Study on heat dissipation structure of air-cooled Lithium ion battery module

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Abstract. The battery cooling system is an important part of the battery thermal management system. Its main function is that when the battery temperature is too high, it can carry out effective heat dissipation to reduce the battery surface temperature, and reduce the temperature difference to ensure the stability of the battery temperature field. In this paper, a simplified model of air-cooled lithium-ion battery module is established, and based on computational fluid dynamics (CFD) theory, Fluent software was used to simulate the temperature field and flow field of the battery module in different inlet directions. The influence of the distance between the battery and the air inlet wind speed on heat dissipation was simulated. Under the condition of comprehensive consideration of the battery volume energy density and heat dissipation energy consumption, the final result is that the heat dissipation structure of the air-cooled battery module reaches the optimal when the lateral ventilation is used, the battery spacing is 5 mm, and the wind speed is set at 4 m/s.

1. Introduction
With the continuous development of social economy, new energy vehicles have gradually become a solution to the problem of non-renewable energy such as oil and natural gas. However, the power battery in the charging and discharging process, due to the chemical reaction will produce a lot of heat, if these heat can not be discharged in time, will make the temperature rising. The change of temperature will also lead to the inconsistency of the battery, which will lead to the following problems: capacity loss, life loss, increase of internal resistance, etc.[1]. The battery thermal management system is one of the main management systems of the battery management system of new energy vehicles. The addition of the thermal management system can adjust the temperature difference of the whole battery pack to keep it in a smaller range. The cell with more heat generation still has a high temperature rise, but it will not be separated from other cells, and there will be no significant difference in deterioration level[2]. Gou Piao et al.[3] designed a liquid-cooling heat dissipation structure with 20 lithium-ion batteries arranged in staggered rows, and conducted simulation and optimization on the influence of coolant flow rate and pipe connection mode on the cooling performance of battery module. The experimental results show that: Increasing coolant flow rate can effectively improve cooling efficiency, but the choice of flow rate should weigh the advantages and disadvantages of cooling effect and power consumption. Mohammadian[4] et al. installed spoilers in the air passage to improve the uniformity of the temperature field of the battery pack in the air cooling system. The results show that the installation of spoiler can obviously improve the uniformity of temperature field of battery pack. Chang Guofeng[5] et al designed the structure of thermal management system for 120 6 Ah nickel-metal hydride batteries. Based on the theory of
uniform air supply, the uniformity of air velocity in thermal management system is deeply analyzed. The influence of battery tilt Angle, air flow rate and air duct opening on air flow rate was studied.

This article will adopt compulsory cooling way to heat dissipation of battery module, different inlet position of the battery module, temperature field and flow field simulation, and in the right position of air inlet conditions, influence the cooling effect of the cell spacing considering the volume energy density and inlet wind speed and the cooling energy consumption constraint, for parameter optimization.

2. Model construction and simulation setting of lithium ion battery pack

2.1 Battery heat generation model
Due to the complex and precise internal structure of lithium ion battery, it is difficult to directly measure its heat generation power. In order to supervise and control the change of internal temperature of lithium battery, many methods have been summarized to simulate and calculate the heat generation rate of lithium battery.

Sato[6] believes that battery heat generation is mainly divided into four parts through experimental analysis, which are reaction heat \(Q_r\), side reaction heat \(Q_s\), Joule heat \(Q_J\) and polarization heat \(Q_p\). It was not until 1985 that Bernadi[7-8] from University of California Berkeley simplified the battery thermal model and believed that the heat generated by the battery was composed of reversible reaction heat and irreversible heat. As follows:

\[
q = \frac{I}{V} \left[ (E_0 - E) + T \frac{\partial U}{\partial T} \right]
\]

(1)

\(q\) is the heat generation rate of the battery per unit volume in W/m\(^3\), \(E_0\) is the open circuit voltage, and \(E\) is the real-time operating voltage. \(V\) is the volume of the battery, \(T\) is the temperature, \(\partial\) is the temperature entropy coefficient. \(I\) is the current of the battery during charging and discharging. Charging is positive and discharging is negative.

In the formula, \((e_0-e)\) can be replaced by \(IR\), and \(R\) is equivalent internal resistance. It can be obtained from HPPC experiment that the equivalent average internal resistance of the battery is 25 m\(\Omega\), and the constant of the average temperature entropy coefficient is 0.3 mV/K[9]. The heat generation rate of the battery can be obtained by substituting the above formula:

\[
q = 0.025I^2 + 0.0003IT
\]

(2)

Discharge simulation of the battery at different discharge rates is carried out at ambient temperature of 25 °C, and the heat generation rate of the battery at different discharge rates is shown in the following table:

| Discharge Rate | 0.5C | 1C | 1.5C | 2C |
|---------------|------|----|------|----|
| Average rate of heat generation/W·m\(^3\) | 12416.25 | 36738.75 | 64811.25 | 104790 |

2.2 Simplified model and battery parameters of air-cooled cooling battery module.
NCR21700T lithium ion battery of Panasonic company is selected in this paper, and 3×6 battery module is used for simulation. The following table describes the parameters.

| Nominal capacity/Ah | 4.5 | Operating temperature range /°C | 0-60 | Charging cut-off voltage/V | 4.2 | Specific heat/J·kg\(^{-1}\)·K\(^{-1}\) | 1000 | Discharge cut-off voltage/V | 2.6 | Density/kg·m\(^{-3}\) | 2889 |
|---------------------|-----|---------------------------------|------|--------------------------|-----|---------------------------------|------|--------------------------|-----|--------------------------|------|
| Size /mm            | Φ21*70 | Thermal conductivity/W·m\(^{-1}\)·K\(^{-1}\) | \(\lambda_x:1.2\) \(\lambda_y:20\) \(\lambda_z:1.2\) |
According to the battery layout, the heat dissipation structure can be divided into forward ventilation and measurement ventilation. As shown in Figure 1, forward ventilation is on the left and lateral ventilation is on the right. To compare heat dissipation effects under the same air inlet and outlet area, set the air inlet area and air outlet size of forward and lateral ventilation to 103 mm x 20 mm. When the battery compartment is set to 3.5 mm, the volume of the two battery layouts is the same.

![Forward ventilation and heat dissipation](a)  ![Lateral ventilation and heat dissipation](b) Figure 1. simplifies the initial model

2.3 CFD boundary condition setting and grid independence verification

When a fluid flows over the surface of an object in a fixed space, the fluid changes from laminar flow to turbulent flow as conditions change. At this point, friction coefficient, drag coefficient and so on have significant changes. The Reynolds number at this critical state is 2000-2600. In the simulation model, the air density is 1.225 kg·m⁻³, and the air viscosity is 1.789×10⁻⁵ kg·m⁻¹·s⁻¹. [9] According to the Reynolds coefficient, the air velocity in the critical state can be calculated to be 0.29-0.38 m/s, while in the forced convection heat transfer, the wind speed is set as 3 m/s. Much larger than the value of wind speed in the critical state. Therefore, turbulence model can be selected for calculation in Fluent [10].

The model was meshed by unstructured grids. Since the velocity and pressure of the fluid on the solid surface changed greatly during the contact between the fluid and the solid, the grid density at the boundary could be improved by setting the boundary layer to increase the accuracy of calculation. Set the number of boundary layers as 10, growth coefficient as 1.2, and maximum thickness as 1 mm. The battery area adopts hexahedral mesh, while the fluid area adopts tetrahedral mesh. The selection of mesh size can affect the mesh accuracy. As the mesh size decreases, the number of meshes increases from 223668 to 10208429. Therefore, the grid independence of the model should be verified. Since the outlet is set as pressure outlet 0Pa, the outlet pressure value can be used as a verification standard to test the grid independence. See the following table.

| Discharge | 223668 | 328365 | 720180 | 2070422 | 10208429 |
|-----------|--------|--------|--------|---------|----------|
| 31.8      | 31.67  | 31.55  | 31.38  | 31.33   |          |
| 0.1163    | 0.0917 | 0.0703 | 0.0485 | 0.0354  |          |

When the number of grids reaches 2070422, the air outlet pressure is only 0.0485Pa, and the calculation accuracy is less than 0.05%. When the grid size is reduced again, the number of grids reaches 10208429, and the air outlet pressure is 0.0354Pa, and the calculation accuracy is only reduced 0.01%. The average temperature changed by only 0.16 percent, but the amount of calculation increased significantly. Therefore, when the number of meshes reaches 2070422, the accuracy requirements are met and the calculation time is greatly shortened.

2.4 Experimental verification of battery simulation model

In order to verify the accuracy of the simulation experiment data, relevant experimental equipment was used for verification, including a master control computer, A New well battery charging and discharging device, PT100 thermal resistance temperature measuring instrument and two Panasonic 21700 batteries. In charge and discharge experiments, the battery surface temperature changes at...
different discharge rates were verified and compared with the simulation results, as shown in the figure below.

(a) New Will Equipment        (b) PT100 Temperature Measurement      (c) 21700 lithium battery

Figure 2. Experimental Instruments

| Table 4. Experimental validation data |
|--------------------------------------|
| Discharge fold rate | 0.5C | 1C | 1.5C | 2C | 2.5C | 3C |
| Experimental value     | 29   | 36 | 41   | 58 | 59   | 62 |
| Simulation value       | 28.65| 37.35| 42.02| 59.67| 62.56| 68.13|
| temperature error      | 0.35 | 1.35| 1.02 | 1.67| 3.56 | 5.13|

It can be seen that with the increase of the discharge rate, the battery temperature keeps rising. The simulation results in this paper have the same change trend as the experimental results, and the temperature error is about 1 °C when the discharge rate is low, so the simulation method in this paper can be used in the process of charging and discharging at a lower rate.

3. Simulation analysis of different heat dissipation structures

3.1 Forward and lateral heat dissipation simulation

Different battery arrays affect the flow rate of the flow channel in the battery module, which changes the heat dissipation effect of the battery module. The general arrangement in the battery module is forward and lateral arrangement. The simulation is carried out for these two arrangements respectively. The wind speed of the air inlet is set as 2 m/s, and the external heat transfer coefficient of the outer wall of the battery box is set as 5 W/(m²·K). SIMPLE algorithm and second-order upwind scheme are adopted for momentum equation, energy equation, continuity equation and turbulent dissipation equation [11-13].

The result is as follows:

(a) Lateral heat dissipation temperature cloud map        (b) Speed vector diagram

Figure 3. Simulation diagram of lateral ventilation and heat dissipation

The simulation results of lateral ventilation show that the maximum temperature of the cell reaches 35.17 °C, the minimum temperature is 28.84 °C, and the maximum temperature difference is 6.33 °C in the lateral heat dissipation process. The lowest temperature on the battery surface is above the first row of batteries close to the air inlet, and three batteries reach the lowest temperature. According to the velocity vector diagram, the maximum wind speed in the battery box is concentrated at the exit and reaches 5.64 m/s, while the wind speed at the lower left corner far from the air outlet is small.
By observing the simulation results of forward ventilation, it is found that the maximum temperature, minimum temperature and maximum temperature difference of the battery with forward heat dissipation reach 34.27 °C, 28.07 °C and 6.2 °C. The lowest temperature of the battery surface is on the first row of batteries near the air inlet, and three batteries reach the lowest temperature. Among other batteries, three batteries in the lower left corner far from the air outlet reach the highest temperature, and the average temperature of the remaining 12 batteries ranges from 28°C to 32°C. The overall average temperature is 32 °C. According to the velocity vector diagram, the wind speed in the battery box is 5.66m /s at the air outlet, and the wind speed is the lowest at the lower left corner far from the air outlet.

3.2 Simulation analysis of ipsilateral inlet and outlet

According to the analysis of the above simulation data, although the temperature difference of the cell in the lateral ventilation is slightly smaller than that in the forward ventilation, the average temperature of the lateral ventilation reaches 41.2 °C, 9.8 °C higher than the average temperature of the forward ventilation battery module 31.4, so the heat dissipation effect of the forward ventilation is better than that of the lateral ventilation. In order to improve the positive ventilation cooling uniformity of internal flow field, can be by changing the outlet position, change to the lower left corner to the lower right corner of the outlet position, make the air inlet and outlet position in the same side, at the same time, in order to increase the uniformity of the flow field in the module, the increase in the battery module, heat dissipation structure a spoiler, as shown in the figure below:

(a) Heat dissipation structure of the same side inlet and outlet outlet       (b) Add a spoiler
Figure 5. Schematic diagram of the same lateral inlet and outlet structure

Under the same simulation conditions, the simulation results of the heat dissipation structure are as follows:

(a) Temperature cloud map on the same side of the air inlet and outlet position     (b) Speed vector diagram of the air inlet and outlet position
Figure 6. Simulation diagram of air inlet and outlet on the same side
Figure 7. Simulation diagram after the spoiler

Table 5. Summary table of the simulation effect of different heat dissipation structures

| Ventilation form               | maximum temperature /C | minimum temperature /C | Maximum temperature difference / C | average temperature /C |
|-------------------------------|-------------------------|-------------------------|------------------------------------|-------------------------|
| natural convection            | 58.9                    | 57.6                    | 1.3                                | 58.1                    |
| Side ventilation              | 35.17                   | 28.84                   | 6.33                               | 32.83                   |
| Forward ventilation           | 34.27                   | 28.07                   | 6.2                                | 32.0                    |
| Forward wind on the same side | 28.47                   | 25.91                   | 2.56                               | 27.52                   |
| Forward and lateral inlet and exit wind + spoiler | 26.68 | 25.31 | 1.37 | 26.14 |

As can be seen from the figure above, when the positions of the air inlet and outlet are set on the same side, the flow field distribution in the battery module becomes more uniform. At this time, the average temperature of the battery decreases significantly, and the maximum temperature difference also decreases. After the addition of the spoiler, the uniformity of the flow field distribution in the battery module is further strengthened, and the average temperature of the battery decreases while the maximum temperature difference is also reduced to 1.37 °C. Therefore, after the addition of the spoiler to the structure of the same side inlet and outlet, the heat dissipation effect of these several heat dissipation structures is optimized.

4. Optimize the heat dissipation of the battery module for forward ventilation

According to the simulation results, the main factor affecting heat dissipation lies in the size and uniformity of air flow channel distribution [14]. In the battery box, the factors that can change the velocity and distribution are mainly battery spacing and air inlet wind speed. In the process of changing the battery spacing, not only the cooling effect is affected, but also the influence on the space energy density of the battery module should be considered. At the same time, the increase of wind speed will also increase the heat dissipation energy consumption of the battery module. On the basis of effective heat dissipation, the energy consumption of heat dissipation should be reduced as far as possible.

4.1 Impact of Battery Spacing on Heat dissipation.
Set the wind speed as 4 m/s, and change the battery spacing D to 1 mm and 2 mm...... under the condition that other simulation conditions remain unchanged 10 mm [15]. Simulation of its heat dissipation effect. The influence of maximum temperature and temperature difference is shown in the figure below.
Figure 8. Effect of the battery spacing on the heat dissipation effect

By the chart shows that decreases as the distance between battery and battery are gradually become smaller, the highest temperature and temperature difference in battery after the spacing to 3 mm, however, as the cell spacing continues to increase, the battery module, the highest temperature and the maximum temperature difference of change within the 1 °C, and with the cell spacing after reaching 7 mm, continue to increase the cell spacing. The maximum temperature and maximum temperature difference of the battery module decrease rapidly. The average temperature of the battery module decreases as the battery space increases from 1 mm to 5 mm. From 5 mm on, the average temperature of the battery module increases. Therefore, when the battery spacing reaches 5 mm, the temperature field uniformity in the battery module is the best.

4.2 Influence of air inlet wind speed on battery heat dissipation

Based on the above analysis, the heat dissipation structure of the battery module with the battery spacing of 5 mm was obtained, and its influence on the heat dissipation of the battery module was simulated by changing the wind speed of the air inlet under the condition that other conditions remained unchanged. The results are shown below:

Figure 9. Effect of wind speed on heat dissipation effect

According to the simulation results, with the increase of the wind speed of the air inlet, the maximum temperature and minimum temperature of the battery module are decreasing, and the maximum temperature difference is also decreasing. However when inlet wind speed reach 4 m/s, battery module, the maximum temperature and minimum temperature significantly lower decline, winds reach 4 m/s, the wind speed significantly lower impact on the battery module of heat dissipation, continue to increase wind speed, the average temperature of the whole module decreased slower, but still can cause the battery fan power continues to increase. Increase the energy loss in the process of heat dissipation. Therefore, when the wind speed reaches 4 m/s, the heat dissipation optimization can be achieved with as little energy consumption as possible, realizing the goal of energy saving.
4.3 Influence of battery spacing on space energy density of battery module

Battery energy density refers to the electric energy released per unit volume or mass of the battery. Battery volume energy density = battery capacity x discharging platform/volume, and the basic unit is Wh/L (watt-hour/liter) [16]. In the simulation process, the battery spacing is changed, and the volume of the battery module is also changed, resulting in the change of its volume energy density. In the process of 2C discharge on the discharge platform, the influence of battery spacing on the volume energy density of the battery module is shown as follows:

![Figure 10. Effect of the battery spacing on the volume energy density](image)

According to the simulation results, the volume energy density of the battery module decreases with the increase of the battery spacing, and when the battery spacing reaches 5 mm, the influence of the battery spacing on the volume energy density of the battery module becomes smaller.

Considering the influence of battery spacing on heat dissipation effect and battery module volume energy density, the maximum temperature difference of the battery module is within the appropriate range, and the maximum battery temperature is low while maximizing the battery volume energy density. The most appropriate heat dissipation structure is the battery spacing of 5 mm.

5. Conclusion

Based on the battery heat generation model, CFD simulation method was used to simulate the heat dissipation structure of air-cooled battery module, explore the influence of forward and lateral ventilation on heat dissipation effect, and conduct single-objective optimization analysis on the battery spacing and air inlet wind speed that affect heat dissipation effect. The following conclusions were obtained:

1. The average temperature of the battery module with positive ventilation and heat dissipation is much lower than that of the battery module with lateral ventilation and heat dissipation. On the basis of positive ventilation, after changing the location of the outlet and adding a spoiler, the uniformity of the flow field in the battery module becomes better, and the maximum temperature and maximum temperature difference are also reduced. The heat dissipation mode of inlet and outlet on the same side and spoiler makes the heat dissipation effect reach the best. This new heat dissipation structure has certain guiding significance to the design of heat dissipation structure of battery pack.

2. As the air inlet wind speed increasing, the battery module, the maximum temperature and maximum temperature decrease, but when the winds reach 4 m/s wind speed gradually reduce the influence of the heat dissipation effect, at this point, the demand for heat dissipation has been met. On the need to consider with the improvement of inlet wind speed, battery cooling energy consumption is also increasing, under the condition of setting the battery module inlet wind speed of 4 m/s. The heat dissipation structure of the battery can effectively meet the requirements of heat dissipation and energy consumption reduction.

3. The cell spacing on the cooling effect in cell spacing between 3 mm to 7 mm, significantly decreased, and cell spacing and the influence of the energy density of battery module volume decreases gradually after 5 mm, so after comprehensive consideration, set the cell spacing is 5 mm.
will make the cooling effect is good at the same time, the volume energy density of battery module is higher.

In this paper, the thermal simulation analysis of the heat dissipation structure of the battery pack shows that a new type of heat dissipation structure with forward ventilation can effectively increase the contact area between the air and the battery to improve the heat dissipation efficiency. At the same time, two factors affecting the heat dissipation of the battery pack are explored: battery spacing and wind speed. To improve the heat dissipation effect by increasing the battery spacing, the influence on the space energy density of the battery pack should be considered. Increase the wind speed to improve the heat dissipation effect of the battery pack, and pay attention to the energy consumption of heat dissipation.

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