ELEKTROTEHNIŠKI VESTNIK 83(1-2): 54-60, 2016
ORIGINAL SCIENTIFIC PAPER

# Calculation and Analysis of Thermal Safety Performance of the Lithium-ion Power Battery

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**Abstract.** The paper research is the thermal safety of the lithium-ion power battery of 11Ah rated capacity used in electric vehicles. The FEA software is employed to conduct the finite-element modelling and analysis. The effects of different discharge rates, environmental temperatures and cooling conditions on the thermal performance of the battery are investigated. The simulation results show that a higher discharge rate leads to a more uneven temperature distribution and a better cooling condition leads to a better consistency of the internal temperature and also to a stable life of the battery. Simulation and experimental research provide guidelines for the design optimization and thermal-management system of the lithium-ion power battery monomer.

**Keywords:** Electric vehicles, Lithium-ion power battery, Thermal analysis, FEA

**Izračun in analiza termične varnosti in zmogljivosti Li-ionskih baterij**

V članku je predstavljena analiza termične varnosti in zmogljivosti Li-ionskih baterij kapacitete 11 Ah, ki se uporabljajo v električnih vozilih. Za analizo smo uporabili metodo končnih elementov. Upoštevali smo vpliv različne obremenitve baterije, temperaturo okolja in način hlajenja na termične lastnosti baterije. Rezultati simulacij so potrdili, da večja obremenitev baterije vpliva na neenakomerno porazdelitev temperature v notranjosti baterije in da učinkovitejše hlajenje baterije vpliva na bolj konsistentno temperaturo v bateriji in na njeno življenjsko dobo. Na podlagi rezultatov simulacij in meritev predlagamo pravila za optimizacijo termičnega delovanja Li-ionskih baterij.

## 1 INTRODUCTION

The today's environmental pollution and energy shortage problem is increasingly serious. The traditional vehicles use fuel as power, they do not only consume the non-renewable energy but also exacerbate environmental pollution. While the low-emission electric vehicles, as an ideal zero pollutant, are paide more and more attentions, the countries worldwide are increasing research and development efforts on them [1]. The lithium-ion power battery with the advantages of a high energy density, low self-discharge rate and good stability has become the preferred energy source vector for the electric vehicles[2]. However, with its wide use its power is growing while its size is becoming smaller and smaller, and the heat generation increases correspondingly. Therefore the safety problem of the lithium-ion power battery needs to be honored. Because of the large charge or discharge current and the effect of the environmental temperature, the lithium-ion power battery temperature rises rapidly and produces potentially serious safety problems [3]. For example, the spontaneous combustion event of the Tesla electric vehicle puts the lithium-ion power battery heat problem under an extensive attention. This paper proposes a general calculation method of finite-element simulation based on the Ansys14.0 software, and simulates the temperature field distribution and the rise of temperature in the center and edges of the lithium –ion power batteries of different discharge rates, cooling conditions, and environmental temperatures for discharge to the cut-off voltage. The simulation and experiment results provide a theoretical basis for determination of the lithium-ion battery temperature field in engineering practice and offer a wealth of data for the design and optimization of the lithium-ion power battery thermal-management system.

## 2 MATHEMATICAL MODEL OF THE BATTERY THERMODYNAMICS

The model should be able to describe the thermal generation and distribution and changes in the lithium-ion power battery in detail [4]. Since the actual thermal conditions of lithium-ion power battery are very complicated, it is usual to make the following simplification of the physical properties of the battery to reduce the complexity of calculation of heat distribution: the thermal conductivity and thermal cpacity of various materials of the battery are not affected by the changes in the temperature and SOC; the materials of the battery are distributed uniformly, the thermal capacity of the same material is constant and

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*Received 16 February 2015*
*Accepted 1 December 2015*

the thermal conductivities in the same direction are equal; in the process of charge and discharge, the battery core heat generation rates are the same everywhere and the current density is uniform. Based on the above simplifications, a simplified three-dimensional thermal model of the lithium-ion power battery is derived [5], as shown in (1)

$$\rho C_{\mathrm{p}}\frac{\partial T}{\partial t}=\lambda_x\frac{\partial^2 T}{\partial x^2}+\lambda_y\frac{\partial^2 T}{\partial y^2}+\lambda_z\frac{\partial^2 T}{\partial z^2}+q \tag{1}$$

where $T$ is the battery temperature change time, $\rho$ is the average density of the material inside the battery, $q$ is the heat-generation rate per unit volume of the battery, $C$p are the specific thermal capacity of the battery, $\lambda_x$, $\lambda_y$, $\lambda_z$ is the thermal conductivities of the battery along the X, Y, Z axis direction.

By solving (1), the temperature field of the battery is derived. The left side of the formula represents the thermodynamic energy increments of the battery unit volume in per unit time, the first three on the right side show the heat increment of the battery unit volume generated by the surface heat transfer in unit time, $q$ is calculated as the average heat-generation rate per unit volume [6]. The following problems need to be solved before implement the model: (1) get the thermal parameters $\rho$, $C_P$, $\lambda$ of the model; (2) establish the model of the heat-generation rate per unit volume $q$; (3) determine the initial and boundary conditions of the model.

There are two kinds of methods to implement the model of the heat-generation rate per unit volume $q$, experiments and theoretical calculation, the experimental method is very complicated [7-10]. At present, the D. Bernardi heati-generation rate model is commonly used [8], as shown in (2):

$$q=\frac{I}{V_b}[(U-U_0)+T\frac{dU_0}{dT}]=\frac{I}{V_b}[I\times R_r+T\frac{dU_0}{dT}] \tag{2}$$

where $V_b$ is the volume of the battery, $I$ is the charge and discharge current, $U$ is the voltage of the battery, $U_0$ is the open-circuit voltage of the battery, $dU_0/dT$ is the temperature coefficient.

The heat-generation rates of the positive and negative poles are shown in (3) and (4),

$$q_{Al}=\frac{Q_{Al}}{V_{Al}}=\frac{I^2R_{Al}}{V_{Al}} \tag{3}$$

$$q_{Cu}=\frac{Q_{Cu}}{V_{Cu}}=\frac{I^2R_{Cu}}{V_{Cu}} \tag{4}$$

where $Q$ is the heat generation of the positive and negative pole, $V$ is the volume of the poles.

The thermal capacity of the battery is determined by the factors such as the battery type, working state, temperature conditions and SOC etc. The thermal capacity can be measured by calorimeter or calculated by a mathematical method of the mass-weighted average. Generally the mass-weighted average method is used, as shown in (5),

$$C_p=\frac{1}{m}\sum^{i}C_i m_i$$

(5)

where $C_P$ is the battery specific thermal capacity, $m$ is the battery mass, $C_i$ and $m_i$ are the specific thermal capacity and mass of different materials of the battery.

The thermal conductivity is shown in (6)-(8):

$$\lambda_x=\frac{l}{\sum_i\frac{dx_i}{\lambda_i}}=\frac{l}{\frac{dx_p}{\lambda_p}+\frac{lx_n}{\lambda_n}+\frac{dx_s}{\lambda_s}} \tag{6}$$

$$\lambda_y=\sum_i\frac{\lambda_i dy_i}{b}=\frac{\lambda_p dy_p+\lambda_n dy_n+\lambda_s dy_s}{b} \tag{7}$$

$$\lambda_s=\sum_i\frac{\lambda idzi}{h}=\frac{\lambda_p dz_p+\lambda_n dz_n+\lambda_s dz_s}{h} \tag{8}$$

where $\lambda_s$, $\lambda_p$, $\lambda_n$ are the average thermal conductivities of the battery diaphragm, the positive and negative electrode materials respectively.

Set the initial conditions as

$$T(\mathrm{x, y, z}, 0)=T_0 \tag{9}$$

where $T$ is the initial temperature which equaling the environmental temperature $T_\infty$

The boundary conditions can be derived on the basis of the surface heat transfer coefficient of the battery. According to the Newton's law of cooling, the formulas are:

$$-\lambda_x\frac{\partial T}{\partial x}=\alpha(T-T_\infty),\quad x=0,\ l \tag{10}$$

$$-\lambda_y\frac{\partial T}{\partial y}=\alpha(T-T_\infty),\quad y=0,\ b \tag{11}$$

$$-\lambda_z\frac{\partial T}{\partial z}=\alpha(T-T_\infty),\quad z=0,\ h_b \tag{12}$$

## 3 FINITE ELEMENT ANALYSIS OF LITHIUM-ION POWER BATTERY

### *3.1 Building and meshing of the battery geometric model*

The paper analyzes the heat distribution of an iron-phosphate-based lithium-ion power battery manufactured under different discharge rates, cooling conditions and environmental temperatures. The main parameters of the battery are: nominal capacity 11Ah; mass 355g; size 0.07m× 0.027m ×0.088m; total resistance 65Ω; rated voltage 3.2v; discharge cut-off voltage 2.0v. The positive-pole material is aluminum alloy and the negative-pole material is copper.

The ANSYS 14.0 software is used to build the battery geometric model based on the above parameters. To directly build the geometric model, the ANSYS 14.0 software or other drawing software is used and then imported into the software to process. As the battery geometric model is simple, the geometric-model building process uses the software directly. The model and messing result are shown in Fig.1. The improved pole mesh density improves the calculation accuracy.

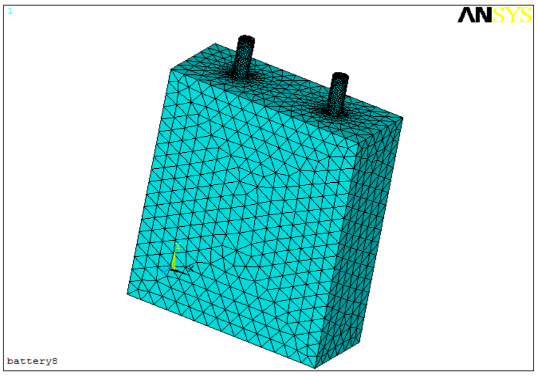


Figure 1. Meshing model of the battery

### 3.2 Thermal simulation of the model

The thermal physical parameters of each part in the model are determined and set. The parameters of copper and aluminum can be determined by using the thermal manual and the battery core parameters by calculating. The parameters are shown in Table I.

The lithium-ion power battery working on the electric vehicle generates heat as a heat source. The results from the U.S. National Renewable Energy Laboratory show that the heat generation rate of the battery is affected by the internal current, resistance, SOC and other factors [11-13]. The heating condition of the battery changes dynamically according to the power demand and working conditions of the electric vehicles [14-18]. Therefore, it is necessary to obtain the heating condition of the battery of different discharge rates and environmental temperatures. This experiment calculates the heating conditions of the battery at different discharge rates (1C, 2C, 3C), different environmental temperatures (-20 °C, 25 °C, 40 °C) and different cooling conditions (natural convection, forced air-cooled, water-cooled). The heat generation rates of the battery core and poles can be calculated by (2)-(4). The calculation results are shown in Table II.

After setting the initial temperature, environmental temperature, convective heat-transfer coefficients and heat-generation rate parameters on the ANSYS interface, the software automatically iteratively calculates and displays the results. The calculation time for the battery sustainable discharge time is in theory shown in Table III.

Table 1: The thermal physical parameters

| Battery components | Material | Density Kg/m3 | Specific heat J/(Kg*k) | Thermal conductivity W/(m*k) |
|---|---|---|---|---|
| Battery core | Mixed material | 2329 (Average) | 291 (Average) | *Kx*=1.1,<br>*Ky*=1.4,<br>*Kz*=1 |
| Positive pole | Aluminum | 2730 | 963 | 201 |
| Negative pole | Copper | 8450 | 390 | 116 |

Table 2: Heat generation rate

| Discharge rate | Current A | Battery heat generation rate *q* | Positive pole *q*Al | Negative pole *q*Cu |
|---|---|---|---|---|
| 1*C* | 11 | 6329.5 | 8799.2 | 22012.5 |
| 2*C* | 22 | 19789.6 | 34551.8 | 89218.1 |
| 3*C* | 33 | 43336.3 | 77741.5 | 200732.2 |

Table 3: Theory discharge time

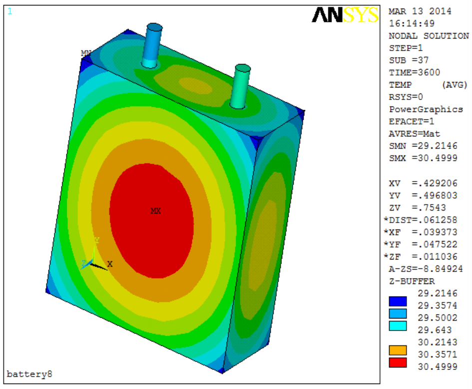
| Discharge rate | 1*C* | 2*C* | 3*C* |
|---|---|---|---|
| Battery current (A) | 11 | 22 | 33 |
| Theory discharge time (S) | 3600 | 1800 | 1200 |

### 3.3 Results and Analysis

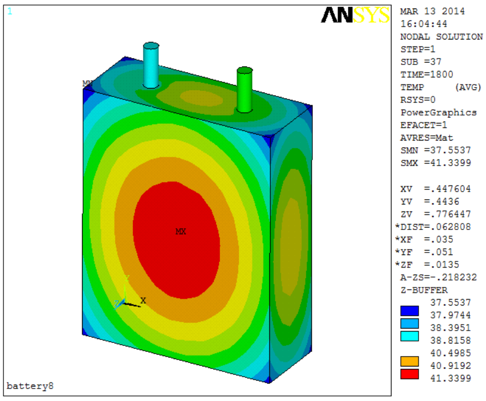
#### 3.3.1 Under condition of different discharge rates

When the battery is under condition of different discharge rates such as 1*C*, 2*C* and 3*C*, the battery heat distribution is as shown in Fig. 2. And also when the battery is under condition of natural convection, the heat transfer coefficient is *hx*=10W/(m2·K) and the ambient temperature is 25 °C, discharged to the time of the cut-off voltage.

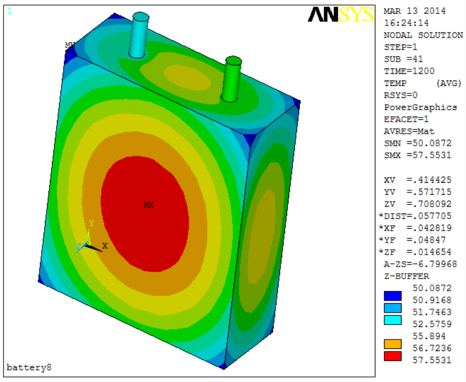
The results show that the heat distribution of the battery monomer is very uneven. The bigger is the battery discharge rate, the shorter is the discharge time and the higher is the temperature rise. When the battery discharges rate is 1*C*, the temperature rises from 25°C to 30.5°C. The highest temperature is 30.5 °C and the lowest temperature is 29°C; the temperature difference is only 1.5°C. When the battery discharge rate is 2*C*, the temperature rises from 25°C to 41°C. The highest temperature is 41°C and the lowest temperature is 37°C; the temperature difference is 3°C. When the battery discharges rate is 3C, the temperature rises from 25°C to 57°C; the temperature difference is 7°C. It is obvious that the higher is the discharge rate of the battery is, the higher is the battery temperature and the heat distribution is more uneven.



(a) Charge rate of 1*C*



(b) Charge rate of 2*C*



(c) Charge rate of 3*C*

Figure 2. Battery heat distributions under different discharge rates

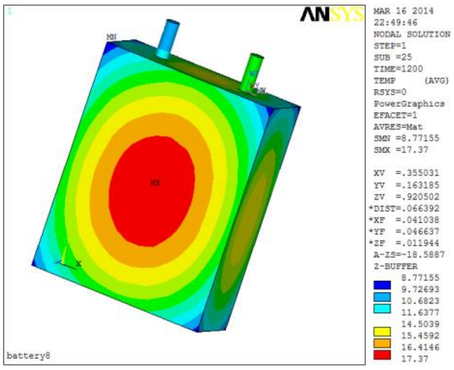
### *3.3.2 Under condition of different environmental temperatures*

When the battery is in three different temperature states such as -20°C, 25°C and 40°C, the heat distributions are shown in Fig.3. When it is under condition of natural convection, the heat transfer coefficient is *hx* =10W/(m2•K); and the discharge rate 3*C*.

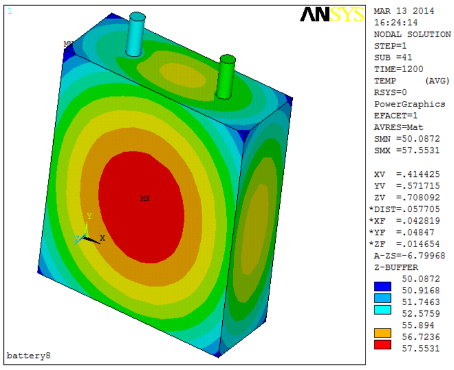
The results show that the thermal conditions of the battery and environmental temperature are closely related. In addition to that, the battery temperature increases to 37°C under the condition of -20°C, and it increases to 32°C under the condition of 25°C. However, it increases only to 28°C under the condition of 40°C. At the same discharge rate and cooling conditions, at lower environment temperature, the battery can give off more caloric value, and its temperature is higher.

### *3.3.3 Under condition of different cooling modes*

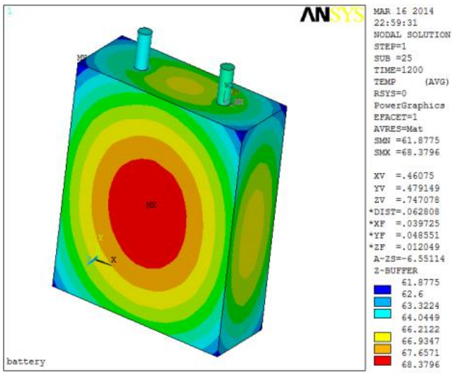
When the lithium-ion power battery is under different cooling conditions, such as natural convection, the heat transfer coefficient is *hx*=10W/(m2·K), the forced air -cooling is *hx* =25W/(m2·K) and the water-cooling is *hx* =390W/(m2·K). The heat distribution is shown in Fig.4. Also the environmental temperature needs to be 25°C and the discharge rate 3*C*.



(a) Environmental temperature of -20°C



(b) Environmental temperature of 25°C



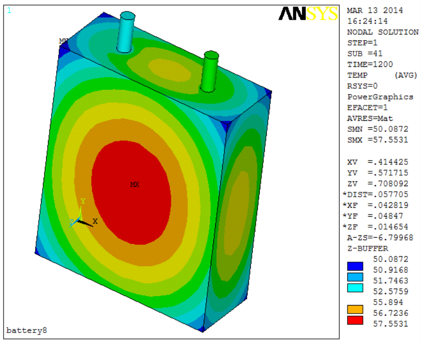
(c) Environmental temperature of 40°C

Figure 3. Heat distribution at different environmental temperatures

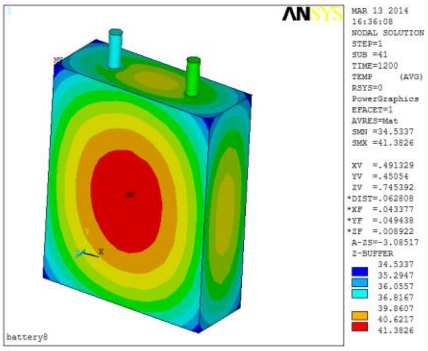
The results show that the effect is more obvious when using water-cooling. The temperature of the battery increases from 25°C to 26.4°C; the temperature difference is only 1°C. Air- cooling also has certain effects. The temperature of the battery increases to 41°C. The temperature increases to 57.5°C when no heat dissipation is added. When the temperature of the battery rises, it accelerates the aging rate of the materials inside the battery. What's worse, it reduces the working efficiency and operational life of the battery. So at lower temperatures the battery as much as possible in order to improve its stability and longevity. Water cooling should be considered when designing the battery cooling system as the first choice. If it is limited by the space size and the economic factors, using efficient forced air-cooling heat dissipation is also possible. Forced air-cooling methods include selecting a reasonable ventilation mode, choosing a matching fan, setting a grille to reject the heat and so on [19-22].

As seen from the 3D heat distribution surface figures, most of the heat generated by the center position of the battery is of the highest temperature. So the center position should be paid more attentions in the analysis and optimization. Under the condition of natural convection and a high discharge rate (3*C*), the simulated temperature change curves of -20°C, 25°C and 40°C environmental temperatures are shown in Fig. 5. By observing the trend of the three curves, it is clear that when the environmental temperature is higher, a gentler curve appears. The figure shows that when the battery is under the same operating conditions, there is less heat generated by the battery at higher environmental temperature

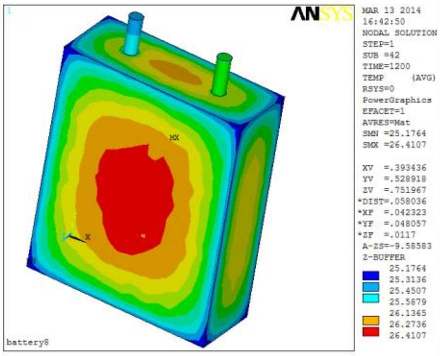
Fig. 6 shows the lithium-ion power battery temperature curves under different thermal conditions at the center of the battery for a 3*C* rate discharge at an environmental temperature of 25°C. It can be clearly seen that when using water cooling mode, even the heat up and cooling effect at the center position of the battery is still very good, followed by air-cooling, the worst natural convection. This data provides a strong support in designing the battery thermal-management system.



(a) Natural convection



(b) Forced air-cooling



(c) Water cooling

Figure 4. Heat distribution for different cooling conditions

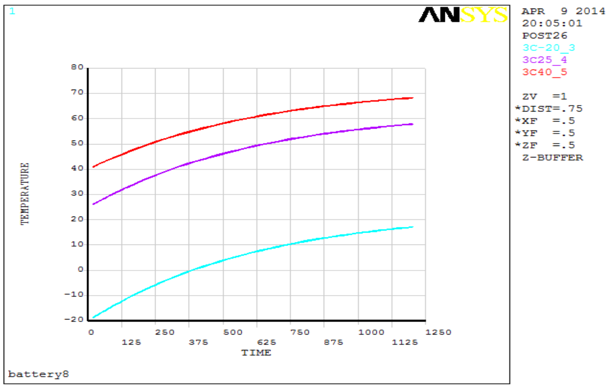


Figure 5. Temperature change curves of the centre position of the batteries in different environmental temperatures

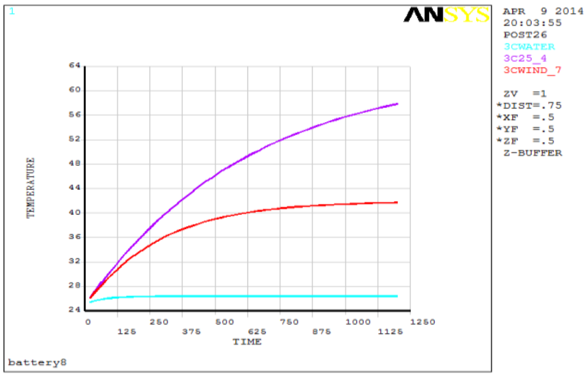


Figure 6. Temperature rise curves at different heat dissipation conditions with the environmental temperature 25°C and 3*C* discharge rate

## 4 EXPERIMENTAL RESULTS

To verify the simulation results, an experimental set-up is built as shown in Fig. 7. It includes the KIKUSUI charge/discharge system controller PFX2511, DC power supply PWR 800L, electric load PLZ1004W and the Salvis thermo-center. With its specific application software, an accurate data can be derived from the thermo-sensors. Fig.7 shows the testing experimental set-up for this application purpose, and its schematic illustration of testing experiment system combination of each component is displayed in Fig. 8. The charge / discharge rate and environmental temperature conditions are set with the predetermined ones. The temperature changing curves, natural convection and forced air-cooling conditions are shown in Figs. 9 and 10 respectively. As seen from the figures, there are relatively apparent temperature rise trends in the discharge process of the battery. In Fig. 9, the upper two curves are discharge process with a 2*C* rate and 34°C, the lower two curves are the discharge process with a 1C rate and 26°C.

Figure 7. Testing experiment platform

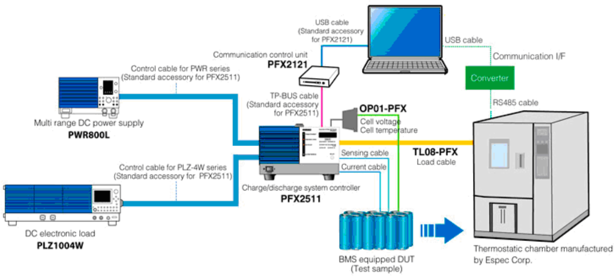


Figure 8. Schematic illustration of testing experiment system combination

A higher discharge rate and a higher environmental initial temperature mean higher upward trend in the temperature-change curves. Similarly, in Fig. 14, when the initial environmental temperature and cooling condition are set of 26°C and 22°C with a forced air-cooling condition, the curves show a trend consistent with Fig. 10. It can also be found that the temperature data affirmed with the experiment of measurements is a little lower than the simulation results, which due to simplification of the model and computation errors. In general, the simulation and experiment results are in consistent fit, thus, proving the effectiveness of the presented simulation scheme and built model.

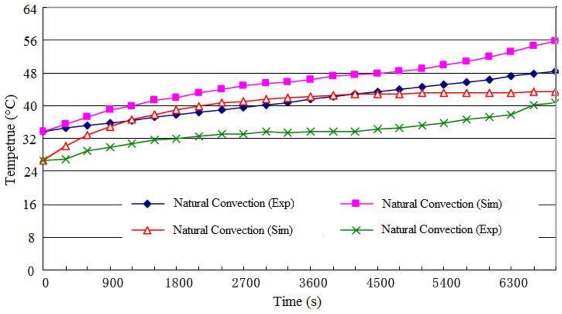


Figure 9. Comparison of the temperature changing curves under the natural convection condition

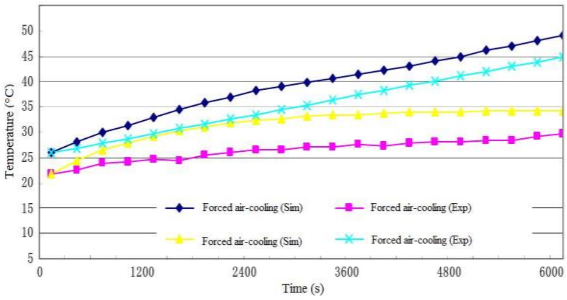


Figure 10. Comparison of the temperature changing curves under the forced air-cooling condition

## 5 CONCLUSION

The thermal safety performance is studied of the lithium-ion power battery at different discharge rates, cooling conditions and environmental temperatures. Based on the study results, the following conclusions can be drawn:

(1) The discharge rate obviously affects the thermal characteristics of the battery. The higher is the discharge rate, the higher is the battery temperature and the heat distribution of the battery centre and edge is more uneven. So it is necessary to consider the battery central-part heat-dissipation problem when designing a battery monomer.

(2) The environmental temperature and thermal characteristics of the battery are closely related. At a lower environmental temperature, the temperature rise of the battery is higher.

(3) The experimental results verify well the natural convection and forced air-cooling effects when the battery is under a high discharge rate, which is an important guiding significance in developing a thermal-management system of the battery.

The presented scheme is believed to provide a reference for further research and investigation of similar calculation problems of the lithium-ion power battery thermal safety performance.

## ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (No. 51577048, 51107031), the Natural Science Foundation of Hebei Province of China (No. E2014208134), and the Program for the Top Young Innovative Talents of Hebei Province of China, the Open Funds of Five-Platform of Hebei University of Science and Technology, and the open project of Hebei Industrial Technology Research Institute of Additive Manufacturing (Hebei University of Science and Technology).

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