Research on Lithium-Ion Battery Module Thermal Characteristics Based on Vortex Tube and Semiconductor Refrigeration

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Abstract: In order to improve the safety performance of electric vehicle power batteries at medium and high temperatures, this paper proposes a new battery module heat dissipation method combining vortex tube refrigeration and semiconductor refrigeration. It has advantages of safety, reliability, fast heat dissipation and uniform temperature field distribution. Through installing and testing the solid model of the new battery pack cooling system, graphs of thermal characteristics of the battery module under different discharge rates (1C/3C/5C) were obtained. Compared with the traditional air-cooling mode, this heat dissipation system can effectively control and adjust the temperature of the battery module.

1. Introduction

Power battery is the key component of electric vehicles. Its advantages and disadvantages directly affect the safety performance of electric vehicles. If the lithium-ion battery is operated in the environment of medium or high temperatures for a long time, the battery performance will be reduced and the service life will be shortened. In serious cases, thermal runaway will lead to explosion accidents, endangering the safety of the vehicle. In addition, if the internal temperature of lithium-ion battery is not evenly distributed, the performance of each cell module will be uneven; the battery capacity and charging times will be affected. Therefore, the research on the thermal characteristics of lithium batteries has significant impacts on the safe and reliable operation of modern electric vehicles.[1]

Currently, the power battery thermal management system ensures the battery pack to work within a certain temperature range by means of air cooling, liquid cooling and air conditioning cooling. Main functions of the battery pack include rapid cooling when the internal temperature is too high, fast ventilation when the exhaust gas is generated, fast preheating to make the battery work normally under the low temperature operation condition, and ensuring the uniformity and consistency of the temperature field distribution inside the battery.

2. System Overall Design and Modeling

2.1 Internal Control of the Power Battery Pack

This system combines the vortex tube refrigeration technology with the thermo-electric semiconductor refrigeration technology to control the thermal management of power batteries in electric vehicles. As shown in Figure 1, semiconductor refrigeration chips are packaged on both sides of the single battery pack. After being electrified, the refrigeration sheet generates the Peltier effect. The inner end absorbs heat and can quickly absorb the heat in the single battery pack to reduce the internal temperature. The hot air flow is discharged through the outer channel. The vortex tube is installed in the battery pack. High-pressure gas enters the vortex chamber along the tangent direction at a very high speed to form the inside and outside vortex; the air flows in the central layer, losing energy and forming the cold air flow. On the contrary, the outer air flow forms hot air flows; the cold

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and hot air flows which are separated from the vortex tube are responsible for the thermal management and control of the battery pack.

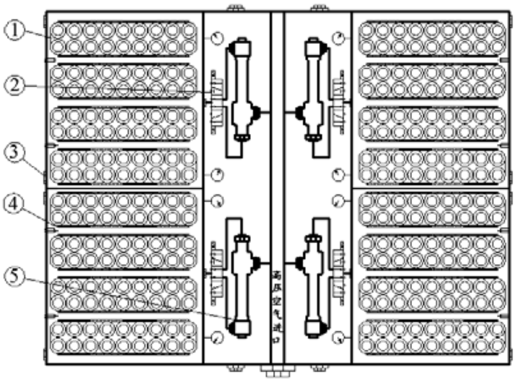

Fig.1 Internal Structure of the Power Battery Pack

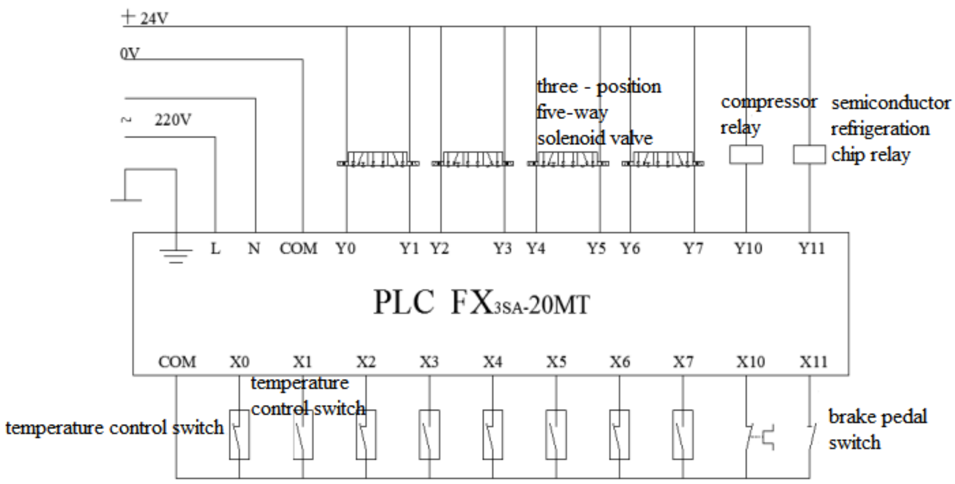

Fig.2 System Plc Control Chart

1:Single battery pack, 2: three - position five-way solenoid valve, 3: vent hole,
4: semiconductor refrigeration unit, 5: vortex tube

2.2 Battery Management Plc Control Module

As shown in Figure 2, the system takes Mitsubishi PLC FX3SA as the control unit; the input terminal X has temperature control switches 1-4, the thermal relay and the brake pedal switch. The output terminal Y has three-position five-way solenoid valves 1-4, the compressor relay solenoid coil and the semiconductor refrigeration chip relay coil. Each solenoid valve is responsible for controlling hot and cold air flows of the battery pack.

For example, when the temperature in the battery pack 1 is lower than 15 degrees, the temperature control switch 1 (normally closed) is connected with x0; the PLC output terminal Y10 has signals, and the air compressor starts to work. At the same time, the PLC output terminal Y6 has output signals; the three-position five-way solenoid valve 1 (in left position) is in the upper position. The hot air flow enters the battery pack through the solenoid valve for preheating; the cold air flow is discharged through the solenoid valve, and discharged from the power battery pack through the battery outlet. When the temperature in the battery pack 1 is higher than 15 degrees, the temperature control switch 1 (normally closed) x0 is disconnected; the PLC control output terminals Y6, Y7 and Y10 have no output signals. The solenoid valve 1 is in the middle position; the air compressor does not work. The 15 degrees - 40 degrees thermal management system does not work. This is the best working temperature of the power battery. When the temperature in the battery pack 1 is higher than 40 degrees, the temperature control switch 1 (normally open) x1 is connected; the PLC output terminal Y7 has output signals; the right position of the solenoid valve 1 is powered on and in the lower position. Cold air flows into the battery pack through the solenoid valve 1 for cooling, and the hot air flows through the air outlet to discharge from the power battery pack. At the same time, when the temperature is higher than 40 degrees, the PLC output terminals Y10 and Y11 work. The relay coil of the semiconductor refrigeration chip is powered on, and the power supply of the semiconductor refrigeration chip is connected to start refrigeration. During this period, the semiconductor refrigeration plate and vortex tubes are combined for heat dissipation, so that the temperature in the power battery pack is cooled to the best state (15 to 40 degrees).

2.3 Control Principle and Material Object of the Electric Drive System

The schematic diagram of the electric drive system is shown in Figure 3. The electric drive system accessories include, the vehicle controller, the battery module, the display screen, the motor controller, the electronic throttle, DC / DC, the vehicle charger, the motor, and so on. According to the control principle and performance requirements of the system, we install real objects of the system, as shown in Figure 4.

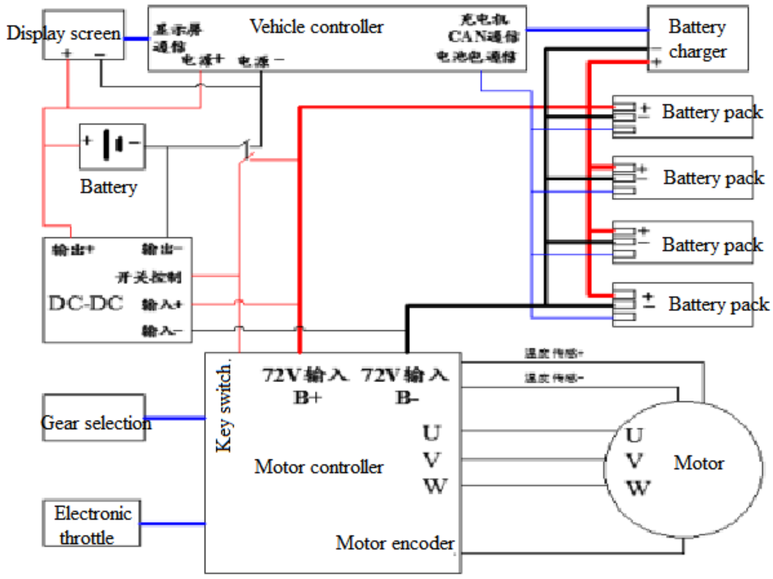

Fig.3 Schematic Diagram of the Electric Drive System

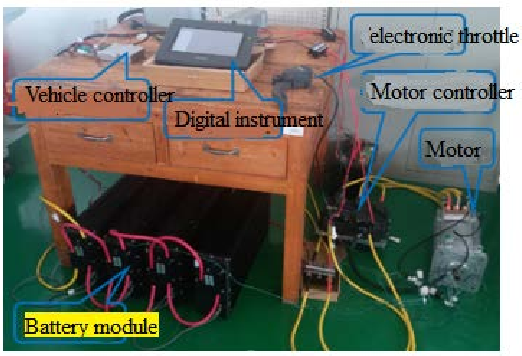

Fig.4 Electric Drive System Physical Display

3. Analysis of the Thermal Characteristic of Lithium-Ion Batteries

3.1 Heat Generation Mechanism of the Lithium Battery

During the charging and discharging process of the lithium-ion battery, the reaction equation is as follows.

The positive electrode:

$$LiMO_2 \rightleftharpoons Li_{1-x}MO_2 + xLi^+ + xe \qquad (1)$$

The negative electrode:

$$nC + xLi + xe \rightleftharpoons Li_xC_n \qquad (2)$$

The total reaction formula:

$$LiMO_2 + nC \rightleftharpoons Li_{1-x}MO_2 + Li_xC_n \qquad (3)$$

Where M is Co, Ni, Fe, Mn, etc.

The internal heat of the lithium-ion battery is produced in above chemical reaction process. Main heat sources include the positive and negative electrodes, as well as the decomposition and reaction of the electrolyte and the electrolyte interface.[2][3] In addition, a certain amount of heat will be generated when the current passes through the internal resistance of the battery. The total heat production Q is:[4]

$$Q = \sum ja_{sj}i_{nj}(\phi_s - \phi_e - U_j) + \sum ja_{sj}i_{nj}T\frac{\partial U_j}{\partial T} + \sigma^{eff}\nabla\phi_s\nabla\phi_s + k^{eff}\nabla\phi_e\nabla\phi_s + k^{eff}\nabla \ln c_e \nabla\phi_e$$

(4)

In the formula, T is the temperature; a_{sj} is the interface area (cm^2/cm^3), i_{nj} is the current density (A/cm^2), ϕ_s, ϕ_e and U_j are the matrix potential, the solution potential and equilibrium potential (V) respectively; σ^{eff} is the effective conductivity (Ω^{-1}cm^{-1}); c_e is the electrolyte concentration (mol/cm^3). [5]

3.2 Heat Generation Rate of Single Cell

In fire accidents of electric vehicles caused by the thermal runaway of lithium-ion batteries, the main reason is that the heat dissipation rate of the battery is lower than the heat generation rate, and the internal heat of the battery is not dissipated in time, resulting in a large amount of accumulation. Therefore, in 1985, Bernardi established the Bernardi model for the heat generation rate of the battery.[6] The model assumes that the heat rate is uniformly distributed, and determines the relationship between the internal heat generation rate and the electric field of the cell. The heat generation rate q is :

$$q = \frac{I}{V_b}[(E_0 - U_I) - T\frac{dE_0}{dT}](J/m^3s) \qquad (5)$$

Where E_0 is the open circuit voltage; U_I is the terminal voltage; V_b is the battery volume, and I is the battery charging and discharging current.

The relationship between the internal resistance R and temperature t is:[7]

$$R = -0.0001t^3 + 0.0134t^2 - 0.5345t + 12.407(m\Omega) \qquad (6)$$

As $E_0 - U_I = IR$, equation (5) can be expressed as:

$$q = \frac{1}{V_b}[I^2R - IT\frac{dE_0}{dT}] \qquad (7)$$

It can be seen from the above formula that the heat generation rate q of the single cell changes with the temperature t. [8]

4. System Test and Data Analysis

4.1 Performance Debugging of the Battery Module

The battery module produced by Guangzhou Yiwei Electric Vehicle Co., Ltd. is used as the research object. As shown in Figures 5 and 6, the total battery voltage is 78V; the maximum single battery voltage is 3.931V; the motor working current is from 0A (when the motor is stationary) to 25A (when the motor speed is 4700r/min). The experiment was carried out at room temperature of 25 degrees and relative humidity of 67 ± 5%. The measured values of various parameters are shown in Figures 7 and 8.

Fig.5 Battery Module Main Parameter Debugging

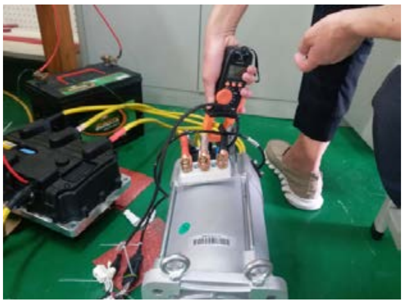

Fig.6 Motor Performance Parameters Detection

Fig.7 System Operation Information

Fig.8 Single Battery Pack Work Information

4.2 Analysis of Thermal Characteristics of the Battery Module under Different Discharge Rates

Under the high temperature condition inside the battery, the 1C, 3C and 5C rates constant current discharge tests were carried out on the single battery by using the traditional air cooling mode and this cooling system. The measured data curves are shown in Figures 9 to 11. According to the curve 11, under the high temperature condition (40 degrees) at the 5C rate, the battery temperature began to rise slowly, and the average temperature of this cooling system was always lower than that of the air cooling mode. At the time points of 40 minutes and 44 minutes, the air cooling mode and this system reached the maximum temperature of 51.4 degrees and 48 degrees; the temperature difference was 3.4 degrees. After reaching the maximum temperature, the temperatures of the two systems show a downward trend. The cooling rate of this system is fast, which is obviously better than that of the air cooling mode.[9]

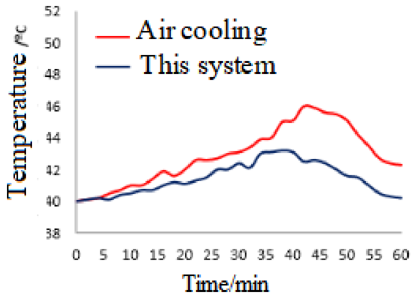

Fig.9 Temperature Curve of 1c Rate Discharge

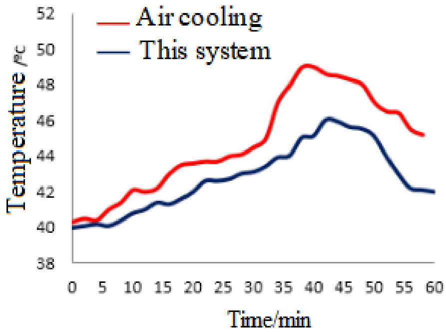

Fig.10 Temperature Curve of 3c Rate Discharge

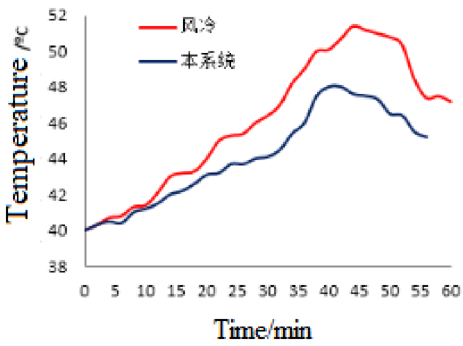

Fig.11 Temperature Curve of 5c Rate Discharge

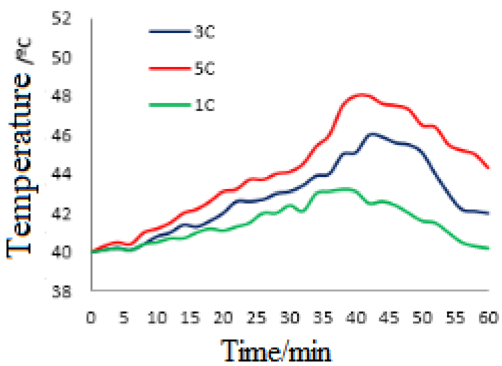

Fig.12 Temperature Contrast Curves of Different Discharge Rates

温度 Temperature 时间 Time

The temperature rise curves of 1C, 3C and 5C rates of this cooling system can be obtained through the constant current continuous discharge of the single battery module with different discharge rates, as shown in Figure 12. In 1C discharge, the temperature slowly increases from 40 degrees to 43.2 degrees, while in 5C discharge, the temperature rises from 40.1 degrees to 48 degrees. The maximum temperature difference between them is 4.8 degrees. The data shows that the temperature rise of the single battery module increases with the increase of rate. Therefore, when discharge at high rates at high temperature, the lithium-ion battery needs heat dissipation to achieve the best working state.[10]

5. Summary

In this paper, based on the electric drive system accessories of electric vehicles provided by Guangzhou Yiwei Company, a new cooling modeling method of the battery module is designed. The method applies the vortex tube and semiconductor refrigeration technology in the power battery thermal management system. Through the establishment of the system entity model, constant current discharge tests of the single battery module were carried out with different rates. The analysis of experimental data shows that, with the increase of the discharge rate of a single battery, the current also increases; the phenomenon of battery heat generation can become more serious. Compared with the temperature curve of the air-cooled battery module, the average temperature of this system after heat dissipation is always lower than that of the air-cooled mode, and the cooling speed is faster. It indicates that the battery cooling system combined with the vortex tube and semiconductor refrigeration has certain advantages. However, this experiment is limited to the no-load operation of the electric drive system of vehicles. In the future, the thermal characteristics of the battery should be studied based on the actual driving conditions of electric vehicles, and the cooling system of the battery module should be optimized to match the design of the whole vehicle. These researches on the thermal characteristics of the battery can be more in line with the actual situation of electric vehicles, and can increase the circularly charging and discharging times of the electric vehicle power battery and improve the driving safety.

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