Research on Thermal Management System of Liquid Direct Contact Battery

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Abstract. This paper proposes a thermal management system based on liquid direct contact with battery. The paper first uses the principles of heat transfer and computational fluid dynamics to establish a thermal model for single cells and 48V battery module, the performance of thermal management system which liquid indirect contact with battery and thermal management system which liquid direct contact with battery are compared and analyzed by simulation. The results show that the latter is better than the former in battery temperature rise control and single cell temperature consistency control, and has good application and promotion value.

Keywords: Electric vehicle, Lithium-ion batteries, direct contact, thermal management

1. Introduction
Lithium-ion battery is a vital part of electric vehicles. It is also a key factor affecting the development and promotion of electric vehicles. However, Lithium-ion battery generates a lot of heat during charging and discharging, and the accumulation of heat makes battery temperature continuing rising [1]. In addition, the small space inside the battery pack also bounding to cause uneven accumulation of battery heat. High temperature and uneven temperature distribution will greatly reduce battery cycle life and charge/discharge efficiency [2]. For this reason, a thermal management system which liquid direct contact battery is proposed. This system can not only effectively control the temperature rise of the battery, but also ensure the uniformity of the temperature of individual cells in the battery pack, so it has a good application prospect and promotion value.

2. Structure of thermal management system
In this thermal management system, the battery pack is filled with liquid which means the battery is completely immersed in liquid, this requires the liquid to have good insulation. Transformer oil has the advantages of large specific heat capacity, good thermal conductivity, high ignition point, good insulation. Comprehensive analysis, select transformer oil as the circulating medium of the thermal management system. As shown in Figure 1, the thermal management system described in this article includes batteries, battery box, radiator, oil pump, and filter. The pump is used to circulate the transformer oil in the system, the filter is used to filter the tiny impurities in the transformer oil to ensure the insulation of the transformer oil.
3. Establishment and verification of thermal model of single cell

A rectangular ternary lithium battery is taken as the research object, and the battery shape is shown in Figure 2.

3.1. Battery heat transfer model

To establish the mathematical model of a square battery, you can choose rectangular coordinates. The differential equation for heat conduction of the battery in the rectangular coordinate system can be obtained by Fourier’s law as:

$$\rho C \frac{dT}{dt} = \frac{\partial}{\partial x} (\lambda_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (\lambda_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (\lambda_z \frac{\partial T}{\partial z}) + q$$  (1)

Where, $\rho$ is the battery density, $c$ is heat capacity of battery, $T$ is the battery temperature, $\lambda$ is the thermal conductivity, $q$ is the heat generation rate per unit volume of battery, $\partial T/\partial x$, $\partial T/\partial y$, $\partial T/\partial z$ respectively represent the temperature gradient direction.

3.2. Calculation of battery heat generation rate

The heat generated by battery during work process mainly includes: Heat of reaction $Q_r$, heat of polarization $Q_p$, Joule heat $Q_j$, and heat of side reaction $Q_s$. The battery itself generates heat as:

$$Q = Q_j + Q_p + Q_s$$  (2)

According to the calculation theory proposed by D. Bernardi [3], the heat of polarization reaction can be equivalently processed into a part of the Joule heat, related research shows [4] that when the battery temperature does not exceed 70°C, the total heat generated by battery can be simplified as:

$$Q = I^2 R$$  (3)

Heat per unit volume $q$ as:

$$q = \frac{Q}{V} = \frac{I^2 R}{V}$$  (4)
Where $V$ is the battery core volume.

From formula (4), the heat generation rate of battery is a function of internal resistance which will change with batter's SOC, if a fixed value of internal resistance is used to calculate the heat generation rate, there will be a large error with the actual situation. In this paper, the method of HPPC (Hybrid Pulse Power Characteristic) is used to measurement internal resistance.

Figure 3 depicts the battery charging/discharging current and voltage recorded by the battery test system during the HPPC test. The battery discharge internal resistance is calculated, and the calculation formula obtained after fitting the internal resistance is:

$$R = 4.782SOC^3 - 14.38SOC^4 + 8.941SOC^5 + 4.787SOC^6 - 5.276SOC + 2.715$$  \hspace{1cm} (5)

Put the formula (5) into the formula (4):

$$q = 17.35I^2SOC^3 - 52.17I^2SOC^4 + 32.44I^2SOC^5 + 17.37I^2SOC^6 - 19.14I^2SOC + 9.85I^2$$  \hspace{1cm} (6)

3.3. Obtaining battery thermal properties

In order to simulate the heat transfer process of battery, it is necessary to determine heat capacity, conductivity and density of the battery. According to the data provided in the battery manual, the parameters are shown in Table 1.

| Heat capacity/(J·kg$^{-1}$·k$^{-1}$) | Density/(kg·m$^{-3}$) | Conductivity/(W·m$^{-1}$·k$^{-1}$) |
|-----------------------------------|----------------------|----------------------------------|
| 1387.76                           | 2219.1               | 0.98/5.38/5.38                   |

3.4. Establishment and verification of thermal model of single cell

Figure 3. HPPC test

Figure 4. Three-dimensional model and grid model of battery
A three-dimensional digital model of the battery is established, the grid is divided, and the structured grid is used to improve the grid quality. The three-dimensional digital model and grid model of the battery are shown in Figure 4.

In order to verify the reliability of the thermal model, a temperature monitoring point was set at the center of the battery surface during the simulation, and the battery charging/discharging system was used to record the temperature rise at the center of the battery surface in real time during the battery charge/discharge experiment. Figure 5 shows the relationship between battery temperature test value and the simulation value under the condition of 1C rate discharge. The maximum error between the simulation value and the experimental value is within 3%, so the simulation calculation model can be considered reliable.

4. Thermal management system performance comparison by simulation analysis
This section will compare the difference in heat dissipation effect between indirect thermal management system commonly used in electric vehicles and the liquid direct contact thermal management system proposed in this article by means of simulation. Taking 12 single cells in series to form a 48V battery system for analysis, Extend this model to the battery module level on the basis of single battery thermal model, the physical model and grid model of the two different thermal management systems are shown in Figure 6 and Figure 7.
4.1. Simulation analysis of heat dissipation effect
Taking NEDC operating condition and UDDS operating condition as examples. Under this operating condition, the battery current changes are shown in Figure 8. According to formula (4), the heating power of the battery under the two working conditions are calculated as shown in Figure 9.

Import the divided mesh model into Fluent, and set the initial conditions, boundary conditions and heat source of the model. Both two model use a velocity of 1m/s as the inlet boundary condition, and the temperature is 25°C. The outlet boundary condition is set as the pressure outlet, standard k-ε model is used to calculate the flow of the fluid. In order to better reflect the temperature change of the battery surface during discharging, two temperature monitoring points are specially set up as shown in Figure 10.

Figure 8. Current changes under NEDC and UDDS conditions

Figure 9. Heat generation under NEDC and UDDS conditions

Figure 10. Temperature monitoring points
Calculating the temperature changes of the battery module under the conditions of no cooling, indirect contact cooling and liquid direct contact cooling when the battery are working in NEDC and UDDS conditions, The results are shown as Figure 11 and Figure 12.

From the simulation results, it can be seen that the battery running under NEDC and UDDS conditions produce few heat under normal temperature condition, the battery temperature rise does not exceed 4°C after one cycle of working condition even without cooling. However, if no cooling measures are taken, the battery temperature will exceed the optimal operating temperature range after driving multiple working conditions. Due to the good thermal conductivity and large specific heat capacity of transformer oil, the heat dissipation effect of liquid direct contact is much higher than that of indirect contact. The simulation results show that under the same situation, the cooling effect of the direct contact with transformer oil is more than twice that of the indirect contact cooling method. After simulation, the temperature field distribution of batteries are shown in Figure 13 and Figure 14. From the perspective of batteries surface temperature consistency, the cooling method based on liquid direct contact can well control the battery surface temperature difference within 1°C instead of indirect contact cooling reaches 2°C or more, this is because the indirect contact system takes away the heat by the cooling liquid circulating in the cold plate by means of thermal conduction. The bottom of the battery is closest to the cold plate, and the heat taken away is higher than the top, thus making battery temperature distribution present the situation of increasing from bottom to top seriously damages the battery temperature consistency.
5. Conclusion
This paper compares and analyzes the difference of heat dissipation performance between liquid direct contact battery thermal management system using transformer oil as the medium and the indirect contact battery thermal management based on cold plate through simulation. The results show that the heat dissipation effect of the former is twice of the latter and has better temperature consistency of single battery. This thermal management method has good engineering promotion and application value.

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