Design of a Liquid Cooling Plate for Power Battery Cooling System

ZHANG Ju\textsuperscript{1,2}, LI Xueyun\textsuperscript{1,*}

\textsuperscript{1} School of Vehicle Engineering, Hubei University of Automotive Technology, Shiyan 442002, CHINA
\textsuperscript{2} Key Laboratory of Automotive Power Train and Electronics, Hubei University of Automotive Technology, Shiyan 442002, CHINA

Abstract. A liquid cooling plate is designed for the cooling system of a certain type of high-power battery to solve the problem of uneven temperature inside and outside the battery in the liquid cooling process. According to the thermal characteristics of the battery, the structure of liquid cooling plate is designed and a coil-type liquid cooling plate structure is proposed. The structure can ensure that the coolant reaches the center of the high temperature first, and then flows around. The temperature field of cell monomer under natural convection is simulated, and the conjugate heat transfer of liquid cooling plate is simulated, and the simulation results of temperature field is compared. The results show that relative to natural convection, the battery temperature under natural convection, the maximum temperature difference in the high temperature region of the battery with liquid cooling plate drops by 13.19 °C, and the highest temperature drops by 25 °C. Furthermore, temperature of battery distribution is more uniform, and the battery could work in the optimum temperature range, and the surface temperature of the battery is basically constant, this shows the effectiveness of the design.

1. Introduction

With the development of electric vehicle technology, it is urgent to solve the problem of rapid temperature rise under charging and discharging, ensure that the battery works in the appropriate temperature range, and reduce the influence of temperature on the working state of power battery.

At present, air cooling\textsuperscript{[1-6]} and liquid cooling are two main ways of battery cooling. The structure of air cooling is simple and economical, but the cooling uniformity is not good; liquid cooling\textsuperscript{[7-10]} adopts indirect heat dissipation, and the heat dissipation effect is good, but there are still some problems such as poor uniformity of cooling and control of coolant.

The research work of this paper is carried out for a certain type of high-power battery developed by an enterprise. The structure of the battery box and the layout of the heat dissipation system have been preliminarily completed. The parallel liquid cooling method is adopted. The structure of the battery box is shown in Figure 1.
This paper mainly solved the problem of temperature unevenness in liquid cooling process through the structure design of liquid cooling plate.

2. Design of liquid cooling plate

The liquid cooling plate is a component that contacts directly with the battery cell, and its structure directly affects the heat dissipation efficiency of the battery. There are two kinds of traditional liquid cooling pipes: U-shaped structure and snake-shaped structure, which are generally integral cooling structure, or special structures for battery cell. However, there exist problems of coolant entry sequence. Take U-shaped structure as an example which is shown in Figure 2.

As can be seen in Figure 2, the coolant enters from point A and then flows through B, C, and D to complete the cooling. Assuming that the temperature of coolant reaching point A is the original temperature, the temperature of coolant increases continuously during it flows through B, C and D. But for batteries in groups, because of the heat radiation between the cells and the heat generated by the cells themselves, the temperature at the center of the battery cell is high and the temperature at the battery edge is relatively low. Therefore, when the coolant reaches the center position through A and B, the temperature of the coolant begins to rise, and the heat that can be taken away at this time is limited; The more backward the coolant flows, the less heat it can take away, which leads to the problem of local temperature inhomogeneity in the cooling process.

In order to solve this problem, a coiled structure is proposed, as shown in Figure 3. The coolant preferentially reaches the center and then spreads around, so that the coolant can take more heat from the center at high temperature to ensure uniformity of the battery temperature and heat dissipation efficiency.
Because the new cooling pipe has more bending, it is necessary to check the flow loss. Resistance in the pipeline includes resistance along the path and local resistance. The cooling pipe is a smooth copper pipe with a circular cross section, and its Reynolds number $Re$ is:

$$ Re = \frac{vd}{\gamma} \quad (1) $$

In the formula, $v$ is the velocity of coolant, m/s, $v = 1$ m/s in this paper; $d$ is the inner diameter of the cooling pipe, m, $d = 0.008$ m in this paper; $\gamma$ is the kinematic viscosity of the coolant, m²/s, and $\gamma = 1.2 \times 10^{-6}$ m²/s when 95% ethanol coolant at 30 ℃. Get the $Re = 670$, it is larger than the critical Reynolds number, calculation according to the turbulent flow and Blasius experimental formula, the friction coefficient $\lambda$ is:

$$ \lambda = \frac{0.3164}{Re^{0.25}} = 0.062 \quad (2) $$

Calculate the pressure loss along the path:

$$ \Delta p_1 = \lambda \frac{\rho v^2}{2d} = 1.22 \times 10^4 \quad (3) $$

In the formula: $\rho$ is Density of 95% ethanol coolant at 30 ℃.

The local pressure loss is as follows:

$$ \Delta p_2 = \xi \frac{\rho v^2}{2} \quad (4) $$

In the formula, $\xi$ is the local resistance coefficient. This paper takes 12. Calculated:

$$ \Delta p_2 = 5.65 \times 10^4 \quad (5) $$

The pressure loss is 0.016Mpa. Similarly, the pressure loss of the pipeline under different coolant flow rates can be calculated, as shown in Figure 4.
As can be seen from Figure 4, as the flow rate of the coolant increases, the pressure loss increases, and the flow rate of the coolant can be reasonably selected according to the curve.

3. Thermal analysis of liquid cooling plate

3.1. Model of battery heat production

The heat effect model of lithium-ion battery is a mathematical model for analyzing the temperature distribution and variation of the battery. Since the maximum temperature area during working is not the surface of the battery but the inside of the battery, the temperature cannot be determined. Therefore, finite element calculation and simulation are used to obtain the distribution of the internal temperature field of the battery.

Before the simulation, it is necessary to determine the heating rate of the battery. Bernardi[11] were used to establish the heating rate model of the battery and to estimate the heating rate \( q \). The calculation formula of the heating rate \( q \) of the battery was as follows:

\[
q = \frac{1}{V} \left( I^2 R - IT \frac{\partial U_0}{\partial T} \right)
\]  

In the formula: \( I \) indicates the large current of the battery during charging and discharging, the value is positive when the battery is charged, and the value is negative when discharging (A); \( V \) indicates the volume of battery; \( \frac{\partial U_0}{\partial T} \) is a constant 0.5mV/k when the temperature influence coefficient in the range of 20-50 °C. \( T \) is the temperature of battery(°C). \( I^2 R \) and \( \frac{2U_0}{\partial T} \) respectively indicate Joule heat and reversible heat of reaction in battery heat generation.

The heat generation rate is constantly changing during the operation of the battery. However, considering the complexity of the charge-discharge ratio under the actual operating conditions of the battery, and for the convenience of modeling, the heating rate is assumed to be a fixed value. The initial temperature of the battery is set at 25 ℃, the volume of the cell \( V \) is 0.0123 m³, and \( R \) is 1.6Ω. The heating rates of batteries at 2A, 3A, 4A and 5A are calculated by formula (2), as shown in Table 1.

| Discharge Currents/A | Heating Rate/(W/m³) |
|----------------------|---------------------|
| 2                    | 518                 |
| 3                    | 1168                |
| 4                    | 2077                |
| 5                    | 3247                |
3.2. Temperature field simulation of battery heating

Material properties of lithium batteries can be obtained by consulting technical manuals. Batteries are made of mixed materials, molar mass is 96.461g/mol, average density is 1600kg/m³, average specific heat is 891J/(kg·K), the shape of battery cell is octahedron, and the overall length, width and height are 89mm, 470mm, 470mm, thermal conductivity:

- X direction is 0.34W/(m·K),
- Y direction is 0.51W/(m·K),
- Z direction is 0.57W/(m·K).

Import 3D models created by CATIA into Workbench and generate hexahedral meshes using Sweep method. The initial temperature is set to 25 °C, the convective heat transfer coefficient under natural conditions is set to 5W/(m²·K), and the heat rate at 2A, 3A, 4A and 5A constant current discharge is shown in Table.1. The residual convergence accuracy is 10⁻⁴, the number of iteration steps is 65, and the simulation results are shown in Figure 5.

![Figure 5. Minimum and maximum temperatures of different discharge currents](image)

It can be seen from Figure 5 that when the discharge current increases, the lowest temperature, the highest temperature and the temperature difference of the battery increase, the main reason is that as the discharge current increases and the depth of discharge increases, the remaining capacity of the battery decreases, the internal resistance increases, and the internal heat also increases, which leads to the increase of temperature and temperature difference. When the power battery cells are connected in series to form a battery pack, the temperature difference will increase. And when the car is driving, it may need high-power discharge. If it cannot be cooled or cooled in time, the problem of temperature rise will endanger the life of the battery and the safety of the car.

3.3. Analysis of conjugate heat transfer of liquid cooling plate

Because the designed battery and the liquid cooling plate are arranged in phase, they are symmetric structures, so only one of the cells needs to be analyzed. Conjugate heat transfer analysis of liquid cooling plate by ANSYS/CFX. The 3D model is built by CATIA and imported it into Workbench. The mesh is divided automatically. The grid of coolant in the battery and water pipes is a hexahedral mesh, and the others are tetrahedral meshes. The mesh model is shown in Figure 6.

Analyze the temperature field of the water jacket when the battery is discharged at 5A constant current. The solution domain of the liquid cooling plate model includes the fluid domain in the liquid cooling plate pipe and solid domains such as batteries, cover plates, and water pipes.

The heat rate of the internal heat source of the battery is set to 3247W/m³. Coolant inlet boundary: flow rate is 5m/s, static temperature is 25 °C, turbulent density is 5%; Coolant outlet boundary: average static pressure is 5 kPa. The contact surface between battery and cover plates, between adjacent cover plates, between water pipe and cover plates, and between water pipe and coolant are all set as coupled
heat transfer boundary conditions. The temperature field of the liquid cooling plate and the cell and the flow path of the coolant are simulated as shown in Figure 7, and the temperature distribution of the cooling tube is shown in Figure 8.

![Figure 6. Mesh Model of Liquid Cooling Plate](image)

![Figure 7. Temperature field of the cell and coolant trajectory diagram](image)

From Figures 7 and 8, it can be seen that the coolant circulates in the cooling pipe, and the heat generated by the battery is transmitted to the flowing coolant through the left and right cooling pipe. The circulating coolant takes away the heat to achieve the purpose of cooling. Coolant flows through the central position preferentially, and the temperature of the cooling pipe increases gradually from inside to outside, so the central temperature is lower than the peripheral temperature, the peripheral temperature is 31.2 °C, the central temperature is 25 °C, and the temperature difference is 6.21°C. Temperature distribution map of battery cell is shown in Figure 9.

![Figure 8. Temperature distribution map of cooling pipe](image)

![Figure 9. Temperature distribution map of battery cell](image)

It can be seen from Figure 9 that the highest temperature of the battery cell is 31.2 °C, the lowest temperature is 25 °C, and the temperature difference is 6.21°C. The temperature distribution of the battery cells is relatively uniform. The front and rear end faces of the battery cells are directly in contact with the cold plate, and the surface of the battery is directly in contact with the liquid cooling plate, so the temperature is low, and the temperature difference is the smallest, and the cooling effect is the best.

In order to analyze the temperature distribution inside the battery cell, the temperature field at the position of the battery cell YZ plane $x=0$ mm, $x=10$ mm, $x=20$ mm, $x=30$ mm, $x=44.5$ mm are analyzed, and the results are shown in Figure 10.
Figure 10. Temperature field at different positions of the YZ section of the battery

The highest temperature, lowest temperature and maximum temperature difference of the battery increase with the increase of X. When x=44.5mm, the maximum temperature difference of the symmetrical section of the battery is 1.72°C, which indicates that the temperature distribution of the battery cell in the YZ plane is relatively uniform. The main reason is that the cooling tube is located in the YZ plane, which makes the coolant reach the center of the battery preferentially, and then gradually flows from the center to the outside, making the temperature of the battery more uniform. The center position where the battery temperature is high is preferentially cooled, and the surrounding area with low temperature is cooled later, so the temperature distribution in the YZ plane is uniform.

From the temperature distribution of the entire battery cell, it can be seen that the highest temperature is 31.21°C and the maximum temperature difference is 6.21°C. Compared with the natural convective battery under the same discharge conditions, the maximum temperature difference decreases by 13.19°C, the highest temperature decreases by 25°C. The surface temperature of the battery is constant, the internal temperature distribution is uniform, and the battery can work in the optimal temperature range.

4. Conclusion

Based on the previous research, a liquid cooling plate was designed, including:

(1) The structure of the liquid cooling plate was designed to ensure that the coolant preferentially reaches the center where the temperature is high, and to ensure the uniformity of the battery temperature and efficiency of heat dissipation.

(2) The heat model of the battery was established to calculate the heat rate at different discharge currents. The temperature field of cell at different discharge currents was simulated at natural conditions. The results show that the lowest temperature, the highest temperature and the maximum temperature difference of battery increase with the increase of discharge current.

(3) The temperature field of the unit composed of liquid cooling plate and battery cell was analyzed under the condition of initial temperature 25°C and discharge current 5A. The results show that the temperature of the cooling tube of liquid cooling plate increases gradually from inside to outside, the highest temperature is 31.2°C, the lowest temperature is 25°C, the temperature difference is 6.21°C, and the purpose of preferential cooling center position is achieved. The highest temperature, the lowest temperature and the maximum temperature difference of the battery increase with the increase of x, and the highest temperature, the lowest temperature and the maximum temperature difference of the battery of the symmetrical plane reach the maximum.

Compared with the natural convective battery under the same discharge conditions, the maximum temperature difference decreases by 13.19°C, the highest temperature decreases by 25°C, which can ensure that the battery works in the optimal temperature range, and the internal temperature distribution
of the battery is relatively uniform, the surface temperature of the battery is basically constant, and the cooling effect achieves the design purpose.

Acknowledgments
This work was supported by the Hubei Key Laboratory Open Fund (ZDK1201905)

References
[1] LIU Yan, GU Feng, CHEN Cheng. Cooling Structure Optimization of Battery Module for Hybrid Electric Vehicle. Journal of Tongji University (Natural Science), 2018, 46(11), 1543-1549.
[2] ChenLeitao, XuSichuan, ChangGuofeng. A Study on the Flow Field Characteristics of HEV Battery Thermal Management System. Automotive Engineering, 2009, 31(03), 224-227.
[3] Sui Yanhui, Wang Wen, Xia Baojia, et al. Optimal Analysis on Ventilation Structure of Ni-MH Battery Pack for HEV. School of Mechanical Engineering, Automotive Engineering, 2010, 32(03), 203-208.
[4] Mohammadian S K, Zhang Y. Thermal management optimization of an air-cooled Li-ion battery module using pin-fin heat sinks for hybrid electric vehicles. Journal of Power Sources, 2015, 273, 431-439.
[5] Tao W, Tseng K J, Zhao J, et al. Thermal investigation of lithium-ion battery module with different cell arrangement structures and forced air-cooling strategies. Applied Energy, 2014, 134(1), 229-238.
[6] CHEN Xiyun, ZHENG Yihua. Numerical Simulation of Turbulent Pulsating Flow and Heat Transfer at Constant Heat Flux. Journal of Qingdao University, 2015, 30(01), 58-62+72.
[7] Jarrett A, Kim I Y. Design optimization of electric vehicle battery cooling plates for thermal performance. Journal of Power Sources, 2011, 196(23), 10359-10368.
[8] Xu X M, He R. Review on the heat dissipation performance of battery pack with different structures and operation conditions. Renewable and Sustainable Energy Reviews, 2014, 29, 301-315.
[9] Hao Y, Lifang W, Liye W. Battery Thermal Management System with Liquid Cooling and Heating in Electric Vehicles. Journal of Automotive Safety and Energy, 2012, 3(4), 371-380.
[10] Luo Yutao, Luo Buersi, Lang Chunyan. A Research on the Direct Contact Liquid Cooling Method of Lithium-ion Battery Pack. Automotive Engineering, 2016, 7, 909-914.
[11] Bernardi D, Pawlikowski E, Newman J. A General Energy Balance for Battery Systems. Journal of Electrochem. 1985, 132(1), 5-12.