Simulation of thermal characteristics of lithium batteries for electric vehicles

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Abstract. To study the thermal characteristics of lithium batteries in electric vehicles, a single lithium ion battery under natural convection, forced air cooling and water cooling conditions were simulated. On this basis, a parallel water-cooling model for battery pack is proposed, and CFD method was used to simulate and analyze the heat characteristics and temperature field distribution of the model at different flow rates, and an optimum flow rate of the cooling water was determined at which the battery pack has the best cooling result and thermal homogeneity corresponding to the given discharge rate.

1. Introduction
Lithium ion batteries are widely used in the energy system of electric vehicles for their advantages of high energy density, low self-discharge, long life and good stability. However, with the widely application of lithium batteries in electric vehicles, the volume is getting smaller and the power is getting larger, and the heat is increasing correspondingly, which affects the battery life and safety [1]. Bandhauer et al [2] researched the capacity of lithium battery under different temperature, and pointed out that the capacity of the battery will be reduced when the working temperature exceeds 50°C, and suggested the working temperature be controlled below 50°C. PESARAN [3] compared air cooling with liquid cooling and concluded that although the structure of liquid cooling is more complex than air cooling, the heat exchange efficiency and temperature controlling effect of liquid cooling are better. Chen [4] made a comparative analysis of serial ventilation and parallel ventilation by using CFD method, and improved the air inlet and outlet to optimize the temperature field of the battery pack. An et al [5] compared the effects of flow pipe Numbers, section shape of flow passage, and length-width ratios of flow passage on the maximum temperature rise and thermal homogeneity of battery pack.

In this paper, first of all, the heat dissipation of single lithium battery under different cooling modes and different ambient temperatures is simulated by virtue of FLUENT, and the problems of air cooling are pointed out. On this basis, a new type of parallel water cooling model of the battery pack including heterogeneous components is established, and detailed simulations are carried out on the heat dissipation and temperature field of the battery pack.

2. Thermophysical model
The actual thermo genesis of lithium ion battery is quite complex. When solving the internal temperature field of the battery, a simplified three-dimensional thermal mathematical model can be adopted, as shown in equation (1) [6]:

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\[ \rho C_p \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + q \] (1)

Where, \( t \) stands for time, \( T \) stands for battery temperature, \( \rho \) stands for the average density of the battery, \( q \) stands for the heat generation rate per unit volume of the battery, \( C_p \) stands for the specific heat capacity of a single battery, \( \lambda_x, \lambda_y, \lambda_z \) respectively stands for the thermal conductivity coefficient of the battery along the x, y, z axis.

D Bernard’s heat generation model is commonly used to calculate the heat generation rate of batteries [7], expressed as:

\[ q = \frac{I}{V_d} \left( U_0 - U \right) - T \frac{dU_0}{dT} \right] = \frac{I}{V_d} \left[ I \times R_r - T \frac{dU_0}{dT} \right] \] (2)

Where, \( V_d \) represents the volume of battery; \( I \) represents the charge or discharge current; \( U_0 \) represents the open circuit voltage of the battery; \( U \) represents the load voltage; \( dU_0/dT \) represents the temperature coefficient, which is negligible because of its small value. \( R_r \) is the internal resistance of the battery.

The heat generation rate of the positive and negative poles of the battery is:

\[ q_{Al} = \frac{Q_{Al}}{V_{Al}} = \frac{I^2 R_{Al}}{V_{Al}} \] (3)

\[ q_{Cu} = \frac{Q_{Cu}}{V_{Cu}} = \frac{I^2 R_{Cu}}{V_{Cu}} \] (4)

Where, \( q_{Al}, q_{Cu} \) represents the heat generation rate of positive and negative pole column; \( Q_{Al}, Q_{Cu} \) represent the calorific value of the positive and negative pole column; \( V_{Al}, V_{Cu} \) represent the volume of positive and negative pole column; \( R_{Al}, R_{Cu} \) represents the resistance of positive and negative

In general, the heat capacity of lithium ion batteries can be obtained by using the weighted average method based on the specific heat capacity of components. The expression is:

\[ C_p = \frac{1}{m} \sum C_i m_i \] (5)

Where, \( m \) is the mass of lithium battery; \( C_p \) is the specific heat capacity of lithium ion battery. \( m_i \) and \( C_i \) represent respectively the mass and specific heat capacity of each component in the battery.

For the analysis of heat generation and conduction of heterogeneous materials, some valid methods such as partition of unity finite element method are presented [8-10].

3. Heat dissipation simulation of single battery

3.1. Numerical model of battery

![Figure 1. Model mesh of single battery.](image-url)
The research object here is a certain type of cuboid lithium iron phosphate battery for electric vehicle, which size is 70 mm × 27 mm × 88 mm. Hypermesh was used to conduct the modeling and meshing for the battery. The model finished is shown in figure 1.

### 3.2. Physical parameters of battery
The physical parameters of copper and aluminum materials were determined by query, and the thermal conductivity and specific heat capacity of the core of the battery obtained by calculation. The specific parameters are shown in Table 1.

| Component        | Material         | Density/(kg/m$^3$) | Specific heat capacity/(J/(kg·k)) | Thermal conductivity coefficient/(W/(m·k)) |
|------------------|------------------|-------------------|---------------------------------|-------------------------------------------|
| Battery body     | Mixed material   | 2329              | 291                             | $K_x=1.1, K_y=1.4, K_z=1$                 |
| Positive poles   | Aluminum alloy   | 2730              | 963                             | 201                                       |
| Negative poles   | Copper           | 8450              | 390                             | 116                                       |

The heat generation rates of the battery core, positive and negative poles under different discharge rates are shown in Table 2.

| discharge rates/C | Current /A | $q_{Al}$  | $q_{Cu}$   | $q_{C}$   |
|------------------|------------|----------|------------|-----------|
| 1                | 11         | 6 329.5  | 8 799.2    | 22 012.5  |
| 2                | 22         | 19 789.6 | 34 551.8   | 89 218.1  |
| 3                | 33         | 43 336.3 | 77 741.5   | 200 732.2 |

The heating condition of lithium battery in electric vehicle will change dynamically with the working condition and power demand of the vehicle. For different working conditions, it can be expressed by the charge or discharge rate of the battery (1 C, 2 C, 3 C). The higher the discharge rate, the higher the heat generation. Limited to the paper space, here only give analysis of the battery under 3C discharge rate, environmental temperature 25°C and 40°C, under three different cooling conditions (natural convection, forced air cooling and water cooling (water temperature is 25°C)). In order to save the calculation time, the simulation of single battery does not include the fluid part, and the fluid effect is realized by setting the ambient temperature and the heat transfer coefficient of the battery surface. The heat transfer coefficients under the three cooling conditions are: natural convection $\alpha=10$ W/(m$^2$·K), forced air cooling $\alpha=25$ W/(m$^2$·K), and water cooling $\alpha=390$ W/(m$^2$·K).

### 3.3. Results and analysis

![Figure 2. Temperature curves.](image-url)
Figure 2 shows the changes of highest temperature of the battery with the time under environmental temperature 25°C, three different cooling conditions. It is obvious that with the increase of time, the highest temperature rises nonlinearly. At the beginning the curves rise fast, and then after a certain time, the heating and cooling gradually come into balance, temperature curves become flat. In the meanwhile, among the three cooling conditions, the effect of water-cooling is the best, as it can achieve the heat balance in a short time, and the final temperature is the lowest.

Figure 3 shows the comparison of battery temperature distribution after the battery reaches thermal equilibrium under two ambient temperatures and three cooling conditions. When the environment temperature is 25°C, the highest center temperature under natural convection exceeds 50°C, which does not meet the requirement of the heat dissipation. When the environment temperature is 40°C, the highest center temperatures under natural convection and forced air cooling both exceed 50°C. However, the overall temperature of the battery is quite low with water cooling, and the heat dissipation effect is good.

![Temperature Distribution Images](image)

**Figure 3.** Final temperature distribution under different ambient temperatures and cooling conditions. (a) 25°C, natural convection, (b) 25°C, forced air cooling, (c) 25°C, water cooling, (d) 40°C, natural convection, (e) 40°C, forced air cooling and (f) 40°C, water cooling.

Meanwhile, under the conditions of natural convection and forced air cooling, the maximum temperature of the battery rises with the change of the ambient temperature. Under the same cooling condition, the change of the maximum temperature of the battery is nearly the same as that of the ambient temperature. Therefore, according to the calculation results, the maximum temperature of the battery can be inferred from the ambient temperature under natural convection and forced air cooling conditions. But water cooling effect is less affected by environmental temperature, when the environmental temperature change from 25°C to 40°C, the highest temperature of battery only increased by 1°C. Therefore, water cooling is more suitable for accurate control of battery temperature.

4. **Battery pack with water cooling**
4.1. Model and settings

In general, there are two modes of heat dissipation for battery pack: serial heat dissipation and parallel heat dissipation. For serial heat dissipation, as the coolant flows in the pipe, the farther it is from the inlet, the higher the temperature of the coolant is, which leads to poor temperature uniformity of the battery pack. In addition, the longer the pipe is, the greater the flow resistance is, and the more energy is needed. Therefore, a new parallel water-cooling model is designed here, as shown in figure 4. This model is composed of 12 single batteries, cooling pipes and aluminum alloy frames, and the batteries and pipes are embedded together, and they are in close contact with each other. The cooling water flow passage has 4 entrances and 4 exits, both of which are 10 mm in diameter. Considering the symmetry of the model, quarter model is used for calculation, as shown in figure 5. The model is composed of 418,487 tetrahedral elements and 64,271 nodes.

![Figure 4. Parallel cooling model.](image)

![Figure 5. Quarter model.](image)

Since the cooling water flow passage was plate-shaped, the laminar flow model was selected according to the Reynolds number. The inlet is set to speed entry, the flow rates were 0.01 m/s, 0.03 m/s and 0.05 m/s, and inlet water temperature of 25℃; The outlet is set as the pressure outlet; The heat exchange between different parts of the pack adopts the coupling model, and the software calculates the heat transfer automatically. Radiation is used for the heat exchange between the frame, battery body, electric poles and the external environment; Setting the environment temperature at 40℃.

4.2. Results and analysis

Figure 6 shows the final temperature distribution of the battery pack after reaching the heat balance under different flow rates. It can be seen that the highest temperature appears in the negative pole, and the internal temperature of the battery body is relatively low. In flow rate of 0.01 m/s, top temperature of the battery pole is 42℃, and the two batteries adjacent has certain temperature difference. The temperature near the entrance is relatively low, far away from the entrance, the temperature is higher, which indicates that the flow rate is too small. In flow rate of 0.03 m/s, top temperature of the batteries is 37℃, the battery body temperature distribution is quite uniform, indicating that heat dissipation of the battery and thermal homogeneity are good. In 0.05 m/s, the highest temperature is still 37℃, and battery temperature distribution is similar to that of 0.03 m/s, only a slight decline in local.

Figure 7 shows the variation of the battery's temperature uniformity at different flow rates. It tells that when the flow rate is 0.03 m/s, the temperature difference between the center and the edge of a single battery and the difference between the two adjacent battery centers are the smallest. It is meaningless to increase the flow rate to improve the heat dissipation and temperature uniformity of the battery after 0.03 m/s. Therefore, the flow rate of 0.03 m/s can be used as the optimum rate to control the temperature under 3C discharge rate.
Figure 6. Battery pack temperature distribution in different flow rates. (a) 0.01 m/s, (b) 0.03 m/s and (c) 0.05 m/s.

Figure 7. Uniformity of battery temperature at different flow rates.

Figure 8. Movement and temperature distribution of cooling water in flow passage. (a) 0.01 m/s, (b) 0.03 m/s and (c) 0.05 m/s.

Figure 8 shows the movement and temperature distribution of cooling water in the flow passage in different flow rates. It can be seen that, near the inlet, vortexes generate along the height of the flow passage, and with the increase of the flow rate, the range of vortexes gradually expand, which is to
increase the flow loss of the fluid, and increase the energy consumption of the system. From the perspective of energy conservation and temperature control, the inlet flow rate of cooling water in this model should be set at 0.03 m/s under 3C discharge rate.

5. Conclusions
In this paper, the thermal characteristics of lithium battery under natural convection, forced air cooling and water cooling are simulated and analyzed by changing the ambient temperature and heat transfer coefficient, and the results of natural convection and forced air cooling and the effect of water cooling are obtained. On this basis, a parallel water-cooling heat dissipation model of the battery pack was proposed, and the thermal characteristics, temperature field and water movement of the model at different flow rates were simulated and analyzed using CFD method, and the optimum flow rate was determined through analysis. The research method and calculation results can provide reference for the design and optimization of the thermal management system of power lithium battery.

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