Multiple Dynamic Heat Sources Thermal Modeling of a Pouch LiFePO4 Lithium-ion Battery

Qiaoyan Guo, Fengchong Lan, Jiqing Chen and Yigang Li

ABSTRACT

To research the temperature field of lithium-ion battery for electric vehicle during working condition, a thermal model of a pouch LiFePO4 lithium-ion battery is established to obtain more accurate and dynamic changing distribution of battery temperature field. Time varying heat sources model, coupling thermal effect of plate lug, was established based on the characteristic of heat generation in battery caused by its internal resistance. The analysis of battery heat generation character, heat transfer character, and heat dissipation character are also carried out. Three dimension temperature field of battery are analyzed, and the corresponding experiments are conducted. The experimental result indicate that, the multiple dynamic heat sources thermal model built in this research can preferably reflect the real temperature of the pouch LiFePO4 lithium-ion battery.

INTRODUCTION

Traction battery is the key energy storage device for EV (electrical vehicle). Lithium-ion battery has several merits such as, high voltage, high power and energy density. So it is the priority selection for traction battery, and has good application prospect. But in charge/discharge process, the lithium-ion battery generate huge heat due to resistance heat, reaction heat and polarity heat. Battery temperature has great
effect on battery’s performance. The cycle life, reliability and security of lithium-ion battery decay sharply in high temperature [1].

Bemadi et al. [2] developed a classical theory model method which assume the heat generation of inner material is uniform. Sato et al. [3] employed experimental method to analyze the heat generation rate of battery, and built a battery thermal model based on it to calculate the temperature field of battery. Doughty et al. [4-5] built a 3D battery thermal model, including multilayered battery body, battery pack shell, and the air gap between them. The effect of heat convection and radiation heat transfer on battery temperature field distribution under natural convection and forced convection condition were simulated and analyzed. Zhang et al. [6] built a lithium-ion battery thermal model based on the temperature rise caused by its resistance. And employed this model to obtain the variation laws of battery temperature distribution and rise with discharging current magnitude.

The above method mainly simplify the battery thermal model to battery core body and battery shell. But in the actual work condition, the heat generation sources not only include battery core body, but also include positive/negative plate lug. Because the joule heat generation rate on plate lug is non-negligible. At present, such literature is still seldom. Zhang et al. [7] analyze the influence of plate lug from theory. Feng et al. [8] regard the battery core body, positive plate lug, and negative plate lug as three constant heat resources. And employed this model to simulation the battery temperature field.

In order to investigate dynamic temperature distribution of the lithium-ion battery under working conditions, a thermal model, more conforms to reality, needed be established. In this paper, a multiple dynamic heat sources thermal modeling of a pouch LiFePO4 lithium-ion battery is proposed. As the resistance of the battery vary with the battery SOC (state of charge), the thermal model regard the battery core body, positive plate lug, and negative plate lug as three dynamic heat resources. The analysis of battery heat generation character, heat transfer character, and heat dissipation character are also carried out. The model is verified and modified by experiment at last.

BATTERY THERMAL MODEL

Geometrical Model

A pouch LiFePO4 lithium-ion battery(3.2V/10Ah) was studied in this paper. The appearance of this battery is shown in figure 1, and the parameter of this battery is listed in table 1. The dimension of the battery main body part is 102mm*9mm*155mm. The position plate lug and negative plate lug is 0.2mm thick aluminum foil and nickel foil, respectively. The battery is packaged in 0.2mm thick aluminum-plastic film. The property of this battery are listed in table 1.
Finite volume method is adopted to generate the mesh of lithium battery geometry model. The mesh of plate lug was refined. The mesh model is shown in figure 2. In the mesh model, positive plate lug, negative plate lug, and core body of lithium battery are create as part, named posbody, negbody and cellbody, respectively.

**Characteristic Analysis of Lithium Battery Multi Heat Source Model**

**HEAT GENERATION CHARACTERISTIC**

In this research, the plate lug resistance value change with temperature is ignored, so the heat generation rate of plate lug is only depend on current magnitude. Heat generation in core body of lithium battery is mainly including resistance heat and reaction heat. When battery working in -20~60℃ temperature, resistance heat is the dominating heat resource. The heat generation rate of positive plate lug, negative plate lug and core body can be calculated by Eq.1, Eq.2, and Eq.3, respectively.
\[ q_p = \frac{Q_p}{V_p} = \frac{I^2R_p}{V_p} \]  
\[ q_n = \frac{Q_n}{V_n} = \frac{I^2R_n}{V_n} \]  
\[ q_c = \frac{Q_c}{V_c} = \frac{I^2R_c}{V_c} \]

Figure 2. Mesh model of battery.

Where \( q \) is heat generation rate, \( Q \) is heating power, \( V \) is volume, \( I \) is current, \( R \) is resistance value. Subscript \( p \), \( n \) and \( c \) represent battery positive plate lug, negative plate lug and core body, respectively.

The resistance value of lithium battery is a function depending on SOC, so it fluctuate in charge-discharge process. Based on the analysis above, the finite element model of lithium battery is composited by three time varying heat resource, and the heat generation rate of core body is a function depending on SOC.

The simplified equivalent circuit model is shown in figure 3. Lithium ion battery is equivalent to combination of ideal voltage source \( U \) and resistance \( R \). Ideal voltage source \( U \) is the battery OCV (open circuit voltage), which is a function depend on SOC. Resistance \( R \) is composed by three part, they are positive plate lug resistance \( R_p \), negative plate lug resistance \( R_n \), and core body resistance \( R_c \).

The positive plate lug and negative plate lug material are aluminum and nickel, respectively. Resistivity of positive plate lug is 3.12×10-8Ω·m. Resistivity of negative plate lug is 1.27×10-8Ω·m. The resistance value of positive plate lug is 1.95×10-4Ω, and the resistance value of negative plate lug is 7.89×10-5Ω. The resistance value of positive plate lug is almost 2.5 times the value of negative plate lug.
lug. The heat generate in positive plate lug is much more than negative plate lug. The temperature difference between them will be greater, in large current charge discharge process. Resistance value of positive plate lug and negative plate lug are then fed into Eq.1 and Eq.2 to obtain the heat generation rate of them.

Battery total resistance $R$ can be obtained for R-SOC characteristic curve. Total resistance $R$ is the sum of positive plate lug resistance $R_p$, negative plate lug resistance $R_n$, and core body resistance $R_c$. Core body resistance $R_c$ can be calculated when known $R_p$ and $R_n$. Its heat generation rate can be calculated by substituting core body resistance $R_c$ into Eq.3.

**HEAT TRANSFER CHARACTERISTIC**

The heat transfer method between plate lug and core body is heat conduction. So, the heat sources in battery are not independent. 3 dimension transient heat-transfer mathematic model of battery is Eq.5.

$$\rho C_p \frac{\partial T}{\partial t} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + q_v \quad \text{(5)}$$

where $\rho$ is material’s resistivity; $C_p$ is specific heat capacity; $T$ is temperature; $K_x$, $K_y$, and $K_z$ are the heat transfer coefficient of three direction in rectangular coordinate system. Property of each part in LiFePO4 lithium-ion battery are listed in table 2.

![Figure 3. Lithium ion battery equivalent circuit model.](image-url)
### TABLE II. PROPERTY OF EACH PART IN LIFEP04 LITHIUM-ION BATTERY.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Density / (Kg·m⁻³)</th>
<th>Specific heat capacity / (J·Kg⁻¹·K⁻¹)</th>
<th>Thermal conductivity / (W·m⁻¹·K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive plate lug</td>
<td>Aluminum</td>
<td>2719</td>
<td>871</td>
<td>400</td>
</tr>
<tr>
<td>Negative plate lug</td>
<td>Nickel</td>
<td>8900</td>
<td>460.6</td>
<td>91.74</td>
</tr>
<tr>
<td>Core body</td>
<td>Hybrid material</td>
<td>1239</td>
<td>133.9</td>
<td>$\lambda_x=\lambda_z=2.0, \quad \lambda_y=0.6$</td>
</tr>
<tr>
<td>Outer package</td>
<td>Aluminum-plastic film</td>
<td>961</td>
<td>2100</td>
<td>6.6</td>
</tr>
</tbody>
</table>

### THERMAL BOUNDARY CONDITION

Thermal boundary condition describe the relation of battery surface temperature and environment temperature. Thermal boundary condition is indispensible in thermal analysis. There are mainly three kinds of thermal boundary conditions.

First boundary condition is setting the temperature on boundary to a definite value, mainly adopted to describe unsteady thermal phenomenon. In the calculating time domain, the temperature is a definite value in every moment. Second boundary condition is setting the heat flux on boundary to a definite value, mainly adopted to describe transient thermal phenomenon. Third boundary condition preset the heat transfer coefficient and ambient fluid temperature of boundary. This kind of boundary condition can be described by Eq. 6. The third boundary condition is chosen to solve the temperature distribution in battery. The ambient temperature is 303K.

$$-\lambda \left( \frac{\partial T}{\partial n} \right)_w = h \left( T_w - T_f \right) \quad (6)$$

### BATTERY PARAMETERS IDENTIFICATION

When battery working in -20~60 °C temperature, resistance heat is the dominating heat resource. The aim of experimental is obtaining the R-SOC characteristic curve of the battery.

#### Experimental Setup

The experimental setup is composed of a battery test system (HEF battery test system), a data acquisition system (Agilent 34970A), several T-type thermocouples, and a computer. A computer control the battery test system to charge/discharge the test battery. Temperature of battery is measured by T-type thermocouples, and collected by data acquisition system, and then stored in the computer. All the experiments were conducted at room temperature of 303K.
Battery Characterization Result

A series of characterization tests for battery, including OCV test, capacity test, and HPPC (hybrid pluse power characterization) test [9], are conducted to obtain the R-SOC characteristic curve of the battery. This research mainly investigate the influence of SOC on battery resistance, the influence of temperature is ignored. The result of battery R-SOC is listed in table 3. The relation between the battery resistance value and SOC is fitted with a five-order poly-nominal function. The function of charge resistance and SOC is Eq.7, the coefficient of the function is listed in table 4. The fitting curve is shown in Figure 4. The battery resistance increase with the SOC decrease. When SOC is less than 0.2 the resistance increase dramatically.

\[ R = A_0 + A_1 \text{SOC} + A_2 \text{SOC}^2 + A_3 \text{SOC}^3 + A_4 \text{SOC}^4 + A_5 \text{SOC}^5 \quad (7) \]

MODEL VALIDATION

The battery is charged/discharged in room temperature 303K, the current is constant 10A. Three T-type thermocouples are pasted on the surface of battery by insulating tape, as showed in Figure 5. The location of three thermocouples are on the center of positive plate lug, negative plate lug, and core body. They are numbered as 1, 2, and 3.

<table>
<thead>
<tr>
<th>SOC</th>
<th>1.0</th>
<th>0.9</th>
<th>0.8</th>
<th>0.7</th>
<th>0.6</th>
<th>0.5</th>
<th>0.4</th>
<th>0.3</th>
<th>0.2</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery charge resistance (m(\Omega))</td>
<td>8.29</td>
<td>8.28</td>
<td>8.3</td>
<td>8.35</td>
<td>8.6</td>
<td>8.8</td>
<td>9.1</td>
<td>9.6</td>
<td>10.0</td>
<td>18</td>
</tr>
<tr>
<td>Battery discharge resistance (m(\Omega))</td>
<td>10.5</td>
<td>10.8</td>
<td>10.9</td>
<td>11.0</td>
<td>11.1</td>
<td>11.3</td>
<td>11.6</td>
<td>12.0</td>
<td>14.0</td>
<td>22.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Battery charge resistance</th>
<th>A0</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery discharge resistance</td>
<td>0.03794</td>
<td>-0.29607</td>
<td>1.14399</td>
<td>-2.07846</td>
<td>1.77683</td>
<td>-0.57603</td>
</tr>
<tr>
<td>Battery discharge resistance</td>
<td>0.04087</td>
<td>-0.27081</td>
<td>0.9702</td>
<td>-1.67385</td>
<td>1.38316</td>
<td>-0.4391</td>
</tr>
</tbody>
</table>
The temperature of three measure points obtained by measurements and simulation at 10A constant current charge/discharge process were all shown in figure 6 and figure 7. The simulation result accord with experimental result. In charge process, the maximum temperature differences between simulation and experimental measurement are 0.55K, 0.48K and 0.64K, respectively. In discharge process, the maximum temperature differences between simulation and experimental measurement are 0.52K, 0.48K and 0.58K, respectively. At the beginning, the temperature increase rapidly in both charge and discharge process. The heat generation rate is greater than heat dissipation rate in this period. Then, in charge condition, with the increase of SOC, the resistance decrease dramatically, the temperature on battery surface decrease rapidly. In the last period, as the resistance do not change dramatically, the temperature tend to be stable. In discharge condition, after beginning period, the resistance of the battery is still not change much, so the battery temperature is stable in middle period. In the last period, as the battery
resistance increase dramatically, the heat generation rate increase rapidly, the temperature soared. Not matter in charge or discharge condition, the temperature of positive plate lug is greater than temperature of negative plate lug and core body. This means that the heat generation on plate lug is not negligible.

Figure 6. Battery temperature of simulation and experiment under 1C charge condition.
Figure 7. Battery temperature of simulation and experiment under 1C discharge condition.

CONCLUSIONS

The thermal model of a LiFePO4 lithium-ion battery is established in this research. Firstly, the Geometrical and mesh model of battery is built. The analysis of battery heat generation character, heat transfer character, and heat dissipation character are also carried out. A simplified equivalent circuit model is built, and the heat generation rate of every heat sources are calculated. A HPPC experiment is conducted to get battery R-SOC characteristic curve. The model is verified and modified by 1C constant current charge/discharge experiment. The experimental result indicate that, the Multiple dynamic heat sources thermal modeling built in this research can preferably reflect the real temperature of the pouch LiFePO4 lithium-ion battery.

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