. This data facilitates the design of effective cooling systems to manage battery heat, particularly in applications such as electric vehicles.

Table 2 Heat production from Standard HEV/EV Modules Using the Calorimeter from NREL [10]

		Heat Generation (w)/Cell	**Heat Generation (w)/Cell**	**Heat Generation (w) /Cell**
Battery Type	**Cycle**	**0 °**	**22-25 °**	**40-50 °**
VRLA,16.5 Ah	C/I Discharge,100% to 0% State of Charge	1.21	1.28	0.4
VRLA,16.5 Ah	5C Discharge,100% to 0% State of Charge	16.07	14.02	11.17
NiMH,20 Ah	C/I Discharge,70% to 35% State of Charge	-	1.19	1.11
NiMH,20 Ah	5C Discharge,70% to 35% State of Charge	-	22.79	25.27
Li-Ion,6 Ah	C/I Discharge,80% to 50% State of Charge	0.6	0.04	-0.18
Li-Ion,6 Ah	5C Discharge,80% to 50% State of Charge	12.07	3.50	1.22

To accurately analyse the thermal behaviour of a battery pack, designers need to know each module's heat capacity, which also aids in calculating the pack's total thermal mass. This is required in order to conduct a meaningful transient thermal analysis. The total or average heat capacity of the battery pack is calculated by measuring the heat capacities of each component in calorimeter and using a mass-weighted average. For instance, the average heat capacities of Li-Ion (6 Ah), VRLA (16.5 Ah), and NiMH (20 Ah) batteries are, respectively, 660 J/kg/K, 677.4 J/kg/K, and 795 J/kg/K. Heat generation and heat capacity both affect how much an electric vehicle (EV) module's temperature rises during air cooling.

IV. DISTRIBUTION OF MODULE TEMPERATURE

This way that individual battery cells are designed affects the distribution of temperatures within a battery module. A number of factors, such as the number and shape of cells, the aspect ratio, the heat conductivity of the module casing, the location of the terminals, the size and configuration of the cell interconnects, and differences in current density among the cells, can cause uneven heat generation within the module. The temperature distribution within the module may become uneven as a result of this erratic heat generation.

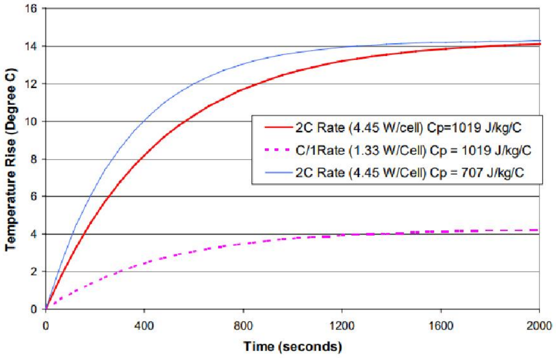

Figure 5Momentary Temperature Increase in a Module with Continuous Heat Production[10]

Temperature distribution is affected by the designs of various battery types, as demonstrated by thermal images. For example, the 6-cell Optima lead-acid HEV battery experienced some temperature variation on the same side and mild axial heat generation at 20°C. On the other hand, Saft's high-power lithium-ion cells' dual terminal locations, hollow core for cooling, and high thermal conductivity in the active materials and casing contributed to a more consistent temperature distribution with variations of less than 2°C.The incorporation of liquid cooling, which envelops each cell to maintain consistent temperature throughout the module, allowed Ovonic Battery Company to enhance temperature control in their high-power NiMH modules.

V. AIR COOLING VS LIQUID COOLING

Thus, the battery thermal management system's cost and functionality are greatly impacted by the choice of the heat transfer medium. It could be any combination of these, a liquid, air, or the phase-changing material. The air is guided or blown across the modules in the method that uses air as the heat transfer medium. However, there are several ways to achieve liquid heat transfer: covering each module by a jacket or discrete tubing, immersing the modules in a dielectric fluid and having them in direct contact, or mounting the modules on a plate which can be cooled and heated by the liquid-a heat sink. If the liquid is in tubes or jackets and not in contact with the modules, it could be water, glycol, or even other common automotive fluids like refrigerants. Liquid-based heat transfer may be superior to air-based heat transfer, despite the fact that air-based heat transfer is most likely the least complex method.

The degree to which heat is transferred between a module's walls depends on a heat transfer fluid's density, velocity, viscosity, and thermal conductivity. Because they have a thinner boundary layer and higher thermal conductivity than air, direct-contact liquids like oil usually transfer heat at a much higher rate than air at the same flow rate. However, due to its higher viscosity, oil requires a lower flow rate when pumping. Oil has a heat transfer coefficient that is only 1.5–3 times higher than air's... Researchers used finite element analysis to account for the non-uniform heat generation while conducting transient and the steady-state thermal performance assessments of a 12-V, 6-cell HEV VRLA module with both liquid and air cooling. The maximum temperature at the top, middle, and bottom of the cell is plotted against the duration of the air and oil cooling processes.

Lastly, it should be mentioned that because oil has a higher thermal conductivity than other liquids, it cools down and stabilizes considerably faster than an air-cooling case. [4,5]

VI. BATTERY DEGRADATION CHALLENGE

One of the main issues we are currently dealing with is global warming. Every day, enormous amounts of carbon dioxide emissions cause the earth's temperature to rise. one of the main reasons why cars running on gasoline or diesel emit carbon dioxide. Batteries are being used more and more frequently as a result.[5] It has been observed that battery usage has increased lately. Li-ion batteries are the most popular type of batteries despite the existence of other battery types because of their high energy density, extended lifespan, low self-discharge rate, and high efficiency. Numerous advantages are offered by Li-ion batteries.[5]

Temperature is another factor in battery deterioration. It has been noted that the battery performs more consistently when it is at room temperature. Because of the way they are made, they can operate at room temperature. At low temperatures, the internal resistance of the battery increases, reducing its capacity. A battery that can produce 100% of its capacity at 27°C (80°F) will typically only produce 50% of that at –18°C (0°F), according to observations. For example, operation temperature has a big influence on battery cycle life. The cycle life of a battery starts to shorten at temperatures above 45°C, and it significantly shortens at 80°C.[5]

VII. FUTURE RESEARCH DIRECTION

Researchers are also trying to integrate multiple conventional thermal cooling systems in an attempt to reduce material thermal resistance and increase thermal efficiency. Traditional cooling systems include heat pipe cooling, liquid cooling, PCM cooling, direct two-phase refrigerant cooling, air cooling, and oscillating cooling. The number of pipes, pipe width, 3D orientation in heat pipe cooling, and the material properties of PCM materials are all being altered by researchers[5, 6]. In addition, they are trying to change the direction and rate of the airflow as well as the kind of liquid used for both liquid and air cooling.

Additionally, researchers are devoting time and resources to improving PCM material thermal conductivity, lowering thermal resistance, and raising latent heat. The conductivity of composite materials, such as PCM mixed with other conductive materials, increases along with the system's overall efficiency. A significant component of the thermal management system is also the selection of the ideal PCM[5,7]. High latent heat, high thermal conductivity, low thermal resistance, low cost, and availability are desirable characteristics for PCM, and research is being done to attain these qualities. Cooling materials have certain drawbacks.[6]

Choosing the right PCM is a crucial part of the thermal management system. Researchers are working to give PCM the desirable properties of high latent heat, high thermal conductivity, low thermal resistance, low cost, and availability. Cooling substances have certain drawbacks[6].

VIII. CONCLUSION

This study examined and contrasted the advantages and disadvantages of various BTMSs, including liquid cooling, hybrid cooling, air cooling, and others. It also discussed needs, usage restrictions in the context of contemporary technology, and related studies. The advancement of the electric vehicles (EVs) and hybrid electric vehicles (HEVs) is closely linked to the development of battery technology, with effective Battery Thermal Management Systems (BTMS) being crucial to enhancing vehicle efficiency, safety, and battery longevity[6,7]. These cars run on a battery pack, so it must be carefully regulated to prevent issues like reduced longevity and capacity. There are advantages and disadvantages to various BTMS technologies.

VCC-based BTMS are widely used because they can be integrated with existing air conditioning systems; however, they are energy-intensive and may have an impact on cabin climate control. Cabin air cooling systems are simple, inexpensive, and have good cooling performance, but they take up a lot of space. Secondary liquid loop systems offer better cooling, but at the cost of increased complexity, weight, and expense. The direct refrigerant two-phase cooling system is more complex and efficient, but it still requires the VCC to function[6].

Considering that EVs operate in a range of climate conditions, it is imperative to develop BTMS that optimize the operating temperature range and adapt to local climates. More study and development in BTMS is required to get past these challenges, enhance thermal management efficacy, and reduce the overall cost and weight of EVs[7]. This will ultimately promote the wider adoption of EVs and make them more competitive with cars powered by internal combustion engines.

Table 3 Comparison of air, liquid, and PCM cooling BTMS [9]

Type	Thermal conductivity	Structure complexity	Compactness	Weight	Uniform Temp. Distribution	Coolant Viscocity	Cost	Maintenance
Air cooling	M	L	H	L	L	L	L	L
Liquid cooling	H	M	L	H	M	M	M	M
PCM based cooling	L	H	L	H	H	H	H	H

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