The study of the physical characteristics and cooling plate thermal control below the lithium battery based on FEA

Dazhou Yang1, *, Mengjun Jiang1

1 School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, Guangdong, 516000

*Corresponding author: dazhouyang@scut.edu.cn

Abstract. Four types of cooling plates with serpent channel structures are established to study the cooling effect of rectangular lithium-ion power battery under different cooling plates. Then, the number of serpent bends is analyzed, whether the fillet and pipe wall thickness is set on the cooling performance of the liquid cooling plate. According to the analysis results, a new liquid flow structure form of liquid cooling plate is designed. Numerical simulation results show that the newly designed cooling plate is integrated with the front flow of water and the internal liquid side flow, achieving a cooling effect with the maximum temperature is 309.55K and a pressure drop of 6032.1pa, which has the most effective cooling performance. Under the requirement of controlling reasonable temperature and low-pressure drop, a liquid cooling plate with better performance can be designed by innovatively setting the direction of the water inlet and outlet and the water channel's internal flow. The above results will provide some ideas for the design of a lithium-ion battery liquid cooling plate.

Keywords: cooling plate; thermal management; FEA

1. Introduction

With the progress of the science and technology development, significant commercial and academic progress has been made on lithium-ion batteries technologies [1]. In the automotive industry, power batteries can be used as the power source for electric vehicles [2]. Electric vehicles have various power batteries, such as nickel-hydrogen batteries, lead-acid batteries, hydrogen fuel cells, and lithium-ion batteries [3,4]. Lithium-ion batteries have higher energy and longer cycle life than other batteries. Therefore, it has become a valuable product widely used in electric vehicles. Li-ion battery packs will generate much heat when working under extreme conditions, such as high ambient temperature and high current ratio during charging or discharging [5,6]. Therefore, battery temperature consistency is vital, and the battery thermal management system (BTMS) [7] has received extensive attention from all walks of life in recent years.

A liquid cooling plate is an essential part of the battery thermal management system. Among the cooling structure of liquid cooling plates, the serpentine structure is a cooling structure that has received more attention in recent years. Its excellent performance makes it commonly used in research. Many researchers study the cooling effect of the liquid cooling plate by changing the geometric parameters of
the liquid cooling plate or changing the materials used. The research method is mainly multi-objective optimization [8-13].

Through the research and summary of the documents as mentioned above, it can be found that the advantages of the serpentine shape [14] are that the cooling effect and thermal performance are better, the temperature of the lithium battery is more uniform, and comprehensive optimization analysis can be performed. The factors that can be modified in the optimization process include multi-objective optimization of parameters such as the width of the serpentine, the number of pipe bends, the position of the water inlet and outlet, and the flow rate. Therefore, this paper chooses the number of serpentine curves, the distance between serpentine curves, and the water inlet and outlet section's width as the model parameters to be modified. According to the contradictory relationship between maximum temperature and pressure drop, the designed model [15] is continuously improved. Finally, a liquid-cooled plate structure is optimized under suitable temperature, pressure drop and other evaluation criteria are obtained.

2. Models and method

2.1. Battery model

A battery module is usually composed of multiple battery bodies in an electric vehicle. Nowadays, the battery of an electric vehicle usually adopts a rectangular soft pack battery. The battery parameters used are shown in Table 1.

| Properties     | Dimension(mm) | Density(kg·m$^{-3}$) | Specify-Heat(j·kg$^{-1}$·k$^{-1}$) | viscosity (Pa·s) | Thermal conductivity | Anisotropic thermal conductivity X/Y/Z |
|----------------|---------------|----------------------|-----------------------------------|------------------|----------------------|---------------------------------------|
| Battery        | 131*65*16     | 2350                 | 900                               |                   |                      | 3.4399/6.084/6.084                   |
| Cooling plate  | 131*65*3      | 2719                 | 871                               |                   |                      | 202.4                                |
| Water          | /             | 998.2                | 4182                              | 0.001003          | 0.6                  | /                                    |

In a battery module, the battery body is placed so that there is the largest contact area between the battery and the cooling plate. The cooling plate is sandwiched between the two batteries and fits closely together, and the heat generated by the battery is carried out through heat conduction. The layout of the battery and the liquid cooling plate is shown in Figure 1.

2.2. Analytical method

Finite element analysis was carried out to evaluate the temperature and pressure drop in the lithium-ion battery's cooling plate. It has a wide range of applications in fluid simulation, which has a wealth of
physical models, advanced numerical methods, and powerful pre-processing functions. It is used in heating transfer and fluid mechanics calculations. There are good accuracy and credibility in it. Therefore, the 3D model was numerically analyzed by Fluent. The mesh of the model is shown in Figure 2.

![Figure 2. Grid graph](image)

The cooling plate is set to be isotropic, and water is used as the coolant to simplify the calculation. The battery module is assumed to be relatively closed, omitted the convective heat, and thermal radiation could break a little effect [16]. The related numerical analysis parameters are shown in Table 2.

| Table 2. CFD analysis parameters |
|----------------------------------|
| Volumetric heat generation rate of battery (W/m³) | 722052 |
| Coolant inlet temperature(K) | 300 |
| Coolant outlet pressure (Pa) | 0 |
| Coolant inlet mass flow (kg/s) | 0.005 |
| ambient temperature(K) | 300 |

In the simulation calculation, the energy conservation equations, mass and momentum conservation equations are used, which were written as follow.

\[
\frac{\partial}{\partial t}(c_{pl}\rho_l T_l) + \nabla \cdot (c_{pl}\rho_l \nu_l T_l) = \nabla P(k_l \nabla T_l) \tag{1}
\]

\[
\frac{\partial \rho_l}{\partial t} + \nabla \cdot (\rho_l \nu_l) = 0 \tag{2}
\]

\[
\frac{\partial}{\partial t} (\rho_l \nu_l) + \nabla \cdot \left( \frac{\partial}{\partial t} (\rho_l \nu_l \nu_l) \right) = -\nabla P \tag{3}
\]

Where \(c_{pl} (\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1})\), \(T_l (\text{K})\), \(P (\text{Pa})\), \(k_l (\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1})\) are specify-heat, fluid temperature, static pressure, respectively.

3. Result and discussion

3.1. Water inlet and outlet from the front
In order to study the influence of the placement of the water inlet and outlet, the number of channels, and the fillet structure on the cooling performance, the models of the different water inlet and outlet methods are designed to be marked as Z1 to Z5. Z1 is top in and top out, and the other models are top
in and bottom out. The number of channels is designed as 7, 6, 4, 4, 4. Z1-Z3 has no fillet at the corner, Z4 has a small transition fillet, and Z5 has a large transition fillet.

Figure 3 shows a thermodynamic diagram of the temperature distribution of the channels arranged along the length direction. It can be seen that the lower temperature area appears in the area through which the liquid flows. The low-temperature area expands as the number of channels increases, and the maximum temperature gradually decreases simultaneously. Besides, the temperature is lower near the inlet area and higher in the outlet area. This phenomenon can be explained by the fact that the coolant absorbs heat during the flow of the channel, so the temperature rises in the direction of the outlet.

Figure 4 shows the temperature and the pressure drop along the longitudinal direction arranged in the channel. In the case of the lowest temperature approaching, the maximum temperature from Z1-Z5 shows an upward trend. On the contrary, the Z1-Z5 pressure drop shows a downward trend. The pressure drop of Z1 is the highest, the pressure drop of Z5 is the lowest.

![Fig 3. temperature distribution of Z1-Z5](image1)

![Fig 4. temperature and pressure drop graph of Z1-Z5](image2)
Based on the above analysis, the following conclusions can be drawn:
As the number of serpentine turns decreases, the maximum temperature will increase. That is, the heat transfer effect is not good. As the number of serpentine turns decreases, the pressure drop will decrease, and the required power will decrease. Taking the rounded corner of R=5mm at the transition, the maximum temperature will increase, and the pressure drop will decrease. If R=11mm, the maximum temperature is unchanged, and the pressure drop decreases too. From the above, a comprehensive conclusion can be obtained. In the liquid-cooled plate with front water inlet and outlet, the maximum temperature and pressure drop are a pair of contradictory goals, and a trade-off needs to be made. Since different inlet and outlet positions will affect the maximum temperature and pressure drop, the next step is to study the side water inlet and outlet.

3.2. Water inlet and outlet from the side
To study the influence of the number of channels and the fillets of the transition on the cooling performance in the case of side water inlet and outlet, the water from C1 to C4 enters from the side. The number of channels is 12, 6, 6, 6, respectively. C3 contains transition fillets, and the C4 pipe cross-section is enlarged.

Figure 5 shows the temperature distribution thermodynamic diagram of the channels arranged in the width direction. It can be seen that the lower temperature area appear in the area where the liquid flows, and the area where no fluid flows is higher in temperature, which affects heat dissipation, and the maximum temperature at the same time gradually decreases. Besides, the temperature is lower near the inlet area and higher in the outlet area. It is consistent with the situation of Z1-Z5.

![Fig 5. temperature distribution of C1-C4](image-url)
Figure 6 shows the trend graph of the temperature and pressure drop of the channels arranged in the width direction. In the case of the lowest temperature approaching, the maximum temperature from C1-C4 shows a trend of first rising and then falling, with the lowest maximum temperature in C1 and the highest maximum temperature in C3. On the contrary, the pressure drop between C1-C4 shows a downward trend and then an upward trend. The pressure drop of C1 is the highest, and the pressure drop of C3 is the lowest.

Combined with the image mentioned above analysis, the conclusions obtained are consistent with Z1-Z4, indicating that the temperature and pressure drop can be affected by water inlet and outlet from the side as it from the front of cooling plate.

3.3. Wall thickness
Based on previous research on Z1-Z5 and C1-C4, to study the influence of the thickness of the liquid-cooled plate and the size of the cross-section at the turning point on the cooling performance, a group of research objects B1-B4 was designed. The inlet and outlet modes of B1 to B4 are all the water inlet and outlet above the front. The number of channels is 4. The serpentine spacing is 1, 2, 3, and 2, respectively. Among them, B1-B3 is to study the influence of wall thickness on the cooling effect, and B4 is to study the influence of the cross-section at the turning point on the cooling effect.

Figure 7 shows the temperature distribution heat of the channel arranged along the length direction, which shows that the lower temperature area appears in the area through which the liquid flows, and the temperature is lower near the inlet area and higher in the outlet area. This phenomenon is consistent with the fore mention.
Figure 8 shows a trend chart of the temperature and pressure drop of channels arranged in the direction of length. In the case of the lowest temperature approaching, the maximum temperature of B1-B3 shows a downward trend. The maximum temperature of B1 is the highest and B3 is the lowest. In contrast, the pressure drop of B1-B3 shows an upward trend, with the highest pressure drop of B3 and the lowest pressure drop of B1. Besides, B4 relative to B2, both maximum temperature and pressure drop decrease.

![Temperature and Pressure Drop Graph of B1-B4](image)
Combined with the above image analysis, the following conclusions can be obtained:

In the case of the lowest temperature approaching, with the increasing wall thickness, the maximum temperature decreases, while the pressure drop is increased. When the channel width at the corner is enlarged, the maximum temperature and pressure drop can be decreased together.

After a comparative analysis of the above three groups, it can be found that the maximum temperature is lower while the pressure drop becomes higher, exhibiting the opposite characteristics as the number increases. Meanwhile, the maximum temperature will increase if the transition fillets is designed. The variety of wall thickness from 1 to 3 mm can bring on the lower maximum temperature and the higher pressure drop. The maximum temperature appears at the side inlet and outlet, and the maximum pressure drop appears at the front inlet and outlet. The maximum temperature and pressure drop is a pair of contradictory goals that need to be balanced.

Based on the above conclusions, the next design cases are inferred. Water in and out from the side, flows up and down inside. More bend. The pipe wall should be thick. Increasing the width of the channel at the turn.

3.4. The innovative design

Based on the design of the design above goals, to study the number of serpentine channels of the newly designed water inlet and outlet and the influence on the cooling performance, a group of research objects ZC1-ZC5 was designed, as shown in Fig.9. The inlet and outlet of ZC1-ZC3 are arranged on the side, and the internal waterway flows up and down. The number of serpentine curves is 2, 4, and 6, respectively. The serpentine spacing is 2 mm. Two vertical water channels is set up at the inlet and outlet as shown in ZC5.

Figure 10 shows the trend graph of the temperature and pressure drop of ZC1-ZC5. In the case of the lowest temperature approaching, ZC1 has the maximum temperature, and ZC3 has the lowest maximum temperature. On the contrary, ZC3 has the highest pressure drop, and ZC1 has the lowest pressure drop. ZC4 and ZC5 are improved versions carried out by ZC2.
In Figure 10, the maximum temperature of ZC2 is 309.55K, the lowest temperature is 301.32K, and the pressure drop is 6032.1pa. At present, ZC2 is a more appropriate design result, and it also verifies the previous conclusions. In the front view, ZC2 adopts the side water inlet at the upper right corner and the side water outlet at the lower left corner, with the internal pipeline in the form of vertical flow.

![Fig 10. temperature and pressure drop graph of ZC1-ZC5](image)

4. Conclusion
In this work, the serpentine curves of the cooling structure of the liquid cooling plate are studied in number and distance and the width of the water inlet and outlet section of temperature and pressure. The maximum temperature and pressure drop are a pair of contradictory goals. The number of serpentine curves, the size of the fillet and the wall thickness has opposite effects on them. The increasing number of serpentine turns, a wider wall thickness, and transition fillets are favorable conditions to acquire a lower temperature. However, these are the opposite if the lower pressure differential is required that the fewer number of serpentine curves, the narrower wall thicknesses, and the presence of transition fillets.

Water inlet and outlet from the side and innovative serpent structures are designed to achieve better liquid cooling plates, which could help improve heat dissipation and extend battery life.

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