RESEARCH ON THERMAL EQUILIBRIUM PERFORMANCE OF LIQUID-COOLED LITHIUM-ION POWER BATTERY SYSTEM AT LOW TEMPERATURE

by

Xudong SUN, Xiaoming XU*, Jiaqi FU, Wei TANG, and Qiuqi YUAN
School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang, China

Original scientific paper
https://doi.org/10.2298/TSCI200118155S

The development of electric vehicles is an important trend in the automotive industry, in which the performance of power batteries is greatly affected by temperature. In recent years, it has been widely concerned that the performance of power batteries at low temperature will lead to the vehicle failure to start because of the bad thermal equilibrium of power battery heating system. This paper studies the thermal equilibrium performance of battery liquid heating system at low temperature. Inlet temperature, heating time, ambient temperature, and their coupling relationship to battery thermal equilibrium performance are studied by orthogonal experimental design method. It is expected that this study can provide reference for the parameter selection of battery heating system.

Key words: *power battery, liquid heating system, orthogonal experimental design, heating time, thermal equilibrium performance*

Introduction

Since the 21st century, as environmental pollution has intensified and resources have gradually become scarce, the world is looking for green energy. The electrification of transportation has also become a technological trend, the most important of which is the vigorous development of new energy vehicles. The electrification of vehicles has attracted widespread interest from major car companies and research institutes worldwide [1]. As the power source of new energy vehicles, the performance of the power battery system determines the performance of the car. At the same time, the operating temperature has a significant impact on the performance of lithium-ion batteries [2, 3]. Lithium-ion batteries have a narrow temperature range. If the temperature is too low or too high, battery performance will decline, which will affect battery safety and cycle life [4]. If the temperature is too high, it may cause permanent battery failure or even thermal runaway, which may cause fire or explosion [5, 6]. In addition to the overall temperature of the battery, thermal equilibrium performance between the batteries is also very important. If the temperature difference between the batteries is too large, the battery capacity will be attenuated if it is light, and a certain battery will fail if it is heavy [7]. An efficient thermal management system is so important for the power battery system that it can guarantee the ability of the battery to continue to work, and it can also prevent thermal runaway. Therefore, the thermal flow field characteristics of power battery systems can be studied by

* Corresponding author, e-mail: xuxiaoming3777@qq.com

experiments or CFD methods to analyze the advantages and disadvantages of thermal management systems [8-10].

According to the difference in the form of thermal management, the methods of battery thermal management can be divided into air cooling, liquid cooling (including microchannel cooling [11]), and phase change material cooling [12, 13]. Based on the field synergy principle, Xu *et al.* [14,15] used the CFD method to study the thermal flow field characteristics of air-cooled battery pack. The research results show that: to improve the heat dissipation effect of the battery system, the speed of the cooling air can be increased and the temperature of the cooling air can be reduced, which can improve the synergy between the speed field and the temperature field. Saw *et al.* [16] analyzed the air cooling capacity of the battery system based on the CFD method. Numerical simulations show that the heat dissipation performance of the thermal management system is positively related to the cooling air-flow, heat transfer coefficient, and pressure drop. Shang *et al.* [17] designed a battery liquid cooling system that can change the contact surface. At the same time, he used a combination of single factor analysis and orthogonal experiments to optimize the mass-flow, inlet temperature, and cooling plate width. In addition, in order to optimize thermal management performance, he analyzed the effects of cooling plate width, mass-flow, and inlet temperature to get the best matching design. Zhang *et al.* [18] established a phase change memory (PCM) model and numerically simulated it. As a result, it was found that the battery system using PCM has good heat dissipation performance.

Lithium-ion battery systems can dissipate heat through a thermal management system at high temperatures, or they can be heated by a thermal management system at low temperatures. With the decrease of temperature, the discharge voltage and discharge capacity of the battery were significantly reduced especially below 0 °C. At –20 °C, the capacity of the lithium-ion battery will be permanently attenuated when it is working, and at –40 °C, the lithium-ion battery basically cannot work. In order to ensure that the battery pack of the emergency traction battery system can be normally discharged under extremely low temperature environment, the battery pack needed to be heated. Low temperature heating of lithium-ion batteries had been studied by some scholars [19-22]. Shuai *et al.* [23] proposed the self-limiting temperature heating method that was a strip-like constant temperature electric heating material. When the heating temperature reached 75 °C, the heating cable was in a high-impedance state, the current was infinitesimal and the auxiliary heat was automatically suspended. Lei *et al.* [24] proposed a wide-wire metal film heating method in which a copper film was coated on both sides of a wide-line metal film and the battery was heated through a copper film to generate resistance heat through a current to heat the battery at a low temperature. Luo *et al.* [25] proposed a heating system consisting of a heating source electric heating film, a heat transfer medium transformer oil and a thermal insulation layer silica aerogel plate. Stuart and Hande [26] designed a heating method that heated the lithium battery and used a 60 Hz low-frequency alternating current to heat the nickel-metal hydride battery against a lead-acid battery and 10~20 kHz high frequency current. Salameh and Alaoui [27] used the Peltier effect to conduct heating experiments on the batteries of electric vehicles. Li *et al.* [28] placed the thermistor heating tape on the inner wall of the battery pack and heated the lithium battery pack through heat transfer. This method had many advantages such as no overheating, safety, reliability, energy conservation, and rapid temperature rise. Pan and Guo [29] applied an electric heating film to a single side of each battery cell for heating and the heating effect was better, but the heat dissipation of the monomer was affected. Zhang *et al.* [30] attached a wide-line metal film to the two larger sides of the battery cell for heating. The temperature uniformity and heating efficiency of the method were better, but it was necessary to accurately control the system, which will affect to a certain extent heat dissipation of the battery cells. These low temperature heating schemes of lithium-ion batteries had the following problems. Firstly, the lithium-ion battery may not be discharged at very low temperature and these low temperature heating schemes may cause heating of the lithium-ion battery out of balance and reduce the discharge capacity of lithium-ion batteries. What's more, continuous discharge in extremely low temperature environment would shorten the life of the battery.

This paper studies the thermal equilibrium performance of battery liquid heating system at low temperature. Inlet temperature, heating time, ambient temperature and their coupling relationship to battery thermal equilibrium performance are studied by orthogonal experimental design method.

Lithium-ion battery system model

Geometric model

The power battery system of a new energy vehicle usually consists of multiple battery modules. In addition, there are battery management system components, wiring harnesses, high and low voltage components, structural supports, and thermal management system components. To explore the thermal management performance of liquid cooling systems, these components are often simplified. Figure 1 shows a simplified battery module in which electrical and mechanical accessories are omitted. There is a layer of thermal pad between the battery and the liquid-cooled plate. The thickness is 2 mm and the thermal conductivity is 2 W/(m^{2}K). The purpose is to improve the temperature uniformity between the batteries. In engineering applications, because the installation of the cooling system is affected by the narrow space, the liquid cooling plate with straight channels is shown in fig. 2.

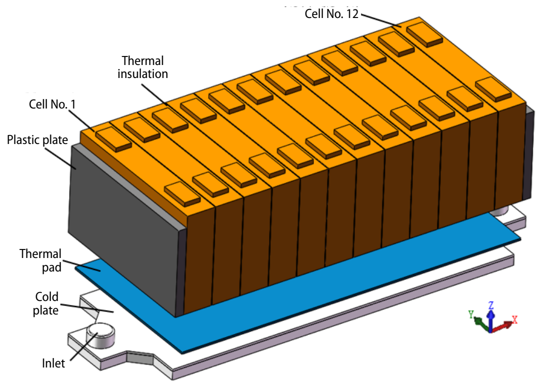

Figure 1. Module components

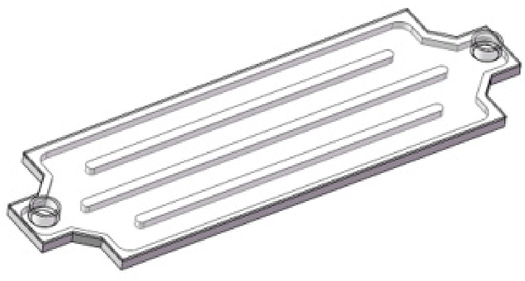

Figure 2. Liquid cold plate with straight channel

Mathematical model

The heat transfer characteristics inside and outside of lithium-ion batteries follow three basic modes of heat transfer. Because of the side shell of lithium batteries inside was filled with a large number of electrodes and the active substances, such as material, so the internal main way of heat transfer for thermal conduction, when the temperature difference in inner of batteries, its heat transfer follows the Fourier law, it will be linked to the temperature field and heat flow, and is suitable for a variety of different temperature field, also suitable for steady and unsteady, 1-D or multidimensional, its expression is:

$$q_x'' = -k\frac{\mathrm{d}T}{\mathrm{d}x} \tag{1}$$

where q''_x [Wm^{-2}] is called heat flux, indicating heat transfer rate per unit area in the x-direction, and k [Wm^{-1}K^{-1}] – the thermal conductivity of the material. The negative sign in the equation indicates the direction of heat transfer. Similarly, in the case of linear temperature distribution, the temperature gradient and heat flux density can also be expressed:

$$\frac{\mathrm{d}T}{\mathrm{d}x} = \frac{T_2 - T_1}{L} \tag{2}$$

$$q''_x = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L} \tag{3}$$

where T_1 and T_2 represent the temperatures on the front and back surfaces of the heat transfer path, respectively, and L [m] – the length of the heat transfer path. Usually, when measuring the heat transfer capacity of A certain structure, the heat conduction rate q_x of the flat wall with an area of A is adopted for evaluation, namely:

$$q_x = q''_x A \tag{4}$$

When the lithium-ion battery carries on the heat exchange with the outside world, its heat transfer mode mainly is the heat convection and the heat radiation. Heat convection occurs when the surface of a lithium battery is not at the same temperature as external fluids such as air and coolant. According to the flow properties, when the flow is generated by external forces such as fans and pumps, it is called forced convection. When the lithium-ion battery is in free flow, the temperature of the fluid is high, and the temperature difference with the surrounding fluid is formed, resulting in the density difference between the fluids, and the floating lift force causes the natural convection of the fluid. The energy transfer rate mode of thermal convection has the following form:

$$q'' = h(T_s - T_\infty) \tag{5}$$

where q'' [Wm^{-2}] is convective heat flux density. It is directly proportional to the difference between surface temperature T_s and fluid temperature, h [Wm^{-2}K^{-1}] is called convective heat transfer coefficient. It is related to boundary-layer conditions, such as the surface roughness of boundary-layer, flow direction and flow pattern of fluid on the boundary-layer surface.

Boundary

Thermal management evaluation indicators

In order to evaluate the thermal management performance, there are two indicators. The maximum temperature rise of the battery refers to the maximum value of the final and initial temperature of the battery, which reflects the overall effect of thermal management. The maximum temperature difference between the batteries refers to the maximum difference in the average temperature of the battery cells, which reflects. The heat balance effect is good or bad. The maximum temperature difference between batteries reflects the thermal equilibrium between the batteries. An excellent battery thermal management system should be able to maintain the best overall heat dissipation or heating effect while ensuring good thermal balance.

Orthogonal experimental design

In order to carry out orthogonal experiments, it is necessary to select experimental factors, which are some parameters that may affect the results. The selection of test factors should be uniform, dispersed and representative. In this study, to heat the battery module, hot liquid is assumed to flow into the liquid cold plate. The factors to influence the system temperature difference are liquid temperature, heating time and environment temperature, the orthogonal table can be made as tab. 1.

Table 1. The orthogonal table

Level	Factor		
	Inlet temperature T_{in} [°C]	Heating time t [s]	Ambient temperature T_A [°C]
1	10	180	–30
2	20	360	–20
3	30	540	–10
4	40	720	0

Simulation boundary

In the simulation, 3-D incompressible equations Navier-Stokes and achievable model k-ε were used. Compared with the k-ε model, the achievable k-ε model can keep the Reynolds stress consistent with real turbulence, and can more accurately simulate the diffusion velocity of plane and circular jets [31]. In order to obtain the physical quantity of the control panel, the second-order upwind difference method is adopted, and the SIMPLEC method is used for iterative calculation. In the calculation, the velocity inlet boundary conditions are taken into account, and the proportion of turbulence is set to 2%. The pressure outlet boundary is standard atmospheric pressure, the non-slip boundary condition is also taken into account and the velocity value is set to 0.

Results and discussion

Orthogonal experimental results

When analyzing the importance of the influence of heating parameters on the thermal equilibrium performance of the battery system, an L16 orthogonal table was selected for orthogonal experiments. The system temperature difference, T_s, and the cell temperature difference, T_c, are selected as the evaluation index. In this study, a parametric modeling method was used, and the completed model was numerically simulated [32]. Table 2 is the test scheme and corresponding simulation results of 16 orthogonal experiments.

Figure 3 shows the cloud diagram of the temperature field distribution of the cell module under the condition of orthogonal test design experiment 1, namely hot water at 10 °C, heating time of 180 seconds and ambient temperature at –30 °C. As can be seen from fig. 3, because the liquid cooling plate is placed at the bottom of the battery module, heat is transferred from the bottom of the cell, and the overall temperature distribution of the battery module shows a trend of low at the upper end and high at the lower end. In addition, due to the influence of the plastic end plate, the temperature distribution of the cell on the two most sides of the battery module is more severe, so the heat insulation with the plastic end plate should be considered in the heating design process. Under the heating time of 180 seconds, the temperature at the top of the cell is about –27 °C. It can be seen that the short heating time leads to the fact that the heat from the bottom has not yet been transferred to the top, which is limited by the longitudinal heat transfer coefficient of the cell itself.

Table 2. Orthogonal test and results

Number	Factor			Evaluation index	
	T_{in} [°C]	t [s]	T_A [°C]	T_s [°C]	T_c [°C]
1	1	1	1	1.201	24.00
2	1	2	2	1.522	15.55
3	1	3	3	1.278	8.65
4	1	4	4	0.7	3.61
5	2	1	2	1.205	24.00
6	2	2	1	2.534	25.93
7	2	3	4	1.277	8.65
8	2	4	3	4.099	10.83
9	3	1	3	1.206	24.01
10	3	2	4	1.519	15.56
11	3	3	1	3.832	25.95
12	3	4	2	3.494	18.04
13	4	1	4	1.203	24.01
14	4	2	3	4.492	46.68
15	4	3	2	3.828	25.95
16	4	4	1	4.899	25.26

Range analysis

In order to deal with the results of orthogonal experiments, a range analysis method was used. This method can evaluate the influence of different factors on the results in orthogonal experiments, and can obtain the best match between different parameters. In this study, the optimal design of the thermal management system can be achieved [33]. Through the test results in tab. 2, the factor level and k of the corresponding evaluation index in each column and the water average value k of the related factors can be obtained in turn, and each k value is substituted into the range calculation formula shown in eq. (6), according to the calculation. As a result, the range test can be performed on the orthogonal test:

$$R_j = \max\{k_1, k_2, k_3, k_4\} - \min\{k_1, k_2, k_3, k_4\} \tag{6}$$

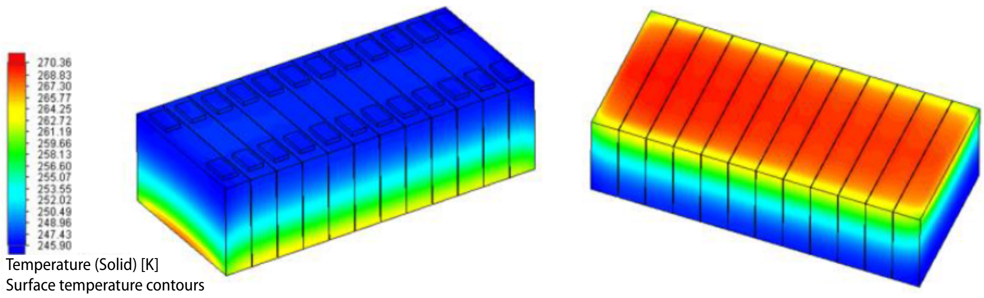

Figure 3. Battery module temperature distribution of No. 1 experiment

Table 3. Range analysis results

Parameter		Factor		
T_{in} [°C]		t [s]	T_A [°C]	
T_s [°C]	k_1	1.175	1.204	3.117
	k_2	2.279	2.517	2.512
	k_3	2.513	2.554	2.769
	k_4	3.606	3.298	1.175
	R	2.431	2.094	1.942
T_c [°C]	k_1	12.952	24.004	25.285
	k_2	17.353	25.931	20.886
	k_3	20.890	17.299	22.542
	k_4	30.473	14.434	12.955
	R	17.521	11.497	12.330

The R is the range of each orthogonal test factor, and its value can clearly reflect the sensitivity of different parameters to the effect of the results. If the difference in range is larger, it indicates that the factor is more sensitive to the evaluation index. Therefore, comparing the results of R can obtain the analysis results of the orthogonal test. The best system parameters are in the middle column. Table 3 is the result of the range analysis calculated according to eq. (6).

As shown in tab. 3, for the temperature difference, T_s, of the thermal management system, the magnitude of the influence of different parameters is $T_{\text{in}} > T_A > t$. For the temperature difference T_c of the battery, the magnitude of the influence of different parameters is $T_{\text{in}} > T_A > t$. The inlet temperature of the cooling medium is the most important factor, which has a great influence on the system temperature difference T_s and the battery temperature difference T_c. The effects of different orthogonal test factors on different evaluation results are shown in figs. 4-6.

As is shown in fig. 4, when the temperature of inlet water increases, T_c and T_s also increase. This is because the temperature difference between the ambient temperature and the inlet temperature changes due to the change in the inlet water temperature. At the same time, the battery has less heat transfer in the longitudinal direction and greater heat transfer in the transverse direction. Finally, T_c changed from 12.2 °C when the inlet temperature was 10 °C to 30.4 °C when the inlet temperature was 40 °C. The T_s changed from 1.15 °C when the inlet temperature was 10 °C to 3.59 °C when the inlet temperature was 40 °C.

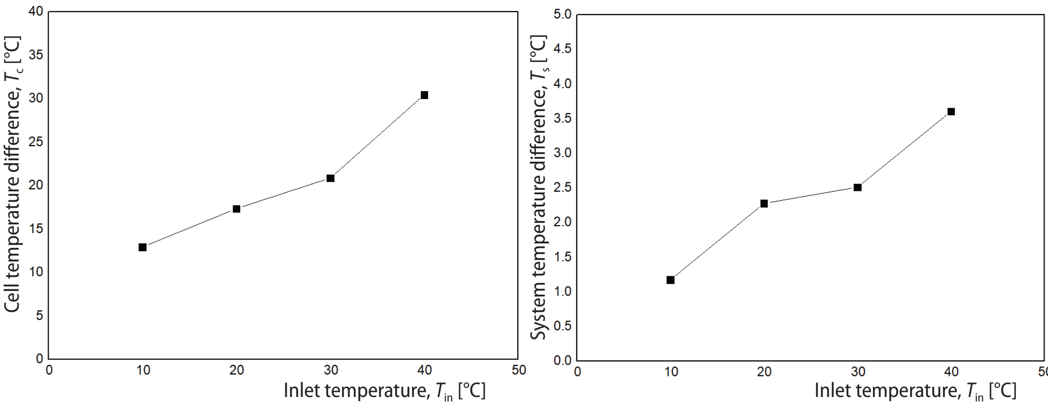

Figure 4. Effect of cooling medium inlet temperature on T_c and T_s

As is shown in fig. 5, when the heating time increases, T_c tends to decrease, while T_s tends to increase. The reason T_c decreases is that the longer the heating time, the more heat is transferred from the bottom of the battery to the top. The reason for the increase in T_s is that the liquid near the water inlet in the heating system can maintain a high temperature, which is basically consistent with the preset temperature; but the temperature of the liquid far from the water inlet is relatively low, because part of the heat of the liquid is transferred to the battery.

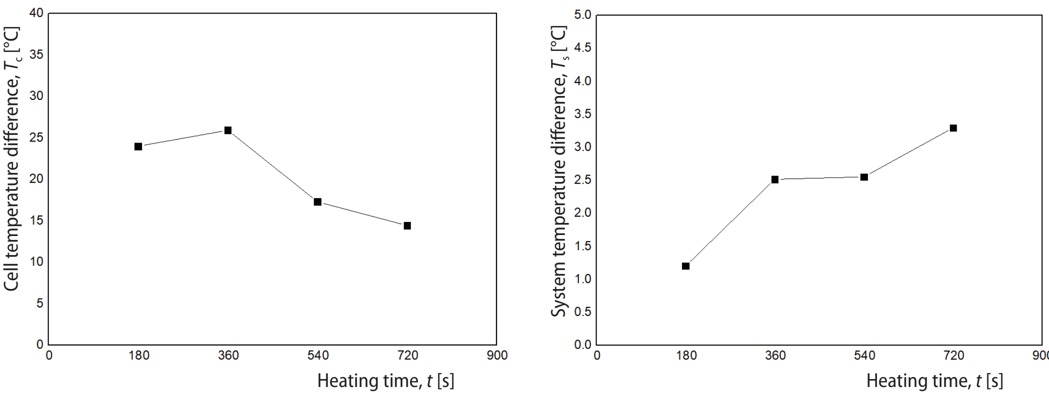

Figure 5. Effect of heating time on T_c and T_s

The temperature consistency of the heating medium itself has deteriorated. When the heating time was extended from 180- 720 seconds, T_c changed from 23.8 °C to 14.3 °C, and T_s changed from 1.17 °C to 3.23 °C. This phenomenon can be improved by optimizing the structure of the flow channel in the liquid cooling plate to reduce the flow resistance.

As is shown in fig. 6, T_c and T_s decrease with the increase of ambient temperature, and the decreasing trend remains the same. This is because the increase in ambient temperature reduces the temperature difference between the heated liquid and the external environment, which is conducive to the improvement of heat balance performance. The T_c decreased from 25.2 °C at –30 °C ambient temperature to 12.4 °C at 0 °C ambient temperature, and T_s decreased from 3.11 °C at –30 °C ambient temperature to 1.22 °C at 0 °C ambient temperature.

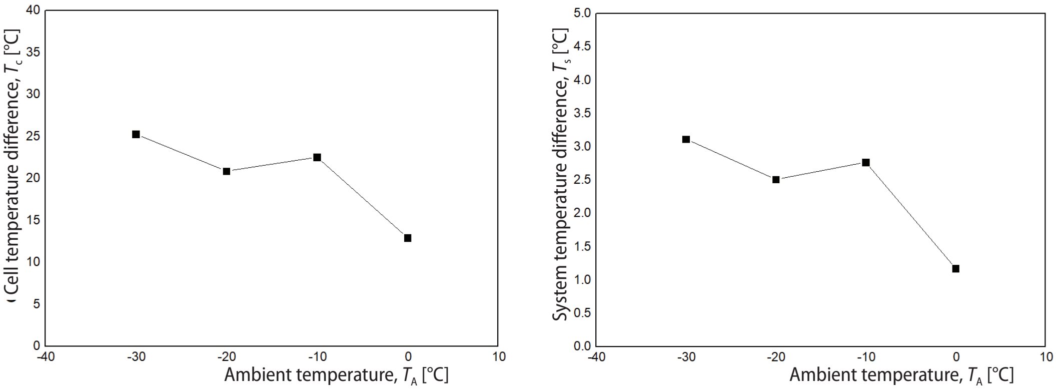

Figure 6. Effect of ambient temperature on T_c and T_s

Coupling relationship between inlet temperature and heating time

It can be seen from the analysis in the previous section that the inlet water temperature, heating time and external environment temperature of the battery heating system all have influences on the thermal equilibrium performance. Therefore, this section studies the pairwise coupling relationship between the system temperature difference and the three variables on this basis. Figure 7 is the system temperature of inlet water temperature and the relationship between the heating time distribution, it shows that the contour map along the axis of a heating time increased, the heating time of system influenced by the temperature difference, when the heating time increases, should consider the appropriate to reduce the water temperature to reduce the system temperature, such as when the heating time is higher than the 600 seconds, can consider to choose water temperature distribution in the 600 seconds the trough of the heating time corresponding position, namely 20 °C water temperature.

Figure 8 shows the distribution diagram of the relationship between system temperature difference and inlet temperature and ambient temperature. It can be seen from fig. 8 that the distribution diagram generally increases gradually from left to right, indicating that between the inlet temperature and the ambient temperature, the inlet temperature has a great influence on the system temperature difference, and there are two obvious valleys between the inlet temperature of 15 °C and the ambient temperature of –25 °C, the inlet temperature of 30 °C and the ambient temperature of –5 °C.The increase of the inlet water temperature makes the overall temperature difference of the system rise, which indicates that the inlet water temperature should not be too high when the battery heating system is designed.

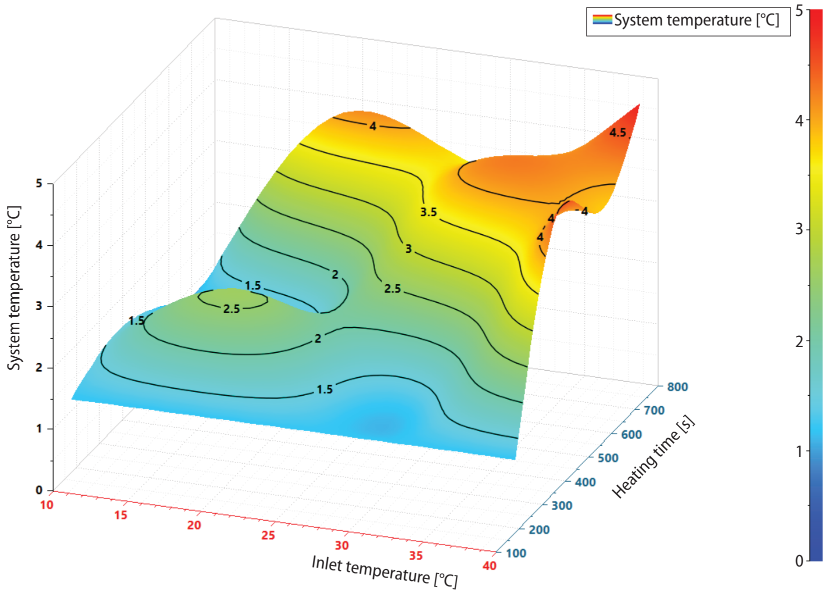

Figure 7. Effect of inlet temperature and heating time on system temperature difference

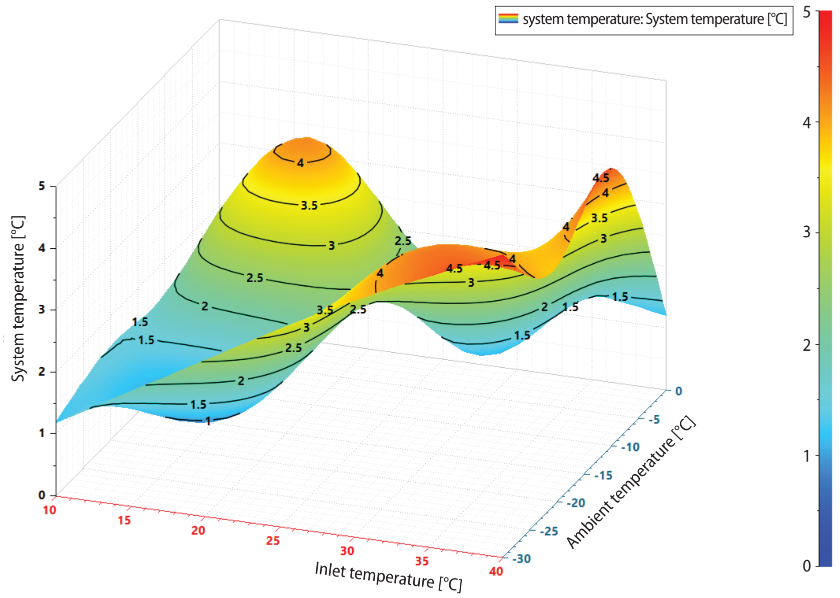

Figure 8. Effect of inlet temperature and ambient temperature on system temperature difference

Conclusions

This paper studies the effects of thermal equilibrium performance and thermal management system parameters of lithium-ion battery systems at low temperatures. Inlet temperature, heating time, ambient temperature and their coupling relationship to battery thermal equilibrium performance are studied by orthogonal experimental design method. The specific conclusions are as follows.

- When the temperature of inlet water increases, T_c and T_s also increase. This is because the temperature difference between the ambient temperature and the inlet temperature changes due to the change in the inlet water temperature. At the same time, the battery has less heat transfer in the longitudinal direction and greater heat transfer in the transverse direction.
- When the heating time increases, T_c tends to decrease, while T_s tends to increase. The reason T_c decreases is that the longer the heating time, the more heat is transferred from the bottom of the battery to the top. The reason for the increase in T_s is that the liquid near the water inlet in the heating system can maintain a high temperature, which is basically consistent with the preset temperature; but the temperature of the liquid far from the water inlet is relatively low, because part of the heat of the liquid is transferred to the battery.
- The T_c and T_s decrease with the increase of ambient temperature, and the decreasing trend remains the same. This is because the increase in ambient temperature reduces the temperature difference between the heated liquid and the external environment, which is conducive to the improvement of heat balance performance.
- According to the matching of inlet temperature, ambient temperature, and heating time, when the ambient temperature is relatively low, for example, below –30 °C, a heating strategy with a low inlet temperature and a long heating time should be adopted. For example, the inlet temperature should be 10 °C, and the heating time should be 600 seconds. This can ensure the best thermal balance performance of the battery. When the ambient temperature is relatively high, such as –10 °C ~ 0 °C, a heating strategy with a high inlet temperature and a short heating time can be selected. For example, the inlet temperature is selected around 30 °C, and the heating time is 300 seconds. In this way, the heating time can be shortened as much as possible while ensuring the thermal balance performance.
- It is hoped that the conclusion of this paper can provide a reference for the low-temperature heating strategy of the thermal management system of electric vehicle power batteries.

Acknowledgment

This work was supported by National Natural Science Foundation of China (51875259), National key research and development program (2018YFC0810504), Foundation of State Key Laboratory of Automotive Simulation and Control (20180103), Postgraduate Research & Practice Innovation Program of Jiangsu Province (SJCX19_1169).

References

[1] Takaki, A., *et al.,* Development of a High-Power Battery Cooling System for Series HEVs, EVS-15, Brussels, Belgium, 1998
[2] Guo, G., *et al*., Three-Dimensional Thermal Finite Element Modeling of Lithium-Ion Battery in Thermal Abuse Application, *Journal of Power Sources*, *195* (2010), 8, pp. 2393-2398
[3] Wu, M. S., *et al.,* Thermal Behaviour of Nickel/Metal Hydride Batteries During Charge and Discharge, *Journal of Power Sources*, *74* (1998), 2, pp. 202-210
[4] Jiateng, Z., *et al.,* Thermal Management of Cylindrical Power Battery Module for Extending the Life of New Energy Electric Vehicles, *Applied Thermal Engineering*, *85* (2015), June, pp. 33-43
[5] Bitsche, O., Gutmann, G., Systems for Hybrid Cars, *Journal of Power Sources*, *127* (2004), 1-2, pp. 8-15
[6] Khateeb, S. A., *et al.,* Thermal Management of Li-Ion Battery with Phase Change Material for Electric Scooters: Experimental Validation, *Journal of Power Sources*, *142* (2005), 1-2, pp. 345-353

[7] Ishikawa, H., *et al.,* Thermal Characteristics of Lithium Ion Secondary Cells in High Temperature Environments Using an Accelerating Rate Calorimeter, *Journal of Renewable and Sustainable Energy*, *5* (2013), 4, pp. 043122
[8] Weidmann, E. P., *et al.,* Under Hood Temperature Analysis in Case of Natural Convection, SAE Paper, 2005-01-2045, 2005
[9] Bhutta, M. M. A., *et al.,* CFD Applications in Various Heat Exchangers Design: A Review [J], *Applied Thermal Engineering*, *32* (2012), Jan., pp. 1-12
[10] Kim, K. B., *et al.,* Active Coolant Control Strategies in Automotive Engines, *International Journal of Automotive Technology*, *11* (2010), 6, pp. 767-772
[11] Mohammadian, S. K., *et al.,* Internal Cooling of a Lithium-Ion Battery Using Electrolyte as Coolant Through Microchannels Embedded Inside the Electrodes, *Journal of Power Sources*, *293* (2015), Oct., pp. 458-466
[12] Kizilel, R., *et al.,* Passive Control of Temperature Excursion and Uniformity in High-Energy Li-Ion Battery Packs at High Current and Ambient Temperature, *Journal of Power Sources*, *183* (2008), 1, pp. 370-375
[13] Bandhauer, T, M., Garimella, S., Passive, Internal Thermal Management System for Batteries Using Microscale Liquid-Vapor Phase Change, *Applied Thermal Engineering*, *61* (2013), 2, pp. 756-769
[14] Xu, X. M., *et al.,* Research on Heat Dissipation Performance and Flow Characteristics of Air-Cooled Battery Pack, *International Journal of Energy Research*, *42* (2018), 11, pp. 3658-3671
[15] Xu, X. M., *et al.,* Research on the Heat Dissipation Performance of Lithium-Ion Cell with Different Operating Conditions, *International Journal of Energy Research*, *41* (2017), 11, pp. 1642-1654
[16] Saw, L. H., *et al.,* Computational Fluid Dynamic and Thermal Analysis of Lithium-Ion Battery Pack with Air Cooling, *Applied Energy*, *177* (2016), Sept., pp. 783-792
[17] Shang, Z., *et al.,* Structural Optimization of Lithium-Ion Battery for Improving Thermal Performance Based on a Liquid Cooling System, *International Journal of Heat and Mass Transfer*, *130* (2019), Mar., pp. 33-41
[18] Zhang, Z. Q., *et al.,* Numerical Simulation of Flow and Heat Transfer in Composite Pcm on the Basis of Two Different Models of Open-Cell Metal Foam Skeletons, *International Journal of Heat and Mass Transfer*, *112* (2017), Sept., pp. 959-971
[19] Zhao, S. X., *et al.,* Development on Low-temperature Performance of Lithium Ion Batteries (in Chines), *Journal of the Chinese Ceramic Society*, *44* (2016), 01, pp. 19-28
[20] Li, G., *et al.*, Design Research on Battery Heating and Preservation System Based on Liquid Cooling Mode (in Chines) [J], *Journal of Hunan University*, *44* (2017), 2, pp. 26-33
[21] Zhang, R, Q., *et al.,* Evaluation and Research on the High Performance 18650 Type Lithium Batteries of Rate and Low Temperature Electrochemical Performance (in Chines), *Chinese Battery Industry*, *20* (2016), 01, pp. 9-12
[22] Song, H. S., *et al.,* Experimental Study on the Effects of Pre-Heating a Battery in a Low-Temperature Environment, *Proceedings*,Vehicle Power and Propulsion Conference (VPPC), Seoul, S. Korea, 2012 IEEE
[23] Shuai, X. F., *et al.,* Research on Low-Temperature Auxiliary Heat Method for Lithium-Ion Batteries (in Chines) [J], *Henan Science and Technology*, *22* (2015), 65
[24] Lei, Z. G., *et al.,* Low-Temperature Performance and Heating Method of Lithium Battery in Electric Vehicles (in Chines), *Journal of Beijing University of Technology*, *39* (2013), 9, pp. 1399-1404
[25] Luo, Y. T., *et al.,* Investigation into Heating System of Lithium-Ion Battery Pack in Low-Temperature Environment (in Chines), *Journal of South China University of Technology (Natural Science Edition)*, *44* (2016), 9, pp. 100-106
[26] Stuart, T, A., Hande, A., HEV Battery Heating Using AC Currents, *Journal of Power Sources*, *129* (2004), 2, pp. 368-378
[27] Salameh, Z. M., Alaoui, C., Modeling and Simulation of a Thermal Management System for Electric Vehicles, *Proceedings*, IECON'03. 29th Annual Conference of the IEEE Industrial Electronics Society, IEEE, Roanoke, Va., USA, 2003
[28] Li, B., *et al.,* Research on Influence of Pre-heating to Charging Character on Lithium Iron Phosphate Battery (in Chines), *Bus & Coach Technology and Research*, *34* (2012), 03, pp. 25-27
[29] Pan, C. J., Guo, H. F., Research on Insulation and Heating of Battery Packs for Electric Vehicles (in Chines), *Proceedings*, Annual Meeting of China Automotive Engineering Society, Shanghai, 2013
[30] Zhang, C. N., *et al.,* Method for Heating Low-Temperature Lithium Battery in Electric Vehicle (in Chines), *Transactions of Beijing Institute of Technology*, *32* (2012), 9, pp. 921-925

[31] Zhao, W. D., *et al.*, Research on the Adaptability and Heat Dispersion of Battery Pack Turbulence Model (in Chines), *Journal of Hunan University of Technology*, 29 (2015), 02, pp. 8-13
[32] He, F., *et al.,* Combined Experimental and Numerical Study of Thermal Management of Battery Module Consisting of Multiple Li-Ion Cells, *International Journal of Heat and Mass Transfer*, *72* (2014), May, pp. 622-629
[33] Liu, Y. P., *et al.,* Design and Parametric Optimization of Thermal Management of Lithium-Ion Battery Module with Reciprocating Air-Flow, *Journal of Central South University*, *22* (2015), 10, pp. 3970-3976

Paper submitted: January 18, 2020
Paper revised: March 1, 2020
Paper accepted: March 6, 2020