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Review

A Review of the Power Battery Thermal Management System with Different Cooling, Heating and Coupling System

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Abstract: The battery thermal management system is a key skill that has been widely used in power battery cooling and preheating. It can ensure that the power battery operates safely and stably at a suitable temperature. In this article, we summarize mainly summarizes the current situation for the research on the thermal management system of power battery, comprehensively compares and analyzes four kinds of cooling systems including air cooling, liquid cooling, phase-change materials and heat pipe, two types of heating systems including internal heating and external heating, and the corresponding characteristics of the coupled system in no less than two ways. It is found that liquid cooling system and its heating system, phase-change material cooling system and it is heating system, heat pipe cooling system, coupling cooling system and its heating system have great research prospects, it also provides a certain reference for future research directions.

Keywords: power battery; thermal management system; cooling system; heating system

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1. Introduction

New energy vehicles have the advantages of less pollution and low emissions. To alleviate a series of problems such as global temperature warming and energy depletion, the use of new energy can not only reduce greenhouse gas emissions by about 20% but also significantly reduce the use of non-renewable energy compared with traditional fuel vehicles. With these advantages, new energy vehicles have attracted much attention in various countries in recent years [1,2]. With the continuous improvement of people's awareness of new energy vehicles, their possession is also increasing year by year, more and more favored by people, but a series of failures related to power batteries are also known to people, so it is urgent to seek relevant solutions. The temperature has a great impact on battery performance, battery life, and battery safety. When the temperature is too low or too high, the power battery may have thermal runaway, capacity decline, internal resistance increase, life attenuation, and charging and discharging difficulties [3,4]. Therefore, it is necessary to develop a complete, efficient and reliable battery management system to ensure the safety and smooth operation of power batteries. As an important part of the battery management system, the battery thermal management system plays a significant role in dealing with the battery thermal-related problems and ensuring the performance, safety, and life of the power battery [5].

At present, there are many research kinds of literature on power battery cooling technology and heating technology, but there is no paper summarizing their research status of them. To meet this demand, in this paper, we focus on three types of papers: experimental works, simulation works, and prototypes, systematically review and summarize the existing methods and technologies of cooling and heating, and provide suggestions and guidance for future research and development trends.

In this paper, the thermal management system of the power battery is divided into a single cooling system, a single heating system, and a coupling system with no less than two single cooling or heating methods. Among which: the common cooling system has air cooling system [6], liquid cooling system [7], phase-change material (PCM) cooling system [8,9] and heat pipe type cooling system [10]; common heating systems include internal heating system and external heating system [11]. The internal heating system includes a self-heating system [12], AC heating system [13], and pulse current heating system [14]. The external heating system includes a hot air heating system [11], a Liquid heating system [11], a phase-change material heating system [15], a heating element heating system [16,17], Peltier effect heating system [18]; common coupling systems mainly include systems such as phase-change material coupling with air, coupling with liquid, and coupling with heat pipe. The detailed classification is shown in Figure 1.

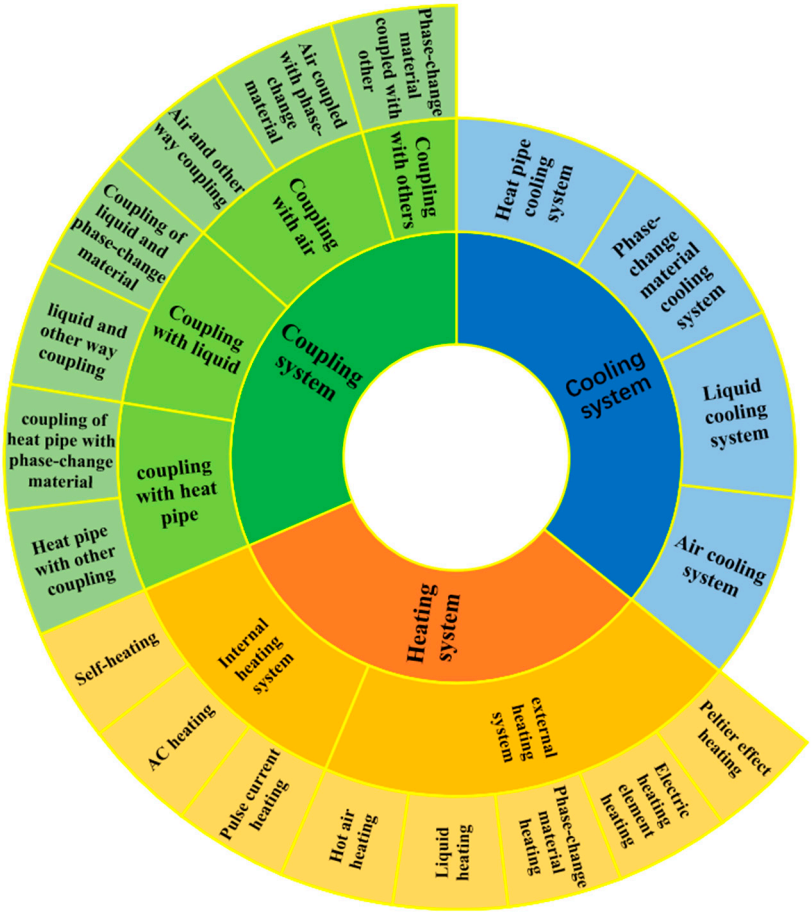


Figure 1. Classification of power battery thermal management systems.

2. Cooling System

The safe working range of the power battery is generally about −40 °C to 60 °C, and the best working range is generally between 15 °C to 35 °C [19,20], and the temperature difference should be kept within 5 °C [21,22]. When the temperature is too high, the battery working environment may exceed the scope of its work safety, so that the power battery respect to the failure of large area, the thermal runaway phenomenon occurring, serious when a battery or spontaneous combustion explosion, to make the battery working temperature control within the scope of the safety or the best work, for heat dissipation of the battery is necessary.

2.1. Air Cooling System

Air cooling systems can be divided into natural convection cooling systems and forced convection cooling systems, which use the natural convection of external air or forced convection of air by mechanical devices so that the external cold air flows through the surface of each cell of the power battery to conduct heat exchange to achieve the purpose of cooling. Air cooling systems have the simplest structure among all cooling systems and low manufacturing cost, but it also has the defects of a poor cooling effect and slow cooling speed [23,24], which cause the heat dissipation requirements of electric vehicle battery modules not to be well-met present. In recent years, research on air-cooled heat dissipation systems has mainly focused on the arrangement of single components in battery modules, new ventilation forms, and optimization of air channel structures. According to different ventilation modes, the air-cooling battery management system can be divided into serial air supply mode and parallel air supply model [25]. Figure 2 is a schematic diagram of the structure of serial air supply and parallel air supply.

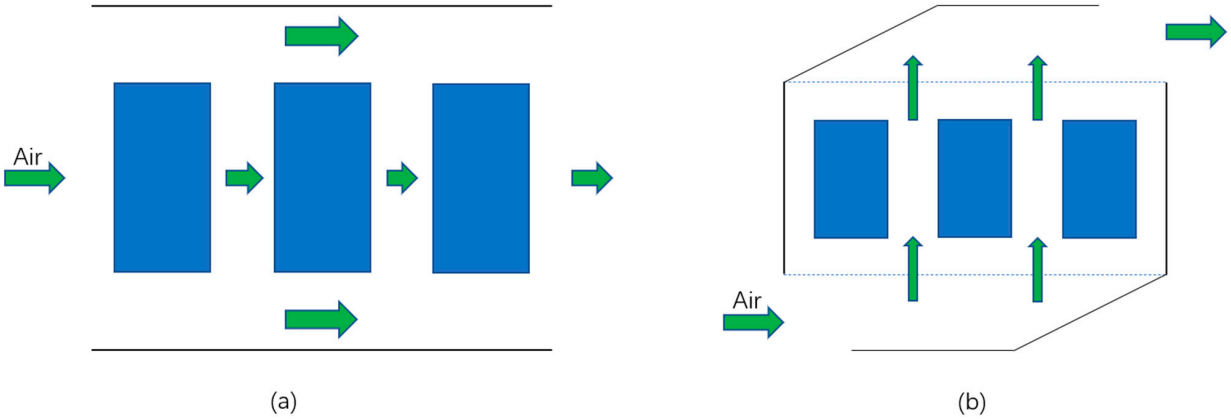


Figure 2. The schematic diagram of the air supply mode of the air-cooling system, (**a**) the serial air supply, (**b**) the parallel air supply.

When ventilating in series, the air enters the ventilation duct and flows over the surface of the battery in turn, during the flow, the temperature of the air gradually increases, and the temperature difference between the air and the battery continues to shrink, resulting in the uneven temperature of the battery pack. The temperature and flow rate of the upstream and downstream are different. The upstream cell is close to the air inlet, the flow rate is high, and the temperature is low. The downstream battery is close to the air outlet, and the heat transfer efficiency of the downstream battery surface decreases, and the temperature is high. Therefore, the temperature consistency of the battery module is poor. In parallel ventilation, the air flows through the battery surface at the same time, the air velocity and airflow through the battery surface are relatively uniform, the heat exchange conditions of each battery surface are almost the same, and the temperature uniformity of the battery module is improved, Therefore, the air-cooled battery the heat dissipation method of parallel ventilation in the thermal management system is widely used. Zhang et al. [26] found that adding a spoiler in the cooling channel of the battery pack can further improve the cooling performance and temperature uniformity of the battery, the experimental results show that compared with the battery without spoilers, the maximum temperature and the maximum temperature difference of the battery pack are dropped by 1.86 °C and 2.51 °C. Pan et al. [27] studied a method of adding fans in parallel ventilation mode to improve the uniformity of battery pack temperature. The experiment found that adding a fan in the air inlet duct can effectively improve the uniformity of the gas flow of the battery module. When the flow rate of the cooling air at the inlet is greater than 7 m/s, the average temperature difference of the battery pack is maintained at about 1.4 °C. Li et al. [28] Studied the effects of battery arrangement, battery spacing and

air velocity at the air inlet on the temperature field distribution of serial 18650 cylindrical lithium-ion battery pack. The experimental results show that when the battery spacing is 4 mm and the wind speed is 4 m/s, the battery pack is arranged in sequence to obtain the best cooling effect under the condition of ensuring the consistency of other parameters. Xu et al. [29] studied the heat dissipation performance of ventilation ducts at the bottom of different battery packs under forced air convection cooling. Through four working conditions of continuous acceleration, continuous deceleration, shelving, pulse discharge, and vehicle operation, the temperature rise and internal temperature difference at the bottom of different battery packs using double "U" type air ducts and double "I" type air ducts are simulated and analyzed. The experimental comparison results show that the temperature rise and internal temperature difference of double "U" type air ducts are lower than that of double "I" type air ducts, and the temperature difference of battery pack can be controlled at about 3 °C. Yuan et al. [30] studied a new type of air-cooling system with a z-shaped structure, and reduced the maximum temperature, temperature difference, and non-uniformity of the battery pack by adjusting the deflector plate and round chamfer. The experimental results found that when the deflection angle is 60°, when the round chamfer is 5mm, the cooling performance of the battery pack is the best, and the maximum temperature can be reduced by 2.52 °C, the temperature difference and unevenness can be reduced by 366.66% and 36.50%.

2.2. Liquid Cooling System

A liquid cooling system refers to a thermal management system in which the cooling liquid directly or indirectly contacts the power battery module, and then the heat generated by the power battery is taken away in time through the continuous circulation of the cooling liquid. The liquid cooling system can be divided into direct contact and indirect contact according to the contact mode between the coolant and the battery, the direct contact mode requires coolant insulation. Compared with the air-cooled heat dissipation system, the liquid cooling system generally has a higher heat dissipation capacity and a more obvious cooling effect. However, it requires external components such as pumps and heat exchangers, which not only makes the structure more complex and increases the cost of production, maintenance, and maintenance but also causes secondary losses when the battery has to supply power to external components. Although the liquid cooling and heat management system has been quite perfect and mature and is widely used in the heat dissipation system of new energy vehicles, there is still a lot of room for development. At present, the research and development of the liquid-cooling heat dissipation system of electric vehicles at home and abroad focus on the optimization of the cooling medium runner structure and the expansion of the contact area between the cold plate and the battery module. In order to compare the thermal management performance of the small cooling channel and the larger cooling channel, Yates M et al. [31] conducted a study under the condition of a discharge rate of 5 C and an ambient air temperature of 24.85 °C. Under this circumstance, the maximum temperature of the two designs can be controlled below 34.85 °C, and the temperature difference can be controlled within 3.15 °C. The maximum temperature of the battery pack using the small cooling channel is lower than the maximum temperature of the battery pack using the larger cooling channel, but the temperature has Poor consistency and high cost. Propane is often used as a coolant because of its stable chemical properties and no chemical reaction. Al-Zareer et al. [32] use propane as a cooling medium by comparing the influence of the spacing between batteries on thermal management. Simulation results show that reducing the spacing between batteries will improve the maximum temperature of the battery, but it can improve the temperature consistency of the battery; the larger cell spacing reduces the maximum temperature of the cells, but also increases the temperature difference between the cells. Tang et al. [33] studied the method of adding fins to the liquid cooling plate to improve the cooling efficiency of the thermal management system, established a liquid-cooled battery system model, and studied the heat balance performance of the parallel liquid cooling system through

numerical analysis. Its position structure is shown in Figure 3. The research results show that the optimized parallel liquid cooling system can keep the maximum temperature of the battery system below 44.31 °C, and the temperature difference of the battery system is within 3 °C, which meets the temperature requirements of the power battery system.

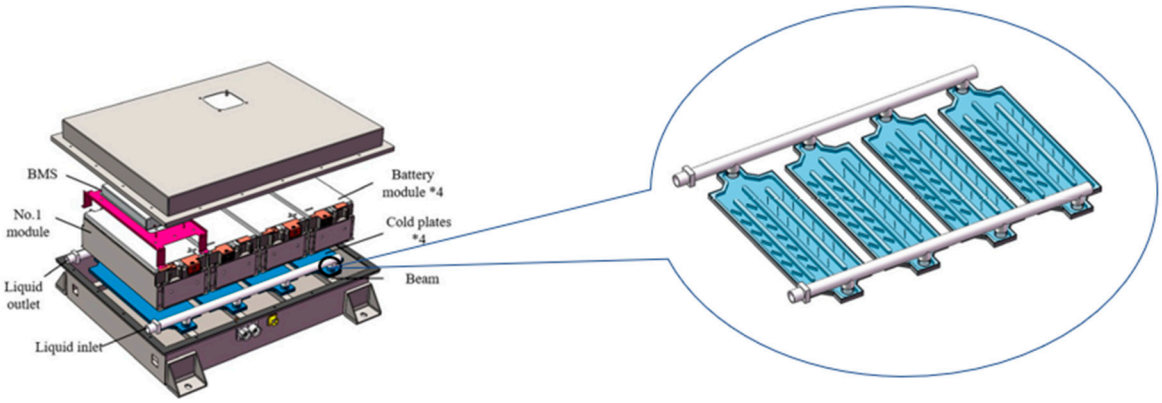


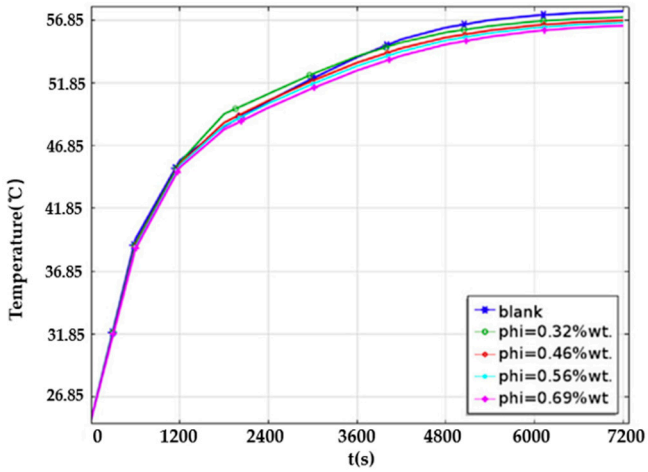
Figure 3. Position structure diagram of fin-liquid cooling plate [33]. R Reproduced from reference [33], with permission from AIP, copyright 2020.

Rao et al. [34] to keep the maximum temperature and local temperature difference of columnar battery in an appropriate range, proposed a columnar battery cooling method based on a microchannel liquid cooling cylinder. The effects of the number of channels, mass flow rate, flow direction, and inlet size on the heat dissipation performance of pipes were studied numerically. The results show that when the number of small channels is not less than 4 and the inlet mass flow rate is 1103 kg/s, the maximum temperature of 42,110 cylindrical batteries can be controlled below 40 °C. Considering both the maximum temperature and local temperature difference, only when the number of channels is greater than 8, the cooling mode of the liquid cooling cylinder can show greater advantages than natural convection cooling. The ability to reduce the maximum temperature by increasing the mass flow rate is limited. When the inlet mass flow rate is constant, the heat dissipation capacity increases first and then decreases with the increase of the inlet size. Min et al. [35] established a liquid-cooled battery module based on the micro-channel wavy flat tube for heat dissipation of cylindrical power battery, the results showed that increasing the contact angle of the wavy flat-tube could improve the heat dissipation efficiency of the liquid-cooled structure and improve the uniformity of temperature distribution of battery pack. Pan et al. [36] designed a parallel multi-channel liquid cooling plate, established a three-dimensional thermal model of the battery module and the liquid cooling plate and analyzed the effects of the thickness of the cooling plate, the thickness of the cooling pipe, the number of channels and the coolant mass flow on the cooling performance of the battery module after the influence, the four factors were optimized by orthogonal experiments, and the optimized results showed that the maximum temperature control and temperature uniformity of the liquid-cooled battery module was significantly enhanced.

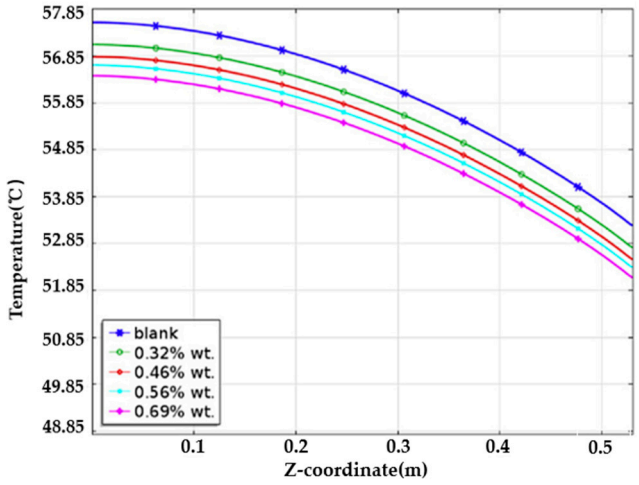
2.3. Phase Change Material Cooling System

The phase-change material cooling system uses phase change material as a heat transfer medium, which can store energy and release energy during the phase change, to achieve the effect of low-temperature heating and high-temperature heat dissipation of the power battery. According to the form of phase-change material, it can be divided into solid-solid phase-change materials, solid-liquid phase-change materials, solid-gas phase-change materials, and liquid-phase-change materials. At present, the focus of industry research is mainly on solid-solid phase-change materials and solid-liquid phase-change materials on the material. The phase-change material heat dissipation system has the advantages of relatively simple system design and low cost, but the thermal conductivity of the current

phase-change material is still relatively low, resulting in a low heat dissipation rate, so it is not particularly widely used in new energy vehicles. Due to the low thermal conductivity of phase-change materials, at present, the main effort is to add a highly conductive matrix to the structure of the phase-change material to increase its thermal conductivity and optimize the arrangement. Temel et al. [37] added graphene nanoplatelets (graphene nanoplatelets, GNP) with different mass fractions into phase change materials to study the instantaneous thermal response of composites in energy storage units. The results show that the thermal conductivity of the composite increases linearly with the increase of the GNP mass fraction, and the temperature difference in the energy storage unit decreases significantly. When the mass fraction of GNP is 7%, the thermal conductivity increases by 253%, and the effective utilization time of the energy storage unit is prolonged by 32 min. A. Babapoor et al. [38] increased the thermal conductivity of the phase-change material by adding carbon fiber to the phase-change material. The results show that the presence of carbon fiber increases the thermal conductivity of the phase-change material, thereby affecting the temperature distribution inside the battery, and the carbon fiber content the higher the phase-change material, the more uniform the temperature distribution. The distribution of the effect of carbon fiber content on the battery temperature is shown in Figure 4.



(**a**)



(**b**)

Figure 4. *Cont.*

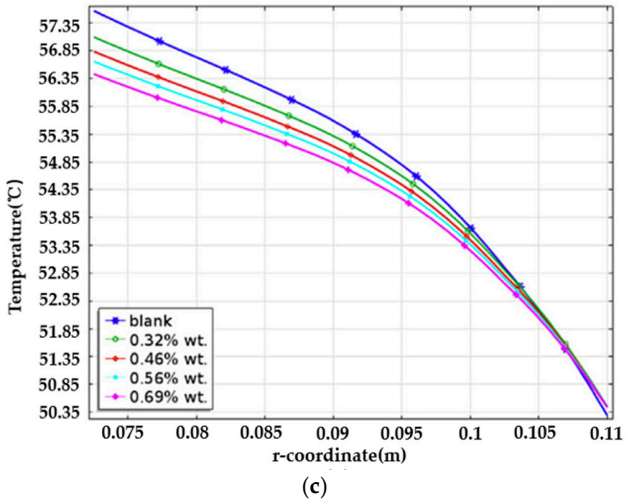


Figure 4. The effect of different carbon fiber loadings on the battery: (**a**) the change of the battery surface temperature with time; (**b**) the change of the battery surface temperature with the height; (**c**) the change of the radial battery temperature [38]. Reproduced from reference [38] with permission from Elsevier B.V., copyright 2016.

Adding high thermal conductivity metal to the phase-change material or using foam metal to adsorb the phase-change material, the obtained composite phase-change material system also has a good thermal management effect. Wang et al. [39] used foamed copper/phase-change materials to thermally manage different types of lithium-ion batteries and compared the effects of phase-change materials and natural air convection in an insulating environment. The temperature control effect of the phase-change material is better than that of air convection, and the maximum temperature of 26,650, 42,110 and square batteries can be controlled below 44.37 °C, 51.45 °C and 50.69 °C for a longer time. In contrast to this, Jilte et al. [40] analyzed the arrangement of traditional battery cells and phase-change materials and reduced the thickness of phase-change materials between battery cells to discharge heat into the voids faster and improve battery performance. For heat dissipation efficiency, the study found that a 4 cm thickness of the phase-change material around the battery cell is sufficient for heat dissipation. When the ambient temperature is 35 °C and the discharge rate is 5 C after the discharge cycle is over, the maximum temperature of the battery is controlled at 41 °C, and the maximum temperature difference between the battery cells is controlled at 0.05 °C. As shown in Figure 5, the left is the traditional rectangular PCM-filled battery pack, and the right is the improved PCM-filled battery pack.

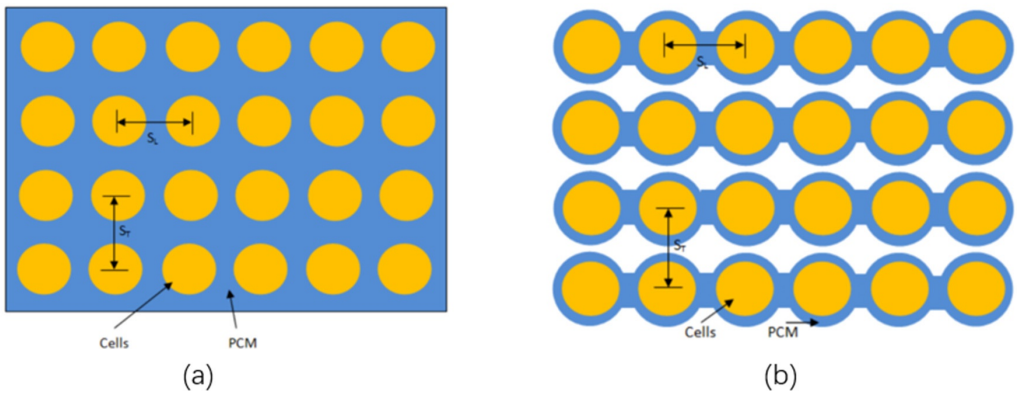


Figure 5. Structure of PCM-filled battery pack, (**a**) traditional rectangular PCM-filled battery pack, (**b**) improved PCM-filled battery pack [40]. Reproduced from reference [40] with permission from Elsevier B.V., copyright 2019.

2.4. Heat Pipe Cooling System

Heat pipe cooling technology was first applied in the aerospace industry and military industry. The essence of heat transfer is the phase change reaction of the working medium in the tube. Heat can be rapidly transferred from the heat source through a heat pipe, and this thermal conductivity exceeds all the known metals at present. Due to the immaturity of pipes, production standards, production equipment, etc., the application in thermal management of power batteries is mostly in the research stage and has not been popularized and used. Tian et al. [41] designed a heat pipe-aluminum plate heat dissipation module for lithium-ion batteries, which increased the contact area between the heat pipe and the battery and enhanced heat exchange. Through numerical simulation and orthogonal experiment Analytic Hierarchy Process (AHP), the influence degree and weight of each factor on the cooling performance of the module are studied, and the parameters are optimized. The experimental results show that under each experimental scheme, the temperature difference of the battery module is controlled within 3 °C, indicating that the temperature uniformity of the battery module using this heat dissipation has been enhanced. Dan [42] studied a battery thermal management system based on a Micro heat pipe array (MHPA), the schematic diagram of the structure of the micro heat pipe array is shown in Figure 6.

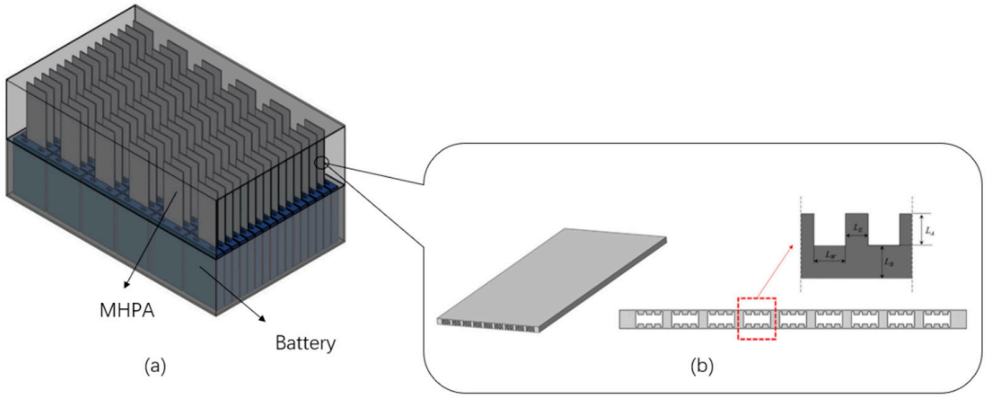


Figure 6. Schematic diagram of the thermal management system of the micro heat pipe array (**a**) the schematic diagram of the combination of the micro heat pipe array and the battery, (**b**) the schematic diagram of the MHPA structure [42]. Reproduced from reference [42] with permission from Elsevier B.V., copyright 2019.

At the rate of 3 m/s in forced airflow, simulation analysis of the single battery module and a single equipped with battery module of micro heat pipe array thermal performance, and on the basis of the comparison, found in forced to shed, single battery module temperature is 41.2 °C, and equipped with micro heat pipe array of single battery module temperature is 36.1 °C, when a sudden increase or decrease in the charging rate, behave more moderate heat pipe cooling system, it has very good cooling efficiency, and is made up of 96 battery monomer battery pack to simulate the temperature changes within the battery pack and distribution situation, the study found that the heat pipe cooling system is better than that of forced air convection on the temperature control system, at the end of the discharge, battery control within 40 °C, the highest temperature the maximum temperature difference is only 2.04 °C, the simulation results show that the battery pack equipped with heat pipe can significantly improve the temperature uniformity. To obtain the influence of the liquid filling rate and heat flow density on heat pipe heat transfer performance, Nandy Putra et al. [43] conducted an experimental study using a flat plate loop heat pipe (FPLHP) as a heat exchanger for the thermal management system of an electric vehicle lithium-ion battery. They simulated the heat generation process of the battery by using a cylinder heater, and adopted stainless steel sieve for the capillary core, the working liquid is distilled water, alcohol, and acetone, and the filling ratio is 60%. The experimental results show that the flat circular heat pipe has certain application potential in the thermal management

system of lithium-ion batteries. In addition to the heat pipe heat transfer with high thermal conductivity, excellent isothermal property, heat flow density variable, and the advantages of the reversible heat flow direction, and heat pipe cooling way very easily with other coupling is used, such as heat pipe air cooling, heat pipe cooling, heat pipe - liquid cooling phase-change materials, etc., in short, heat pipe cooling system has very good prospects for development. The advantages and disadvantages of the four cooling systems are shown in Table 1.

Table 1. Features of the four cooling systems.

Serial Number	Cooling System	Advantage	Shortcoming
1	Air cooling system	Simple structure, low cost, small footprint, lightweight, etc.	Low thermal conductivity, poor cell uniformity control, etc.
2	Liquid cooling system	Good thermal conductivity, good cooling effect, relatively uniform heat dissipation, etc.	There is a risk of liquid leakage, difficult maintenance, heavyweight, complex structure, etc.
3	Phase-change material cooling system	High heat density, large latent heat, good stability, fast heat dissipation, high-temperature control uniformity, etc.	The heat absorbed by the phase change material cannot be well dissipated to the external environment, etc.
4	Heat pipe cooling system	High thermal conductivity, high heat dissipation efficiency, fast heating rate, good uniform performance, good safety, high reliability, etc.	High cost, difficult to control the amount of heat exchange medium, complicated structure, inconvenient installation, etc.

3. Heating System

The low-temperature environment will seriously attenuate the available capacity and power of the power battery, reduce the service life, and make charging and discharging difficult, and even a series of battery failures such as potential safety hazards and thermal runaway due to a short circuit inside the battery [44–48], to solve the above problems, it is necessary to heat the power battery under low-temperature conditions. The heating system can be divided into an internal heating system and an external heating system [11]. Internal heating is to heat the battery through the resistance in the battery and the heat generated by the chemical reaction inside the battery. This method has high efficiency and low energy efficiency, but it is easy to cause the attenuation of battery performance. The purpose of external heating is to heat the battery by connecting heating components to generate heat. This method is simple to heat and has high safety, but the efficiency is relatively low.

3.1. Internal Heating System

The internal heating of the battery has the advantages of high efficiency, the lack of limitation by the size and space of the battery box and the way of installation [49], and the ability to rapidly and uniformly increase the temperature of the battery. The internal heating of the battery can be divided into three ways: battery self-heating, high- and low-frequency AC heating, and pulse heating.

(1) Self-heating

The self-heating of the battery is controlled by the battery pack itself, which can easily cause the inconsistency of the heating time between the battery cells, resulting in a temperature difference between the battery cells inside the battery pack, thus affecting the service life and performance of the battery. Research on the consistency of the internal

temperature of the battery pack and the balance of the battery system. Ji et al. [50] studied two discharge methods, constant current discharge (cc) and constant voltage discharge (cv). Three curves of cc-mode, cv-mode, and battery temperature change, the effect of discharge mode on iSOC, and internal heating efficiency are obtained, respectively. The cv protocol is superior to the cc protocol, and under the cv protocol, the iSOC can be maintained at a stable level and the heating efficiency of self-heating is not higher than 50%, and electrical energy is mostly used for internal resistance heating. Lei et al. [51] proposed the intermittent self-heating lithium-ion battery (SHLB) heating method by establishing a three-dimensional heating finite element model, which improved the temperature uniformity of lithium-ion batteries in the heating process. Xu et al. [52] established a battery temperature rise model based on the equivalent circuit and verified the accuracy of the model by making a low-temperature self-heating method that adaptively adjusts the amplitude of pulse current, and concluded that the battery could be charged with more electric energy after heating, which would help solve the problems of poor battery performance and difficulty in charging at low temperature. To solve the problem of low temperature preheating of power batteries, Chen et al. [53] proposed an electric-triggered extreme self-heating method based on short-term current self-discharge, taking lithium-ion power batteries as the research object, and the experimental results show that this method can heat the power battery from ambient temperature −20 °C to 20 °C in only 87 s, has little effect on the service life of the power battery, and the standard deviation of temperature during heating is less than 2.7 °C.

(2) AC heating

Alternating current heating is to apply an alternating current at both ends of the battery to generate heat through the ohmic impedance inside the battery, thereby heating the battery. Compared with DC, AC is less affected by amplitude and duration, which can make the battery heat up quickly and efficiently, while avoiding substantial changes in battery SOC. Ji et al. [50] heating strategy by analyzing the external power source, such as found in alternating current heating to the battery heated evenly, battery internal temperature, and the advantages of small and easy to obtain, depending on the external power source of choice for heating, and further studied based on the Stuart and Hande frequency to the effects of heating rate, found that use of high-frequency signals can save a great amount of time. He et al. [54] studied the influence of frequency change on the heating rate and designed a variable frequency and amplitude AC low-temperature heating strategy. The experimental results showed that under the same conditions, the battery temperature rises of variable frequency and amplitude, 1700 Hz and 3500 Hz constant frequency and amplitude AC self-heating strategies within 700 s were 47.67 °C, 40.83 °C and 44.01 °C respectively. It shows that the variable frequency and amplitude AC self-heating strategy has obvious advantages. Guo et al. [55] Based on the design of an alternating current in the trapezoid heating method, to solve the problem is not suitable for trapezoid heating method in parameter Settings easy to endanger the battery health problem because of the adverse event, created a three-electrode cell is used to study trapezoidal heating in low temperature can affect the health of the battery, the experimental results show that the research of heating methods on the battery does not affect health. Shang et al. [56] studied a high-frequency AC heater based on buck-boost transformation and developed an electrical model of a high-frequency thermal control heater based on ohmic resistance heating and lithium-ion transport. Experiment by studying the high-frequency AC heating topology and the effectiveness of the thermal model of different root mean square (RMS) current AC heating frequency, the results showed that the electrical flow in the same RMS AC frequency can significantly improve the heat rate and thermal efficiency, thus shows the ohmic resistance and lithium-ion battery transfer heat will not cause the damage of the battery. Due to the cost, quality, installation space, and other factors involved in the ac generation device, this method has not been widely used in electric vehicles.

(3) Pulse current heating

Pulse current preheating is similar to AC heating. Pulse AC heating utilizes a discontinuous high-current discharge method to generate heat through the ohmic impedance inside the battery, thereby heating the battery. Compared with air heating, pulse current heating has a more uniform temperature distribution inside the battery, which reduces the battery capacity degradation problem caused by the internal temperature difference of the battery pack. However, pulse current heating requires an additional discharge loop in the battery pack. The cost of the battery is increased. Therefore, the heating method is still in the research stage and has not yet been implemented in the commercial stage. In 2013, the Ji et al. [50] team established an electrochemical-thermal coupling (ECT) model and completed the five heating strategies of self-heating, convective heating, convective heating, mutual pulse heating, convective heating with external power supply, and AC heating. The comparative analysis found that mutual pulse heating not only consumes the least volume but also combines the advantages of internal uniform heating and no forced convection. Wu et al. [57] proposed a thermoelectric coupling model based on electrochemical impedance spectra of batteries at different temperatures, combined with the pulse variable frequency method to formulate an effective internal preheating strategy, and developed a preheating strategy using frequency conversion pulses. The results show that the optimized frequency conversion pulse preheating strategy can heat the lithium-ion battery from −20 °C to 5 °C in 1000 s. At the same time, from the aspects of power consumption, capacity attenuation, internal resistance change, reduce the damage to the health of the battery, improve the performance of the battery in cold weather. Qu et al. [58] studied the low-temperature pulse heating of lithium-ion battery, and compared it with dc heating, and found that when the battery was heated from −10 °C to 10 °C, the pulse heating time was 175 s, 105 s less than the DC heating time. Huang [59] and other experiments studied the control effect of the pulse heating method based on fuzzy logic control. First, the effects of pulse frequency and amplitude on battery temperature changes were studied, then according to the real-time internal resistance and temperature of the battery, a fuzzy logic control strategy is designed to obtain the variable pulse amplitude criterion. The experiments were carried out at the same pulse frequency and different initial states of charge of the batteries, compared with the equal-amplitude pulse preheating strategy, this strategy can shorten the heating time by 2 to 4 min and save 50% of the energy loss. The respective characteristics of the three internal heating systems are shown in Table 2.

Table 2. A simple comparison of the characteristics and rates of three internal heating methods.

Serial Number	Internal Heating	Advantage	Shortcoming	Temperature Rise Rate (°C/s)
1	Self-heating	High heating efficiency, no additional equipment required	It is necessary to change the existing battery structure and existing battery production process, which has certain safety risks	0.46 [52]
2	AC heating	Higher heating efficiency and better cell temperature consistency	Low-frequency alternating current has great damage to the battery, and the system control is complicated	0.063 [54]
3	Pulse current heating	Cell temperature consistency is good	Complex system control, high cost, and high energy consumption	0.025 [57]

3.2. External Heating System

(1) Hot air heating

Hot air heating is to pass the hot air through the designed airflow channel to achieve heat exchange for the battery cells, to achieve the purpose of heating the battery. Hot air heating has the advantages of low cost, simple structure, and lightweight. The source of hot air can be divided into two ways: introducing external hot air and realizing thermal circulation inside the battery box through a heater. Compared with other heating methods, the temperature change of hot air heating is relatively large, so the design requirements for the airflow channel inside the battery pack are relatively high. Ji et al. [50] designed an air convection heating system. The principle is that when the power battery discharges, the current flows through the heating element to generate heat to heat the surrounding air, and the hot air is conveyed to the battery pack by the fan, to achieve the purpose of heating the battery. Its schematic diagram is shown in Figure 7.

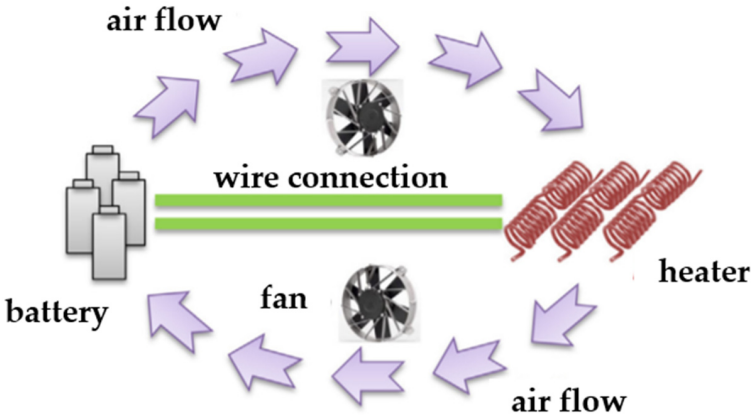


Figure 7. Schematic diagram of the convection heating system [50]. Reproduced from reference [50] with permission from Elsevier B.V., copyright 2013.

The research shows that when the element resistance is 0.4 Ω, it only takes 85 s to rise from −20 °C to 20 °C in the heating system, greatly shortening the heating time, but the heating mode requires a flow loop and a fan for air circulation, and the battery, the battery heating more difficult, to increase the cost and complexity of the system, reduce the reliability of the system. Wang [60] established an electric heating wire heat exchange model according to the principle of heat transfer. Through the study of air heating experiments and low-temperature battery heating experiments, it is proved that using high-temperature air heated by electric heating wire to heat a low-temperature battery pack is an effective method. Huang et al. [61] developed a thermal management control for electric vehicle power batteries using eddy current tube cooling and heating technology. The thermal management system converts the kinetic energy of the vehicle into air pressure by recovering the braking energy of the electric vehicle, which can provide energy for thermal management. The experimental results show that under the conditions of laboratory temperature 32 °C and pressure of 0.7 Mpa, the temperature of the hot air after passing through the system is 56.4 °C, which is beneficial to the improvement of the heating efficiency of the power battery. The temperature difference inside the battery pack heated by the hot air is relatively large, so the safety requirements inside the battery pack and the design of the airflow channel are relatively high.

(2) Liquid heating

Liquid heating is to heat the battery pack bypassing the heated liquid around the battery through the flow channel. Compared with air, the thermal conductivity of the liquid is higher, so liquid heating will be better than air heating, but liquid heating is very important to the insulation and sealing of the battery box, so when using liquid as

a heat transfer medium, prevent liquid leakage, to fully consider its safety, sealing and insulation, as well as the overall quality of the battery pack. Yuan et al. [62] designed a battery management system with an optimal U-shaped structure of liquid cooling and self-heating plate. The purpose is to control the average temperature of the battery system within the range of 20 °C to 45 °C and control the temperature gradient within 3 °C. It is found that the system can reduce the temperature standard deviation of the heating plate surface to 2.61 °C, indicating that the system can uniformly heat the battery. Li [63] and so on for power battery cannot be recharged in a low-temperature environment, with surface power battery system as the research object, combined with the low-temperature heating and insulation of the power battery needs, construct the liquid-cooled power battery pack low-temperature heating and heat preservation system, the results show that performance of the system low-temperature heating and heat preservation performance is good. Yan et al. [64] designed a thermal management system with heat dissipation and heating liquid directly in contact with the battery. According to the requirements of high-temperature heat dissipation and low-temperature heating of batteries, the simulation analysis of the thermal management system with top parallel "U" flow channel, bottom parallel "U" flow channel, and high and low staggered "U" flow channel is carried out at 3 C discharge rate and low-temperature heating at −30 °C. Its three "U" flow channel structures are shown in Figure 8.

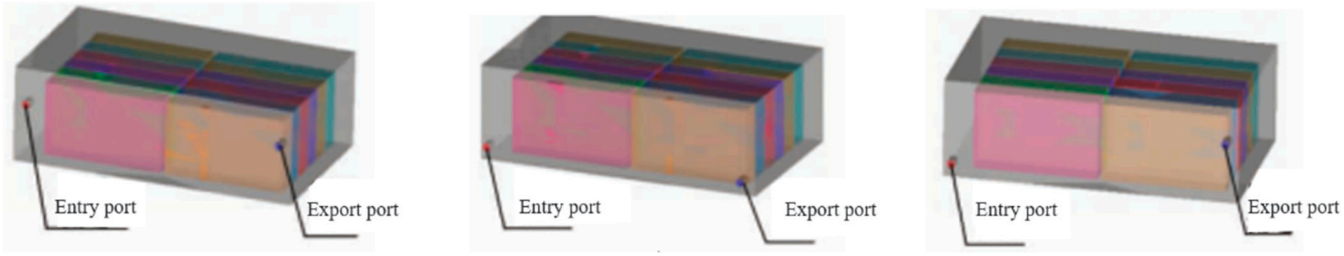


Figure 8. Three "U"-shaped runner structures [64].

The heat dissipation and heating effects are compared, the experimental results show that the bottom parallel U-shaped structure has good low-temperature heating performance but poor heat dissipation performance, and the oil temperature difference in the box after low-temperature heating is 6 °C, and the battery temperature difference is 3 °C, The high and low staggered "U"-shaped structure is relatively balanced in both aspects, and the oil temperature difference of the battery box after low-temperature heating is 12 °C, and the battery temperature difference is 6 °C.

(3) Phase-change material heating

The phase-change material has a strong heat storage capacity. The heating of the phase-change material is to release and absorb heat through the phase-change material during the phase-change process, to realize the heating and heat dissipation of the battery pack. The phase-change material can control the temperature of the battery within at the excellent area value avoids the phenomenon that the temperature of the battery is too high or too low, so the use of phase-change materials can improve the uniformity of the battery temperature. Ling et al. [65] prepared a phase-change material with a phase transition temperature of 28 °C (RT28)/fumed silica composite phase-change material and conducted a comparative study on the thermal and electrochemical properties of the 18650 battery. After 40 charge-discharge cycles tests, the results show that PCM increases the average temperature during full charge-discharge cycles, reducing the loss of battery capacity operating at low temperatures. Zhu et al. [66] studied a thermal management system for electric vehicles based on phase-change materials. The phase-change materials were embedded in cooling pipes, and the flow of coolant was used to realize heat exchange between the battery and phase-change materials. The simulation results showed that the battery heated faster at low temperature and the final temperature could be increased by

at least 11.3 °C. It is beneficial to improve the range of electric vehicles. Huo et al. [67] established a lattice Boltzmann model of thermal management cold temperature of phase-change material batteries and considered the effects of thermal conductivity, latent heat, and ambient temperature. The research results show that under the action of latent heat of phase-change materials, the temperature of the battery drops slowly and the temperature distribution is guaranteed. It is found that once PCM is close to the interface between the battery and PCM, the temperature drops faster and the temperature standard deviation rises sharply. With the increase of latent heat of PCM, the temperature distribution of the battery becomes more uneven, which will reduce the cycle life of the battery. However, low thermal conductivity, high latent heat, and high ambient temperature can slow down the solidification process of PCM and keep the temperature of the battery. The schematic diagram of the thermal battery management structure using phase-change materials is shown in Figure 9.

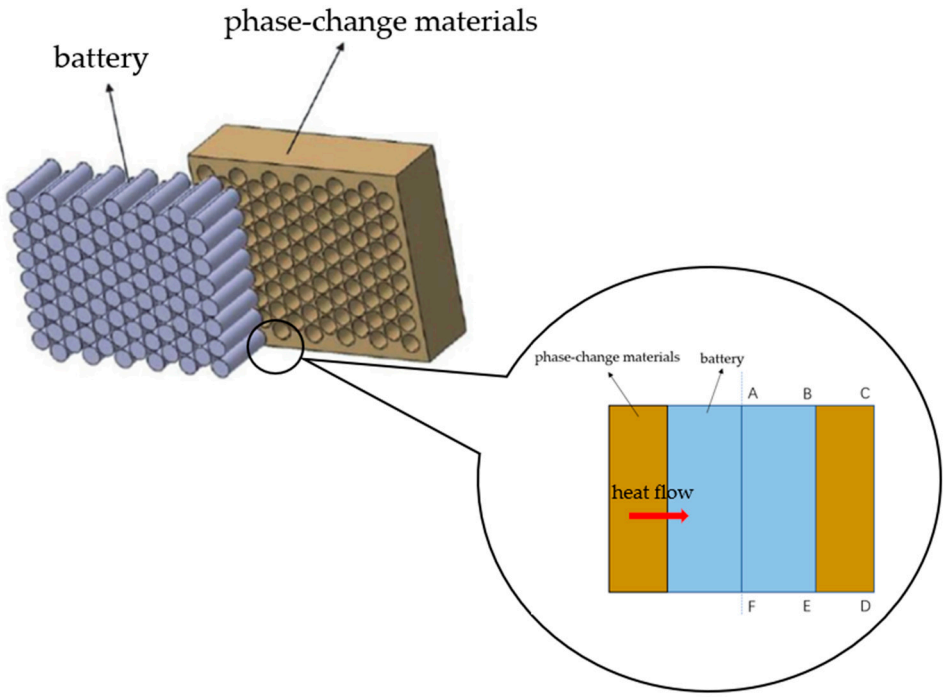


Figure 9. Schematic diagram of the thermal management structure of the battery using phase-change materials.

Ghadbeigi et al. [68] studied the performance of pure paraffin and paraffin graphite composite phase-change materials and modules without phase-change materials in the low-temperature environment of high-power lithium-ion batteries. After experimental tests, a comparative analysis was conducted, and the results showed that after 10 min cold soaking, modules containing PCM had smaller advantages than modules without PCM. After a long time of cold soaking, pure paraffin loses more energy in battery heating than the paraffin-free group. Compared with commercial PCM or modules without PCM, the heating rate of paraffin PCM is 29% slower, resulting in significant energy loss.

(4) Electric heating element heating

Electric heating element heating can be divided into metal heating elements and non-metal heating elements according to different materials. In the power battery heating system, metal heating elements are mainly represented by electric heating films, and non-metal heating elements are mainly represented by PTC ceramic heating elements. The electric heating film can be made of metal foil and insulating material and alloy wire and insulating material in two ways, it has the advantages of lightweight, thin thickness, good flexibility, rapid and uniform heating after electricity, large heating area, fast temperature

rise, good temperature consistency during heating in the battery box. [69] Figure 10 shows the electric heating film.



Figure 10. Electric heating film.

The PTC heater is composed of PTC ceramic heating element and aluminum tube, with a low thermal resistance of the heating body, heat exchange efficiency up to 99%, good safety, no overheating phenomenon under any application. Liu [70] and others established a low-temperature heating model for power batteries and compared and analyzed the PTC heater method and the electric heating membrane method. The low-temperature heating, dry burning, battery heat dissipation, and battery insulation experiments were carried out through the power battery. The results show that the electric heating film heating scheme is significantly better than the PTC heating scheme for the low-temperature effect, will not affect the heat dissipation of the battery module, and has good thermal insulation performance. Wu et al. [71] attached the electric heating film to the surface of the cell to improve the preheating efficiency of the power battery. The research results show that by pasting the electric heating film on the two sides of the battery, the battery temperature can be heated from −15 °C to 5 °C in 408 s, which is beneficial to shorten the preheating time and improve the temperature uniformity. Zhang [72] and others studied the low-temperature heating simulation model of battery module with electric heating film as an external heat source, using polyimide electric heating film as the heating element, and using finite element method to simulate different heating film layout schemes. The heating effect in the process of heating the battery pack from −20 °C to an average temperature of 10 °C is simulated and analyzed. The simulation results show that when the heating film is arranged on the side and bottom of the battery pack at the same time, the temperature uniformity between cells can be maintained within 0.5 °C, the maximum temperature difference will also decrease with the increase of heating power, which improves the uniformity of battery temperature distribution. Cao [73] took advantage of the working characteristics of PTC and further improved the heating effect of PTC by improving the electrical circuit design of the power supply system and optimizing the control and control method the average heating temperature rise reached more than 0.4 °C/min and reduced the heating time of the power battery.

(5) Peltier effect heating

The Peltier effect means that when current flows through two different conductor interfaces, heat will be absorbed from the outside or released to the outside, therefore, using this principle, the purpose of heating and cooling is achieved by changing the direction of the current, while the temperature can be controlled by controlling the current amplitude. Troxler et al. [74] used Peltier elements to heat lithium batteries under isotherm and non-isotherm conditions. By controlling the temperature gradient of a single battery,

the maximum temperature difference between the entire battery was controlled at 40 °C. Figure 11 is a schematic diagram of the Parr element.

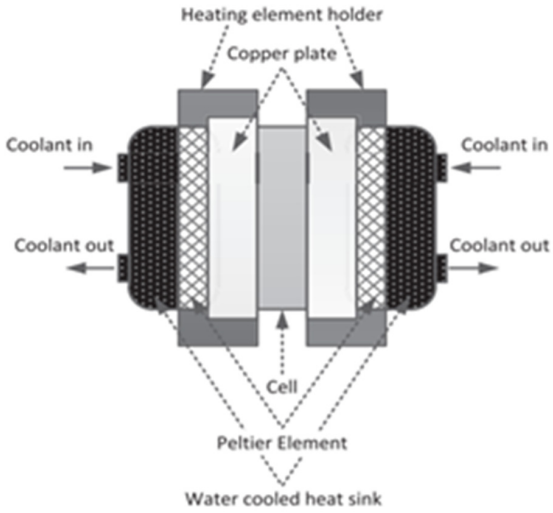


Figure 11. Schematic diagram of Parr element [74]. Reproduced from reference [74] with permission from Elsevier B.V., copyright 2014.

Alaui et al. [18] applied the Peltier effect to the thermal management system of electric vehicles. The experiment found that the maximum temperature in the heating mode was 52 °C, the lowest temperature in the cooling mode was 9.5 °C, and the initial temperature was 17 °C, after heating for 20 min, the temperature difference between the cells was 8 °C, indicating the feasibility of this technology. The advantages, shortcoming, and temperature differences of the five external heating systems are shown in Table 3.

Table 3. Features of five external heating systems.

Serial Number	External Heating	Advantage	Shortcoming	ΔT/°C
1	Hot air heating	Simple structure, low cost, and easy control	Large space and low heating efficiency	≤5
2	Liquid heating	High heating efficiency and good cell uniformity	High tightness requirements and high costs	≤5
3	Phase-change material heating	Simple structure, small footprint, low energy consumption, good battery temperature uniformity	Relatively immature process, high thermal conductivity, and high cost	≤5
4	Electric heating element heating	Simple structure, small footprint, and high heating efficiency	Less secure	≤5
5	Peltier effect heating	High heating efficiency and high battery temperature control accuracy	High cost, complex structure, and immature process	≤8

4. Coupling System

The coupled thermal management system is to combines two or more thermal management system methods according to their different advantages, to achieve higher thermal performance than the original thermal management system. At present, most of the coupled thermal management system is based on phase-change materials and other forms of coupling, so it can be divided into air coupled with phase-change material, air, and

other way couplings, coupling of liquid and the phase-change material, liquid and other way couplings, coupling of heat pipe with phase-change materials, heat pipe with other coupling, and coupling phase-change material coupled with other.

4.1. Coupling with Air

(1) Air coupled with phase-change material

The air-cooled heat dissipation system has the advantages of low cost and simple structure, but its heat dissipation is low, so many researchers focus on coupling it with other heat dissipation methods to realize comprehensive heat dissipation to improve this defect, at present, forced convection is usually used to dissipate the battery for secondary heat dissipation, which significantly improves the temperature uniformity of the battery [75–78]. Qin et al. [79] studied a new type of battery thermal management system coupled with forced air convection and phase-change materials, and analyzed the maximum temperature and maximum temperature difference of the battery in forced convection mode and convection mode through experiments, and found that the charge-discharge rate is greater than or equal to 3 C, the maximum temperature of the battery in forced convection mode can be controlled below 50 °C, while natural convection cannot, and the maximum temperature difference is also better than that in natural convection mode. Yang et al. [80] proposed a battery thermal management system for coupled cooling of air and phase-change materials, through the electrochemical model for natural convection and natural convection coupled with phase change material and the forced convection coupled with phase-change material has carried on the contrast experiment analysis, the experimental results show that in 1 c under the condition of charge and discharge rate, the latter two couplings are superior to the natural convection cooling way when the charge and discharge rates continue to increase, the forced air convection coupled with PCM cooling is better than the natural convection coupled with PCM cooling, and the forced air convection coupled with PCM thermal management system can prevent heat accumulation, which is beneficial to improve the temperature stability of the battery pack. Lv et al. [81] studied a serpentine phase-change material (S-CPCM) to replace the traditional composite phase-change material (CPCM) and compared the battery module using S-CPCM and the battery module using CPCM under the premise of forced air convection. It is found that the maximum temperature of the latter decreases slightly, while that of the former decreases greatly, which demonstrates the feasibility of using the snake-like phase-change material in battery thermal management. Figure 12 shows the battery pack using serpentine phase-change material and its serpentine phase-change material.

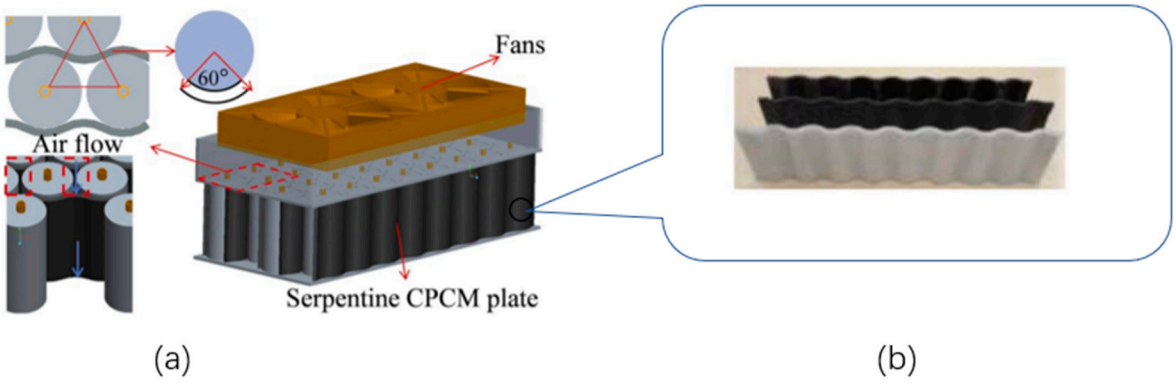


Figure 12. Schematic diagram of the structure of the serpentine phase-change material battery pack, (**a**) the arrangement of the serpentine phase change material in the battery pack, (**b**) the serpentine phase-change material [81]. Reproduced from reference [81] with permission from Elsevier B.V., copyright 2020.

(2) Air and other way couplings

Li et al. [82] studied an air-cooled heat dissipation system using double silicon oxide combined with copper mesh and forced air convection coupling. Through experimental comparison and analysis, the optimal parameters were obtained. The results showed that under optimal conditions, forced air convection was used, the charge-discharge rate is 5 C, the temperature of a single battery using a copper mesh combined with a 1.5 mm double silica cooling plate is 45.55 °C, and the maximum temperature difference is 0.86 °C, in a battery pack composed of five single cells, the average temperature is 49.76 °C, the maximum temperature difference is 0.53 °C. Luo et al. [83] studied a bag battery thermal management system based on the coupling of sulfur dioxide cooling plate-aluminate hot plate and forced air convection. By comparing the traditional battery module, the battery module containing SCP-ATP and the SCP-ATP battery module containing 0%, 30%, and 50% acetone respectively under natural air convection and forced air convection, the experimental results show that the bag battery module containing SCP-ATP with acetone is better than the first two kinds of heat dissipation and temperature uniformity. And when coupled with forced air convection, the effect is better when filled with 50% acetone.

4.2. Coupling with Liquid

(1) Coupling of liquid and phase-change material

The liquid cooling system of the battery pack can achieve an excellent cooling effect, while the phase-change material for heat dissipation can make the temperature distribution of the battery pack more uniform. Therefore, the coupling of the two has become a hot research topic in recent years [84–86]. Rao et al. [87] studied the battery thermal management system coupled with phase-change materials and microchannels. By establishing a three-dimensional battery thermal model, the liquid mass and flow rate, the number of microchannels, the phase-change temperature, and the thermal conductivity of the phase-change material were simulated and analyzed and determine the value of each parameter. The results show that the maximum temperature of the battery module is predicted to be 47.45 °C by the experimental simulation at the optimal value of each parameter. Ping et al. [88] to make up for the current power source, such as setting up a uniform heat source mainly through to implementation and given the prismatic shape of the structure of the battery module is rarely used in the liquid pipe defect of the non-uniform heating model is studied, and the design of the phase- change material/liquid pipe coupling of battery thermal management system, and join the ethylene glycol in the phase-change materials to improve the thermal conductivity, The results show that the coupling thermal management system has good heat dissipation performance at 45 °C, and the maximum temperature and temperature difference of the battery pack is controlled at 47 °C and 4.5 °C. The coupling model of the phase-change material and the liquid tube is shown in Figure 13.

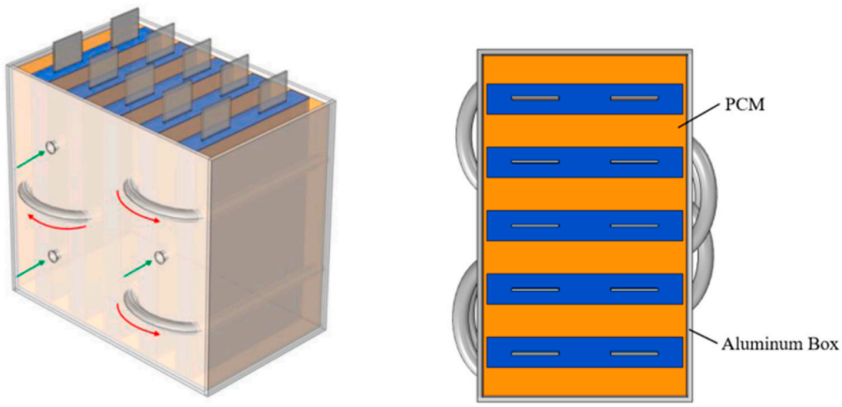


Figure 13. Coupling of phase-change material with liquid tube [88]. Reproduced from reference [88] with permission from Elsevier B.V., copyright 2021.

Kong et al. [89] proposed a novel coupled thermal management system of phase-change materials and liquid, in which liquid cooling can timely recover latent heat of phase-change materials in the charging process. The coupled thermal management system was simulated under 3 C and 0.5 C charging cycles. The results show that the thermal performance of the coupled thermal management system is good when the ambient temperature is 30 °C, and the maximum temperature and temperature difference of the battery pack is controlled at 41 °C and 4 °C. At the same time, the liquid cooling control strategy is optimized, that is, the temperature of the phase-change material PCM area, which is easy to accumulate heat and has the worst heat dissipation, is used as the control index of the cooling liquid speed of the liquid cooling system, and the temperature of the cooling liquid inlet is adjusted in time according to the change of the ambient temperature, which improves the temperature uniformity of battery pack and the utilization rate of latent heat of PCM. Liu et al. [90] studied a heat dissipation system coupled with liquid cooling of a composite phase-change material of paraffin/expanded graphite/high-density ethylene/nanosilver. By changing the connection between the hose and the copper tube, formed the different composite phase-change materials and the coupling of the surface cooling schemes, the experiment results show that 6 kinds of solution heat dissipation effect are best, the minimum-maximum temperature difference, and in the 3 C discharge, At the charging rate of 1 C, the influence of the flow rate and temperature of cold water on the heat dissipation effect of the battery pack was studied when the flow rate and temperature of cold water were 36 L/min and 17 °C respectively. Combined with scheme 6, it was found that the maximum temperature of the battery pack was only 44.5 °C, and the maximum temperature difference was less than 5 °C. Figure 14 shows the battery pack without the hose installed, the liquid flow scheme after the hose is installed, and the liquid flow scheme model of the battery pack.

Liu et al. [91] studied a battery thermal management system based on phase-change material/copper foam coupled with a spiral liquid channel. By studying the helical pitch, helical diameter, number of pipes, inlet fluid velocity, foam porosity, pore density, and a melting point of phase change materials of the helical channel. Considering the battery temperature, pumping power cost, and liquid fraction, it can be concluded that 40 mm screw pitch is the best choice, the larger the screw diameter is, the more pipes there are, the higher the battery temperature will be. The battery temperature will decrease with the increase of flow rate. When the flow rate is greater than 0.05 m/s, the flow rate does not affect the temperature of the battery. By controlling the difference of a variable between porosity and pore density, it is found that the optimal porosity is 0.92, the larger the density of the pores is, the larger the interface surface area is. The thermal performance of the battery is always affected by the melting point of the phase-change material, the lower the melting point is, the greater the utilization rate of latent heat is.

(2) Liquid and other way couplings

To solve the problems that the battery may leak liquid after a rigid collision and the battery module is easily damaged when the battery is overheated and overcharged, xu et al. [92] studied and designed a new battery cooling system with a composite silicone plate coupled with a cooling pipe. Through the new composite silica gel plate/forced air convection coupling with the silica gel plate and liquid cooling coupling, the discharge rate at 4 C is compared. The results show that the composite silica gel plate/liquid cooling coupling can control the highest temperature of the battery pack within 45 °C, and the maximum temperature difference is controlled within 3 °C. The coupling system greatly improves the safety of the battery and also improves the heat dissipation efficiency because the copper tube inserted into the new composite silicone plate does not need to pass directly through the interior of the battery module to obtain well-mixed cooling. Xu et al. [93] studied the multistage heat dissipation system coupled with flat heat pipe and liquid cooling, innovatively applied the multistage cooler to the battery pack thermal management system, and studied the regularity between the uniformity of battery temperature and cooler layout and cooling power through simulation analysis. The research results show

that, when the cooler is placed in the flat heat pipe where the module is located, the temperature uniformity of the battery pack is improved, and it is found that adding the cooler can improve the heat dissipation efficiency of the system. When the cooler is placed in different temperature regions, the temperature difference can be kept within 2.5 °C, and the temperature rise can be controlled within 9 °C.

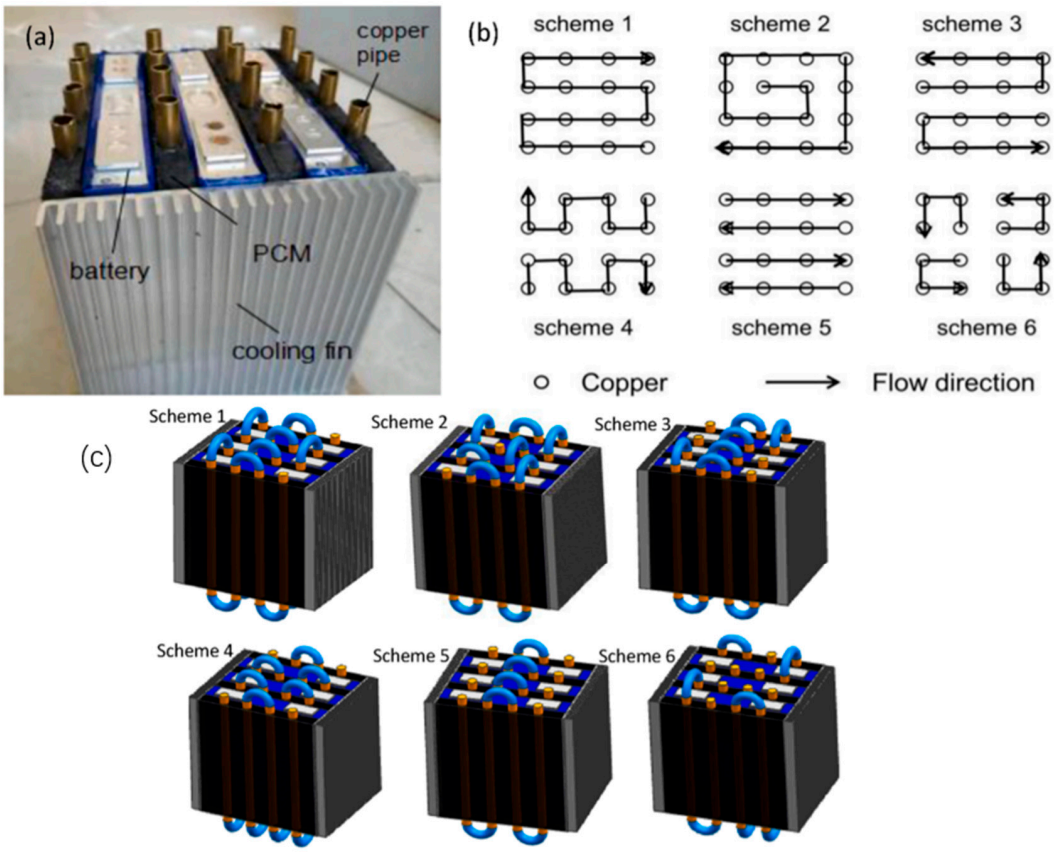


Figure 14. Deformation material and liquid coupling heat dissipation system, (**a**) is the battery pack without the hose installed, (**b**) is the liquid flow direction after the hose is installed, (**c**) is the liquid flow direction model of the battery pack in different schemes [90]. Reproduced from reference [90] with permission from Elsevier B.V., copyright 2021.

4.3. Coupling with Heat Pipe

(1) Coupling of heat pipe with phase-change material

The heat pipe is a heat transfer element with high thermal conductivity and good environmental adaptability. Coupling with the phase-change material can greatly improve its heat dissipation [94–96]. Zhao [97] studied a thermal management system based on the coupling of phase-change materials and heat pipes and conducted experiments on the temperature rise, maximum temperature difference, and overall temperature uniformity of the battery module. The results show that the temperature rise and temperature uniformity of the thermal management system is improved, and the maximum temperature is controlled within 50 °C. Compared with filling the phase-change material in the battery module, this coupling method can further reduce the maximum temperature difference by 28.9%. Wang [98] et al. to further reduce the battery temperature, improve the thermal performance of the battery system, design a kind of based on phase-change materials/the coupling of the oscillating heat pipe battery cooling system, it was found that phase-change materials thermal management system on the cooling of heat pipe coupling oscillation pipe is better than the battery thermal management system, and increase to 50 °C the former significantly longer than those used in the long, to evenly distribute the temperature of the

battery module, the battery replacement terminal should be far away from the adiabatic part. The battery thermal management system coupled with heat pipe and phase change material is shown in Figure 15.

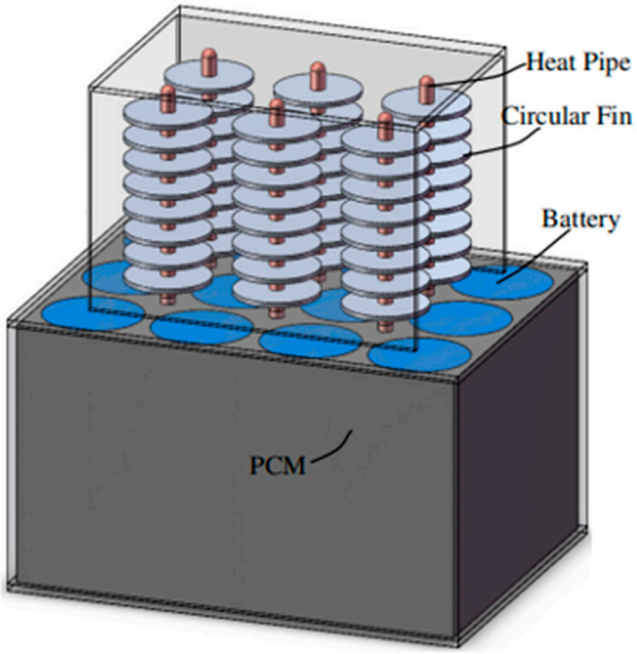


Figure 15. Thermal management model of battery coupled with heat pipe and phase change material [97]. Reproduced from reference [97] with permission from Elsevier B.V., copyright 2017.

Zhao et al. [99] In order to improve the thermal performance of latent heat energy storage system and heat pipe system, combined with the advantages of phase-change materials and the oscillating heat pipe respectively, oscillating heat pipe is studied and the relative material coupling thermal management system, the preparation and tests the paraffin/expanded graphite composite phase-change materials and the closed-loop oscillating heat pipe coupling thermal performance under different working conditions, the experimental results show that, when the power is constant, the closed-loop oscillating heat pipe oscillation frequency with the increase of angle, and the thermal resistance is affected by the installation angle is large, found that the phase-change materials to melt before using closed-loop oscillating heat pipe with paraffin/expanded graphite composite phase-change materials coupled battery module temperature changing trend is far less than the closed-loop oscillating heat pipe and the coupling of the paraffin battery module. Qu et al. [100] studied the thermal management system coupled with phase-change materials and three-dimensional oscillatory heat pipes (four-layer three-dimensional oscillatory heat pipe and three-layer three-dimensional oscillatory heat pipe), and phase-change materials and two-dimensional oscillatory heat pipes (four-layer oscillatory heat pipe and three-layer oscillatory heat pipe) the cooling performance of the coupled thermal management system under different operating conditions. The experimental results show that the cooling performance of the paraffin/3D oscillating heat pipe coupled thermal management system is significantly better than that of the paraffin/oscillating heat pipe coupled thermal management system, which proved that three-dimensional oscillating heat pipe can enhance the thermal performance of battery management module. The multi-dimensional oscillatory heat pipe type diagram is shown in Figure 16.

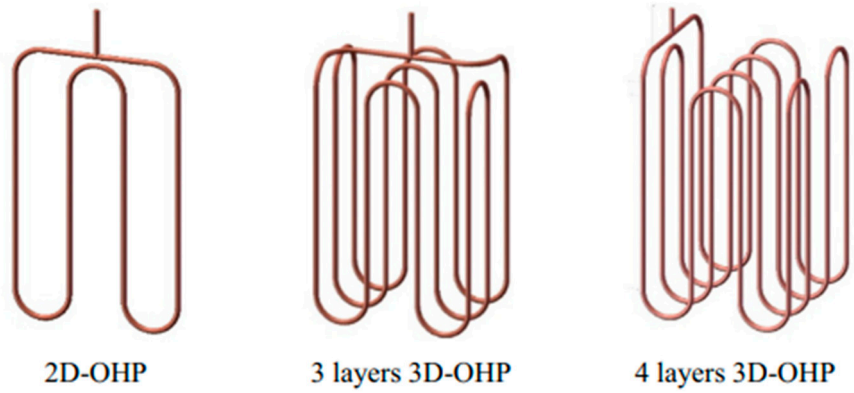


Figure 16. Multi-dimensional oscillatory heat pipe [100]. Reproduced from reference [100] with permission from Elsevier B.V., copyright 2019.

Yuan et al. [101] to solve the battery thermal management system has not been able to meet the needs of lithium-ion battery cooling and heating, the research designs a thermal management system based on paraffin/heat pipe coupling, and through the three-dimensional modeling to determine in lithium-ion battery under different discharge rate of cooling and heating under low-temperature environment, the simulation results show that, as the discharge rate increases, the average temperature inside the battery gradually increases, with the highest temperature between the two ends when cooling the battery. The designed coupled thermal management system can heat the temperature of the battery from −20 °C to 20 °C in a low-temperature environment at about 1500 s.

(2) Heat pipe with other couplings

Jin et al. [102] combined the good cooling efficiency of liquid cooling and the good uniformity of phase-change material cooling and developed a three-dimensional battery thermal management system coupled with a composite plate and a heat pipe. To determine the optimal strategy, the pipes with the same area are arranged horizontally and vertically, and the experiment was carried out. The finite element method was used to simulate. It was found that the combination of the vertical arrangement and the horizontal arrangement of the pipes was more cooling-efficient than the single arrangement of the pipes. When the charge/discharge rate was 3 C and the pipeline arrangement was the best combination, the maximum temperature of the battery was 25.7 °C, and the temperature difference was 3.29 °C, which also showed that the contact area between the battery and the battery pack case had a great influence on the cooling performance of the battery. Yuan et al. [103] proposed a battery management system coupled with liquid cooling and heat pipe. The coupling system was a battery liquid cooling structure composed of a cold plate and heat pipe, and the condensation section did not directly contact the cooling medium. The cooling performance of the structure was optimized to study the influence of coolant flow rate, inlet liquid temperature, and battery discharge point rate. The experimental results showed that the longer the length of the evaporation part and condensation part, the better the cooling effect of cold plate-heat pipe structure; the faster the coolant flow rate is, the slower the maximum temperature drops. The maximum temperature and temperature difference of the battery increased with the increase of discharge rate. At 2 C discharge rate, the maximum temperature and temperature difference of the battery were controlled at 34.1 °C and 1 °C. Behi [104] studied a battery thermal management system based on the coupling of air and heat pipes. At room temperature of 22 °C and a discharge rate of 8 C, experiments were carried out on whether the lithium titanate battery was cooled by a heat pipe. The experimental results showed that the maximum temperature of the battery without heat pipe under natural convection reached 56 °C, and the maximum temperature of the battery with heat pipe under natural convection was 46.3 °C. The heat pipe has high thermal conductivity, and the thermal management system coupled with the heat pipe

can not only reduce the temperature of the battery but also improve the uniformity of the temperature of the battery pack.

4.4. Coupling Phase Change Material Coupled with Other

In addition to coupling with the above-mentioned methods, phase-change materials are also coupled with phase change materials, thermoelectric elements, etc., and also show good thermal properties. Zhong et al. [105] studied a thermal management system based on PCM/resistance wire coupling given the difficulties in controlling battery modules in composite PCM thermal management systems and the problems of thermal saturation in the charging and discharging process of batteries. And the heat sink is used in the coupled thermal management system to alleviate the thermal saturation problem. It is found that the coupled system discharges at a rate of 5C under the temperature condition of 45 °C, and the maximum temperature of the battery can still be controlled below 45 °C, and the temperature difference is not more than 5 °C, compared with the pure resistance wire system, although the energy consumption of the coupling system is slightly increased, the preheating rate is faster, so the battery can be preheated quickly. Cao et al. [106] studied a new cooling system coupled with composite phase-change material and nano-phase-change material emulsion. The thermal behavior of the water/composite phase-change material coupling system and the nano-phase-change material emulsion/composite phase-change material coupling system were compared under the same conditions, and it was found that the latter was better than the former in terms of cooling. To improve the energy efficiency of the composite phase-change material and reduce the power consumption of the liquid cooling system, a delayed cooling strategy was proposed. The experimental results show that, with the support of this strategy, after several continuous charge-discharge cycles, the maximum temperature of the battery is controlled within 48 °C, and the maximum temperature difference is controlled within 4 °C. Its conceptual diagram is shown in Figure 17.

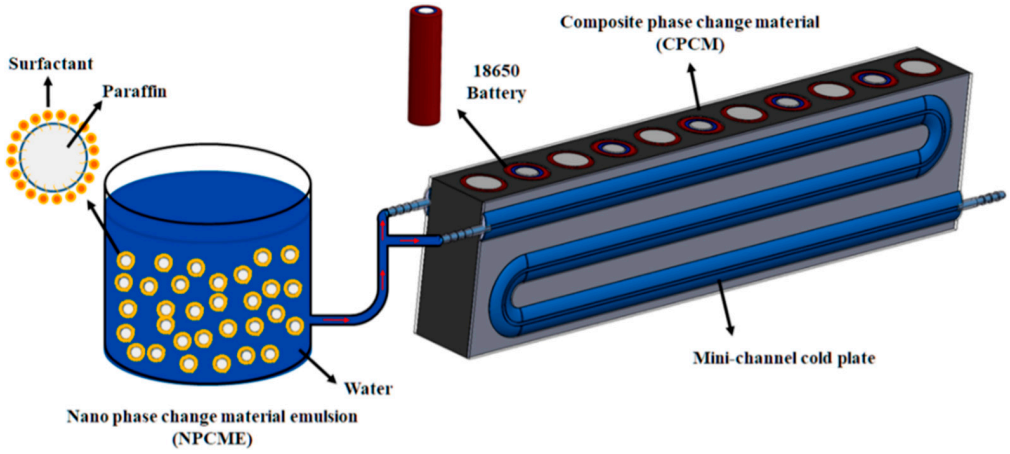


Figure 17. Conceptual diagram of coupling between phase-change material and nanophase-change material emulsion [106]. Reproduced from reference [106] with permission from Elsevier B.V., copyright 2021.

To solve the problems of overly complex structure and poor heat transfer coefficient between the phase-change material and the air surface due to preventing the leakage of the phase-change material, Lv et al. [107] studied a novel thermal management system based on expanded graphite, paraffin, and low-density polyethylene composite phase-change material coupled with low fins. The coupling system has better strength and hardness and simplifies the traditional leakproof structure. Experimental results show that the maximum temperature and temperature difference of the battery can be controlled within 50 °C and 5 °C at the discharge rate of 3.5 C. He et al. [108] studied a thermal management heating module based on the coupling of a thermal fin and a phase-change material and compared

the heating and cooling processes of the air/thermal fin coupled battery module and the phase-change material/thermal fin battery module respectively. It is found that when the hot sheet surface temperature is 50 °C, it takes 10 min for the former to heat the temperature from −15.75 °C to 11.07 °C, but it takes 34 min for the latter to heat the battery temperature from −15.58 °C to 10.9 °C because the phase-change material absorbs a lot of latent heat during the heating process. After stopping hot sheet heating, it was found that it takes 44 min for the temperature of the former to drop from 10.89 °C to −15.01 °C, while it takes 60 min for the temperature of the latter to drop from 10.91 °C to −15.05 °C, indicating that the temperature stability of the cell module coupled with phase-change material and hot plate is better than that of the air-hot plate coupling.

5. Conclusions

This paper systematically reviews the research status of power battery cooling methods and heating methods, compares and analyzes the advantages and disadvantages of existing heating methods and heat dissipation methods, the uniformity of temperature, the size of the temperature difference and other aspects, and summarizes the future research and development trends as follows:

(1) The cooling system: The research on air cooling systems focusses on the arrangement, new ventilation forms, air channel structure optimization, etc. However, compared with the other three types, the advantages are not obvious, and there may be relatively little research on it in the future. The mainstream cooling system in the battery thermal management system is still the liquid cooling system, and the research on it is relatively mature, but the weight is great and the heat dissipation effect of the traditional cooling medium is poor, the research on cooling media and lightweight design are mainly inclined in the future. The phase change material cooling system is superior to the former two in terms of temperature balance and energy consumption performance. With its high thermal conductivity and recyclability, it is the main development direction of the power battery cooling system in the future. Secondly, the heat pipe cooling system is currently subject to the difficult control of the heat exchange medium, the contact with the battery surface may be insufficient, and the temperature uniformity is poor. It is in the research stage and has not yet been applied to electric vehicles, but its thermal conductivity is high, the direction of heat flow is reversible and has a Conducive to lightweight design.

(2) The heating system: the internal heating system has a high heating rate and good heating effect, which has been widely concerned by the industry in recent years. Self-heating needs to change the existing battery structure and production process, so its application in automobiles is still far away. However, ac heating and pulse current heating have the advantages of no need to change the battery structure, relatively small layout space and better uniformity control of battery temperature, which is a major research focus at present. The external heating is relatively inferior to internal heating, although the heating rate and heating effect are poor, the safety is high. At present, the most popular heating system in cars is the air heating system and liquid heating system, but the liquid heating system is far better than the air heating system in heating, so the liquid heating system will be the mainstream application of new energy vehicles in the future. Secondly, the PCM heating system has good control over the temperature uniformity of the battery, but its cost is high and the process is not mature, so it is inclined to improve its process and develop a new composite PCM to reduce the cost in the future.

(3) The coupling system is a major research focus in the future. At present, most of the research is on the coupling between phase change materials and other methods, but the coupling between other methods will also be a research focus, which may increase the cooling and heating methods of two or more coupling methods. in recent years, the research on the power battery heating system, especially the coupling heating system, is still relatively small, so it has great development prospects.

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