Optimisation of a lithium-ion battery package based on heat flow field analysis

Zheng Yuan1, Jin Zhao1, Fuxia Huang1
1Department of Mechanical Engineering, Guizhou University, Guiyang, People’s Republic of China
E-mail: zhaojin9485@163.com

Abstract: A lithium-ion battery package model was established. The influence of inlet velocity, inlet angle and battery space on the heat dissipation capacity of the lithium-ion battery pack was studied by the method of computational fluid dynamics. The single factor analysis and orthogonal test were used to optimise the lithium-ion battery package. The results showed that the best cooling effect was obtained under the conditions of 15 m/s wind speed, 8° inlet angle and equal battery spacing; the maximum temperature and temperature difference were reduced by 11.81% and 35%, respectively.

1 Introduction

The rapid development of the automobile industry has brought great changes to the human life. However, the deterioration of air quality caused by the emission of many fuel vehicles and the shortage of oil resources make it an urgent task to develop new energy vehicles with low emission and low fuel consumption. As one of the most key technologies of new energy vehicles, battery technology development has made great progress in recent years. However, the problem of battery thermal runaway has not been solved very well, affecting the safety of the battery [1]. The power battery is placed in a limited space, and the battery is heated rapidly when the vehicle is running. Heat will be accumulated when cooling condition is bad, causing the overall temperature in the battery box to rise, which will affect the working performance of the battery. High temperature will cause irreversible failure to the battery and even spontaneous combustion [2]. Therefore, in order to improve the heat dissipation capacity of the battery pack, it is of great significance to conduct thermal simulation research on the battery pack.

Lithium-ion battery is commonly used as a power battery. It has an ideal working temperature range of 20–40°C, and the temperature difference should be controlled within ±5°C [3]. Air cooling is the most widely used heat dissipation method in the current thermal management system of electric vehicle power battery, and parallel ventilation is better than serial ventilation. Fan et al. [4] studied the factors influencing the cooling effect of parallel ventilation. The results show that reasonable battery clearance and inlet flow can effectively improve the temperature uniformity of the battery pack and reduce the maximum temperature of the battery unit. Park [5] pointed out that lithium-ion batteries have a high energy density and generate a large amount of heat during long-term working. Therefore, the adoption of forced air cooling can help improve the temperature distribution in the battery pack. The method of increasing air outlet can solve the problem of temperature uniformity effectively. Chang and Chen of Tongji University [6] with 120 NiMH batteries as the research object analysed the influence of the opening size of the air channel, the flow rate of air intake and the angle of the battery on the temperature uniformity in the battery. The results show that the temperature uniformity is related to the air flow structure in the battery pack. The proposed optimisation scheme can reduce the temperature difference by 3°C. This paper constructs a simple battery pack as the research object. Using Fluent software simulation analysis of the temperature and air flow field of the battery pack, the heat dissipation effect of three single factors, namely, wind speed, inlet angle and battery space, on the lithium battery pack is studied. Finally, the orthogonal test is designed to obtain the optimal heat dissipation scheme of the battery pack.

2 Model construction and simulation analysis of lithium-ion battery

2.1 Establishment of the lithium-ion battery pack model

Taking a certain type of battery box as the research object and considering the number and proportioned distribution of battery in the battery box, in order to speed up the operation speed and improve the operation efficiency, the battery pack model is simplified under the condition that the flow field characteristics of the battery pack can be truly reflected, and a row of battery inside and out of the battery pack is taken as the research object. The simplified model includes the battery box body and eight battery monomers, as shown in Fig. 1. The battery is a lithium–iron phosphate battery with a size of 60 mm × 15 mm × 125 mm, rated voltage of 3.2 V and rated capacity of 42 Ah. The lower end of the battery box is the air inlet and the upper end is the outlet; the size of the battery box is 214 mm × 68 mm × 169 mm. The battery is arranged in the battery box at the same distance, and the number of the battery is No. 1–8 and the air passage is No. 1–9.

2.2 Setting of simulation conditions

The geometric model was imported into the Integrated Computer Engineering and Manufacturing code for Computational Fluid Dynamics for grid division. The unstructured grid model was adopted to obtain the whole battery pack with 562,378 grid units. In order to reduce the calculation works and shorten the calculation time, three assumptions are made to the battery: (i) the battery is homogeneous; (ii) internal heat source temperature is within the battery; and (iii) there is no convection or thermal radiation in the battery [7]. The thermal physical parameters of the battery and air are presented in Table 1.

Under the condition of steady-state heat transfer, the battery is under 2 C° discharge rate of heat production rate of 23,000 W/m², the environment temperature is 300 K, the cooling air and convective heat transfer coefficient on the surface of the box body is 5 w/(m² K) and the import of wind speed is set to be 5 m/s. The model adopts the turbulence model [8] and uses the SIMPLE [9].

2.3 Simulation analysis of lithium-ion battery

Through simulation calculation, the temperature cloud diagram of the battery pack and the velocity trace diagram of the fluid area are obtained, as shown in Fig. 2.
The highest temperature at the top of the fluid area can be found that the battery far away from the air inlet has less air flow and lower flow velocity, and the air flow field is not uniform, resulting in the poor temperature consistency of the cell monomer.

3 Study on heat dissipation capacity of the lithium-ion battery

The simulation analysis of the air cooling and heat dissipation capacity of the battery pack shows that the main problems of the original battery pack are as follows: (i) When the battery pack is equidistant, the ventilation volume in the battery passage near the inlet is large and the flow rate is fast. However, due to the influence of structural flow resistance, the flow velocity in the battery passage far away from the air inlet is small, resulting in a higher temperature of the battery far away from the inlet and the poor heat dissipation effect. (ii) The air flows in the battery box and heat convection is at the surface of the battery. The air on the top of the battery is higher than the bottom temperature, which is not conducive to the heat dissipation effect in the top area of the battery pack. Therefore, in order to reduce the maximum temperature of the battery and improve the consistency of the battery temperature, it is necessary to speed up the air flow away from the inlet area and the top area of the battery box and increase the air flow. The influence of inlet air velocity, air inlet tilt angle and battery spacing on the heat dissipation capacity of the lithium-ion battery pack is studied below.

3.1 Influence of air inlet velocity

When the air inlet speed is accelerated, the air volume of the battery box increases, and the heat exchange between the battery monomer and air is accelerated, which makes it easier to reduce the battery temperature. The ventilation speed of the primary battery is 5 m/s, by controlling the fan speed. Now, the air inlet speeds are 10, 15 and 20 m/s, respectively. The influence of wind speed on battery heat dissipation capacity is studied, and other conditions are kept the same. The battery pack is simulated and calculated, and the temperature chart of the battery pack is obtained, as shown in Fig. 3; the velocity polygon diagram of the air passage is shown in Fig. 4.

With the increase of wind speed, the maximum temperature of the battery pack decreased from 37 to 33°C and remained unchanged. The temperature difference between the battery and the battery decreased from 7 to 4°C. When the wind speed is lower than 15 m/s, the speed of wind speed can effectively improve the heat dissipation capacity of the battery group. When the wind speed is >15 m/s, the increase of flow velocity has a little effect on the improvement of the heat dissipation effect of the battery group. According to Fig. 4, with the increase of inlet velocity, the increment of air velocity in the No. 6–9 channel is much smaller than that of the 1–5 channel flow rate, and the increase of air inlet velocity is limited to the heat dissipation effect of the battery far away from the inlet.

3.2 Influence of inlet angle

In order to improve the wind speed in the flow channel between the batteries at the side of the inlet of the battery box, the area of the cross section of the back end inlet area is reduced by changing the angle of the inlet. Under the condition of the same air flow, the flow velocity at the end of the inlet area is accelerated to improve the cooling effect of the battery far away from the inlet of the battery box. The angle between the lower surface and the horizontal surface of the original battery box is 0° and the inlet angles are 4°, 8°, 12°, respectively, and the corresponding model is established. The battery temperature cloud chart obtained is shown in Fig. 5, and the air flow speed polygon chart is shown in Fig. 6.

From Fig. 5, it is found that the top temperature of battery No. 6–8 has been significantly improved with the increase of inlet angle. When the air inlet tilt angle increases from 4° to 12°, the cross section of the inlet end area shrinks; thus, the speed of No. 5–9 channel increases. However, the air velocity of channel 1–4 decreased, and the highest temperature and temperature difference of the battery group first decreased and then increased. The
maximum temperature of the battery pack was located at No. 1 battery. It is shown in Fig. 6 that the angle of the inlet leads to the decrease of the wind speed at the inlet and the constant wind speed at the different inlet, but the flow rate of No. 7–9 channel in the air passage far away from the inlet is continuously increased. When the air inlet angle is 4°, the maximum temperature of the battery pack is 36°. The maximum temperature difference is in accordance with the allowable temperature difference. The air flow rate in the battery box is high and the heat dissipation capacity is uniform.

3.3 Influence of battery spacing

The cell spacing has a great influence on the cooling of the lithium-ion battery group. When the spacing of the two single cells becomes larger, the pressure in the channel is reduced, the resistance is smaller and the air flow will increase. So, in order to reduce the maximum temperature of battery No. 6–8 at the inlet of the battery box and improve its heat dissipation effect, the spacing of No. 1–4 battery should be reduced and the spacing of No. 5–8 battery should be increased. The size of the battery box is limited by the size of the guest space, so the overall size of the battery box is kept unchanged and the batteries are arranged in an equal-decreasing manner [10]. The cell spacing tolerance of the battery pack is 0 mm and the tolerance values are 0.3, 0.6 and 0.9 mm, and the model is set up. The temperature cloud chart of the battery group is shown in Fig. 7, and the flow chart of the air flow passage is shown in Fig. 8.

It can be seen from Fig. 7 that when the battery spacing tolerance value increases, the maximum temperature of the battery pack decreases and the overall temperature uniformity of the battery becomes better. When the tolerance of battery spacing are 0.3 and 0.6 mm respectively, the spacing of No. 1–4 battery
narrow, which leads to the air flow being reduced. The battery temperature increases slightly. Meanwhile, the spacing of No. 5-8 battery is wider. The cooling effect is then improved and the highest temperature of the battery pack dropped from 37 to 35 °C. However, when the cell spacing tolerance is 0.9 mm, the cell gap is too wide, the wind speed is reduced instead and the maximum temperature of No. 7 battery rises to 37 °C. Adjusting the battery spacing, the speed of No. 7–9 battery is stable within a certain range, so that the flow of the air channel is balanced and the temperature consistency of the battery pack is effectively improved.

### 3.4 Orthogonal test simulation analysis

The effect of the three factors on the cooling effect of the battery pack is not independent. The design of the orthogonal design takes into account the influence of the inlet wind speed A, the inlet angle B and the cell spacing variance C on the heat dissipation capacity of the battery pack. The orthogonal test includes three factors: A, B and C. The two levels of A, B and C are 10, 15 m/s; 4°, 8°; and 0, 0.6 mm, respectively. Eight test plans were established, and the model was established for numerical simulation. The results are shown in Table 2.

| A, m/s | B, deg | C, mm | \( T_{\text{MAX}}, ^\circ\text{C} \) | \( \Delta T, ^\circ\text{C} \) |
|-------|-------|------|-----------------|-----------------|
| 1     | 10    | 4    | 0               | 33.76           | 5.07            |
| 2     | 10    | 4    | 0.6             | 34.46           | 6.6             |
| 3     | 10    | 8    | 0               | 33.76           | 5.06            |
| 4     | 10    | 8    | 0.6             | 34.22           | 5.42            |
| 5     | 15    | 4    | 0               | 33.01           | 4.51            |
| 6     | 15    | 4    | 0.6             | 33.60           | 5.28            |
| 7     | 15    | 8    | 0               | 32.63           | 4.51            |
| 8     | 15    | 8    | 0.6             | 32.95           | 4.46            |

It can be seen from the chart that when the intake air velocity is 15 m/s, the air inlet inclination angle is 8°, the battery spacing variance is 0 mm and the heat dissipation effect of the battery pack is the best. At this time, the maximum temperature is 32.63 °C, which is 11.81% lower than that of the original battery pack, and the temperature difference is 4.46 °C. The temperature uniformity of the battery is better. At the same time, it can be found that the influence of battery spacing on the maximum temperature of battery pack is greater than the other two factors.

### 4 Conclusions

This paper mainly discusses the influence of inlet air velocity, air inlet inclination angle and battery spacing on the heat dissipation capacity of the air-cooled battery pack. The wind speed in a certain range can effectively reduce the maximum temperature of the battery pack; the cooling efficiency of the battery is lower than that of a certain value. The increase of the inlet angle of the inlet can strengthen the heat dissipation capacity of the battery at the end of the inlet, and the battery space can be adjusted to improve the consistency of the battery temperature. Through the orthogonal test, the best heat dissipation scheme is 15 m/s, the air inlet gradient is 8°, and the battery spacing is the same. Among the three factors, the battery spacing has a greater influence on the battery pack temperature, and acts as a guiding function for the actual battery pack layout.

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