Experimental measurement of anisotropic thermal conductivity of 18650 lithium battery

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Abstract. The accurate thermal conductivity of the 18650 cell is essential to the thermal management of the battery pack for electronic vehicles and aircrafts. The structure of the cell makes the conductivity anisotropic. Judged from the cell structure, the azimuthal and axial conductivity are approximately the same while the radial conductivity is much different from them. The axial conductivity of a cell is calculated by supplying an axial steady heat rate through the cell and measuring the axial temperature difference over the cell. For the radial conductivity, a steady heat rate is supplied on one quarter of the cylindrical outer surface of the cell, the heat crosses the cell radially and azimuthally to the opposite quarter of the cylindrical outer surface. The temperature difference of the two quarter surfaces is measured, and the radial conductivity of the cell is determined by adjusting the radial conductivity value with known azimuthal conductivity (equals to the axial conductivity) in an accurate CFD heat transfer simulation to match the measured temperature drop.

1. Introduction

With the continuous expansion of lithium-ion battery applications, the safety of lithium batteries has attracted more and more attention and concern. In the past ten years, the accidents caused by the ignition of lithium batteries has occurred in various products with lithium-ion batteries [1] [2] [3]. With the rise of electric vehicles, the safety of lithium batteries in electric vehicles has attracted wide attention. Although lithium battery fire is extremely rare, only one of every 1 million to 10 million manufactured batteries will cause fire problems [4] [5], but for electric vehicles, the frequency of fires has risen to 1/10000, which has caused public concern. Therefore, it is the responsibility of the scientific community to continue to study the thermo-physical properties of lithium-ion batteries and improve the safety of lithium-ion battery products.

In the early studies, researchers did not realize the importance of the anisotropic thermal conductivity
of lithium-ion batteries for the heat transfer of lithium batteries. And the literature on the measurement of the thermal conductivity of lithium-ion batteries is very rare. Yuefei Chen [6] who built a three-dimensional model to simulate the heat transfer of lithium-ion batteries under electrostatic discharge and dynamic power profiles, is the first one to realize that the anisotropic thermal conductivity of lithium-ion batteries is very important. The anisotropic thermal conductivity inside the lithium battery was found to be an important factor affecting the thermal performance of the battery. He also pointed out that the anisotropy of thermal conductivity cannot be ignored when studying the thermal performance of the battery. When Sheldon R.C [7] built the lithium-ion battery model, he found that the thermal conductivity in the direction parallel to electrodes direction is larger, and the thermal conductivity perpendicular to the electrodes direction is smaller. The first to measure the anisotropic thermal conductivity of batteries is Maleki et al [8], who proposed to use xenon flash technology (XFT) and steady-state measurements to measure thermal conductivity and specific heat capacity, but this approach does not provide thermal conductivity for the entire cell, this method is not only inconvenient but also expensive. Christophe’s methods [9] are more simple and easier to implement. A thermocouple is placed on the outer surface and inside of the battery at the same time, and different amplitude of current pulses are applied, through the measured the external and internal temperature, the conductivity and specific heat can be determined. This method can measure the thermal conductivity of the entire cell more accurately. But inserting a thermocouple into a battery will destroy the battery. Most of the experiments on the anisotropic thermal conductivity of batteries before 2014 were carried out by destroying the battery structure. The first literature to measure the anisotropic thermal conductivity of a battery without damaging its structural was published in 2014 by Drake and colleagues [10]. The test method mentioned in the literature is the transient method, which can simultaneously measure the heat capacity of the battery, the axial and radial thermal conductivity, and the experimental and finite element simulation results agree well; the literature also points out that the thermal resistance variation of lithium battery at 20℃~50℃ is less than 0.1%. The literature measures the thermal conductivity of LiFePO4 18650 batteries. There is currently no report on the thermal conductivity data of the NCA ternary lithium battery used in Tesla vehicles.

This paper presents a new method for measuring the anisotropic thermal conductivity of a battery. The measurement accuracy was validated using a standard 316 test piece, then the axial and radial thermal conductivity of the NCA ternary lithium battery was measured.

2. Experiment

2.1 Measurement of axial thermal conductivity of battery

Figure 1 shows a cross-sectional view of a cylindrical lithium ion battery in which cathode sheets, anodes sheets, and separator sheets are rolled to a cylinder. Due to the special configuration of the cylindrical battery, the axial, azimuthal, and radial heat transfer is quite different. In the axial and azimuthal heat transfer, the different layers of material transfer the heat parallelly. In the case of radial heat transfer, the heat will transfer across different layers. So the axial and the azimuthal thermal conductivity should be close and much higher than the radial conductivity.
Figure 1. Internal structure of a lithium ion battery.

Figure 2 shows the test device and the schematic diagram for measuring the axial thermal conductivity of the battery. The outer casing of the whole device is made of POM plastic (full name polyformaldehyde, a thermoplastic crystalline polymer with good strength and stiffness and small thermal conductivity) with a small thermal conductivity. These is an upper brass rod and a lower brass rod (25mm diameter), the test piece is between the rods. A heating rod is placed inside the upper center of the upper brass rod (thermal conductivity is 125.6 W/m/K) and a water cooling passage is placed inside the lower center of the lower brass rod. During the experiment, an adjustable direct current is supplied to the heating rod, the heat is transferred to the lower brass rod and removed by the cooling water. The majority of the heat is transferred to the water and some are dissipated by the brass and test piece walls through natural convection and surface radiation with the POM casing. The DC power supply voltage has a voltage reading accuracy ± (0.02% of reading + 5mv), a current reading accuracy ± (0.3% of reading + 10mA). The whole device is equipped with 12 K-type thermocouples (temperature measurement error is ±0.75% reading), most of them are set on the inner wall of the POM casing. Two of them are set in center of the brass rods, one is in the upper rod and one is the lower rods. They are 7.5mm from the end surfaces of the test pieces (316 stainless steel cylindered battery, the 316 stainless steel cylinder is the same size as the battery and is used to for measurement system accuracy calibration with known thermal conductivity). The measured POM wall temperature is used for the boundary condition of the CFD simulation. When the entire system reaches steady state, the temperature is read and recorded. Since the anode side of the battery is recessed, it is filled with fine brass powder (the anode surface is sprayed with an insulating material before filling).
Figure 2, lithium battery axial thermal conductivity measurement device (a) and schematic (b).

CFD studies were set up using Star-CCM+ software. The CFD simulation simulates the entire heat transfer process of the measurement process, including the heat conduction inside the brass rods rod and the test piece, the laminar natural convection of the air and the surface radiation heat transfer between the solid walls. The gas density is calculated as an incompressible ideal gas. Because of the existence of natural convection, a coupled solver is used to solve the conservation equations. The emissivity of each solid surface was measured using an infrared camera after heating: the emissivity of the brass rod is 0.14, the emissivity of the battery surface is 0.45, the emissivity of the 316 stainless steel is 0.4, and the emissivity of the POM is 0.92. The input heat power of the CFD simulation is consistent with the experimental value, and the POM wall temperature is set according to the measured temperature. In the CFD simulation, the thermal conductivity of the test piece is adjusted to match the temperature difference between the two thermocouple inside the brass rods. The temperature contour and boundary settings of the CFD simulation are shown in Figure 3. During the test, a thermocouple was set at 37.5 mm from the upper surface of the lower brass rod, and this location is lower bound of the simulation domain. Four thermocouples are attached to the inner wall of the POM casing surrounding the upper brass rod. A temperature curve is fitted as the boundary condition of the CFD simulation. The test piece boundary is calculated from the measured temperature at Boundary 1 and Boundary 2. The temperature at the Boundary3, Boundary4, Air-aerogel boundary and Cu-aerogel boundary are from the measured value with the thermocouples.

Figure 3. CFD simulation of the axial thermal conductivity measurement.
2.2 Measurement of radial thermal conductivity of battery

The casing of the radial thermal conductivity measurement equipment is also made of POM plastic. As shown in Figure 4. There are an upper brass cuboid and a lower brass cuboid whose surfaces are cut to fit a quarter of the battery surface. The test piece is between the cuboids and horizontally placed. The heating plate is placed on the upper surface of the upper cuboid. The cooling passage is designed inside the lower cuboid to remove the heat. Four T type (temperature measurement error is ±0.4% reading) thermocouples T1~T4 are set inside the upper cuboid, so as the lower cuboid T5~T8. T1, T2, T3, T4 are 10mm apart from each other, T5, T6, T7, T8 are also 10mm apart from each other, and T4 and T5 are respectively 3mm from the surfaces of the test piece. The gap between the brass surface and the POM casing is small, and the heat transfer is conduction and the heat loss is much smaller than the input power. When setting the CFD simulation, the conduction heat loss is ignored and the side surfaces of the brass cuboid is set to be adiabatic. The input power of the heating plate is not directly from the measured value, instead, it is calculated by the linear fitting of T1, T2, and T3 (The measured values were linearly fitted to the temperature profile. Taking into account the cross-sectional area of the brass cuboid and the thermal conductivity, the heat transfer rate at the T3 position was calculated as the input power).

![Figure 4](image)

**Figure 4.** Lithium battery radial thermal conductivity measurement device (a) and schematic (b, c).
The CFD setting for radial thermal conductivity measurement is similar to that of the above axial CFD setting. In the radial thermal conductivity measurement, the heat is transfer radially and azimuthally inside the test piece. The circumferential thermal conductivity is set as the axial thermal conductivity measured above, and the radial thermal conductivity is adjusted to match the temperature difference between T4 and T5 to determine the radial thermal conductivity. The cold end boundary is set to the convection boundary, and the convection temperature and the convective heat transfer coefficient will only increase or decrease the temperature of T4 and T5 at the same time, and the temperature difference is not changed, so it can be set at will. Figure 5 shows the radial thermal conductivity test diagram and schematic.

Figure 5. CFD simulation of the radial thermal conductivity measurement

3. Measurement accuracy determination

The thermal conductivity was measured for the 316 stainless steel cylinder the battery size to determine the accuracy of the measurement method. The thermal conductivity of 316 stainless steel was measured at 0 °C (14.27 W/m/K) and 100 °C (14.75 W/m/K) using the Hot Disk TPS2500. The thermal conductivity of 316 steel at other temperatures is obtained by linear interpolation.

The thermal conductivity of 316 stainless steel is measured with the axial thermal conductivity measurement device. The DC power input is 12.272W, the temperature of the upper brass rod temperature measuring point is 106.8°C, and the temperature of the lower brass rod measuring point is 31.8°C. The thermal conductivity calculated for the upper and lower temperature difference is 14.4 W/m/K, and the true value is 14.494W/m/. The relative error is -0.649%.

Table 1 shows the temperature data of the radial experiment for the 316 steel. The input heat flux is 10676 W/m². The thermal conductivity calculated by the temperature difference of T4/T5 is 14.841W/m/K, the relative error is 2.394% compared with the actual value of 14.334W/m/K.

Table 1. Experimental data of the 316 steel test with the radial device

| T1  | T2  | T3  | T4  | T5  | T6  | T7  | T8  |
|-----|-----|-----|-----|-----|-----|-----|-----|
| Temperature/°C | 42.9 | 42.1 | 41.2 | 40.1 | 29.3 | 27.5 | 26.6 | 25.6 |
4. Lithium battery measurement results

The measurement data of the axial test for battery is shown in Table 2 (input power, temperature of the measuring point of the upper rod, the temperature of the measuring point of the cold rod). The table also lists the calculated temperature of the CFD simulation using 11.5 W/m/K. It can be seen that the measured thermal conductivity of the lithium battery is about 11.5 W/m/K.

Table 2. Measurement and CFD data when the axial thermal conductivity of lithium battery is 11.5 W/m/K

|                | upper temperature/°C | lower temperature/°C | Temperature difference/°C |
|----------------|-----------------------|-----------------------|---------------------------|
| Test result    | 125.7                 | 31.3                  | 94.4                      |
| CFD result (11.5 W/(m K)) | 125.9                 | 31.54                 | 94.36                     |

Table 3 lists the measurement data for the radial conductivity measurement. Figure 6 shows the temperature difference of the CFD study as the function of radial thermal conductivity. The radial thermal conductivity corresponding to the measured temperature difference is 4.324 W/m/K.

Table 3. Radial thermal conductivity measurement data with input power is 14.5545 W

| T1  | T2  | T3  | T4  | T5  | T6  | T7  | T8  |
|-----|-----|-----|-----|-----|-----|-----|-----|
| Temperature/°C | 63  | 62  | 60.9 | 59.4 | 34.4 | 32.7 | 31.3 | 30  |

![Figure 6](image)

Figure 6. Temperature difference variation with radial thermal conductivity of lithium battery.

5. Conclusion

This paper presents a new method for measuring the axial and radial thermal conductivity of lithium
batteries. The test methods use the combination of experiment and CFD simulation. By adjusting the thermal conductivity of the battery to match the temperature difference between the upper brass part and the lower brass part, the axial and radial conductivity can be obtained. In the axial measurement, because the heat loss of the upper brass rod is high, all heat loss modes are considered in the CFD simulation, and the input power is the measured value. In the radial measurement, since the heat loss is small, the side wall of the cuboids are set to adiabatic, and the input power is obtained by conduction heat transfer rate calculated from the measured temperature. By measuring the 316 steel rod with known thermal conductivity, the accuracy of the measurement method was verified. The error of the axial measurement method was about -0.649%, and the error of the radial measurement method was about 2.394%. The axial and radial thermal conductivity of 18650 Tesla NCA ternary lithium battery were measured to be 11.5W/m/K and 4.324 W/m/K, respectively.

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