# State-of-the-art Power Battery Cooling Technologies for New Energy Vehicles

Yafeng Li [1, *, †], Yang Sun [2, †]

[1] College of Mechanical Engineering, Tianjin University of Commerce, Tianjin, China

[2] School of Energy and Power Engineering, Xi'an Jiaotong University, Shaanxi, China

* Corresponding author: yafeng@stu.tjcu.edu.cn

[†]These authors have the same contribution to this article.

**Abstract.** The creation of new energy vehicles will help us address the energy crisis and environmental pollution. As an important part of new energy vehicles, the performance of power batteries needs to be improved on a significant basis. However, the nonideal inherence of the power battery induced the unexpected heating phenomenon in the battery energy storage system in the electric vehicle, which rising the concerns about reliability and stability. Accordingly, the effectiveness of the heating suppression for battery energy storage system becomes an essential issue for maintaining the reliability and stability of new energy vehicles. Generally, in the new energy vehicles, the heating suppression is ensured by the power battery cooling systems. In this paper, the working principle, advantages and disadvantages, the latest optimization schemes and future development trend of power battery cooling technology are comprehensive analyzed. The research on power battery cooling technology of new energy vehicles is conducive to promoting the development of new energy vehicle industry.

**Keywords:** Air cooling, heat pipe cooling, liquid cooling, phase change cooling, power battery.

## 1. Introduction

The use of traditional fossil fuels and other energy sources has led to serious pollution and greenhouse gas emissions. Having been impacted by the global energy situation and environmental damage in recent years, the optimization of energy structure is imminent. In order to comply with the market and respond to the policy, the new energy vehicle industry has developed rapidly. Compared to conventional fuel-powered vehicles, the driving mode of new energy vehicles is mainly electric energy, which will not produce exhaust emissions, greatly reducing the use of fossil energy and effectively protecting the environment. Therefore, it is critical to develop new energy vehicles. The batteries of new energy vehicles usually include lithium-ion batteries, nickel metal hydride batteries, lead acid batteries and fuel cells, each of which has advantages and disadvantages. Lithium-ion batteries have the application advantages of light weight and low pollution, and their service life is much longer than other types of batteries. NiMH battery has the advantages of long service life and high overall discharge power, but the memory effect is low, resulting in relatively high battery manufacturing cost. The lead-acid battery has large volume and weight, relatively low overall energy release and relatively short service life. However, the cost of raw materials used in the specific production process is not high, and its stability is relatively good, which is convenient for recycling. Fuel cells have the advantages of low emissions of harmful gases and low noise pollution, and there is room for development, but the fuel cell technology level and infrastructure are still not mature [1]. Considering the advantages and disadvantages of various power batteries, lithium-ion batteries are the main power batteries used in electric vehicles. However, during the charging and draining of lithium-ion batteries, there are numerous complicated electrochemical processes. The redox reaction of electrode materials and the disengaging movement of lithium ions between the positive and negative electrodes overcome the resistance and inevitably generate heat. Electrochemical reaction heat, ohmic internal resistance heat, polarization heat, electrolyte breakdown heat, etc. are the basic categories into which the heat source may be categorized. [2]. However, the power battery is in a relatively small and closed environment, which leads to its temperature rising, which is undoubtedly a huge challenge for the thermal management system of new energy vehicles [3]. If the lithium battery is hot for an extended period, on the one hand, its working performance will be affected, such as battery cycle life, battery usable capacity, etc., greatly reducing its working efficiency. On the other hand, too high temperature also has a great potential safety hazard, which may even cause battery thermal runaway and lead to combustion, explosion, and other accidents [4]. There are many means to control thermal runaway events, such as predicting thermal runaway events. However, due to the randomness and complexity of thermal runaway events, it is always difficult to establish accurate prediction models. In addition, fire extinguishing systems are provided for the power batteries of new energy vehicles. In order to prevent the occurrence of thermal runaway events, the most important thing is to do a good job in power battery thermal management to solve the hidden problems from the root, and the cooling of power batteries is an extremely important link in the control of power batteries' thermals. In addition, continuous research and improvement of cooling technology can not only greatly ensure the safety of power battery, but also improve the working performance of new energy vehicles, which is of great significance.

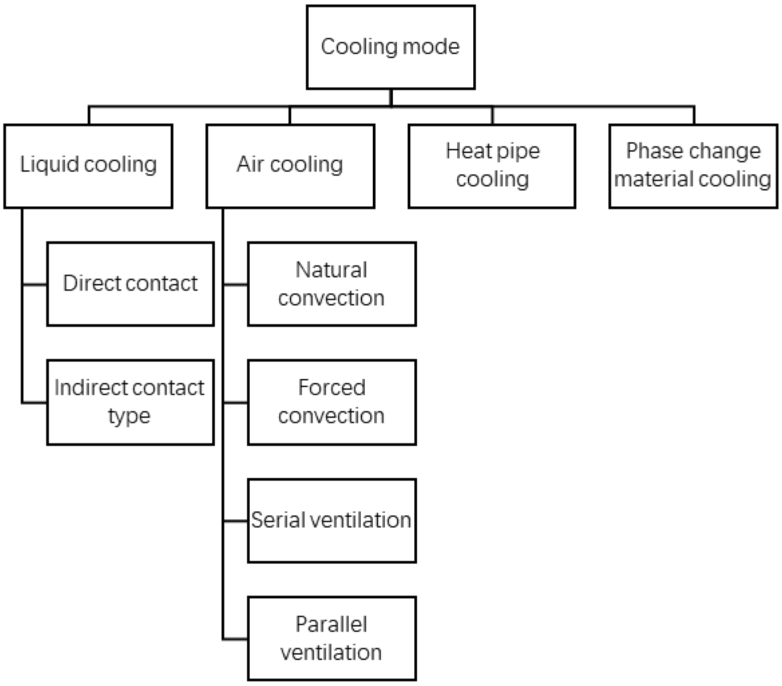


**Figure 1.** Classification of cooling technologies for power battery system

At present, there are four cooling technologies for power batteries, namely liquid cooling (LC) technology, air cooling (AC) technology, heat pipe cooling (HPC) technology and phase change material cooling (PCMC) technology. The classification of the typical cooling technologies is illustrated in Fig. 1. This paper will analyze and discuss the working principle, advantages and disadvantages, the latest optimization scheme and future development trend of power battery cooling technology, to put forward constructive suggestions for the development of power battery. The LC technology has a high heat dissipation efficiency, and the heat dissipation is very uniform, which is very helpful to enhance the stability of the battery system. But the structure is very complex, and has high requirements for sealing and insulation. The latest optimization plan is to change and adjust the internal structure to improve efficiency. The AC technology has simple structure, low manufacturing cost and no risk of coolant leakage, but its heat dissipation effect and temperature uniformity are poor. At present, the latest optimization scheme is to improve heat transfer efficiency and heat dissipation area by optimizing the design of air duct and air inlet/outlet, effectively controlling the air flow rate and flow, and designing battery layout to improve heat dissipation efficiency and temperature uniformity. The HPC technology has the advantages of high heat transfer and thermal conductivity, excellent isothermal performance, and can also be coupled with other cooling methods. But the requirements for production equipment are high. A straightforward design and low production cost are advantages of the PCMC system. But there are still some technical problems in its application, such as relatively low thermal conductivity and relatively poor thermal stability of phase change materials when the temperature is too low. The HPC technology and PCMC technology are still in the research stage and have not been widely used. At present, the main direction is to further optimize mature cooling schemes that have been put into production, such as LC technology and AC technology. And research new cooling schemes and accelerate the process of putting them into production, such as HPC technology, PCMC technology. Studying the cooling technology of power battery is of great significance for improving the working efficiency and safety of its battery pack, and can further promote the development of the entire new energy vehicle industry.

In this paper, the working principles, advantages and disadvantages, the latest optimization scheme and future development trend of power battery cooling technology are analyzed. Meanwhile, the advanced power battery cooling technology of new energy vehicles is conducive to promoting the future perspectives.

## 2. Cooling technology of power battery

### 2.1. Liquid cooling technology

#### 2.1.1. Working principle of liquid cooling technology

LC technology is a technology that uses liquid medium with relatively high thermal conductivity to cool the power battery. According to how the liquid contacts the battery, it may be classified as either direct contact or indirect contact [5]. Fig. 2 showed the schematic diagram of indirect contact type.

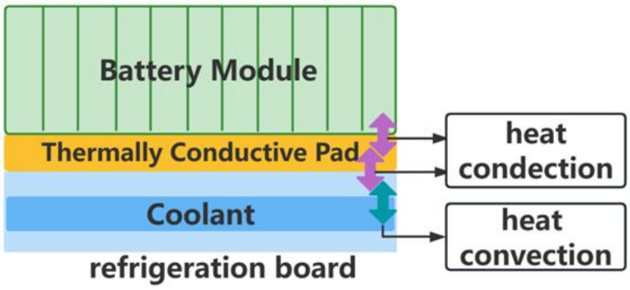


**Figure 2.** Schematic diagram of indirect contact liquid cooling

The direct contact cooling system is to immerse the battery module into a cooling liquid with a certain insulating effect for heat exchange. The medium used is usually a liquid with a high thermal conductivity, such as silicon-based oil, mineral oil, etc. This cooling method can solve the problem of inconsistent temperature between battery modules. But the flow rate, thermal conductivity, viscosity, and other parameters of the selected cooling liquid have a great impact on the cooling effect of the system [6]. In the indirect contact cooling system, the coolant flows in the channel and conducts convection heat transfer with the coolant carrier. The coolant carrier is attached to the surface of the power battery to conduct heat transfer by heat conduction, thus taking away the heat from the power battery. The indirect liquid cooling scheme with cooling medium flowing in the cold plate is the mainstream scheme of thermal management of power battery at present [7].

Excellent-power charging and discharging heat dissipation needs may be satisfied by the LC technology's high heat dissipation efficiency. At the same time, the heat dissipation is more uniform, which is very helpful to enhance the stability of the battery system. However, liquid cooling has high requirements on the sealing performance of the battery pack, and the structure is very complex. Sealing, insulation, and cost must be comprehensively considered [8].

### 2.1.2. Advanced optimization scheme for liquid cooling technology

At present, LC technology is mainly realized by cooling group, pipeline, liquid medium flow, etc. By setting different influencing factors, it is analyzed that the functional attributes of liquid cooling technology in specific implementation under a certain operating condition [9].

JIA and others [10] developed the relevant battery module model through computational fluid dynamics (CFD) simulation analysis to investigate the influence of the packaging degree and the liquid coolant hose wrapping method on the battery coolant efficiency. The results show that, on the premise of ensuring the cooling effect, the quality of the battery module can be reduced and the materials can be saved by appropriately reducing the height of the liquid cooling pipe. At the same time, the cooling effect of the battery module by subsection wrapping is better than that by direct wrapping. Cai and others [11] proposed a liquid cooling plate structure with parallel non equal length DC channels, as showed in Fig. 3. Taking the square lithium-ion battery pack as the research object, the liquid cooling plate structure has sufficient heat dissipation capacity and has obvious advantages over the liquid cooling plate structure with equal length DC channels.

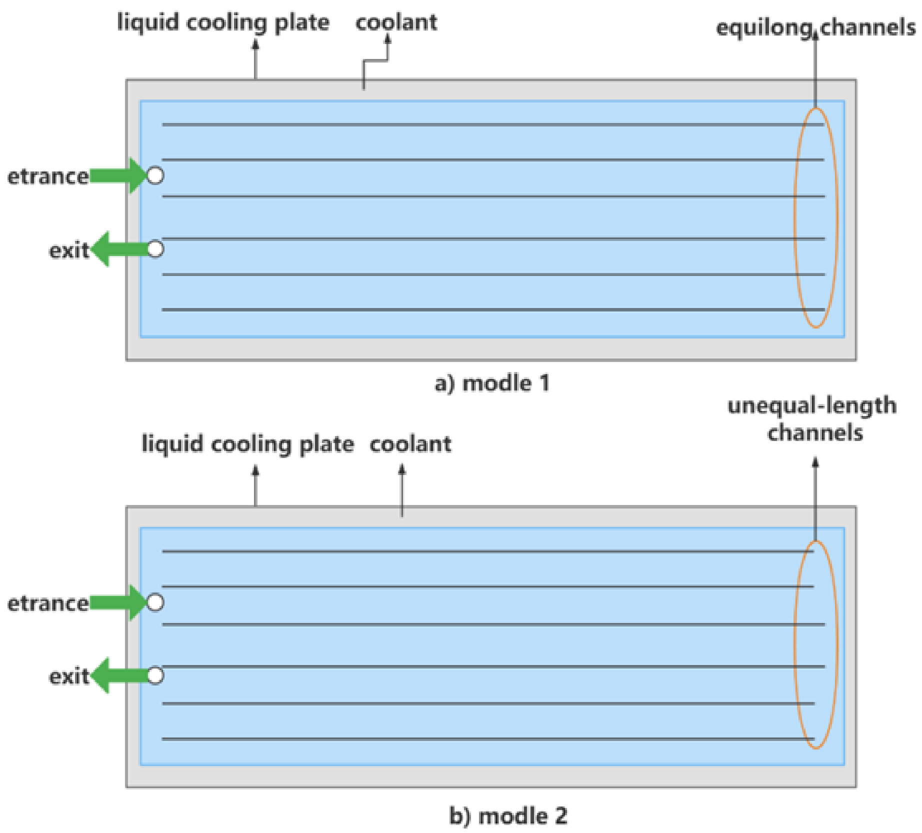


**Figure 3.** Structure diagram of liquid cooling plate [11]

Zhang and others [12] designed a multi battery pack cooling system, and determined the best pipeline connection mode through flow field simulation. The research found that the inlet and outlet positions of the cooling pipeline have a significant impact on the overall flow distribution. Ma and others [13] proposed a nonlinear cooling optimization method, which can improve the system's ability to suppress current disturbance, effectively reduce the system's cooling energy consumption, and provide an important basis for improving the battery cooling speed and energy-saving effect.

### 2.1.3. Challenges of liquid cooling technology

At present, the LC mode is in the development stage of tarpaulin, with high convection heat transfer capacity. It can not only keep the battery temperature stable and reduce the temperature gradient between batteries under ordinary low-speed working conditions, but also maintain better heat dissipation performance under extreme working conditions such as uphill and rapid acceleration. It is mainly applied to pure electric vehicles with large heat dissipation requirements, such as Tesla

Model series, General Volt, BMW i3, etc [14]. However, liquid cooling technology still has some shortcomings. For instance, the complicated design of the cooling system results in high coolant energy consumption and increased vehicle weight. In addition, the high sealing of the battery pack also brings great challenges to the liquid cooling system [15].

## 2.2. Air-cooling technology

### 2.2.1. Working principle of air-cooling technology

AC refers to convection heat transfer by air flow, also known as air cooling. The air duct with a certain structure makes the wind sweep over the surface of the battery module, so that there is direct contact between the fluid and solid. Due to the existence of temperature gradient, the air, and the battery exchange heat, taking away the excess heat of the battery [14].

According on whether power equipment or other auxiliary equipment is employed, AC is classified as either forced convection cooling or natural convection cooling, as showed in Fig. 4. The former refers to the use of the wind generated by the vehicle in operation to take away the heat of the battery pack. The advantages of this method are low cost, simple structure, but poor heat exchange effect. The battery pack installation location must meet specifications, and the car must be in functioning order. The latter is the cooling and heat dispersion of the battery pack using power tools like fans or an auxiliary air conditioning radiator. This method has low cost, simple structure, mature technology, and better cooling effect than natural convection cooling [16].

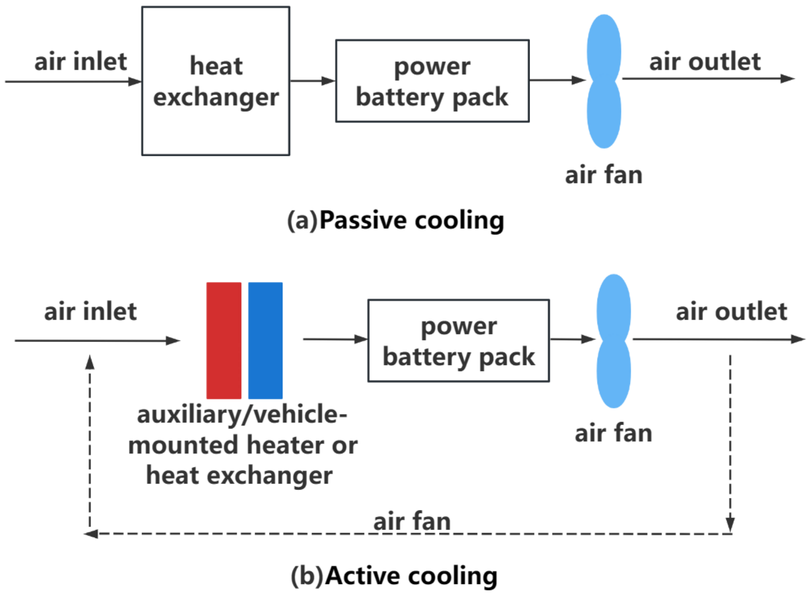


**Figure 4.** Principles of different air-cooling technologies: (a) passive cooling, (b) active cooling

According to the different path structures of air circulation, air cooling can be divided into serial air cooling and parallel air cooling. Serial ventilation is the process of flowing air through each battery in turn while exchanging heat with the battery surface to remove heat from the batteries. Despite the straightforward design and inexpensive cost of this technology, it is possible to significantly alter the battery's starting temperature and unevenly heat the battery. The more the battery is behind, the worse the heat dissipation effect will be. Parallel ventilation removes heat from the battery by having the cooled air go through each cell almost simultaneously, which easily ensures uniform battery pack temperature [16].

### 2.2.2. Advanced optimization scheme for air-cooling technology

Compared with LC technology, AC has simple structure, low manufacturing cost and no risk of coolant leakage, but its heat dissipation effect and temperature uniformity are poor. In order to further improve the cooling effect, the heat transfer efficiency and heat dissipation area can be improved by optimizing the design of air duct and air inlet/outlet, effectively controlling the air flow rate and flow, and designing the battery layout [5].

Reduce the maximum and average temperatures of the battery to enhance the temperature homogeneity of each individual battery in the AC system. Ma and others [17] have improved the heat dissipation capability of the air-cooled battery cooling system by changing the battery cell arrangement and using baffles to interfere with the air in the battery box to enhance the air flow uniformity in the battery box. The results show that the cooling effect of the whole air-cooled battery cooling system is the best when the battery cells are arranged in a horizontal staggered manner, the spacing ratio between partitions is 1:1, and the area is to cover three batteries. WU and others [18] designed the air inlet duct and battery placement mode of the power battery. It has been discovered that the air inlet in the battery pack's middle performs better at dissipating heat than the air inlet on either side. The square battery is placed longitudinally for more uniform heat dissipation, and the overall air duct of the cylindrical battery has better heat dissipation effect than the local air duct. The work in [19] proposed the configuration of single-layer thermal diffusion plate and double-layer thermal diffusion plate, which showed that thermal diffusion plate can effectively improve the temperature consistency of battery modules.

The impact of battery arrangement, battery spacing, and air inlet speed on the temperature field distribution of the battery pack was investigated by Li and colleagues [20]. It has been discovered that raising the air speed at the air intake may considerably enhance the battery pack's ability to dissipate heat. When the battery is discharged at 2C, it is most beneficial for the heat dissipation of the battery pack to arrange the batteries in a row. The maximum temperature of the battery pack can be restrained by reducing the battery spacing. The battery pack's temperature homogeneity is best at 4mm between batteries.

#### 2.2.3. Challenges of air-cooling technology

For AC technology, there are some shortcomings, such as low cooling efficiency and poor heat dissipation effect. However, considering manufacturing cost and lightweight design, AC technology remains the most widely used method to heat manage batteries, mostly used in small passenger cars with normal driving conditions and good urban roads [5]. Additionally, because of how it operates, the cooling effect is quite unstable and is affected by outside variables like vehicle speed and outside ambient temperature when the vehicle is in motion. Forced convection cooling needs further optimization.

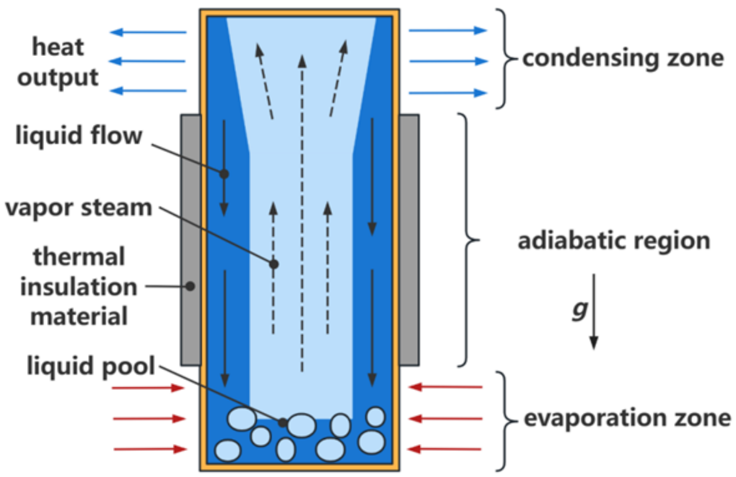


**Figure 5.** Schematic diagram of working principle of heat pipe device

### 2.3. Heat pipe cooling technology

#### 2.3.1. Working principle of heat pipe cooling technology

As illustrated in Fig. 5, the phase change interaction between the working fluids in the heat pipe is the basis for HPC, which absorbs heat in the evaporation zone and releases heat in the condensation zone. The cooling process is generally segmented into evaporation zone, insulation zone and condensation zone along the axis. HPC conducts effective heat transfer through reciprocating circulation and phase change reaction of working fluid [21].

The HPC technology was studied with emphasis because of its high heat transfer and thermal conductivity, prominent isothermal performance, variable heat flow density and reversible heat flow direction. Additionally, it may be used in conjunction with phase change materials, heat pipe-air cooling, and heat pipe-liquid cooling. The future of the HPC technique is bright [21].

#### 2.3.2. Challenges of heat pipe cooling technology

During the use of HPC technology, the pressure of the condensing zone is very high, which leads to higher requirements for pipes, production standards, production equipment, etc. There are additional issues including high manufacturing and maintenance costs, difficulty controlling the quantity of heat exchange medium, and a stronger impact of the battery pack's design on the effectiveness of heat dissipation. Currently, the market has not seen a lot of adoption of the HPC technology since it is still in the research stage [21].

### 2.4. Phase change cooling technology

#### 2.4.1. Working principle of phase change cooling technology

The PCMC technology use phase change materials (PCM) as heat transfer medium. In the process of phase change, energy can be stored and released to achieve high temperature heat dissipation effect of power battery without additional energy consumption. Solid-solid PCM (such as inorganic salt), solid-liquid PCM (such as paraffin), solid-gas PCM, and liquid-gas PCM may all be categorized based on the mechanism of PCM. Among all these materials, solid-liquid PCM have the advantages of large latent heat, small volume change and the needed materials are easy to obtain, which is currently the focus of industry research [21].

#### 2.4.2. Challenges of phase change cooling technology

The advantages of a PCMC system are easy construction and inexpensive manufacturing costs. However, there are still some technical problems in the application of PCMC technology. For instance, when the temperature is too low, phase change materials' thermal conductivity is comparably low and their thermal stability is comparably poor. As a result, it has not been widely used yet.

**Table 1.** Comparison between different cooling technologies

| Cooling mode | Advantages | Shortcomings | Development Trends |
|---|---|---|---|
| Liquid cooling | High heat dissipation efficiency and strong temperature uniformity | Complex structure, high sealing, and insulation requirements | Further optimize cooling group, pipeline, liquid medium flow, etc |
| Air cooling | Simple structure and low cost | Unstable cooling effect, poor heat dissipation effect, unfavorable for lightweight design | Further optimize forced convection cooling mode |
| Heat pipe cooling | Excellent isothermal performance, reversible heat flow direction | The consumption of heat exchange medium is difficult to control and the production and maintenance costs are high | Optimize structure and reduce costs |
| Phase change material cooling | Simple structure and low manufacturing cost | Relatively low thermal conductivity and poor thermal stability at low temperature | Solid-liquid phase change materials have outstanding advantages and are the focus of research |

## 3. Conclusion

In this paper, the working principles, challenges, and the latest optimization schemes of typical cooling technologies for electric vehicles are comprehensively analyzed. The comparison between different cooling technologies is summarized in Table 1. Meanwhile, the advanced power battery cooling technology of new energy vehicles is conducive to promoting the future perspectives. Liquid cooling and air cooling are both mainstream solutions for power battery cooling, but both have their own advantages and disadvantages. Heat pipe cooling, phase change cooling and other new cooling schemes are not mature, and are difficult to put into mass production. The major development goals for the future will focus on optimizing existing cooling schemes or speeding up the process of getting theoretical new cooling technologies into production. Since existing technologies have been relatively mature and the development space is limited, combining the advantages of various technologies may be a good idea. As for the theoretical new cooling technologies, efforts are aimed at reducing costs and simplifying processes. Improving the cooling technical efficiency of power batteries can directly reduce the probability of thermal runaway, improve the safety of new energy vehicles to improve the market acceptance of new energy vehicles and promote the development of the new energy automobile industry.

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