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Numerical simulations and analyses on thermal characteristics of 18650 lithium-ion batteries with natural cooling conditions

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Abstract
As the main power source of electric vehicles and electronic devices, lithium-ion batteries have large capacity and high power density. However, the excessive heat generation often leads to high temperature of the battery, which challenges the safety of the battery. The heat generation and heat dissipation characteristics of an 18650 type lithium-ion batteries in charging process with natural cooling conditions are simulated by using finite element analysis software in this paper. The effects of charging rate and placement direction are analyzed. The results show that the maximum temperatures are 42.33 ºC, 58.84 ºC and 35.62 ºC, i.e. increased by 7.33 ºC, 23.84 ºC and 1.62 ºC after 1C-rate, 2C-rate and 0.5C-rate chargings, respectively. It is unable to cool the battery by natural convection cooling in 2C-rate charging. Forced cooling should be used to ensure the safety of the battery.

Keywords: Lithium-ion batteries; Thermal characteristics; Natural convection; Simulation; Numerical heat transfer.

1. Introduction

Lithium-ion batteries are the main power sources of electric vehicles and electronic devices. They have are capacity and high power density. However, lithium-ion batteries are vulnerable to excessive heat generation during fast charging. The excessive heat generation leads to high temperature of the battery, which challenges the safety of the battery [1]. Statistics shows that most of lithium-ion battery safety accidents are caused by the overheating of the battery. Therefore, the thermal safety of lithium-ion batteries is becoming more and more important.

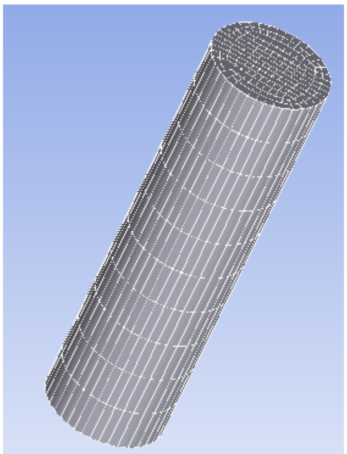
The temperature field of the battery under different conditions is the basis of the thermal safety evaluation of batteries. Battery performance, cycle life and system safety are all dependent on temperature distribution in the battery, which depends on heat generation rate within the battery and on heat removal rate at the battery surface. The methods of solving the temperature distribution include analytical method [2], experimental method [3], simulation method [4] and so on. The analytical method is usually used to solve simple models while the cost of experimental method is too high. Therefore, the simulation method becomes the main method of thermal analysis.

Thermal management system is required to maintain the battery within the safe temperature range. Cooling methods for the batteries include air cooling [5-9], water cooling [10], phase change material (PCM) cooling [11], thermal pipe [12, 13], etc.. Many researchers have studied the thermal properties of lithium-ion batteries with different heat transfer conditions. Fleckenstein et al. [14] analyzed a cylindrical lithium-ion battery in detail. Jeon and Baek [15] presented transient and thermo-electric finite element analysis of cylindrical lithium-ion battery. Forgez et al. [16] developed a lumped-parameter thermal model of a cylindrical lithium-ion battery and determined heat transfer coefficients and the heat capacity. Tong et al. [10] studied the performance of a bipolar-design battery pack numerically in terms of operation and design parameters of an active thermal management system. Ye et al. [13] proposed an optimized heat pipe thermal management system for fast charging lithium-ion battery. Characteristic of mixed charge-discharge cycle is different from the charge or discharge. Lin et al. [17] investigated the electrochemical and thermal performances of a prismatic battery with a focus on the influence of temperature on cell capacity in a mixed charge–discharge cycle.

The 18650 type lithium-ion batteries are commonly used in notebook computers, or electric devices as power sources. It refers to a kind of batteries with a diameter of 18mm, length of 65mm, and cylindrical battery as shown in Figure 1 (a). Fu et al. [18] tested the 18650 lithium-ion batteries at different states of charging using a cone calorimeter to study the burning behaviors. Saw et al. [19] developed a pseudo two dimensional electrochemical coupled with lumped parameter thermal model to analyze the electrochemical and thermal behavior of the commercial 18650 lithium-ion phosphate batteries.

However, research on three-dimensional heat transfer model especially the temperature field of 18650 lithium-ion batteries with different charging rate with natural cooling conditions is rare. This paper will simulate the heat generation and heat dissipation characteristics of 18650 type lithium-ion batteries with natural cooling conditions by using a finite element analysis software ANSYS. The results may provide some guidelines for the charging management of the batteries.

(a) 18650-type battery



(b) Grids of the battery

Figure 1. The 18650-type battery and the grids of the battery.

2. Physical model and parameters determination

In order to facilitate the analyses, the battery is simplified as a uniform heat generation cylinder, and satisfies the following assumptions:

(1) Materials are uniform and isotropic. The specific heat, thermal conductivity, density and other physical parameters are not affected by temperature or the changes of state of charging (SOC);

(2) Internal heat convection is ignored as the internal flow of electrolyte is very poor;

(3) The electrical current and heat generation rate are uniform when the battery is charging and discharging.

The differential equation of heat conduction for the battery temperature is [20]

$$\rho C\frac{\partial t}{\partial \tau}=\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial t}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\lambda\frac{\partial t}{\partial \varphi}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial t}{\partial z}\right)+q_v \tag{1}$$

where t is the temperature of any point in the battery, τ is time, ρ, c, and λ are battery density, specific heat capacity and thermal conductivity, respectively. q_v is battery heat generation rate. r is battery radius. Equation (1) reflects the temperature change of every point with time and space. It can be seen that the battery physical parameters ρ, C, λ and heat generation rate q_v are needed to be determined to solve the equation.

2.1 The determination of physical property parameters

The density ρ of the battery is determined by quality and volume ratio.

Different material layers arranged closely inside the battery, so the battery thermal conductivity and other properties are affected by components properties, thickness, and mass fraction. The battery is equivalent to a kind of materials, whose material specific heat capacity and thermal conductivity are determined by the components [20]. The equivalent specific heat capacity is given by

$$C = \frac{\sum m_i C_i}{m} \tag{2}$$

where m_i and C_i are the quality and specific heat capacity of composition materials, respectively. m and C are the quality and specific heat capacity of the battery. In addition, the precise equivalent heat capacity is determined by adiabatic temperature rise experiment.

Because of the different combinations of the axial and radial materials, the thermal conductivity of the battery is anisotropy. The materials along the axial direction are in parallel, so the axial equivalent thermal conductivity λ_h is given by

$$\lambda_h = \sum_i \frac{\lambda_i \delta_i}{r} \tag{3}$$

where r is battery radius, δ_i is thickness of each layer, and λ_i is the thermal conductivity of each material.

The materials along the radial direction are in series, so the radial equivalent thermal conductivity is given by

$$\lambda_r = \frac{r}{\sum_i \frac{\delta_i}{\lambda_i}} \tag{4}$$

The thickness and thermal conductivity of each layer is provided by the battery manufacturer.

2.2 The determination of the heat generation rate

Thermal battery simulation models include electro-chemical coupling model [21-25], electric-thermal coupling model [6, 26], and thermal abuse model [27]. The most commonly used electro-thermal coupling model is adopted in this paper. According to the lithium-ion battery heat generation classical model established by Bernardi et al. [28], the heat generated inside the battery is determined by

$$Q = I[(E - U) - T\frac{\partial E}{\partial T}] \tag{5}$$

where I is the electrical current through the battery, E is the open circuit voltage in equilibrium state, U is the charging voltage, T is the battery thermodynamic temperature, and $\partial E / \partial T$ is the electric potential temperature coefficient (also called as temperature entropy coefficient), which shows the relationship between the battery voltage and the temperature. The methods of determining the electric potential temperature coefficient include direct measurement method, reversible thermal equivalent method, polarized thermal deduction method, and so on [29]. The electric potential temperature coefficients for the same manufacturer of 18650 batteries are only slightly changed with SOC. According to the test data provided by the manufacturer, the average value is used in this paper.

3. Simulations and analyses of thermal characteristics at different charge rate

In order to ensure the accuracy of the simulation, non-structured hybrid grids containing hexahedrons and tetrahedrons are used. The model includes 20784 elements and 22797 nodes as shown in Figure 1 (b). The model is solved in a 0.2m cube. The ambient temperature is set as 35 ºC. The battery capacity is 2.6Ah.

Due to the temperature change in the charging process, transient simulation is needed. The transient simulation time is set according to the charging rate. The charging times at 1C, 2C and 0.5C are 1800s, 3600s and 7200, respectively. Figure 2 shows the residual curve of the iterative procedure. One can see that the iterative process is converging.

Simulation results show that the maximum temperature appears in the center of the battery. The temperature fields with different rate charging process are similar qualitatively. Figure 3 shows the monitoring point temperature variations at different charge rate. It can be seen that the monitoring point temperature rises with the progress of the charging process. The battery maximum temperatures are quite different after charging with different charging rate. The thermal characteristic of the battery will be analyzed with different charging rate.

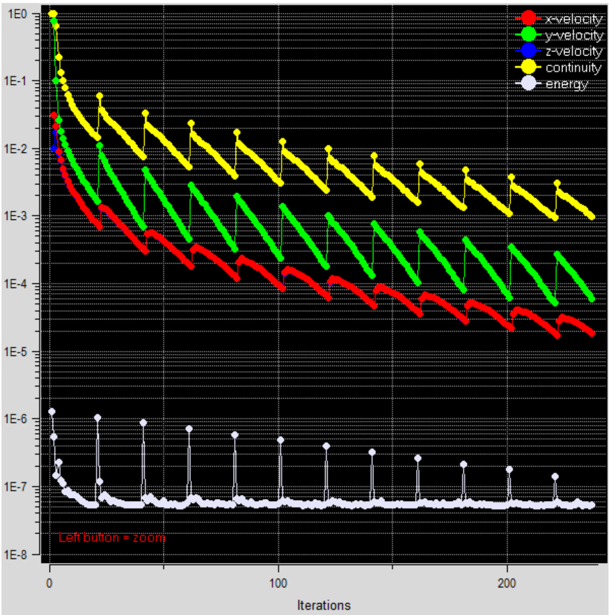


Figure 2. Residual curve of the iterative procedure.

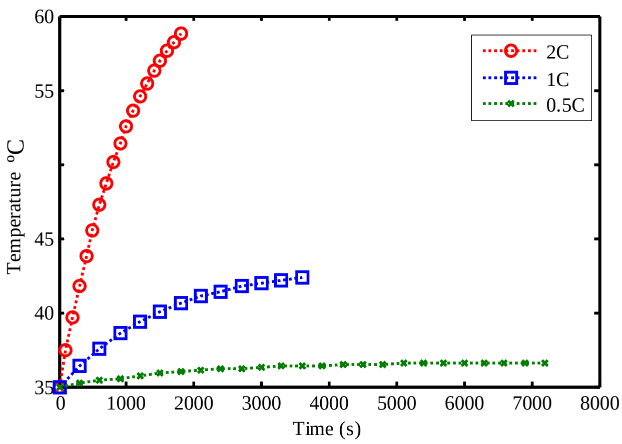
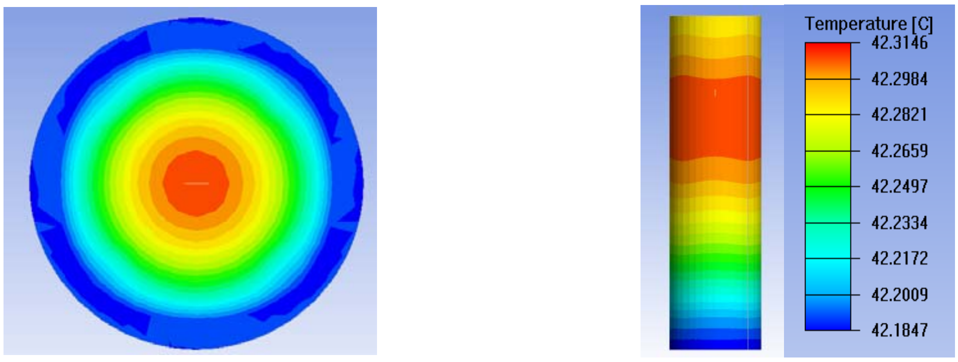


Figure 3. The battery center temperature variation during different charging rate.

3.1 1C-rate charging

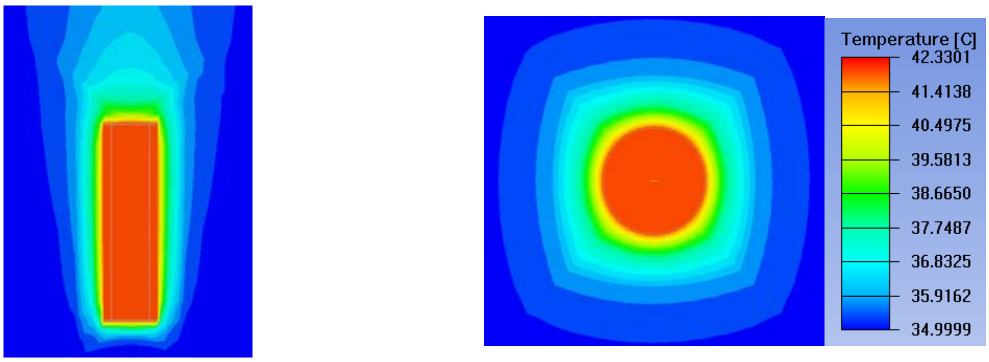
Figure 4 shows the battery surface temperature contours after 1C-rate charging. It can be seen that the battery average temperature, maximum temperature and minimum temperature of each surface are

different. The maximum surface temperature is 42.32 ºC appearing on the side surface while the minimum surface temperature is 42.18 ºC appearing at edge of the bottom surface. Because the natural convective heat transfer of the bottom edge is the strongest, the temperature is the minimum. The natural convective heat transfer of the side surface edge is weakest, so that the temperature is the maximum.
Figure 5 shows the intermediate longitudinal section and transverse section temperature contours after 1C-rate charging. It can be seen that the internal temperature of the battery is nearly uniform. The maximum temperature is 42.33 ºC, i.e. increased by 7.33 ºC in the geometric center of the battery.
The temperature of air above the battery is higher while the temperatures of air at the sides and below are lower. The air temperature decreases to ambient temperature at the double diameter in the side of the battery where the heat dissipation is not affected. Because of the long charging time and small heating power, there is sufficient time for the battery internal and surface temperatures to converge. Therefore, the differences between internal temperature and the surface temperature are very small.



(a) Lower surface (b) Side surface

Figure 4. The surface temperature contours of the battery after 1C-rate charging.

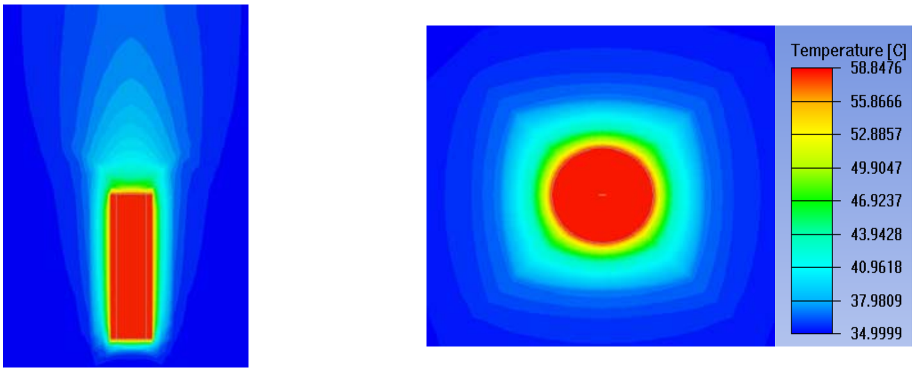


(a) Longitudinal section (b) Transverse section

Figure 5. The section plane temperature contours of the battery after 1C-rate charging.

3.2 2C-rate charging
Figure 6 shows the intermediate longitudinal section and transverse section temperature contours after 2C-rate charging. Because of the large heat generation and short charging time, the battery temperature increases sharply in 2C-rate charging process. The maximum temperature is 58.84 ºC, i.e. increased by 23.84 ºC after charging. The safety temperature of the battery is 50 ºC generally. It shows that it is unable to cool the battery by natural convection cooling. Therefore, forced cooling should be used to enhance the heat dissipation and ensure the safety of the battery.

3.3 0.5C-rate charging
Because the heat generation is very small and charging time is long (7200s) in 0.5C-rate charging process, the heat can be fully dissipated and the battery temperature has sufficient time to converge. Simulation shows that the battery surface and internal temperatures are both close to ambient temperature after charging. The maximum temperature is only 36.62 ºC i.e. increased by 1.62 ºC.

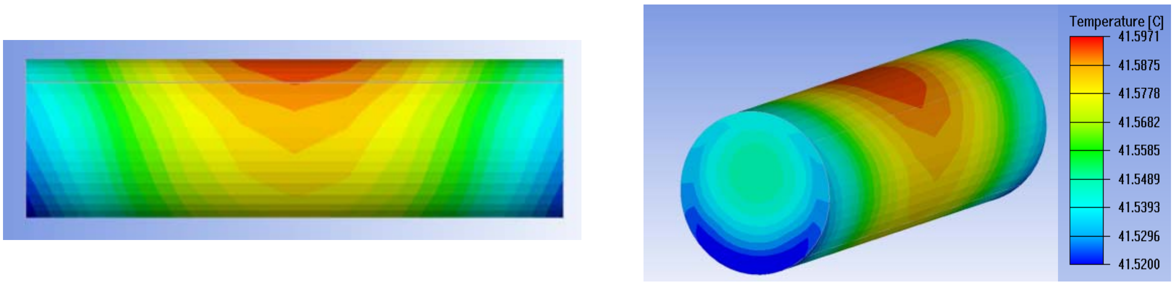


(a) Longitudinal section (b) Transverse section

Figure 6. The section plane temperature contours of the battery after 2C-rate charging.

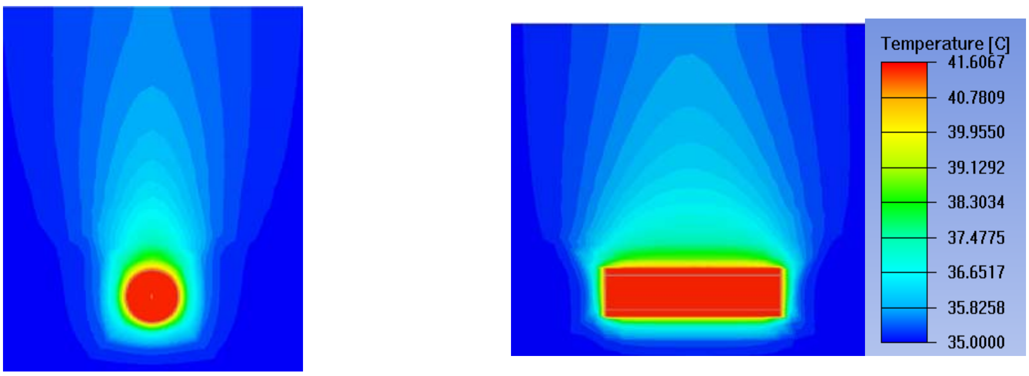
4. Effects of battery placement direction

The analyses mentioned above are performed when the battery is placed vertically. Figure 7 shows the surface temperature contours of the battery after 1C-rate charging when the battery is placed horizontally. The maximum surface temperature is 41.59 ºC appearing on the top while the minimum surface temperature is 41.52 ºC appearing at bottom edge. Figure 1 shows the intermediate transverse section and longitudinal section temperature contours when the battery is placed horizontally. It can be seen that when the battery is placed horizontally, the natural convection type changes from flat wall into rounding a cylinder, the heat transfer is enhanced. The maximum temperature is 41.61 ºC, i.e. increased by 6.61 ºC when charging is completed. Compared to the vertically placement, the temperature of the battery horizontally placed is decreased 0.72 ºC. Thus, placement direction affects the heat transfer distinctly. Horizontal placement is more conducive than the vertical placement for heat dissipation.



(a) Lateral view (b) Isometric view

Figure 7. The surface temperature contours of the battery after 1C-rate charging when the battery is placed horizontally.



(a) Transverse section (b) Longitudinal section

Figure 8. The intermediate transverse section and longitudinal section temperature contours when the battery is placed horizontally.

5. Conclusions

The heat generation and heat dissipation characteristics of 18650 type lithium-ion batteries in charging processes with natural cooling conditions are simulated. The effects of charging rate and placement direction are analyzed. The main conclusions are as follows:

(1) The surface temperature and internal temperature are different after charging, but the difference is tiny.

(2) The maximum temperature appears in the center of the battery while the minimum temperature appears at edge of the bottom surface.

(3) The maximum temperatures are 42.33 ºC, 58.84 ºC and 36.62 ºC, i.e. increased by 7.33 ºC, 23.84 ºC and 1.62 ºC after 1C-rate, 2C-rate and 0.5C-rate chargings, respectively.

(4) It is unable to cool the battery by natural convection cooling in 2C-rate charging. Forced cooling should be used to ensure the safety of the battery.

Acknowledgments

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