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Application Analysis of Heat Pipe and Liquid Cooled Plate Cooling Structure Based on CFD Simulation in Thermal Management of Automotive Power Batteries

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Abstract. In recent years, the rapid popularization of new energy vehicles worldwide has raised higher requirements for the Battery Thermal Management System (BTMS) of power batteries. In response to the problems of high heat flux density and uneven temperature distribution under complex working conditions, the combined cooling structure of heat pipe and liquid cooling plate has attracted attention due to its ability to combine the temperature control accuracy of the liquid cooling plate with the temperature equalization performance of the heat pipe. The results indicate that the combination of flat heat pipes and liquid-cooled plates has significant advantages in terms of structural simplicity and processing feasibility; The combination of a micro heat pipe array and a liquid-cooled plate exhibits higher temperature uniformity in large-sized modules. The loop heat pipe and liquid-cooled plate maintain stable performance under long-distance heat transfer and attitude changes. In addition, the analysis found that the layout of the heat pipe, the geometry of the liquid cooling plate channel, the operation parameters and the refinement of the heat source model were the key paths to improve the performance. Finally, this paper summarizes the deficiencies of current research in modeling standardization, vehicle-level integration analysis and full life cycle assessment, and puts forward the future development directions of multi-physical field coupling, structural integration and lightweight.

Keywords: New energy vehicles, Power battery, Heat pipe–liquid cooling plate, Thermal management

1. Introduction

New energy vehicles (NEVs) have achieved rapid development worldwide in recent years. Thanks to battery technology progress and policy promotion, the market share of electric vehicles has increased year by year. However, the power battery will generate a large amount of heat in the process of high-rate charge and discharge, extreme temperature environment and long-term operation. If it cannot dissipate heat in a timely and efficient manner, it will lead to an increase of peak temperature (Tmax) and temperature difference (Δ T) [1-4]. Uneven temperature distribution will not only accelerate capacity attenuation but also increase the risk of thermal runaway, posing a threat to vehicle safety [3,5]. Therefore, the establishment of a battery thermal management system

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(BTMS) with high efficiency, low energy consumption, and adaptability to multiple operating conditions has become the core technical demand in the field of new energy vehicles [6,7].

Liquid-cooled plate cooling technology is widely used in the thermal management of new energy vehicle power batteries because of its large heat exchange area and high temperature control accuracy [3,6]. However, the single liquid cooling plate scheme still has some limitations in dealing with local hot spots and achieving uniform temperature control. In contrast, the heat pipe relies on the phase change of working fluid and capillary reflux to achieve efficient passive heat conduction, with excellent temperature uniformity and reliability [8,9]. However, there are deficiencies in heat transfer distance and attitude adaptability. Some types of heat pipes are sensitive to attitude/acceleration, which may make their application in mobile vehicles troublesome [10]. The heat pipe and the liquid cooling plate are structurally coupled, and the efficient performance of the heat pipe in hot spot conduction and uniform temperature is used to achieve the comprehensive goals of peak temperature suppression, temperature difference reduction and pump power optimization [4,10].

Previous studies have shown that the heat pipe liquid cooling plate cooling scheme can significantly reduce Tmax and improve ΔT under high heat flux conditions, especially under high rate discharge and dynamic conditions [1,10]. However, there are still some problems in the current research, such as the large differences in model settings (such as boundary conditions, heat source modeling, physical parameters, etc.), resulting in the lack of comparability between different studies; The lack of research on transient conditions, multi physical field coupling and experimental verification limits the reliability of Engineering promotion [3,7,8].

Based on the systematic review of existing work, this paper classifies and compares the two dimensions of structure type and simulation setting, analyzes the advantages and disadvantages of each scheme combined with the unified performance evaluation index (Tmax, ΔT, pressure drop/pump work), and puts forward suggestions for future optimization and research trends.

2. Structural study

2.1. Foundation of flat heat pipe and liquid cooling plate

The combination of flat heat pipe (FHP) and liquid cooling plate is a hybrid cooling scheme with both uniform temperature and precise temperature control ability in the new energy vehicle battery thermal management system (BTMS).FHP relies on the phase transition of working fluid to achieve high-efficiency surface-to-surface heat conduction, which can quickly diffuse local hot spots on the surface of the battery to the area covered by the liquid cooling plate; The liquid cooling plate then takes away heat through the coolant, thereby reducing the overall temperature and improving the temperature distribution. The following will demonstrate the rationality of the combination of a flat heat pipe and liquid cooling plate.

Pan et al. Used response surface method and genetic algorithm to optimize the structural parameters of the microchannel liquid cooling plate. The results showed that under the same pump power, the optimization scheme could reduce the peak temperature by about 6.84%, and the standard deviation of temperature difference by 62.13%, significantly improving the temperature uniformity [5]. Compared with the traditional liquid cooling plate, the cooling scheme based on loop heat pipe (LHP) can reduce the peak temperature by about 3.3k under high rate charge discharge conditions, and reduce parasitic energy consumption, indicating that the participation of heat pipe can improve the thermal performance under the premise of controlling energy consumption. It can be inferred that under the condition of limited pump power, the coupling of FHP or other heat pipe-based

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schemes and a liquid cooling plate can give consideration to energy efficiency and temperature control performance [10].

Illner et al's experiments show that the equivalent thermal resistance of heat pipe will change significantly with temperature [11]. The lumped model of bernagozzi et al. Also reflects the characteristics of physical driving parameters changing with operating conditions. This kind of method is more helpful to capture the performance changes under actual operating conditions [10].

In conclusion, the coupling scheme of FHP and liquid cooling plate has engineering advantages in structural simplicity and processing feasibility, and can effectively reduce the peak temperature and improve the temperature uniformity under the condition of medium and high heat flux.However, its performance is still limited by the heat pipe layout and modeling accuracy [5-8].

2.2. Micro heat pipe array+liquid cooling plate

Micro heat pipe array (MHPA) is composed of multiple micro heat pipes with a diameter of 1 – 3mm in parallel, which are often embedded in the interface layer between the battery and the liquid cooling plate to enhance the temperature equalization ability in a large area and reduce local hot spots. Compared with a single flat heat pipe, MHPA is more outstanding in terms of coverage, heat dissipation area and temperature uniformity [9].

In the study of Wan et al., the combination of a heat pipe array and a cooling channel can reduce the peak temperature by 41.6 – 60.9% under the condition of constant heating power, and significantly improve the temperature distribution inside the module, especially in the long module and high heat flux scenes [9].

The CFD optimization results of Pan et al. Also show that reasonable layout and structural optimization can reduce Tmax and Δ t without significantly increasing the pump work, providing numerical support for the engineering application of mhpa+liquid cooling plate [5].

Liang et al. Experimentally studied the low-temperature preheating performance of the battery thermal management system (BTMS) using the bent plate micro heat pipe array (fmhpa). The results show that the structure can achieve a heating rate of about 1 ℃/min, and control the temperature difference between the module and the cell level within 5 ℃, showing its potential application in cold climates [2]. In addition, in order to simplify the calculation, Wan et al. Made some idealized assumptions on the steam flow inside the heat pipe (such as incompressibility, laminar flow, and full development), which may affect the prediction accuracy of transient characteristics [9]. Table 1 lists two representative MHPA+liquid cooling plate research cases.

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Table 1. Two representative cases of MHPA+liquid cooling plate [2,9]

Technique	Peak temperature reduction (compared with no system)	Maximum temperature difference	Operating mode
Z-bend mhpa as thermal bridge Dry wet separation (physical isolation of battery and coolant) Integrated heating (PTC) and cooling (liquid cooling plate) Space compact design	Not applicable (mainly studying the low-temperature preheating performance, and the goal is to raise the battery from low temperature to working temperature)	<5℃ (during the preheating process from-20℃ to 0℃, the temperature difference at the cell and module levels shall be controlled within 5℃)	Preheating condition: Ambient temperature:-20 ℃,-10℃, 0℃ Heating power: 360W (PTC) Temperature rise rate: about 1℃/min Cooling condition: Coolant: water (25℃) Flow: 1 l/min
Direct mhpa embedded module integrated with liquid cooling plate Traditional direct contact liquid cooling mainly studies cooling performance Compare with copper bar	41.6%-60.9% (compared with the benchmark case using copper bars, mhpa significantly reduces the peak temperature of the battery	1.7℃-3.9℃ (under the working condition of 40w/cell,the maximum temperature difference is about 1.9℃)	Cooling condition: Coolant inlet temperature: 25℃ Flow: 2 l/min Battery heating power: 20-80 w/cell (focus on 40w/cell)

In general, these two cases represent two important and complementary application directions of MHPA in battery thermal management systems: one is the innovative system design for realizing safe, compact and all-weather (integrated cooling and heating) management; The second is the high-performance heat conducting element used to significantly improve the cooling efficiency and temperature uniformity of the traditional liquid cooling system.

2.3. Loop heat pipe+liquid cooling plate

Loop heat pipe (LHP) uses a capillary core to drive the working fluid circulation, which can realize long-distance and high-efficiency heat transfer without an external pump. Compared with the conventional heat pipe, LHP can still maintain stable thermal conductivity under the condition of attitude change and complex layout, so it is especially suitable for the working conditions of new energy vehicles such as limited structure and vehicle inclined operation.

The research of Bernagozzi et al. Focused on verifying the thermal performance of LHP-BTMs in practical application scenarios. This study proposes an innovative design that combines LHP with a graphite sheet. The LHP is arranged at the bottom of the battery module and is responsible for passively transferring heat to the remote refrigerator (HVAC system cooler) of the vehicle; The graphite sheet with high in-plane thermal conductivity is inserted between the cores to promote the transverse diffusion of heat. At the same time, its low normal thermal conductivity is used to isolate the adjacent cores to a certain extent to improve the temperature uniformity [1].

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Monticelli et al's research pioneered a new path and conducted a comprehensive life cycle assessment (LCA) on LHP-BTMs for the first time, and compared it with the current mainstream active liquid cooling plate system. The study covers the stages of raw material acquisition, manufacturing, use, and scrap [4]. Table 2 lists two examples of LHP studies.

Table 2. Two LHP studies [1,4]

Key techniques	Working Medium	Cooling Capacity	Energy Consumption	Other Features
Lhp+graphite sheet	3M Novec 649(environmental protection working medium)	Support 3C fast charging; 7.9℃ lower than natural convection	Zero parasitic power	The current distribution is improved from 1.05A to 0.05A; the life is doubled from 146 times to 310 times
LHP	ethanol	Better than active cold plate > 3 ℃	Zero parasitic power	Stainless steel can reduce weight and increase mileage

Loop heat pipe (LHP) technology has shown great application prospects in the field of battery thermal management of electric vehicles, which can effectively meet the heat dissipation requirements of high-power fast charging, ensure the safe operation of batteries under all-weather conditions, and significantly extend the battery life.Its passive working characteristics completely eliminate the energy consumption and related carbon emissions in the use phase, and the environmental impact in the whole life cycle is far lower than the current mainstream active cooling scheme.

3. Impact of key design parameters on performance

3.1. Heat pipe size and layout

The size and laying direction of the heat pipe directly affect the heat conduction path and temperature uniformity [2].

The size and internal capillary structure of the heat pipe determine its heat transfer limit. Bernagozzi et al. Listed in detail the geometric parameters of the LHP model, such as evaporator length, inner and outer diameters of steam/liquid pipelines, wick porosity and average pore diameter. These parameters jointly affect the capillary force, flow resistance and heat transfer power of the heat pipe. It is estimated that under the given boundary conditions, the maximum heat transfer capacity of a single heat pipe is between 50-100w, which is the key basis for designing the number of heat pipes required by the system [10].

Illner et al. Compared two laying schemes: one is the vertical arrangement of heat pipes (transverse to the driving direction), and the other is the horizontal arrangement (parallel to the driving direction). The traditional thermosyphon (two-phase thermosyphon) depends on gravity reflux, so it is very sensitive to direction. The LHP selected by bernagozzi et al. And the heat pipe (with wick structure) proposed by Illner et al. Overcome the dependence on gravity, and can be more flexibly applied to the complex and changeable spatial layout of vehicles to achieve "longer distance heat transfer" [10,11].

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3.2. Liquid cooling plate channel geometry

The flow channel layout (such as multi-channel, topology optimized microchannel) and fin structure (pin rib, airfoil rib, etc.) of the liquid cooling plate will directly affect the heat dissipation capacity, temperature uniformity and flow pressure drop. The channel shape not only determines the heat transfer area and velocity distribution of coolant, but also affects the pump power demand and system energy efficiency.

Goswami and Guggari analyzed the performance changes of liquid cooling plate under different flow rate, channel height and fin conditions based on CFD simulation. The results showed that increasing the flow rate could reduce the maximum temperature difference, but it would reduce the heat transfer efficiency and significantly increase the pump work; Increasing the channel height can significantly reduce the low pressure drop, but has little effect on the heat transfer efficiency and temperature difference; The installation of fins can improve the temperature uniformity and heat transfer efficiency at the same time, and has little effect on the pump power [7].

Pan et al. Optimized the geometric parameters of the microchannel liquid cooling plate by response surface methodology and multi-objective optimization (NSGA-II). The results showed that the peak temperature decreased from 40.94 ℃ to 38.14 ℃, the standard deviation of temperature difference decreased from 1.69 to 0.64, and the pressure drop decreased from 295.95pa to 291pa. The temperature control performance and flow performance were improved synchronously without significantly increasing the pump power [5].

Li et al. Found in the topology optimization research that compared with the single outlet design, the two outlet design can reduce the maximum temperature by 2.48k and the average temperature by 1.07k; on this basis, the straight channel topology optimization scheme further reduces the maximum temperature of 0.51 ℃; The pressure drop of the uniform channel structure is reduced by 5.22pa, reflecting the significant impact of channel geometry and outlet layout on temperature control and pressure drop [3]. Table 3 lists three examples of the effect of liquid cooling plate channel geometry on Performance

Table 3. Effect of liquid cooling plate channel geometry on performance [3,5,7]

Method	Channel/Configuration Points	Verifiable Performance Data/Conclusions
CFD	Flow, channel height, fin	Flow ↑ ⇒ ΔTmax ↓, heat exchange efficiency ↓, pump power ↑Channel height ↑ ⇒ pressure drop drops significantlyRibbed plate ⇒ temperature difference and heat exchange efficiency are improved, and pump power changes little
CFD + Multi-objective Optimization	Microchannel LCP (width/depth/inlet/outlet diameter & flow optimization)	Tmax: 40.94℃ → 38.14℃TSD: 1.69 → 0.64ΔP: 295.95Pa → 291Pa
Topology Optimization + Numerical Verification	Two outlet, straight channel, uniform distribution	Two outlets vs. single outlet: Tmax ↓ 2.48K, Tavg ↓ 1.07KStraight channel type: Tmax ↓ 0.51℃Uniform distribution type: ΔP ↓ 5.22Pa

3.3. Coolant flow and inlet temperature

In the study of the heat dissipation performance of the liquid cooling plate, coolant flow and inlet temperature are two key operating parameters affecting the battery thermal management system. Pan

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et al. Found through multi-objective optimization that increasing the coolant mass flow (from 11.29g/s to 35.12g/s) can significantly reduce the maximum temperature of the battery module (Tmax decreased by about 6.84%) and improve the temperature uniformity (TSD decreased by 62.13%), but it also leads to an increase in the system pressure drop, thereby increasing the pump power consumption, indicating that the enhancement of heat dissipation effect is at the cost of energy penalty [5]. Madani et al. Further pointed out that although increasing the flow can effectively reduce Tmax and improve the uniformity of temperature distribution, the increase in flow will linearly increase the pressure drop in the channel, thus significantly increasing the energy demand of the cooling system [6]. Goswami et al. Also emphasized that although increasing the flow can enhance heat transfer and reduce Tmax, it will reduce the heat dissipation efficiency of the cold plate and increase the required cooling power, so it is not the optimal control strategy for energy efficiency [7].

In terms of inlet temperature, Wan's numerical study shows that reducing the coolant inlet temperature (e.g. from 35 ℃ to 15 ℃) can linearly reduce the maximum temperature and average temperature of the battery surface, but the improvement effect on Δ t is limited; In addition, too low inlet temperature is easy to cause condensation risk, which may endanger electrical safety [9]. Madani et al. Also found that the change of inlet temperature has little effect on the temperature uniformity, but it will significantly change the overall temperature level of the battery, so it is necessary to carefully balance the temperature control and condensation risk [6].

4. Conclusion

The combination scheme of flat plate heat pipe, micro heat pipe array, loop heat pipe and liquid cooling plate is suitable for different application scenarios.The structure of the fhp+liquid cooling plate is relatively simple, and the processing feasibility is high. It is the basic scheme to achieve efficient "surface to surface" heat conduction and accurate temperature control.As a basis, it can effectively reduce the peak temperature of the battery and significantly improve the temperature uniformity without significantly increasing the pump power through structural optimization.With its larger coverage area and heat dissipation capacity, the mhpa+liquid cooling plate is more outstanding in temperature uniformity and extreme heat management.Its derivative design (Z-shaped curved mhpa) successfully realizes the dry and wet separation and the integrated management of cold and heat, showing the potential of all climate application.The core advantage of lhp+liquid cooling plate scheme lies in its complete passive operation and excellent space adaptability.It uses capillary force to drive the working fluid cycle and realizes zero parasitic power consumption.It can not only meet the heat dissipation requirements of high rate fast charging, but also significantly improve the current distribution and prolong the battery life.Life cycle assessment shows that the environmental impact of the whole life cycle is much lower than that of the active liquid cooling scheme.

The performance of many existing BTMS is not enough to effectively control the battery temperature within the ideal range, resulting in uneven temperature or hot spots, affecting the battery life and safety.For the active cooling system, it requires components such as pumps, compressors and fans, which consumes a lot of energy and reduces the range of electric vehicles.For the passive system, the cooling capacity is limited, unable to cope with high-power fast charging, and lack of active temperature control.Some high-efficiency systems (may have high cost or increase system quality, which will affect the overall performance of electric vehicles. Although LHP system has good performance, it has complex manufacturing process and high cost.Most studies only focus on thermal performance, ignoring carbon emissions, resource consumption and waste treatment in the

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process of manufacturing and operation. The design of the cold plate and heat pipe is often based on experience, lacking optimization based on scientific theory.

In the future, the use of heat pipe technology should be promoted, and the passive characteristics of heat pipes should be used to achieve efficient heat transfer without external energy input, which can improve the cooling efficiency and reduce energy consumption. In terms of structural optimization, we should follow the topology optimization, not just rely on experience. And we should have the idea of life cycle assessment. The design should not only look at the performance, but also consider the impact of service life and carbon footprint, as well as the cost of materials. Experimental simulation is only a simulation after all, and it should be verified by collecting actual operation data. The model should be more accurate, and a more accurate electrical thermal coupling model should be developed. Breakthroughs in materials are also of great significance for thermal management. New materials and technologies can be simulated and tested to obtain more efficient and reliable thermal management solutions.

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