Research on Anisotropic Conductivity of Cylindrical Lithium Ion Battery

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Abstract. In this paper, the anisotropic conductivity of cylindrical lithium ion battery is theoretically analyzed and a calculation model for the thermal conductivity of the cross section of the battery is established. The axial conductivity of the lithium ion battery is simulated by modeling and calculation. A test rig for measuring conductivity of the axial and cross section of a cylindrical lithium ion battery is designed. Compared with the experimental results and simulation results, the reliability of the simulation analysis method in calculating the thermal conductivity of a cylindrical lithium ion battery is determined.

Introduction

With the rapid development of electric vehicle technology, the use and management of power batteries for driving are also increasing. At present, more and more power batteries for electric vehicles use lithium ion batteries. It is reported that the share of lithium ion batteries in automobile power has reached 52\% \cite{1}. Due to the special structure of lithium ion batteries, in the process of high rate charging and discharging, its thermal conductivity of the anisotropic material varies with temperature, humidity and the space structure of the material, which the thermal conductivity of the material in different directions is different \cite{2}\cite{3}. The heat generated by the internal factors caused the temperature rising has a negative effect on the safety and the efficient use of the lithium ion battery.

In this paper, the anisotropy of the special heat conduction process of lithium ion battery is analyzed. A mathematical model is established to analyze and calculate the radial thermal conductivity and axial thermal conductivity. Meanwhile, a test rig is set up to conduct the preliminary test of the anisotropic thermal conductivity.

Model and Calculation

As shows in Figure1, the stacking structure of lithium ion battery is listed from top to bottom: positive collector, aluminum foil, positive collector, separator, negative current collector, copper foil, negative current collector and separator. In the disassembly process of the 18650 type cylindrical lithium ion battery, the related data of the battery are measured directly: the diameter of the inner winding structure of the battery is \(d =17.32 \text{mm}\), the height of the winding structure is \(h =59.4 \text{mm}\), the total number of turns of the winding structure is \(N =18\), the expansion length of the winding structure is \(S =650 \text{mm}\), and the diameter of the battery core is \(r =1 \text{mm}\). According to the spiral equation, the relationship between the three \(S, b\) and \(R_i\) can be obtained. Its spiral line equation for winding structure is shown as in formula (1) and (2).
The experimental data of \( b = 499.8 \mu m \) battery \( m \), other structure and physical parameters such as cell thickness, each layer of the coefficient of heat conductivity, specific heat, density \( \rho \) by \( c_p \) are listed in Table 1. The thickness and thermal conductivity of each layer of the battery winding structure are replaced by the thermal resistance formula for solving the radial heat transfer process of the cylinder wall of the unit length. The equivalent thermal conductivity of the thermal resistance in the axial heat transfer process is shown as in formula (3).

Table 1. Physical parameters of each layer of lithium ion battery.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aluminum foil</th>
<th>Positive collector</th>
<th>Separator</th>
<th>Negative collector</th>
<th>Copper foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta ) (( \mu m ))</td>
<td>15</td>
<td>140</td>
<td>15</td>
<td>80</td>
<td>14</td>
</tr>
<tr>
<td>( \lambda ) (W/(m-K))</td>
<td>238</td>
<td>1.58</td>
<td>0.3344</td>
<td>1.04</td>
<td>398</td>
</tr>
<tr>
<td>( c_p ) (J/(kg-K))</td>
<td>903</td>
<td>1437.4</td>
<td>1978.2</td>
<td>1269.21</td>
<td>385</td>
</tr>
<tr>
<td>( \rho ) (kg/m(^3))</td>
<td>2702</td>
<td>1347.33</td>
<td>1009.0</td>
<td>2328.5</td>
<td>8933</td>
</tr>
</tbody>
</table>

\[
\frac{1}{\lambda_y} = \sum_{i=1}^{n} \frac{1}{2\pi \lambda_i} \ln \frac{d_{i+1}}{d_i}
\]

\[
\lambda_z = \sum_{i=1}^{n} A_i \lambda_i \left( \sum_{j=1}^{n} A_j \right)^{-1}
\]

By taking \( n = 144 \), the radial equivalent conductivity of the battery is \( \lambda_r = 0.82 \) W/(m-K), \( \lambda_z = 19.26 \) W/(m-K).

**Measurement of Axial Thermal Conductivity**

Measurement principle

Because of its special structure and performance of lithium ion battery, there exist many difficult factors to overcome when to measure the thermal conductivity of the battery. Therefore, many scholars have done a lot of research on the thermal conductivity test of lithium ion power battery, and have put forward some plan. In this paper, an experimental scheme for the anisotropic thermal
conductivity of a cylindrical power cell is designed. The axial thermal conductivity and cross section thermal conductivity of cylindrical Li ion power battery are measured, and the axial thermal conductivity experiment of Li ion battery is designed according to the measurement principle \[4\].

**Experimental steps**

Four lithium ion batteries are fixed. A good conducting plate is placed on the upper end. A copper plate with the same size and good thermal conductivity is attached to the hot plate. The purpose of copper bonding is to achieve the consistency of the surface temperature of the plate. The electric heating plate is placed on the copper plate, and an electric wood board with the same size is attached to the electric heating sheet for heat insulation.

Heat conduction plate and copper plate are attached to the lower end. Two thermocouple points are buried between the two ends of the heat conduction plate and the copper plate. The thermocouple is connected to the data acquisition module and connected to the computer, so that the temperature changes of the upper and lower ends of the heating process can be monitored and automatically recorded.

The insulation package for lithium ion battery, heat transfer can be considered only in the direction perpendicular to the plate on the lateral side of the dispersed heat can be ignored, that is to say, the lithium ion battery only with the temperature gradient in the vertical direction, in the same plane, around the same temperature. Experimental schematic shows as in Figure 2.

According to Figure 3, when the voltage is 6.2V, the temperature of 1, 2, 3 and 4 has been stabilized around 20000s. The temperature of each test point is \[t_1=47.19^\circ C, t_2=46.49^\circ C, t_3=26.3^\circ C, t_4=25.64^\circ C\], respectively. According to Fourier law and series parallel thermal resistance formula, the axial thermal conductivity of the battery is obtained. The axial thermal conductivity of the cylindrical lithium ion battery is \[\lambda_z=2.66\text{W/(m}\cdot\text{K)}\].

In the same way, according to figure 4 and Fourier law and the series parallel thermal resistance formula, the axial thermal conductivity of a cylindrical lithium ion battery can be calculated to be \[\lambda_z=3.6\text{W/(m}\cdot\text{K)}\].

**Measurement of Conductivity in Cross Section**

Measuring principle
In this paper, the thermal conductivity of the cross section of the battery is obtained by the experimental method and the simulation method.

Experimental steps

The experimental procedure is similar to the method of measuring the axial thermal conductivity of the battery in Figure 2. It is just a little different in experimental design and data processing.

The experimental process is shown in Figure 5.

![Figure 5. Measuring sketch of cross section conductivity.](image)

![Figure 4. a. 10.4V, temperature at axial-1 and 2 b. 10.4V, temperature at axial-3 and 4.](image)

![Figure 6. a. 6.2V, temperature at point 1 and 2 b. 6.2V, temperature at point 3 and 4.](image)

Experimental results and analysis

According to Figure 6, when the voltage is 6.2V, the temperature of 1, 2, 3 and 4 has been stabilized around 2200s. At stable state, the temperature of each test point is: \( t_1 = 26.86^\circ C \), \( t_2 = 26.22^\circ C \), \( t_3 = 20.09^\circ C \), \( t_4 = 21.17^\circ C \). The average temperature of the upper and lower surfaces of the stable state is 26.25^\circ C and 20.58^\circ C, respectively.

It is known from the experimental map line, during the experiment, the temperature on the whole change is more stable, and there is no larger fluctuation. Only 3 and 4 points have a relatively large vibration from 1100s to 1300s. At about 1100s, the temperature rises abruptly to 22^\circ C, then slows down slowly, and returns to normal after 200s. The reason for the analysis may be that during the experiment, the experimenters accidentally ran into the fan, causing the 3 and 4 thermocouples near the fan side to fall into the thermal conductive material and cause the temperature to rise. After the end of force, it returned to normal.
According to Figure 7, when the voltage is 10.4V, the temperature at point 1, 2, 3 and 4 has been stabilized around 1600s. At stable state, the temperature of each test point is: \( t_1 = 40.37^\circ C \), \( t_2 = 42.02^\circ C \), \( t_3 = 23.05^\circ C \), \( t_4 = 25.22^\circ C \).

It is known from the experimental map line, during the experiment, the temperature on the whole change is more stable, and there is no big fluctuation. Only 3 and 4 point temperatures are relatively large at the beginning of the measuring time of two temperatures. The reason may be that a thermocouple has been heated for a period of time before the thermocouple begins to record the experimental data and causes the initial temperature difference between 3 and 4.

Simulation calculation\(^5\)

The parameters of the simulated working conditions are shown in Table 2. The simulation test process is shown in Table 3, and the final result temperature cloud chart is shown in Figure 8.

<table>
<thead>
<tr>
<th>Steady simulation</th>
<th>Heating end (^\circ C)</th>
<th>Dissipation end (^\circ C)</th>
<th>Heat flux ( W/m^2 )</th>
<th>Conductivity of heat plate ( W/(m \cdot K) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2V</td>
<td>26.25</td>
<td>20.58</td>
<td>421</td>
<td>2.6</td>
</tr>
<tr>
<td>10.4V</td>
<td>41.195</td>
<td>24.135</td>
<td>1205.7</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Table 3. Simulation process.

<table>
<thead>
<tr>
<th>6.2V</th>
<th>The input value of cross section conductivity ( W/(m \cdot K) )</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2.0</th>
<th>1.2</th>
<th>1.3</th>
<th>1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heating end temperature (^\circ C)</td>
<td>28.9</td>
<td>2</td>
<td>26.8</td>
<td>7</td>
<td>25.7</td>
<td>9</td>
<td>25.1</td>
</tr>
<tr>
<td>10.4V</td>
<td>The input value of cross section conductivity ( W/(m \cdot K) )</td>
<td>1.25</td>
<td>1.3</td>
<td>1.2</td>
<td>1.15</td>
<td>1.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heating end temperature (^\circ C)</td>
<td>40.5</td>
<td>8</td>
<td>40.2</td>
<td>8</td>
<td>40.9</td>
<td>3</td>
<td>41.2</td>
</tr>
</tbody>
</table>

Under the working condition of 6.2V, it is assumed that the thermal conductivity of the cross section of the battery is calculated by 0.5\( W/(m \cdot K) \), and the temperature of the heating end is 28.92\(^\circ C\). There is a great difference between the temperatures of the heating end at 26.25\(^\circ C\) in the steady state process measured by the experiment. Obviously it sets too small, therefore, the conductivity of the cross section of the battery is set to 1\( W/(m \cdot K) \) at the second time, and the temperature of the heating end is 26.87\(^\circ C\), and the temperature of the heating end is approaching gradually. The conductivity of the cross section of the battery was increased to 1.5\( W/(m \cdot K) \) and 2\( W/(m \cdot K) \). The temperature of the heating end was 25.79\(^\circ C\) and 25.11\(^\circ C\), respectively. Therefore, the thermal conductivity of the cross section of the battery must be between 1 and 1.5. So its conductivity of the battery is set to 1.2\( W/(m \cdot K) \) and 1.3\( W/(m \cdot K) \) respectively, and the temperature of the heating terminal of the battery is 26.38\(^\circ C\) and 26.15\(^\circ C\) degrees, respectively. Finally, the thermal conductivity of the cross section of the battery was measured between 1.2 \( W/(m \cdot K) \) and 1.3 \( W/m \cdot K \) It is set to 1.25\( W/(m \cdot K) \), and the temperature of the
heating end is 26.27°C, which is close to the average temperature of the experimental heating end of 26.25°C. Therefore, under the condition of 6.2V, the thermal conductivity of the cross section of the battery is 1.25W/(m·K). The simulated temperature cloud chart under the working condition is shown in Figure 8.

The simulation test process of the 10.4V working condition is the same as that of 6.2V. The final heat conduction system of the cross section of the battery is 1.10W/(m·K). The simulated temperature cloud chart under the working condition is shown in Figure 9. The thermal conductivity of the cross section of the battery is compared to the two conditions, and the thermal conductivity of the cross section of the battery is 1.2W/(m·K).

![Figure 8. 6.2V, temperature cloud chart](image)
![Figure 9. 10.4V, temperature cloud chart](image)

**Summary and Discussion**

In this paper, the thermal conductivity of a cylindrical lithium ion battery is calculated with theoretical calculation method. The series of thermal conductivity and the coefficient of parallel thermal conductivity are obtained. In the experiment of axial thermal conductivity, the axial thermal conductivity of two working conditions is measured under the condition of 6.2V and 10.4V, and the data of Fourier transform are used to deal with the data. The thermal conductivity of the two cases is 2.26W/(m·K) and 3.6W/(m·K) respectively.

In the experiment of measuring the thermal conductivity of the cross section, the difficult part is data processing. Because the experiment excavated a hole with the same size as the battery with the known thermal conductivity, and measured the battery in the hole. The final result is ideal. When 6.2V is used, the cross section thermal conductivity of the battery is 1.25W/(m·K) and 10.4V when it is 1.10W/(m·K), and the average value of the two values is 1.175W/(m·K).

**Reference**


