Investigation on Battery Thermal Management of Power Battery Based on Environmental Impact of Electric Vehicle

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Abstract. The present study on battery thermal management performance is mainly based on the research conducted in a single-pack environment, without considering the impact of the vehicle driving environment on the thermal performance of the power battery. Therefore, this paper conducts a research on the thermal management performance of the power battery and considers the effect of heat exchange under the driving conditions of the whole vehicle. In addition, the ohmic heat generation method of a battery pack in the process of charging and dis-charging is established in this paper. The complete heat exchange condition of a liquid cooling power battery is obtained and the research of thermal management performance is carried out. The results indicated that the tested temperature values at sensor NTC position are in good agreement with the predicted data. The maximum temperature deviation between numerical results and experiment data at the same temperature sensor (NTC) position is 1.4 ℃, which demonstrates that the prediction accuracy of numerical simulation methods adopted in this paper is significantly high.

1. Introduction
Lithium-ion batteries are widely used in electric vehicles because of their high power and energy density, long cycle times and low self-discharge rates [1, 2]. But the temperature has significant impact on the performance and reliability of lithium-ion batteries [3].

The appropriate battery heat management system (BTMS) can timely eliminate the heat generated in the battery pack, which reduces the maximum temperature of the battery, improving the temperature uniformity of the battery, so that the battery operates in a proper temperature range.

Many thermal managements focus on analysis of liquid-cooled battery packs module or cell-level, and structural optimization of water-cooled plates and cooling channels. For example, the effects of different serpentine cooling channels, the cross-sectional shapes of different cooling plate channels, and the number of parallel coolant channels on the battery temperature have been investigated by relevant researchers [4, 5]. Zhao [6] et al. studied large liquid-cooled lithium-ion battery packs and found that shorter cooling channels can greatly reduce temperature unevenness. Chung [7] et al. established a three-dimensional model of a system-level battery pack, and the poor thermal conductivity between the bottom of the cell and the water-cooled plate is an important factor restricting the heat transfer efficiency. In addition, they optimized the water-cooled plate structure to improve the uniformity of battery temperature.
The above researches on the thermal management performance of battery pack mainly focus on the study of the module or cell level and also focus on the effect of water-cooled plate optimization on the temperature field. Unlike the research contents in a large number of literatures, in this paper, the heat exchange conditions between the battery pack in the driving process and the external environment are calculated by the whole vehicle CFD model, the thermal power method of the battery is established, and the thermal management performance of the power battery is studied by numerical simulation and experiments.

2. Power battery thermal model establishment

2.1. Power battery structure model.
The research object is an EV liquid cooling battery pack, consisting of a box, lid, module and liquid cooling plate, as shown in Fig. 1. The battery pack consists of 14 module series. The harmonica tube liquid-cooled plate is arranged under the bottom of battery pack as shown in Fig. 2. Each module has two NTC temperature sensors to characterize the temperature performance of the module, as shown in Fig. 3. In this paper, the output temperature value of sensor NTC arrangement is used as a representation of the temperature of the battery.

2.2. Power battery structure model

2.2.1. Three-dimensional thermal battery model. For the battery thermal management analysis at high temperature cooling operational conditions, the heat generation of the power battery is a typical three-dimensional unsteady thermal conduction process. due to the effects of the current, SOC, battery resistance, etc., the thermal model of the square power battery is established as follows:

\[ \rho c \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + Q \]  

(1)

Where \( \rho \) is battery density, \( c \) is heat ratio, \( T \) is battery temperature, \( Q \) is heat generation rate, \( \lambda_x \), \( \lambda_y \), \( \lambda_z \) represent heat conduction coefficient of battery in the x, y, z three coordinate directions. The left side of the formula is the energy increment of the battery per unit time, the first three items on the right are the energy increment caused by heat transfer in the unit time, and the fourth item on the right is the energy increment caused by heat production.
2.2.2. Battery heat generation analysis. When the battery pack is operating at high temperatures, the internal heat-producing components include the cells and the copper that acts as an electrical connection, including the copper within and between the modules.

The heat generation inside the power battery is determined by the battery heat rate model established in the literature [8], which mainly consists of reversible heat and irreversible heat, and assumes that the heat production inside the battery is evenly distributed. The model is described as follows:

\[
Q_{cell} = I(U - E_0) + IT \frac{dE_0}{dT}
\]  

Where I represents the charge and discharge current of battery pack, A; \(E_0\) is open voltage, V; U is operating voltage, V; T denotes battery temperature, K; \(\frac{dE_0}{dT}\) is temperature impact coefficient, mV/K; \(I(U - E_0)\) is joule heat. \(IT \frac{dE_0}{dT}\) is irreversible reaction heat.

The heat production of aluminum/copper rows is mainly joule heat generated when the current passes.

\[
Q_{ele} = I^2R
\]  

Where, I is the battery charge and discharge current, and R is the conductive resistance of copper row.

2.2.3. Battery cooling analysis. The heat generated in the battery pack system is mainly dissipated externally through three ways:

The first is convection heat transfer. The coolant takes away the heat transmitted from cell to water-cooled plate and the air takes away the heat by natural convective cooling on battery surface, which can be expressed as follows:

\[
Q_{convection} = hA(T_f - T_s)
\]  

Where, h is the convective heat transfer coefficient be solid and coolant, W/(m·K); A is the contact area of coolant and solid, m²; \(T_f\); \(T_s\) represent the coolant temperature and the solid temperature.

The second is heat exchange through thermal radiation. It mainly includes the battery pack internal parts between the battery box cover and the environment between the radiation heat exchange. The thermal radiation expression is:

\[
Q_{radiation} = \varepsilon A \left( \frac{T_f}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4
\]

The third is heat exchange by heat transfer between the contact parts in the battery pack.

\[
Q_{conduction} = \frac{\lambda (T_1 - T_2)}{A\delta}
\]

Where, \(\lambda\) is the thermal coefficient; \(T_1, T_2\) is the temperature of the contact part; A is the thermal contact area, and \(\delta\) is the distance of the thermal conductivity.

3. Numerical analysis of high temperature and high-speed conditions and test verification

3.1. Vehicle high-speed ring mold test

The car had been immersed for more than 6 hours at an ambient temperature of 33 centigrade and be soaked until the battery temperature was close to the ambient temperature so as to begin the test. The vehicle was travelling at 120km/h & 3% slope and lasted 30min. At this point, the power requirement of battery’s discharge is 75KW. The initial SOC of battery is adjusted to 95%. The cooling flow request is 10L/min. By the battery CAN signal data, the test data such as battery temperature and battery inlet water temperature can be read.
3.2. Numerical simulation

3.2.1. Heat exchange conditions between the battery case cover and the external environment. The heat exchange between battery box cover and external environment is usually treated as insulation boundary or set a uniform heat transfer coefficient. But the effect of external wind speed and wind temperature on the battery pack temperature in actual driving operating conditions is not considered. The method adopted in this paper is to build the front-end CFD model of the vehicle shown in Figure 4. The main thermal load of the front-end module, including the condenser thermal load and the heat generation from the electric drive circuit, etc. is defined as the vehicle speed of 120km/h and 3% slope. The wind temperature at the entrance of the wind tunnel was set at 35 centigrade and the wind speed of 120km/h is considered. After the calculation reaches a steady state, the surface convection heat transfer coefficient and the fluid convection heat transfer coefficient of the battery box cover could be obtained, as shown in Fig.5. The results are mapped to the battery case lid surface in STAR-CCM.

![Figure 4. The vehicle front-end CFD model](image)

![Figure 5. Convective heat transfer coefficient on battery box case cover](image)

3.2.2. Cell thermal power generation. The temperature effect coefficient $\frac{dE_0}{dT}$ in battery thermal power equation (2) is very important for the calculation of battery heat generation. Getting this data requires testing battery open voltage changes at different temperatures and SOC, which will cost a lot of time [9]. Equation 2 $(U - E_0) = IR_{cell}$, where, $R_{cell}$ is cell inner resistance obtained from HPPC test. Properties of cell is in table 1. Hence, equation 2 can be written as:

$$Q_{cell} = I^2R_{cell} + IR_{cell} \frac{dE_0}{dT}$$  \hspace{1cm} (7)

| Property | Capacity (Ah) | Weight (Kg) | Thermal conductivity (W/mk) | Specific Heat (J/(Kg K)) |
|----------|---------------|-------------|-----------------------------|--------------------------|
| Cell     | 180           | 2.6         | X/Y/Z: 2/25/25              | 960                      |

Table 1. Properties of cell
3.3. Comparison of numerical simulations and experiments

Numerical simulation has been conducted according to above boundary conditions. The temperature simulation results are shown in Fig. 6 and emperature simulation results for NTC position of each module are shown in Fig. 7. Temperature simulation results and test results of the temperature sensor NTC placement are statistically shown in Fig. 8. It can be seen from Fig. 7 that the maximum temperature is 53.9 centigrade at the M8_NTC1. The highest temperature is reasonable here, as the M8_NTC1 is connected to the copper row of the main circuit of the battery pack, and a portion of the heat generated by busbar during the discharge process is passed to busbar in the module. It can be seen from Fig. 8 that the temperature distribution trend of NTC location is basically consistent with the experiment. The temperature difference between simulation and test results at each NTC location is up to 1.4 centigrade, which demonstrates that the prediction accuracy of this method adopted in this paper is exactly satisfactory.
4. conclusion
In this paper, the research on battery thermal management considered the heat exchange between the battery and the outside world in the driving environment of the whole vehicle. The CFD and battery heat management model of the whole vehicle was established. The simulation and test comparison of battery heat management was carried out. The results show that the temperature sensor NTC position test and simulation results are basically consistent, and the temperature difference is up to 1.4 °C, which shows that the analysis method adopted in this paper exhibits high precision. A high-precision thermal management simulation analysis method of power battery can be obtained in this paper, which can effectively support the development of battery thermal management performance.

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