THERMAL PERFORMANCE ANALYSIS AND OPTIMAL CONTROL OF POWER LITHIUM CELL THERMAL MANAGEMENT SYSTEM FOR NEW ENERGY VEHICLES

by

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To improve the service life and performance of lithium cells in new energy electric vehicles, the thermal management system of lithium cells in new energy vehicles is analyzed through simulation experiments in this research. Firstly, the calculation model of set of cells and cooling structure is built, and then a lithium cell management system is designed. On this basis, the cooling structure of lithium cell is optimized. Finally, the simulation results of the calculation model and the simulation results of the heat dissipation performance of the thermal management system in the cooling structure of lithium cell are analyzed, including influence of three factors (coolant flow, inlet temperature of coolant, and discharge multiple) on the heat dissipation of the thermal management system of lithium cell. The results show that the calculation model constructed in this research is feasible. When the optimal structure, coolant flow value, inlet temperature of coolant, and discharge multiple are determined, the thermal management system of lithium cell has a good cooling effect under the optimal parameters. Therefore, the results of this research can provide a good theoretical basis for heat management and heat dispersion technology in new energy electric vehicles.

Key words: *new energy electric vehicle, heat dispersion performance, thermal management system, lithium cell*

Introduction

Nowadays, the car has become one of the main means of transportation for people to go out. Before the 20th century, the power of the car depended on the output of fuel. However, at present, the consumption rate of fuel energy such as oil is too fast, and the environmental pollution caused by energy shortage and exhaust gas emitted by oil-fueled vehicles has become more and more serious. Therefore, scientists began to study new ways to provide power for automobiles. Electric vehicles have won worldwide attention for their high energy conversion efficiency and *zero* emissions [1, 2].

The lithium cell (LC) have the advantages of non-pollution and low cost, which are the largest in the loading of electric vehicles [3]. Compared with other batteries, LC are the most popular in the electric vehicle industry, but LC have the worst safety performance. For new-energy electric vehicles adopting LC, the key is to solve the related problems of driving motor and battery [4]. As a pure electric vehicle, a driving motor with high power but small

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volume is generally adopted. In addition, it must have the characteristics of good braking effect, fast torque response speed, and high instantaneous power. At present, the driving machine with the aforementioned characteristics will generate much heat during driving process of electric vehicle. In the pure electric vehicle, since set of cells is composed of many small battery modules, each battery module is composed of multiple single batteries in series and parallel [5,6]. The continuous accumulation of heat in the sealed narrow space inside the vehicle will have a different degree of influence on the performance of each single battery in the battery module. If the discharge continues, the heat and temperature will be distributed unevenly in the battery module, leading to a series of serious consequences such as the capacity degradation, performance degradation, and explosion of the battery module, which will have a serious impact on the battery life in electric vehicles [7]. Therefore, it is meaningful for development of electric vehicle industry to design a reasonable thermal management method to take away the heat.

To sum up, to extend the service life of LC of electric vehicles, the heat dissipation performance of thermal management system of LC for new energy electric vehicles is analyzed and its cooling structure is optimized. It is hoped that this research will provide a good idea for the improvement of electric vehicle thermal management technology.

Methods

Construction of calculation model for set of cells and cooling structure

In a battery cooling system, heat is transferred from the battery cell to the cooling flat tube, which is then carried away by the flow of coolant in the flat tube. Therefore, mathematical models are used to represent the continuity equation, momentum conservation equation, and energy conservation equation in the whole cooling system [8, 9].

The continuity equation can be expressed:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial v}+\frac{\partial(\rho w)}{\partial w}=0 \tag{1}$$

where ρ [kgm^{-3}] is the density, u, v, and w – the components of the velocity vector on x, y, and z, respectively.

Equations (2)-(4) represent the momentum conservation:

$$\operatorname{div}(\rho u\vec{\mathrm{u}})=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \tau_{zx}}{\partial x}+F_x \tag{2}$$

$$\operatorname{div}(\rho v\vec{\mathrm{v}})=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+F_y \tag{3}$$

$$\operatorname{div}(\rho w\vec{\mathrm{u}})=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+F_z \tag{4}$$

where p is the pressure acting on the computational domain, F_x, F_y, and F_z – the force of micro-elements in the computing domain, τ_{xx}, τ_{xy}, and τ_{xz} – the component of viscous stress acting on the calculated domain element.

The energy conservation:

$$\frac{\partial(\rho T)}{\partial t}+\operatorname{div}(\rho u T)=\operatorname{div}\left(\frac{\lambda}{C_p}\operatorname{grad}T\right)+S_T \tag{5}$$

where T [°C] is the temperature, λ [Wm^{-1}K^{-1}] – the heat transfer coefficient of medium, C_p [Jkg^{-1}°C^{-1}] – the specific heat capacity, and S_T – the viscous dissipative term.

The flow model:

$$\mathrm{Re} = \frac{vl}{\nu} \tag{6}$$

where ν [ms^{-1}] is the kinematic viscosity of fluid medium, l [m] – the characteristic length of pipe, and v [m^{2}s^{-1}] – the velocity of fluid.

In this research, during the process of boundary condition selection and initialization, the inlet boundary condition of the cooling medium is taken as inlet of velocity, the outlet is taken as pressure outlet, and fluid-solid coupling interface is set as the non-slip moving boundary. The cross-ventilation heat transmission is set as natural-convection, the natural-convection coefficient is 6 W/mK, and ambient temperature is 25 °C.

Finite volume method and under relaxation method are adopted to solve the discrete model. However, to ensure the accuracy of the experimental results, the model is discretized with the second order upwind format [10]. The SIMPLE algorithm is used to solve the pressure-velocity coupling problem. Since essence of CFD software is to solve differential equations, the accuracy of iteration depends on the difference between the previous calculation result and the next one. When the difference between the two is 0, it can indicate that the algorithm has high accuracy, but the theoretical accuracy cannot be achieved in the actual test [11, 12]. Therefore, the convergence of the algorithm is judged according to the residual value, and the residual value of fluid velocity, temperature, pressure, and other relevant factors is set as 10^{-4} in the simulation experiment, so as to obtain as accurate a calculation result as possible under the allowed conditions.

Design of lithium battery thermal management system

In new energy electric vehicles, although the structure of fluid cooling is more complicated than that of cooling by means of air, the cooling effect is much higher than that of cooling by means of air. In addition, liquid heating device can be designed in the liquid cooling structure to ensure that the performance of LC in low temperature environment is not affected. Liquid cooling is a method of adopting liquid materials as a cooling medium and removing heat through direct or indirect contact with a heat source. The battery can be cooled by placing a cooling splint around the battery or by immersing the battery module in a liquid material with good insulation, such as insulating oil. However, given the safety of LC and other factors, many researchers attach great importance to indirect contact cooling methods. Figure 1 is the cooling structure of the set of cells with a micro cooling flat tube. The top is the cooling flat tube, which is placed at bottom of set of cells in actual assembly. By adding the cooling flat tube, the cooling medium can eliminate heat generated by the set of cells during movement of flat tube, thus cooling the set of cells. And its structure has the characteristics of small volume and small space.

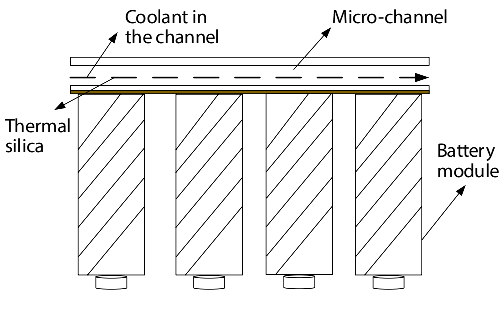

Figure 1. Design of cooling structure of set of cells

The cooling structure of the set of cells is to assemble four batteries into a set of cells. To reduce the wireless generated by the contact thermal resistance between the set of cells and cooling floor, a layer of thermal conductive silica gel is added between the set of cells. In process of conducting the cooling performance experiment, the equipment used is the charge and discharge instrument (model: the HEW series; manufacturer: Di Caro, Germany), the constant temperature water tank, the heat preservation barrel, the adjustable speed water pump, the flowmeter and so on.

Optimal design of lithium battery thermal management system

To optimize thermal management system of set of cells, cooling structure of the set of cells is simplified by modelling. Two schemes are designed to optimize the thermal management system of set of cells. First, the optimization scheme of the micro-channel cold plate placed on side wall of battery. Second, the optimization scheme in which micro-channel cold plate is placed on side wall and bottom of the battery. The effects of the two optimization schemes on thermal management performance of battery under the same cooling conditions are studied by simulation experiments.

Results

Analysis of simulation results of thermal management system calculation model in lithium ion battery cooling structure

In this research, FLUENT software is used to conduct simulation calculation on 3-D model of the set of cells. Parameters of the cooling structure of the set of cells are listed in tab. 1.

Table 1. Main parameters of lithium battery thermal management system

Name of parameter	λ [Wm^{-1}K^{-1}]	ρ [kgm^{-3}]	C_p [Jkg^{-1}°C^{-1}]
Battery core	0.927/2.742	2417	893
Coolant	204	2720	872
Silicic acid that conducts heat	2.1	2100	1900
Flat tube	0.5	1100	4200

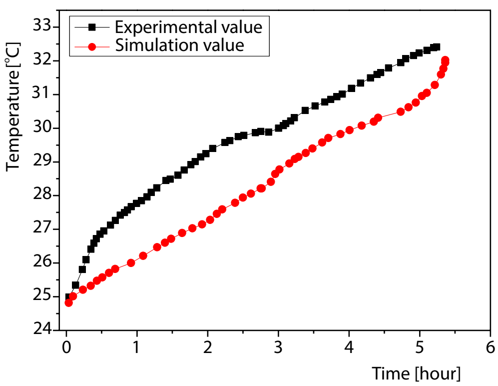

Figure 2. Experimental verification of the calculation model of the set of cells thermal management system

It can be observed from fig. 2 that simulation results of designed model are similar to the experimental results, which indicates that the calculation model designed in this research is accurate and feasible. Temperature inhomogeneity of the battery module is the main reason affecting cooling performance of cooling structure.

Figure 3 indicates maximum temperature rise curve of the set of cells designed with cooling structure under three different schemes. Among them, the three schemes are the initial design scheme, Scheme 1 and Scheme 2. As can be observed from the fig. 3, in the initial design scheme, the battery's maximum temperature rises the fastest, with the maximum temperature rising to about 35 °C, followed by Scheme 1 and finally Scheme 2. In the optimization design of cooling structure, with the extension of discharge time, the maximum temperature in Scheme 1 and Scheme 2 increases first, then decreases, and increases after maintaining for a period of time. When discharging for 1 hour, the maximum temperature distribution of Scheme 1 and Scheme 2 rises to 25.7 °C and 24.9 °C. When the discharge lasts for 5 hours, the maximum temperature is 25.1 °C and 23.5 °C, respectively. Then it begins to rise again, and the maximum temperatures of Scheme 1 and Scheme 2 are 26.5 °C and 24.1 °C. After comparison, it is found that the optimized structure of Scheme 2 has the best effect.

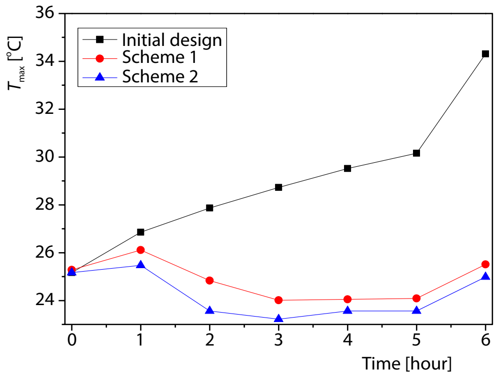

Figure 3. Maximum temperature rise curve of the set of cells with cooling structure under three different schemes

Analysis of simulation results of heat dissipation performance of thermal management system in cooling structure of lithium ion battery

Effect of coolant flow on heat dissipation performance of lithium ion battery thermal management system

Figure 4 shows the influence of different coolant flow on the heat dissipation performance of LC thermal management system at room temperature. As can be observed from the fig. 4, the maximum temperature of the battery thermal management system decreases with increase of coolant flow. When coolant flow is 1 Lpm, the maximum temperature of battery thermal management system becomes 24.8 °C after one hour of discharge, and minimum temperature of battery thermal management system is 23.2 °C after five hours of discharge. Similarly, when coolant flow is 2 Lpm, the maximum temperature is 23.7 °C after one hour of discharge, and maximum temperature of battery is 22.7 °C after five hours of discharge. When coolant flow is 3 Lpm, maximum temperature is 22.7 °C after one hour of discharge, and maximum temperature of battery is 21.3 °C after five hours of discharge. It can be concluded from the change of the flow of three different coolants with the discharge time that the maximum temperature keeps falling with the increase of the discharge time in the first five hours, and the maximum temperature will rise when the discharge time exceeds five hours. Because after discharging for more than five hours, the internal resistance of the battery thermal management system will increase dramatically, resulting in a rapid increase in the point differential heat generation rate and a rapid increase in temperature of set of cells. According to the variation trend of the coolant flow in three groups, when coolant flow is

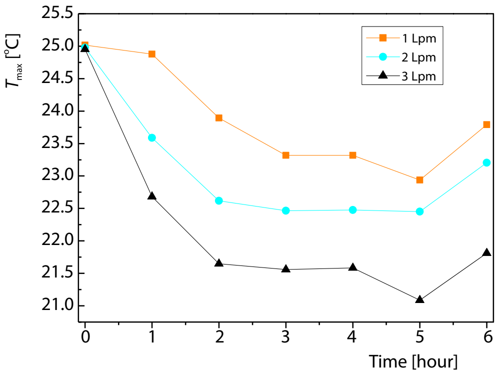

Figure 4. Influence of different coolant flows on heat dissipation performance of lithium ion battery thermal management system

2 Lpm, temperature tends to be stable after discharging for more than one hour, and the temperature is well controlled within 22.5 °C.

Effect of inlet temperature of coolant on heat dissipation performance of lithium ion battery thermal management system

According to the analysis in section *Analysis of simulation results of thermal management system calculation model in lithium ion battery cooling structure*, it can be known that when coolant flow rate is 2 Lpm, maximum temperature control effect of thermal management system is better. Therefore, when discussing the influence of coolant temperature on heat dissipation in thermal management system of LC, 2 Lpm of coolant flow is adopted. Figure 5 shows the influence of different coolant temperatures on thermal management performance of set of cells. In fig. 5, with increase of discharge time, when inlet temperature of coolant is 15 °C, battery's maximum temperature decreases with increase of discharge time, and it suddenly increases after 5 hours, the maximum temperature is 23.1 °C, and then it begins to decline again. Therefore, when inlet temperature of coolant is 15 °C, maximum temperature of battery thermal management system appears at 5 hours. At coolant inlet temperature of 20 °C, change trend of thermal management performance is the same as that at 15 °C. However, the rate of decline and growth is not as fast as the coolant inlet temperature of 20 °C. When temperature of coolant is 25 °C, with the increase of discharge time, the maximum temperature response is unstable, showing a wave type. According to influence of different coolant inlet temperatures on thermal management performance of battery, cooling effect of battery will be better with the decrease of coolant inlet temperature. However, since temperature difference between inlet of coolant at 15 °C and environment is too large, and considering the condition limitation of thermal conductivity of battery cell, battery's maximum temperature will fluctuate greatly at the beginning of discharge. Moreover, LC are more suitable for working in a stable temperature environment, so the inlet temperature of coolant should not be too low, and it is most suitable when coolant inlet temperature reach 25 °C.

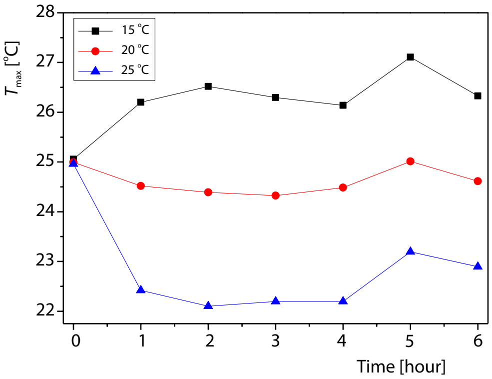

Figure 5. Influence of different inlet temperatures of coolant on battery thermal management performance

Effects of different discharge ratios on the heat dissipation performance of lithium ion battery thermal management system

The previous results determine optimal values of coolant flow and coolant inlet temperature. In this section, optimal discharge rate is analyzed. Figure 6 represents change curve of maximum temperature of each battery with time under the 2C discharge rate. As can be observed from the fig. 6, under the discharge rate of 2C, within 1 hour before discharge, maximum temperature of four single batteries rises rapidly from 25 °C to 26.6 ~27.1°C, which is caused by the limited thermal conductivity in the battery cells. After 1 hour, the rise of the maximum temperature tends to be slow and there is a slight decline trend. At five hours after discharge, the maximum temperature starts to rise sharply again. At the end of the discharge, the temperature distribution of the four different monomers is between 28.3 °C and 28.75 °C. This is because at the end of discharge, the thermal conductivity of battery cell also increases rapidly, and maximum temperature of each cell increases rapidly. After the discharge reaction, the maximum temperature of the set of cells can be cooled to no more than 29 °C. Compared to the discharge rate at 1C, battery's maximum temperature increases, because the cell releases more heat per unit of time when discharge rate is increased. Under the same cooling conditions, temperature of battery can also be controlled within the optimal operating temperature range, indicating that optimized cooling structure still has a satisfactory cooling effect.

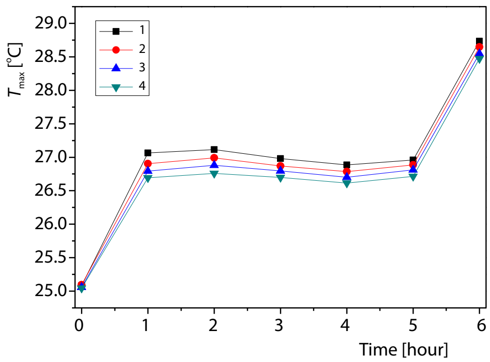

Figure 6. Variation curve of maximum temperature of each battery with time under 2C discharge rate

Figure 7 is the change curve of maximum temperature of each battery with time under 3C discharge ratio. The change curve of maximum temperature of each battery with time under 3C discharge rate is the same as the cooling conditions of discharge rate of 1C and 2C. In fig. 7, under the 3C discharge rate, maximum temperature of each battery increases with increase of time. When discharge reaction starts for 1 hour, the highest temperature of battery rises to above 29 °C. Temperature increases with increase of discharge time. At last, temperature increases to more than 32 °C, but not more than 35 °C. The optimal operating temperature of LC in power state is 29~40 °C, which does not exceed the optimal operating temperature in power state. Therefore, in the case of 3C discharge ratio, the optimized cooling structure of Scheme 2 can also achieve good control of the temperature rise of the set of cells, with better cooling effect.

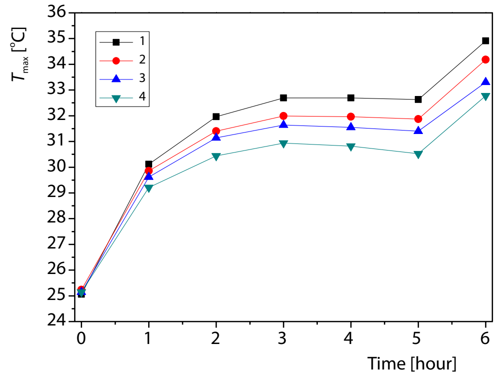

Figure 7. Variation curve of maximum temperature of each battery with time under 3C discharge rate

Discussion

In recent years, new energy electric vehicles have become more and more popular because of their high energy conversion efficiency and zero emission. Many scholars have also conducted related research, for example, Li *et al*. [13] proposed a new liquid cooling system for battery thermal management. Considering that the copper tube and the silicon cold plate have excellent cooling effect of flexibility and elasticity on the battery, the combination of the silicon cold plate and the copper tube constructed in this way was an effective method. For comparison, natural cooling by means of air and forced cross-ventilation cooling systems based on silicon cold plates were put forward. Experimental results indicated that designed cooling system could be achieved at a cooling temperature that the natural air-cooling system could hardly reach. Although this system could improve the cooling effect to some extent, battery module's temperature could not be controlled below 45 °C during cycle test. In this study, thermal conductive silica gel is also adopted in structural design. The LC thermal management system can control the temperature below 35 °C during the heat dissipation performance simulation test. Similarly, Liang *et al.* [14] constructed a 3-D battery model and verified the model through experiments, they studied the effects of different coolant temperatures, lithium ion concentrations, and discharge ratios on thermal management performance of battery. Research results showed that as temperature of cooling liquid was decreased, temperature difference between modules was increased despite the decrease of the maximum temperature, and battery near the inlet had a large local temperature difference. At a discharge rate of 5C, coolant's temperature was decreased to 10 °C, the voltage of the battery module was decreased, and the available capacity was decreased by about 0.88-1.17%. The research of [14] and this research both studied the heat dissipation performance of LC thermal management system through simulation experiments.

Conclusions

In this study, to solve the problems of shortening the life of the new energy electric vehicle LC due to the large driving force caused by too much heat generated by the set of cells during driving process and the potential safety hazards of the vehicle, the cooling structure of lithium electric car of new energy vehicles is optimized, and the heat dissipation property of optimized thermal management system is analyzed. Firstly, construction of set of cells and cooling model is introduced. Through the verification of the model, it is found that the model constructed in this research is accurate and feasible. Moreover, the temperature inhomogeneity of the battery module is the main reason affecting cooling property of cooling structure. Then, two sets of LC cooling mechanism are designed based on the initial cooling structure. After the experiment, it is found that Scheme 2 has better cooling effect. Next, the design structure of Scheme 2 is used as the model to explore cooling property of the LC thermal management system under different coolant flow rates, coolant inlet temperatures, and discharge ratios. It is found that when coolant flow rate is 2 Lpm, coolant's inlet temperature is 25 °C, the discharge rate of three times has a satisfactory cooling effect.

The results in this research have promoted the development of the electric vehicle industry. However, this research still has certain limitations, for example, the internal structure of the battery is not included in the model. It is hoped that the internal structure of the battery can be included in the simulation model in the future to improve the depth of this study.

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