Structural design and thermal performance analysis of hybrid electric vehicle battery pack cooling system

Ye Sun¹ and Yibo Wang¹

¹Department of Vehicle Application, Army Academy of Armored Forces, Economic and Technological Development Zone, Changchun, Jilin Province, China

Corresponding author and e-mail: Ye Sun, 201705024218jcy@ncist.edu.cn

Abstract. In this paper, the flow channel structure and battery of battery cooling system are taken as the research object, and the heat transfer simulation is carried out. In order to analyze the temperature and influencing factors of battery pack in the initial scheme of cooling system structure at high ambient temperature of 40 °C, 50 °C and 60 °C, the temperature of battery pack under many working conditions is simulated, and then the optimization scheme is put forward, and the feasibility of the two schemes is compared with that of the initial scheme.

1. Introduction

In recent years, with the rapid development of industries all over the world, serious problems of energy shortage and environmental pollution have been brought about. With the continuous increase of railway operating speed, the gradual improvement of operating mileage and carrying capacity, the proportion of railway transportation in all modes of transportation is also increasing, and it has gradually become the epitome of my country's scientific and technological development capabilities [1].

Hybrid EMUs have a dual-power traction system of internal combustion engine and electric motor, which is more environmentally friendly than traditional internal combustion EMUs; compared with pure electric EMUs, it has higher power and lower operating costs. Hybrid technology is emerging all over the world due to its unique characteristics of energy saving and consumption reduction, cross-line operation and green environmental protection [2].

As the power core of the hybrid locomotive, the power battery pack directly affects the power system of the hybrid locomotive. When the battery pack works in a closed battery box, the individual batteries are closely arranged together. The small space makes the heat dissipation effect very poor, and the temperature is far beyond the optimal and safe working temperature range. If the temperature continues to rise and does not disperse for a long time, the battery pack may even experience a series of safety accidents such as smoke, fire, and explosion, causing unnecessary losses. Therefore, it is very urgent to take effective and timely cooling measures for the battery pack.

2. Description of battery pack liquid cooling system

Liquid cooling heat dissipation mainly utilizes the characteristics of high heat convection coefficient and easier heat dissipation of the liquid medium. The heat exchanger is used to control the temperature of the liquid medium, and then the heat exchanger is cooled by a fan. The whole system is powered by
a water pump. The liquid medium and the power battery pack are heat exchanged, so as to circulate, so as to control the temperature [3]. As shown in Figure 1.

![Figure 1. Cooling heat dissipation.](image)

3. Basic theory of liquid cooling and heat dissipation

According to the research of Bernardi [4] and others, it is known that the heat generation rate of the battery should be studied from the two key points of entropy change reaction and internal resistance. It is assumed that the heat generation of the battery is uniform and stable, and the polarization heat generation and reaction heat generation of the battery All are the heat of reaction, from which a typical battery rate calculation formula can be derived, which is expressed as follows:

\[ q = \frac{I}{V} \left( (U_0 - U) + T \frac{\partial U_0}{\partial T} \right) \]

In the formula, \( q \) represents the heating rate per cell volume, W/m3; \( I \) represents the current generated by the battery during charge and discharge, A; \( V \) represents the volume of the battery, m3; \( U_0 \) represents the open circuit voltage of the battery, V; \( U \) represents the battery's operating voltage, V; \( T \) is the temperature of the battery; \( \frac{\partial U_0}{\partial T} \) represents the coefficient of voltage affected by temperature.

The simplified deformation of the upper formula is replaced by the product of charge and discharge current and its internal resistance. The formula is as follows:

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

where the \( R \) is the sum of the polarization internal resistance and the ohmic internal resistance of the cell, \( \Omega \). It is generally constant in engineering.

4. Simulation and analysis of the initial scheme of the structure of battery group cooling system

4.1. 3D Model of initial structure scheme

This scheme uses Creo 2.0 software to model, consult relevant information and combine the actual situation, the overall model of the runner pipe is square, the type is parallel runner, with good heat dissipation performance; the two sides of the cold plate have holes, respectively Main inlet and main outlet, the cross-section size of the inlet and outlet is \( 10 \times 10 \) (mm), the thickness of the contact part between the cold plate and the battery is 5mm; 6 batteries are placed between the cold plates, and the batteries are discharged at a rate of 5C. The outer surface of the fluid is in complete contact with the inner surface of the cold plate, and the heat generated by the battery is transferred to the coolant in the flow channel through the cold plate, and the heat is taken away to achieve the cooling effect; the overall model and the flow channel model are shown in the figure.
4.2. Analysis of calculation results
After the runner structure model is imported to the ANSYS Fluent platform, when dividing the model's grid, this solution uses Hexa unstructured for division. The overall size of the grid is 1/20 of the entire computational domain size for grid division, and the grid is divided by control methods such as local refinement, multi-polarization grid Multi-level control, and stepped grid Stair-stepped. The overall number of grids is 2558516, the number of grid nodes is 2614772, the grid quality surface alignment rate is 0.63, and the grid quality is good, as shown in Figure 4 and Figure 5.
Figure 5. Runner grid division.

4.2.1. The following boundary conditions are set:
(1) The flow of fluid is steady-state, incompressible flow;
(2) The material of the cold plate is set to (aluminum aluminum);
(3) The fluid in the cold plate is set to (liquid-water);
(4) The radiation heat transfer is ignored;
(5) Set the air convection heat transfer coefficient to 1W/(m²·k);
(6) The flow pattern is set to turbulence (Two equation);
(7) Open the gravity option ($g = -9.80665 \text{ m/s}^2$);
(8) The inlet of the flow channel is a velocity inlet, and the velocity is 0.26m/s. The velocity and direction of each point of the inlet are the same; the outlet is a pressure outlet.

4.2.2. Analysis of the influence of inlet speed on battery temperature
After ANSYS FLUENT completes the calculation of the cooling system of the scheme, the cloud diagram of each physical quantity inside the battery pack of the cooling system can be obtained.

4.2.2.1. The ambient temperature is 60 °C

Figure 6. Battery temperature when the inlet speed is 1.06m/s.

Figure 7. Battery temperature when the inlet speed is 0.53m/s.
Figure 8. Battery temperature when the inlet speed is 0.26m/s.

4.2.2.2. The ambient temperature is 50 °C

Figure 9. Battery temperature when the inlet speed is 1.06m/s.

Figure 10. Battery temperature when the inlet speed is 0.53m/s.

Figure 11. Battery temperature when the inlet speed is 0.26m/s.
4.2.2.3. The ambient temperature is 40 °C

Figure 12. Battery temperature when the inlet speed is 1.06m/s.

Figure 13. Battery temperature when the inlet speed is 0.53m/s.

Figure 14. Battery temperature when the inlet speed is 0.26m/s.

The above data is summarized in Table 1. It can be clearly seen that the average temperature of the battery when the battery is cooled and dissipated at different inlet speeds in different working environment temperatures. When the ambient temperature is the same, the average temperature of the battery decreases with the increase of the inlet speed; when the inlet speed is the same, the average temperature of the battery increases with the increase of the ambient temperature.

Table 1. The average temperature of the battery when the battery is cooled and dissipated at different inlet speeds in different working environment temperatures.

| Speed(m/s) Average cell temperature(°C) | Ambient temperature(°C) | 40   | 50   | 60   |
|-----------------------------------------|-------------------------|------|------|------|
| 1.06                                    | 36.20                   | 36.22| 36.23|
| 0.53                                    | 40.07                   | 40.11| 40.13|
| 0.26                                    | 46.12                   | 46.15| 46.18|
5. Model optimization

5.1. Three-dimensional model of optimization scheme
In this optimization plan, the flow channel type of the overall model is S-shaped flow channel, and the two sides of the cold plate are open with holes, respectively, the main inlet and the main outlet, the inlet and outlet cross-sectional dimensions are \(10 \times 10\) (mm), and the thickness of the cold plate and the battery contact part 5mm; 6 batteries are placed between the cold plates, and the batteries are discharged at a rate of 5C. The outer surface of the fluid is in complete contact with the inner surface of the cold plate, and the heat generated by the battery is transferred to the coolant in the flow channel through the cold plate, and the heat is taken away to achieve the cooling effect; the overall model and the flow channel model are shown in the figure. The overall model and runner model are shown in the figure.

![Figure 15. Three-dimensional model of the overall structure.](image-url)

![Figure 16. 3D model of runner.](image-url)

5.2. Analysis of calculation results
After the runner structure model is imported to the Ansys Fluent platform, when dividing the model's grid, this solution uses Hexa unstructured grids for division. The overall size of the grid is 1/20 of the entire computational domain size for grid division, and the grid is divided by control methods such as local refinement, multi-polarization grid Multilevel control, and stepped grid Stair-stepped. As shown in Figure 17 and Figure 18.
5.3 Analysis of the influence of inlet speed on battery temperature
After ANSYS FLUENT completes the calculation of the cooling system of the scheme, the cloud diagram of each physical quantity inside the battery pack of the cooling system can be obtained.

5.3.1 The ambient temperature is 40 °C

Figure 19. Battery temperature when the inlet speed is 1.06m/s.

Figure 20. Battery temperature when the inlet speed is 0.53m/s.
5.3.2. The ambient temperature is 50 °C

Figure 22. Battery temperature when the inlet speed is 1.06m/s.

Figure 23. Battery temperature when the inlet speed is 0.53m/s.

Figure 24. Battery temperature when the inlet speed is 0.26m/s.

5.3.3. The ambient temperature is 60°C

Figure 25. Battery temperature when the inlet speed is 1.06m/s.
Figure 26. Battery temperature when the inlet speed is 0.53m/s.

Figure 27. Battery temperature when the inlet speed is 0.26m/s.

The above data is summarized in Table 2. It can be clearly seen that the average temperature of the battery when the battery is cooled and dissipated at different inlet speeds in different working environment temperatures. When the ambient temperature is the same, the average temperature of the battery decreases with the increase of the inlet speed; when the inlet speed is the same, the average temperature of the battery increases with the increase of the ambient temperature.

Table 2. The relationship between battery temperature and speed and ambient temperature.

| Speed(m/s) | Average cell temperature(°C) | 40   | 50   | 60   |
|------------|-------------------------------|------|------|------|
| 1.06       | 33.37                         | 33.53| 33.83|
| 0.53       | 38.94                         | 39.32| 39.51|
| 0.26       | 45.77                         | 45.79| 45.88|

To sort out the above data in Table 3-5, when the ambient temperature is 40°C 50°C, 60°C, and the inlet speed is 0.26m/s, 0.53m/s, 1.06m/s, plan (1) and plan (2) Compared with the average battery temperature, the table can clearly see that under the same conditions, the average battery temperature in solution (2) is slightly lower than the average battery temperature in solution (1), so solution (2) can be better reduced The battery temperature has a better cooling effect.

Table 3. Comparison of the two schemes when the ambient temperature is 40 °C.

| plan | Average cell temperature(°C) | 0.26  | 0.53  | 1.06   |
|------|-------------------------------|-------|-------|--------|
| Import rate(m/s) |    |       |       |        |
| plan (1)  | 46.12 | 40.07 | 36.21 |
| plan (2)  | 45.77 | 38.94 | 33.37 |
Table 4. Comparison of the two schemes when the ambient temperature is 40 °C.

| Plan         | Average cell temperature(°C) | Import rate(m/s) | 0.26 | 0.53 | 1.06 |
|--------------|------------------------------|-----------------|------|------|------|
| Plane (1)    |                              |                 | 46.15| 40.11| 36.22|
| Plane (2)    |                              |                 | 45.79| 39.32| 33.53|

Table 5. Comparison of the two schemes when the ambient temperature is 40 °C.

| Plan         | Average cell temperature(°C) | Import rate(m/s) | 0.26 | 0.53 | 1.06 |
|--------------|------------------------------|-----------------|------|------|------|
| Plane (1)    |                              |                 | 46.18| 40.13| 36.23|
| Plane (2)    |                              |                 | 45.88| 39.51| 33.83|

6. Conclusions
Multi-condition calculations are carried out in the initial scheme, and the simulation results show that
the temperature of the battery is affected by many factors: as the ambient temperature increases, the
temperature of the battery becomes higher; as the inlet coolant speed increases, the temperature of the
battery decreases.

To change the flow channel structure to propose an optimization plan, and perform the same multi-
condition calculations. The simulation results show that the temperature trend of the battery is the
same in the initial plan; the simulation results comparing the two plans show that the battery
temperature of the optimized plan is lower than that of the initial plan, while the cooling effect is better.

References
[1] Chi Songyuan, Ma Xuan. Development analysis of hybrid EMUs [J]. Railway Technical
Supervision, 2016, 44(07): 33-36.
[2] Li Cunjun. Liquid-cooled structure design and heat dissipation performance analysis of lithium-ion
power battery packs [D]. Hefei University of Technology, 2016
[3] Newman, Bernardi, Pawlikowski. A General Energy-Balance for Battery Systems [J]. Journal of
the Electrochemical Society,1985,132(1)
[4] Guo Ligang. Thermal analysis and heat dissipation optimization of lithium-ion power battery [D].
Chang'an University, 2016.