Thermal Management Strategies for Lithium-Ion Batteries in Electric Vehicles

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Abstract. Electric vehicles are now becoming more and more common, rapidly replacing traditional fuel cars. Lithium-ion batteries, as the main power source of electric vehicles, have become the most important part of energy storage technology. However, the performance, safety, and lifespan of these batteries are critically dependent on effective thermal management. This paper provides a comprehensive overview of thermal management strategies for EV batteries. Four primary cooling approaches are reviewed—air cooling, liquid cooling, phase change material cooling, and hybrid systems. Currently, liquid cooling is the mainstream solution to cool the battery because of its superior heat dissipation efficiency and technical maturity. In the future, emerging technologies including refrigerant direct cooling and thermoelectric hybrid systems which are safer, more efficient and longer-lasting are likely to become dominant.

Keywords: Lithium-ion batteries, Electric vehicles, Battery thermal management system (BTMS), Thermal management, Cooling strategies, Liquid cooling, Hybrid cooling.

1. Introduction

The auto industry around the world is changing a lot, mainly because everyone realizes that we must find ways to reduce greenhouse gas emissions to solve the problem of climate change. Recently, the European Union has decided not to sell new fuel vehicles by 2035, and many other countries are also following it, so electric vehicles will certainly play an important role in future transportation. In all current new energy vehicle technology, battery electric vehicles are the dominant solution because of their high efficiency, low cost and zero tail pipe emissions.

The most important part of an electric car is its battery system, and lithium-ion batteries (LIBs) have become the most popular choice due to their high energy density, long cycle life, low self-discharge rate and wide operating temperature range. However, Lithium-ion batteries are highly sensitive to temperature: When temperatures become too high or too low, the performance of batteries will be significantly affected.

The Battery Thermal Management System (BTMS) therefore plays a critical role in ensuring that EV batteries operate within their optimal temperature window, typically considered to be between 15°C and 45°C, with temperature differences between cells ideally maintained below 5°C [1]. An effective BTMS needs to dissipate heat generated during fast charging and discharging, maintain temperature uniformity across the battery pack and keep the internal temperature constant when the external temperature changes dramatically.

This paper aims to provide a comprehensive overview of thermal management strategies for EV batteries. The structure is as follows: Section 2 talks about the fundamental heat generation mechanisms within lithium-ion cells. Section 3 presents common cooling technologies. Section 4 discusses emerging trends and future research directions, followed by concluding remarks in Section 5.

2. Heat Generation Mechanisms in Lithium-Ion Batteries

To figure out why the thermal management system is so important and how to design it better, we must first know how the battery heat is generated. Heat generation arises from multiple physical and electrochemical processes, including Joule heat and heat from side reactions.

2.1. Electrochemical Principles and Heat Sources

The working principle of lithium-ion batteries is mainly based on lithium ions moving back and forth between the positive and negative electrodes to achieve charge and discharge. When the battery is discharged, the lithium ions in the anode material will run out, through the electrolyte and separator in the middle, and finally to the other side of the positive electrode. At the same time, the electrons will also move, but they will go to the external circuit, so that they can provide power to the electric vehicle. In the meantime, heat is generated.

The internal heating of the battery is mainly due to the resistance of the electrode and the electrolyte itself, and the charge transmission resistance of the electrode and the electrolyte contact surface. The resistance will convert the electrical energy into heat. Now many EV owners want the charging time to be shorter, causing the inevitable use of large current. In this case, the heat will become particularly obvious since it is proportional to the square of the current [2].

On top of that, side reaction is also a big source of heat, and it becomes significant under abuse conditions like overheating, overcharging, or mechanical damage. Under normal circumstances, there is a protective film called solid-electrolyte interphase (SEI) layer on the electrode surface of the battery, which can play a protective role. But when the temperature exceeds 80 to 90 degrees, the protective film will begin to decompose, releasing more heat, triggering a series of new chemical reactions. This can escalate into thermal runaway, where internal temperatures soar to hundreds of degrees Celsius, releasing flammable gases and potentially causing fire or explosion [2].

2.2. Thermal Challenges of Fast Charging

More and more consumers now want their cars to charge faster, which puts a lot of heat pressure on the battery and higher demands on the battery thermal management system. During high C-rate charging, irreversible Joule heating caused by the increasing current becomes the main source of heat, so that the temperature exceeds the normal operating range in just a few minutes [2]. Another trouble is the uneven temperature distribution, as high localized current densities generate local high temperature areas, which will accelerate the battery aging, such as the reaction of lithium on the negative electrode [2].

These challenges place higher demands on the battery thermal management system, which requires multiple capabilities. The first is to be able to quickly absorb heat, so as to deal with the heat shock that occurs in the beginning. Moreover, it is necessary to achieve long-term stable heat dissipation, so that the heat can be continuously rejected into the surrounding environment. [1,3].

3. Battery Thermal Management Technologies

With a clear understanding of how heat is generated in lithium-ion batteries, we now turn to technological approaches to manage it. There are four main cooling strategies: air cooling, liquid cooling, phase change material (PCM) cooling, and hybrid systems that integrate multiple approaches [3].

3.1. Air Cooling Systems

Air cooling is the simplest and most economical way for heat management. This method is mainly to let the air flow from the surface of the battery or the cooling channel inside the battery, so that the heat generated by the battery can be taken away by convection. Passive systems rely on natural convection and the airflow generated by the car to dissipate heat; active systems will install a fan or blower and actively blow the air into the heat source.

Air cooling system does not require water pumps, nor does it need to take over the channel or add coolant, so the entire design is particularly lightweight and usually maintenance is also very convenient. Some old electric vehicles running on the road, as well as those cheap cars, often use air cooling. Now research mainly focuses on how to make the air cooling system better, such as improving the shape of the pipe, adjusting the battery arrangement, and optimizing the air flow [3].

However, air cooling does have some problems. The heat conductivity of the air itself is not very good, and the heat it can absorb is limited, which makes it less ideal for fast charging. At high C-rates, air cooling requires extremely high flow velocities to maintain safe temperatures, making the strategy impractical.

Temperature uniformity is another challenge. Air tends to heat up as it flows through the pack. Without careful flow distribution design, downstream cells may experience significantly higher temperatures. Despite these limitations, air cooling can still be used in some places, such as home energy storage equipment, small commercial energy storage systems, and those electric vehicles that are not high in energy consumption.

3.2. Liquid Cooling Systems

In order to make up for the shortcomings of air cooling, a better solution emerged, which is liquid cooling. Liquid cooling has become the most commonly used method of heat dissipation in modern electric vehicles with large power consumption. By circulating liquid coolant through cooling plates or channels, liquid cooling achieves significantly higher heat transfer coefficients than air.

Many electric cars now use cold plates to cool the battery, which is currently the most common cooling scheme. Coolant absorbs heat as it flows through the plates, transporting it to a heat exchanger for rejection to the environment. Research has demonstrated that optimized cold-plate designs can reduce temperature peaks by 20% while maintaining cells within the optimal 15–35°C range [3].

There have been some recent breakthroughs in cold-plate design, mainly in terms of channel shape and liquid flow. The researchers specifically studied the refrigerant direct cooling plates with multi-splitting-merging channels and found that the design worked well. After optimization, the maximum temperature of the board was reduced from 42 degrees to 31 degrees, and the temperature difference of the board was no more than 5 degrees.

Immersion cooling is also an advanced liquid cooling approach where battery cells are directly immersed in dielectric coolant [1]. The advantage of this is to completely avoid the thermal resistance between the battery and the coolant, making the coolant and every part of the battery fully in contact, so that the heat dissipation effect will be excellent, and the temperature inside the battery can be maintained very uniform.

Heat-pipe cooling offers another liquid-based approach which does not require external power to work [3]. Heat pipes are sealed vessels containing a working fluid.

The liquid evaporates at the hot end and condenses at the cold end. This phase- change cycle enables high effective thermal conductivities.

The advantages of liquid cooling are obvious: high heat transfer coefficients, excellent temperature uniformity, mature technology and good scalability. However, liquid cooling systems are often very complex. They require pumps, pipes, valves, coolants, and heat exchangers, increasing the weight and maintenance requirements. Despite these drawbacks, liquid cooling's performance advantages have made it the most popular choice for modern high-performance EVs.

3.3. Phase Change Material Cooling

Liquid cooling is not the only strategy available for thermal management. PCM cooling, which will be discussed later, is also an effective approach and can offer unique advantages in specific applications.

Phase change material cooling is actually a completely different idea. The materials absorb heat during solid-liquid phase transition. As battery temperature rises, the PCM melts, absorbing a lot of heat while keeping the temperature constant. When the battery cools, the PCM solidifies, releasing stored heat for rejection to the environment.

The biggest advantage of PCM cooling is that it works completely passively. The system does not require any moving parts and does not consume electricity, so it is particularly reliable and does not waste extra energy.

However, there are many difficulties when using PCM materials. Most PCMs with suitable phase-change temperatures have poor thermal conductivity, so that heat is difficult to transfer in the material. Without enhancement, the outer PCM layer melts while the inner core remains solid, making a lot of materials useless at all.

Researchers have developed various strategies to overcome the shortcomings, such as adding some particularly well-conducting additives to the phase-change materials, such as expanding graphite, metal foam, or carbon nanotubes, which can make thermal conductivity better and maintain the ability to store heat. In addition, encapsulation technology is also important, it prevents phase change materials from leaking out when melting, which is a big problem in practical applications.

3.4. Hybrid Cooling Systems

All technologies mentioned above are defective in some way. In order to make use of their strengths while make up for the weaknesses, we can integrate multiple cooling strategies to create hybrid cooling systems. Hybrid system is the most advanced technology in battery thermal management, and it is likely to be the future direction of high-performance electric vehicles.

One of these is the combination of PCM materials and liquid cooling, PCM can absorb a large amount of heat generated in a short period of time, so that the temperature distribution is more even, liquid cooling is responsible for continuously taking away heat, and it also allows PCM materials to restore cooling capacity. Another solution is to use heat pipes with PCM, thermal tube has good transfer performance, so it can quickly transfer the heat generated by the battery to PCM, making up for the shortcomings of PCM itself [2].

Recent research has found that other hybrid cooling methods seem to be more promising. Specifically, the combination of direct cooling of refrigerants and phase- change materials, or the use of new cold plate design, so that the refrigerant can be used to absorb heat in the phase change process. The entire system can maintain a relatively small volume, and ultimately achieve a high cooling efficiency [1]. There is also a multi-fluid system which will choose different cooling methods according to different working conditions, such as cooling with air when the load is low. The flexible design allows the thermal management system to better adapt to the actual needs.

Intelligent control algorithms have developed rapidly in recent years, which is particularly important for hybrid systems. Now better BTMS needs to be able to adjust the cooling method at any time, depending on the battery temperature, the charging speed and how much electricity to be used next. Now some techniques use model prediction and neural network observers to study this problem, and some of them have been able to control the temperature control error within 0.5°C.

3.5. Comparative Assessment

Given the diversity of thermal management strategies, we now compare these techniques together to see which is more suitable. In the comparison, we mainly focus on several important aspects, including thermal efficiency, economic cost, scalability and fast-charging stability.

In terms of heat dissipation capability, liquid cooling is the most effective technology in the case of fast charging. Its high heat transfer coefficient directly handles the heat generated during high C-rate charging [1,3]. In contrast, air cooling is unable to dissipate heat quickly, so it is very difficult to deal with fast charging [3]. PCM cooling can buffer temperature spikes with its high passive efficiency, but its effectiveness is limited by its low thermal conductivity, so it is not suitable for high power discharge either [2]. Hybrid systems, such as PCM-liquid, offer the highest efficiency for fast charging by combining the immediate buffering of PCM with the continuous heat rejection of liquid cooling [1]. In summary, liquid cooling and hybrid systems perform better than air cooling and PCM cooling in the case of fast charging.

From the perspective of cost, air cooling is a good choice, because it cost less in the beginning and is convenient to use. However, its lack of scalability means that as the battery pack becomes larger, more powerful fans and more complex pipes are needed. [3]. Liquid cooling, although having higher upfront costs due to pumps, pipes, and coolants, offers superior scalability. Its modular cold-plate designs can be adapted to large packs with minimal performance degradation, making its cost- per-watt more competitive at scale [1]. PCM cooling has a medium cost, but the material will be very large if the battery gets bigger, so the cost will increase rapidly. Hybrid systems are the combination of several cooling methods. Their flexibility is the worst but they are suitable for some applications where the cost is far less important than the performance requirements [1,3]. To conclude, air cooling is the most cost-effective plan if the scale is not very large. When the scale gets larger, liquid cooling and hybrid systems will be a better choice.

Table 1 summarizes some key characteristics of each cooling approach.

Table 1. Characteristics of different cooling approaches

Cooling Strategies	Performance Data	Energy Consumption	Cost
Air cooling	3C fast charge: T_{max} and ΔT are 19°C and 9.8°C higher than immersion cooling [1]	High	Low
Liquid Cooling (Immersion)	4C fast charge: T_{max} =35 °C, ΔT=1°C [1]	Medium	High
PCM Cooling	30 °C ambient: cell temperature reduced by 4°C over 1800 s [4]	Low	Medium
Hybrid Cooling	4C fast charge: T_{max} maintained at 31.8°C [1]	Medium	High

4. Emerging Trends and Future Directions

Current technologies already provide effective solutions for thermal management of EVs, but the demands for greater power and faster charging are continuously driving innovation. Several emerging trends and research directions deserve attention.

4.1. Advanced Cooling Technologies

Now more and more people are replacing traditional liquid cooling with direct cooling of refrigerants. This method allows refrigerants to circulate through the cooling plate in direct contact with the battery, eliminating the intermediate coolant circuit and heat exchanger, making the whole system simpler and improving the cooling efficiency.

There is another method where the battery is soaked in the boiling insulating liquid, called two-phase immersion cooling. Two-phase immersion cooling is the final stage of the development of liquid cooling technology. This strategy can have high transfer coefficients, but it also has some problems, such as fluid compatibility, system sealing, maintenance access, and cost.

4.2. Intelligent and Predictive Thermal Management

Now the battery thermal management system, advanced sensing technology, modeling methods and control algorithms can be combined to make it from a passive response to an active prediction system. Through the Kalman filter and electrothermal coupling model, we can predict the temperature inside the battery with surface managements, which means we no longer need to install sensors inside the battery. As electric cars are now becoming increasingly autonomous, predictive thermal management incorporating route information, traffic conditions, and charging station locations could further optimize battery thermal preconditioning.

5. Conclusion

Lithium-ion batteries, despite their superior energy density and cycle life, remain very sensitive to temperature. In order to continuously develop electric vehicles, the importance of BTMS cannot be ignored.

This paper has reviewed the principal cooling technologies available for EV batteries, from simple air cooling to sophisticated hybrid systems. Although air cooling is cheap, this cooling method has not kept up with the demand as the battery energy density increases. Liquid cooling is currently the dominant solution because of its high heat transfer coefficients and good uniformity at medium cost.

Phase change materials provide passive thermal buffering and exceptional uniformity but require enhancement to overcome low thermal conductivity. Hybrid systems combine the strengths of different technologies, and they will definitely become more and more popular in the future.

Now new technologies are being developed, including refrigerant direct cooling, two-phase immersion, and intelligent predictive control. These new technologies are likely to significantly improve BTMS. However, in practical applications, we have to choose the most suitable thermal management solution according to the specific situation, because different battery materials, battery shapes, vehicle types, usage habits, and cost budgets will affect the final choice.

In the future, it is impossible to simply rely on one of the strategies to develop BTMS, and it is necessary to combine the knowledge of different fields such as electrochemistry, heat transfer, fluid mechanics, material science and control engineering. Now that electric vehicles are becoming more and more popular, the battery performance needs to be more powerful, and how to make the thermal management system safer, more efficient and more durable is a particularly important research direction. Future efforts should prioritize three key areas: developing advanced cooling technologies like two-phase immersion to enable extreme fast charging [1], engineering next-generation composite phase change materials with enhanced thermal conductivity [2,3], and creating intelligent, integrated thermal management systems that optimize energy use across the entire vehicle [1,3]. These research priorities will be critical to unlocking the full potential of next-generation electric vehicles.

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