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Application and Research Progress of Heat Pipe in Thermal Management of Lithium-Ion Battery

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Lithium-ion batteries have the advantages of high energy density, high average output voltage, long service life, and environmental protection, and are widely used in the power system of new energy vehicles. However, during the working process of the battery, the working temperature is too high or too low, which will affect the charging and discharging performance, battery capacity and battery safety. As a result, a battery thermal management system (BTMS) is essential to maintain the proper ambient temperature of the working battery. Thermal management of power batteries is a key technology to ensure maximum battery safety and efficiency. This paper discusses the significance of thermal management technology in the development of new energy vehicles, introduces the main technical means of thermal management of lithium-ion batteries for vehicle, and focuses on the current state of research on the use of various types of heat pipes in lithium-ion batteries. Finally, the use of heat pipes in the thermal control of lithium-ion batteries is promising.

Keywords: Thermal management; Lithium-ion battery; Heat pipe; New energy vehicles

Introduction

Under the dual pressure of energy crisis and environmental pollution, the research and development and promotion of green and environmentally friendly new energy vehicles has become an important direction for the development of the automobile industry, in order to reduce the pressure of oil imports and automobile emissions. In order to cope with the energy crisis, electric vehicles will inevitably develop in the direction of high power, high battery life, and light weight, and the requirements for thermal management systems of automotive power batteries will also become stricter. However, insufficient attention has been paid to battery pack cooling systems and thermal management, and research activities remain limited or insufficient, both in research units and in industry. The cooling system has a certain influence on the actual specific energy of the electric vehicle. During the discharge process, the power battery pack will generate heat. Poor heat dissipation conditions can cause heat build-up and affect battery performance. If the temperature is too high, the side reaction speed of the lithium-ion battery will be accelerated, there will be potential safety hazards, and the battery capacity will be reduced. Typically, for every 15°C increase in the battery temperature, the battery life will be halved. If the temperature is too low, ion diffusion and migration can be restricted, creating dangerous side effects [1-3]. Operating at 40°C, Li-Ion batteries have been shown to last and perform almost identically to room temperature. However, when

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the temperature is higher than 45°C, the life and performance of the battery will be greatly reduced. Ramadass et al. [4] studied the capacity attenuation of an 18650 battery after cycle charge and discharge at various ambient temperatures and found that the battery's rated capacity drops fast as the working temperature rises after many charge discharge cycles. The recommended working temperature for lithium-ion batteries is 20 to 40 °C, with a maximum temperature of 45°C. Researchers normally use 50°C as the highest limit temperature of the battery surface in their battery thermal management system research.

The heat generated by lithium-ion batteries can be attributed to a variety of factors. The Joule heat produced by the internal resistance of the battery when current flows through it and the chemical reaction heat produced by the chemical reaction in the operating process are the two main factors [5]. There is a potential of thermal runaway if the heat generated during the battery's working process is not delivered in a timely manner. This can be caused by mechanical, electrical, or thermal abuse. Mechanical abuse is usually induced by collisions that produce mechanical deformation in some batteries. Extrusion of the battery's internal diaphragm or leakage of flammable electrolyte are both possible outcomes of battery pack deformation [6]. Electrical abuse generally refers to internal short circuit and overcharge/discharge. The current is forcibly injected/discharged into/out of the battery. At this time, the current will generate heat through electrochemical reaction and accelerate, resulting in thermal runaway of the battery [7]. Heat abuse is a term used to describe localized overheating caused by differences in monomer internal resistance and heat dissipation conditions [8]. The battery will deform as a result of mechanical abuse, and the battery will deform as a result of mechanical abuse, resulting in an internal short circuit, or electrical abuse. Thermal abuse of batteries is caused by electrical abuse combined with Joule heat and chemical reaction heat. The thermal runaway chain reaction of a lithium-ion battery is triggered by heat abuse and eventually leads to thermal runaway [9]. Smoke, fire, combustion, and explosion are the most common symptoms of lithium-ion power battery accidents produced by out-of-control heat [10]. The reasons of thermal runaway are summarized in Figure 1.

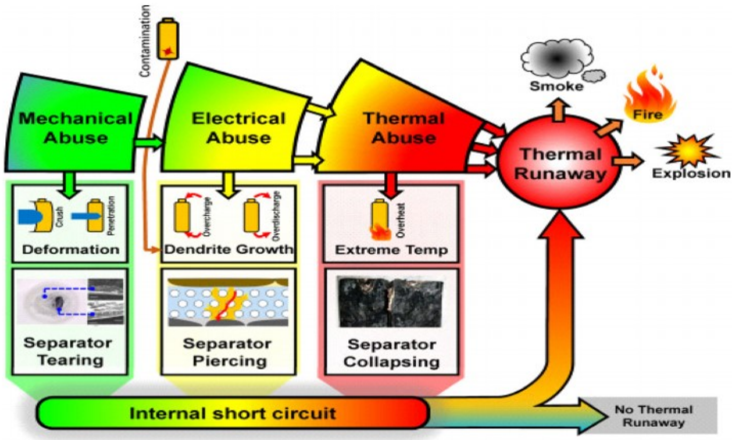


Figure 1. Thermal runaway caused due to rise in battery temperature [11]

Table 1. Electric vehicle accidents in different countries

Date of accident	locale	Accident description	Cause of accident
2014.1	Japan	The power battery pack of Boeing 787 passenger plane caught fire	Thermal runaway caused by short circuit of some battery cells and defects in battery thermal management system.
2015.4	Shenzhen	Wuzhoulong pure electric bus caught fire when charging	When the battery is charged for a long time, the heat of multiple battery boxes is out of control, and the electrolyte leaks, which eventually leads to fire.
2016.1	Norway	Tesla Model s caught fire during fast charging at the super charging station	The charging algorithm has defects and can not detect the faults in the charging process.
2018.5	U.S.A	Tesla caught fire and exploded after collision	External impact
2019.5	Shanghai	Spontaneous combustion during charging of Weilai es8	The impact caused large-area deformation of the power battery pack shell and cooling plate, resulting in short circuit of the battery.
2021.4	Guangzhou	Xiaopeng G3 spontaneous combustion during charging	Thermal runaway during charging caused by collision at the bottom of the battery box.
2021.8	U.S.A	GM bolt EV spontaneous combustion	There are two manufacturing defects in the battery: tearing of the negative pole ear and folding of the diaphragm.

As a result, a cooling system with efficient cooling, effective preheating, and low power consumption is critical for improving electric vehicle performance and alleviating market limitations [13,14].

Common Battery Thermal Management Technology

Air Cooling

Air cooling is the process of using air movement to remove heat from a battery. It is separated into natural convection air cooling and forced convection air cooling depending on the driving mode. Air as a heat exchange fluid to disperse/heat the battery has become the simplest heat management approach, because it is inexpensive and easy to get, does not damage the battery, and has no effect on the electrochemical process inside the battery [15]. It is also the most popular cooling method in the research of battery heat management system [16]. The impact of improving air duct design [17], battery arrangement [18], air intake angle, air flow channel width between battery cells, and other aspects on the thermal management capabilities of the system is now the focus of research on air-cooled thermal management systems.

Zhang et al [19] developed a battery thermal management system (BTMS) based on air cooling. A transient heat transfer model was developed based on the energy equation to compute the temperature distribution of the battery pack in the BTMS. The simulated results matched the experimental results quite well. The widths of parallel channels and divergent/convergent pipes in the BTMS are developed based on the established model, which considerably increases cooling efficiency. Based on systems with varying inlet and outlet positions, Chen et al. [20] built numerous symmetrical flow channel topologies. The symmetrical system outperformed the similar asymmetric system in terms of cooling performance. The system's maximum temperature difference was decreased by at least 43%, and its energy consumption was lowered by at least 33% after the upgrade.

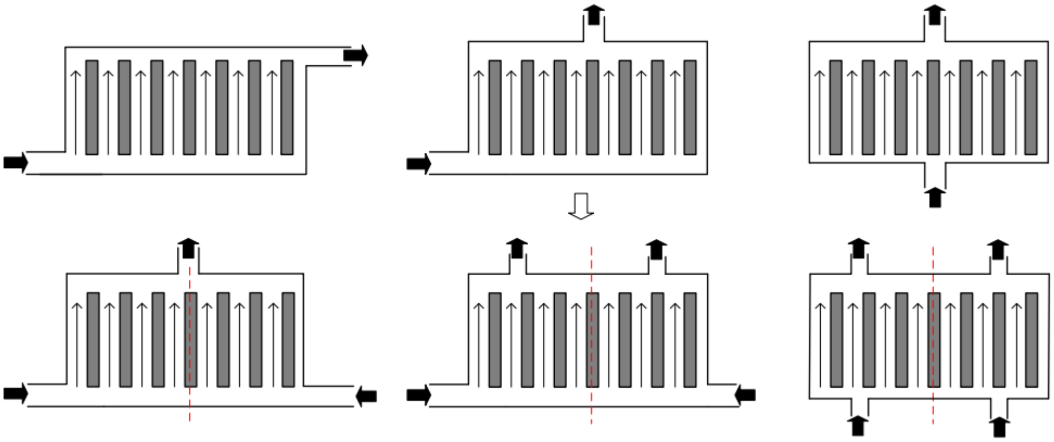


Figure 2. Schematics of the asymmetrical and symmetrical BTMSs [20]

Liquid Cooling

Liquids have a greater specific heat capacity and thermal conductivity than air. Using liquids as heat exchange media to facilitate heat transfer between batteries and the external environment is an important way to improve the efficiency of thermal management systems. Direct contact and indirect contact liquid cooling are the two types of liquid cooling approaches [21]. The direct contact type usually adopts the heat exchange fluid with high heat transfer coefficient and non-conductive, such as mineral oil and ethylene glycol [22]. However, direct contact liquid cooling entails the risk of liquid leakage and requires stringent criteria for cooling medium insulation. In the non-direct contact liquid cooling system, water and antifreeze can be used as heat exchange media, but heat exchange devices such as water jackets must be used, and the liquid cooling system must be designed in conjunction with the battery pack. This results in a loss of heat exchange capacity and skyrocketing system maintenance costs, which is incompatible with the overall lightweight design of the vehicle.

The most common liquid cooling technology is the cold plate. In the cold plate, a flow channel structure is created. The heat dissipation effect is influenced by factors such as the cold plate's positioning, fluid flow velocity, temperature, and pipe configuration. Madani et al. [23] developed a cold plate-based liquid cooling system and investigated the effects of various cooling directions and pipeline distribution on the thermal performance of lithium-ion batteries. The results reveal that when the number of cooling pipes increases from four to ten, the battery's maximum temperature drops and the temperature distribution uniformity improves, but the flow pressure loss increases by 80 %. Mo et al. [24] designed a new cooling plate using topology optimization (TO) method, as shown in Figure 2. The optimized cooling plate is numerically simulated and compared with the traditional linear cooling plate. The results show that at the flow rate of 1.6×10^{-5} m^3/s, the pressure drop and maximum temperature of the optimized cooling plate are reduced by 47.9% and 2.3°C, respectively.

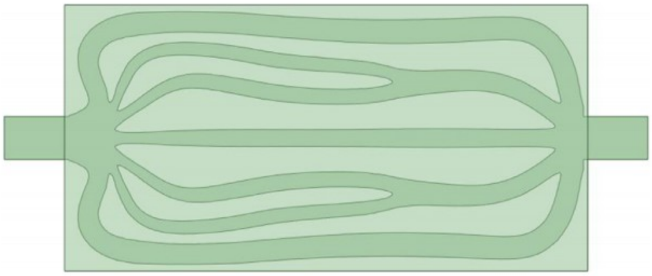


Figure 3. Front view of cooling plate 3D topological structure

Phase Change Material Cooling

Cooling phase change material (PCM) does not waste system energy, but it absorbs or releases a considerable quantity of latent heat during battery pack operation to cool or heat the power battery [25]. Organic, inorganic, and composite phase change materials are the most often used PCM materials. Unlike liquid cooling, which must be paired with a channel construction, phase change cooling immerses the battery module in phase change materials, solving the problem of a small heat transfer interface in the heat dissipation design of cylindrical batteries.

Selman et al. [26] were the first to propose and patent a thermal management system based on phase change materials. They argued that using phase change materials for battery thermal management not only decreases volume but also has a greater heat dissipation effect than using convection heat dissipation. Wang et al. [27] proposed a new type of silica gel combined with PCM for BTMS. The effects of the thickness and thermal conductivity between PCM and silica gel on different cooling systems were studied. The results show that 14 mm thick PCM and 3 mm thick silica gel have the best thermal properties. Compared with the PCM cooling system without silica gel, the maximum temperature of the battery module with silica gel and PCM can be reduced by 24 °C at the 4 discharge rate, indicating that the BTMS can cool the battery well. In order to solve the problem of low thermal conductivity and rapid temperature increase after phase change material (PCM) completely melted, Liu et al. [28] proposed a hybrid system that couples PCM/copper foam composite with helical liquid channel cooling, the results show that the temperature drop of the hybrid system is above zero compared with natural convection. Due to the improvement of heat transfer efficiency between helical channel and PCM, helical tube can obtain lower and better battery performance than traditional liquid tube.

Battery Thermal Management System Based on Heat Pipe

A heat pipe is a high-efficiency heat conduction element that vacuumizes a regular pipe, injects a working liquid, and then seals it. The heat pipe is separated into three sections based on its structure: condensation, insulation, and evaporation. The condensing section converts the working medium in the pipeline from gaseous state to liquid state, and also exchanges heat with the outside world, and transfers the heat in the pipeline to the outside world through the tube wall. The evaporation section exchanges heat with the heat source, receives heat from the heat source through the pipe wall and transmits it to the working medium in the pipe, and simultaneously evaporates the working medium. The adiabatic section serves two purposes: The first is to transfer heat from the evaporation section to the condensation section via a transmission path, which is why it is also known as the transmission section. The second is to provide thermal insulation, which separates the heat source of the evaporation section from the cold source of the condensation section, allowing the heat pipe to be formed into any shape to meet the needs of working conditions. Figure 4 illustrates the heat pipe's functioning concept.

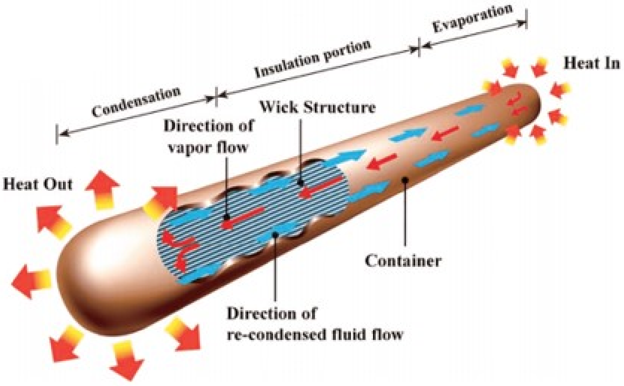
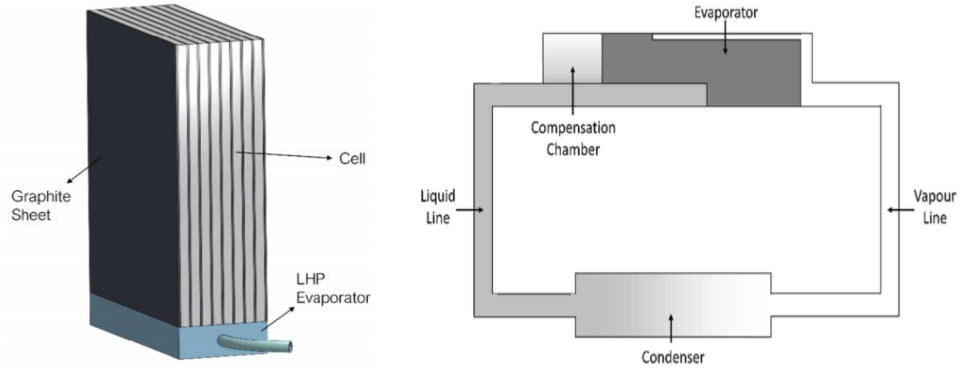


Figure 4. Working principle of heat pipe [29]

Heat pipe cooling was first used in the aerospace industry as a new cooling technology, with impressive results. The heat pipe cooling system for automobile power batteries is currently in the research phase. The thermal diode has good heat flow performance, is reversible, and has a high thermal conductivity [30, 31]. The high thermal conductivity of the heat pipe can quickly export the heat of the battery and realize the separation of sinks and sources at the same time. The excellent isothermal property can flatten the uneven temperature field of the battery, so as to reduce the temperature difference. The reversibility of heat flow direction can realize low-temperature preheating and high-temperature cooling of power battery. The variable heat flux and the performance of thermal diode make the control and management of heat pipe cooling system feasible [32]. Therefore, the introduction of heat pipe cooling technology into the thermal management system of power battery pack has significant advantages, feasibility and application prospects [33, 34]. The inner and outer diameters of the heat pipe, the heat pipe material, the length of each section of the heat pipe, the thermophysical parameters of the working fluid, and the liquid filling rate are all elements that affect heat transfer performance. There are currently just a few studies on the use of heat pipes as a heat dissipation method in the thermal management of electric vehicle power batteries, and the majority of the findings are still in the laboratory research stage. Scholars in the United States and overseas have conducted extensive research on the use of heat pipes in power batteries. The heat pipes used in the research mainly include gravity heat pipe [35], pulsating heat pipe, and flat plate heat pipe [36, 37].

Scholars from various countries have carried out experimental verification and simulation analysis on the application of heat pipe in power vehicle. Hussam et al. [38] investigated the heat generation and cooling of a 16-cell battery module using two distinct heat mat flat heat pipe BTMS layouts. Both structures are capable of successfully absorbing the heat generated by the battery and maintaining its temperature within the appropriate operating range. The maximum temperature difference between the battery and the heat pipe in the horizontal configuration is 6°C, and the maximum temperature difference between the battery and the heat pipe in the vertical configuration is 2°C.

Bernagozzi *et al.* [39] proposed the BTMS 3-cell battery module, which is made up of a flat ring heat pipe and graphite sheet. The loop heat pipe is placed at the module's bottom and can effectively transfer up to 150 W of heat from the battery module to the remote heat exchanger linked to the vehicle's HVAC refrigerator. Indoor experiments are used to validate the model. The results reveal that the system satisfies the battery's heat dissipation requirements. During quick charging, the highest temperature is 31.5°C, and the temperature distribution of the battery layer during an ambient temperature test is 2°C. This novel design reduces the maximum temperature after quick charging by 3.6°C when compared to the standard liquid cooling plate BTMS.



(a) (b)

Figure 5. (a) Schematic diagram of coupling loop heat pipe and a single battery module. (b) Flat Plate LHP schematic.

Hussein et al. [40] designed BTMS based on heat pipe. As shown in Figure 6, the alternative battery is clamped in L-type and I-type heat pipes. The evaporation section absorbs heat from the surface of aluminum plate, and the condensation section transfers heat to the copper support. Heating was carried out at 30, 40, 50 and 60W, and the condensation section of the heat pipe was cooled with water with mass flow rates of 0.0167, 0.0333 and 0.05 kg/s, respectively. The results show that the designed BTMS based on heat pipe can make the maximum temperature (T_{max}) lower than 55°C even under the maximum input power, and the battery temperature difference (ΔT) below 5°C.

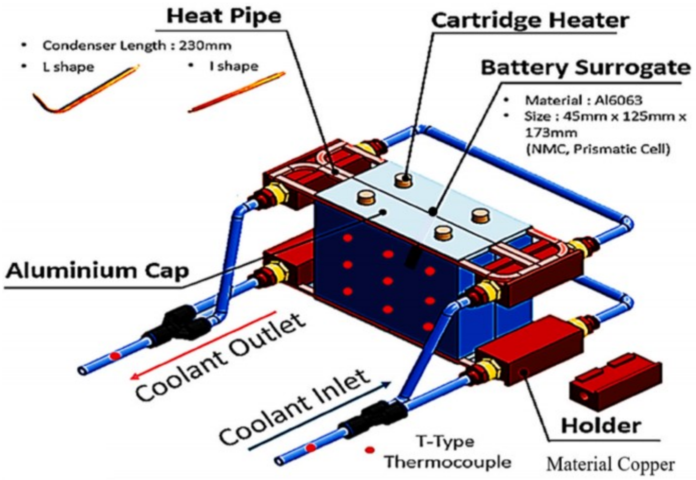


Figure 6. Battery BTMS based on L-shaped/I-shaped heat pipe

Chen and Li [41] applied TiO_2 nanofluid as working fluid in the thermal management system of automotive lithium-ion battery of pulse heat pipe (PHP) and carried out experimental research. The structure of the experimental system is depicted in Figure 7. When the ambient temperature increases, PHP successfully prevents the maximum surface temperature of the lithium battery from increasing. The maximum temperature of the battery must not exceed 42.22°C when the ambient temperature is 35°C and the discharge rate is 1C, and the maximum temperature gradient between batteries must be less than 2°C . The technology may lower the temperature gradient and increase the thermal uniformity of the battery surface at various discharge rates.

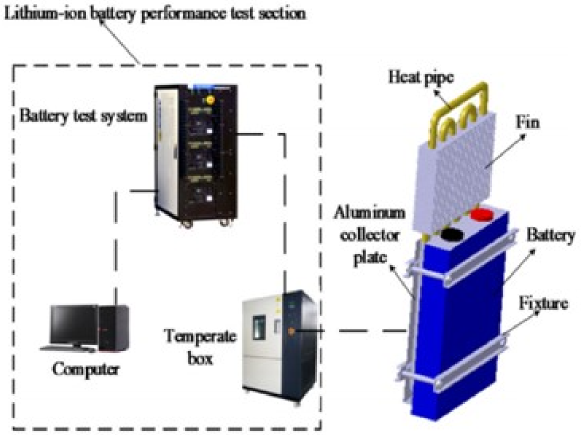


Figure 7. Diagram of the experimental system

Gan *et al.* [42] designed a new thermal management system based on heat pipe for cylindrical battery pack. Figure 8 depicts this BTMS. The connection between the battery and the heat pipe is made with a corrugated aluminum sleeve to maximize the heat exchange area between the heat pipe and the battery. Simultaneously, the effects of coolant flow and the length of the condenser hot pipe on the battery's temperature distribution were investigated. The findings reveal that increasing coolant flow can drastically lower the battery's maximum temperature while having no effect on temperature uniformity. The maximum temperature of the battery pack can be reduced and the temperature uniformity was improved by increasing the length of the heat pipe condensation section and the height of the corrugated aluminum sleeve.

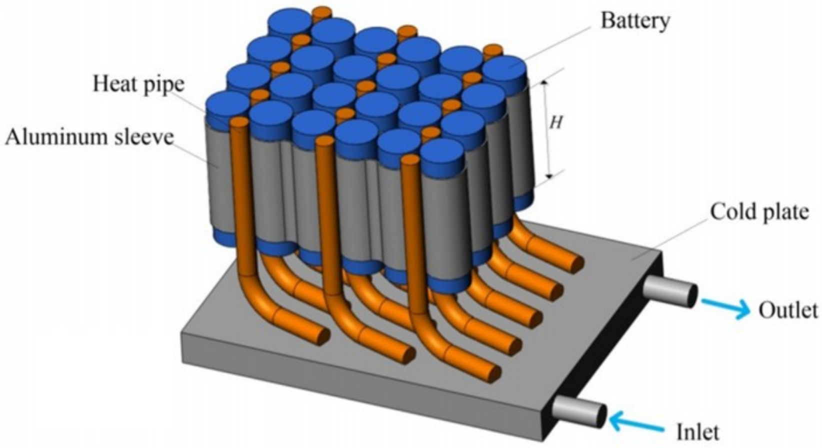


Figure 8 . Geometric model of battery pack and thermal management system

Wei et al. [43] explored the application of plug-in oscillating heat pipe (OHP) flat evaporator in the electric vehicle battery thermal management. The BTMS principle based on oscillating heat pipe is shown in Figure 9. When the volume filling ratio (FRS) is 30%, 40% and 50%, considering the influence of the thermophysical properties of the working fluid on the thermal management system, the binary fluid mixture of pure water, ethanol and their different mixing ratios (MRS) (1:1 to 4:1) are used as the working medium of the heat pipe, respectively. The results show that the cooling effect is better when the ethanol water mixing ratio is 1:1. Under the input power of 56 W, the average temperature of the battery pack can be controlled below 46.5℃. In addition, the temperature uniformity of the battery module is good, and the maximum temperature difference is mostly in the range of 1-2 ℃.

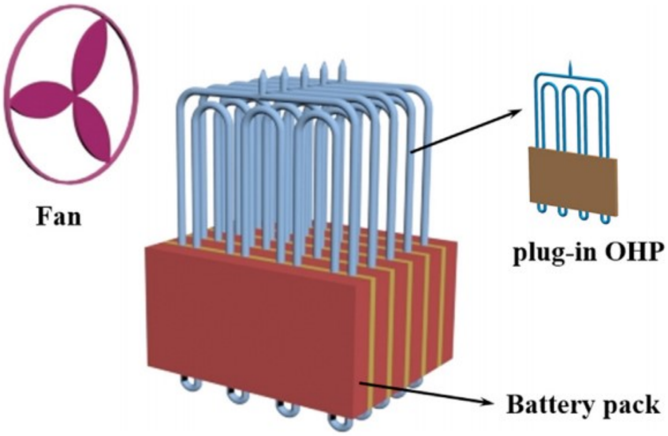


Figure 9. Schematic diagram of BTMS with plug-in OHPs

BTMS with Heat Pipe Coupled with Other Cooling Methods

Dan et al. [44] devised and simulated a micro heat pipe array (MHPA) paired with forced air cooling lithium-ion battery heat management system. The heat pipe is inserted in the midst of each two square cells, the condensation section leaks out, and forced convection heat exchange with the air in the square cavity is carried out, as illustrated in Figure 10. In the transient driving situation, the thermal management system aids in limiting temperature rise and considerably improving temperature uniformity. The new heat pipe will only increase the thermal management system's overall quality by around 6.5 %, but it will significantly improve the battery pack's thermal performance.

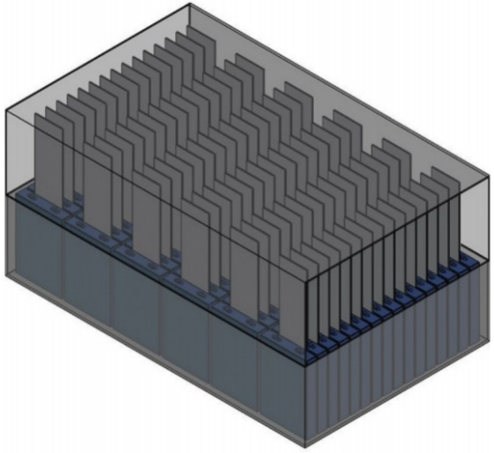


Figure 10. Schematic diagram of the MHPA thermal management system

Chen et al. [45] studied the effect of heat pipe on the temperature distribution in the battery pack by experimental method. The research shows that the PCM heat pipe coupling system has a positive cooling effect on the battery pack, which can basically ensure the operation of the battery in the optimal temperature range. Compared with the pure PCM system, the use of heat pipe can reduce the temperature rise of the battery by 10 °C. Jiang et al. [46] established a lumped heat model considering the coupling of battery heat generation, phase change material melting and heat pipe transient thermal response. The coupling mechanism between battery temperature and phase change process under different ambient temperature, condensation cross-section heat transfer coefficient and thickness ratio of phase change material to battery is revealed. Chen et al. [47] conducted numerical research on the battery thermal management system (BTMS) coupled with phase change material (PCM) and heat pipe (HP). Fig. 11 is the structural diagram of the coupling system. Comparing the BTMS performance of phase change material and heat pipe coupling with that of heat pipe alone, it is found that the coupling system can reduce the temperature difference of battery pack more effectively. Under the condition of ensuring economy, the optimal design of PCM thickness is proposed. After optimization, the maximum temperature difference of battery pack is reduced by about 30%.

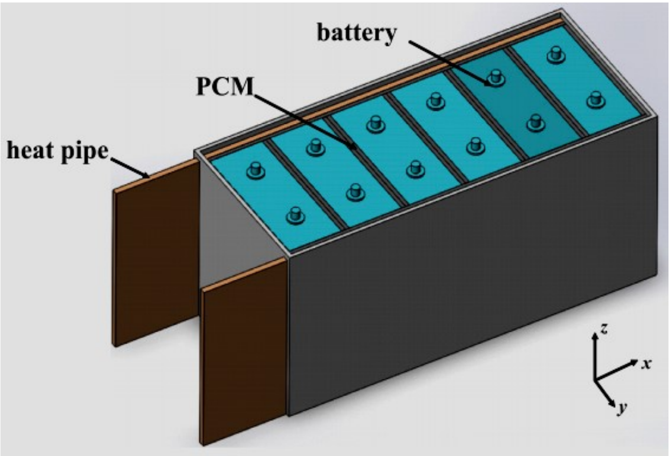


Fig 11. Schematic of the designed BTMS

In addition to the traditional design of heat pipe diameter, length of each section, wick and heat pipe materials, more and more people focus on the working fluid of heat pipe. Nanofluid has good thermal conductivity and phase change characteristics. Adding nano-materials to the base liquid can not only improve the thermal conductivity of the base liquid and reduce the undercooling, but also improve the specific heat capacity and the heat transfer performance of the solution [48]. Shuoman et al. [49] applied alumina nanofluid to thermosyphon, carried out experimental and theoretical research on its thermal properties, and analyzed different methods of using nano materials and their influence on improving the efficiency of BTMS. The results fully confirmed the superiority of nanofluids in improving the performance of heat pipes.

CONCLUSIONS

According to different heat production laws of batteries, different types of heat pipes are selected and designed to meet the needs of battery heat dissipation. The use of a heat pipe in a lithium-ion battery's thermal management system increases the uniformity of temperature distribution and effectively limits the battery's maximum temperature. The heat pipe's working concept and structure are basic, and it's simple to combine with different cooling systems. While increasing the battery's efficiency and safety, it has no effect on the heat management system's overall lightweight design. The battery thermal management system based on heat pipe has emerged as a major study focus for researchers both at home and abroad, yielding numerous scientific findings with application potential.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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