Measurement of the Effective Radial Thermal Conductivities of 18650 and 26650 Lithium-Ion Battery Cells

Harsh Bhundiya and Melany Hunt
Division of Engineering and Applied Science, Caltech
Bruce Drolen
Engineering Consultant

Presented By
Harsh Bhundiya
Introduction

- Recent harmful fires: Boeing 747-400F cargo plane, Samsung Galaxy S7 phones
- Cause: thermal runaway
- Important to understand thermal runaway and its propagation
Disassembly

- Discharged cells using 13.1 ohm and 5.6 ohm resistors
- Disassembled ten cells: 8 INR18650-25R cells (made by Samsung) and 2 LFP26650P (K226P01) cells (made by K2 Energy Solutions, Inc.)
- Not all cells were manufactured in the same way
~34 in.  ~66 in.
Previous Modeling

• Key consideration in previous thermal models: Effective Radial Thermal Conductivity

• Dr. Tanaka (2014) and Coman et al. (2016) used values in the 1 – 4 W/m-K range (assuming perfect thermal contact in “sheet”)

• Drake et al. (2014) used an analytical model and theoretically determined these values: 0.20 ± 0.01 W/m-K for 18650 cell, 0.15 ± 0.01 W/m-K for 22650 cell

• No other experimental values in literature
Modeling

- Created thermal models of cells using equation for thermal resistance of a cylindrical layer from Fourier’s Law:

\[ R_{\text{cyl}} = \frac{\ln\left(\frac{R_2}{R_1}\right)}{2\pi k_1 L} \]

- 18650 cell: 28 “sheets”; 22650 cell: 38 “sheets”
- Included contact resistances between each “sheet” layer calculated by previous researchers
- Were able to predict thermal conductivity values:
  18650 cell: 0.27 W/m-K; 22650 cell: 0.22 W/m-K
- Disregarding contact resistances, model predicted 1.4 W/m-K for 18650 cell
Total Thermal Resistance vs. Cell Radius
(18650 Cell)

Total Thermal Resistance vs. Cell Radius
(22650 Cell)
Experiment

- Inserted 20 AWG nichrome wire into center of the cell’s winding and heated it using a DC power supply at varying currents.
- Placed two Type K thermocouples (36 AWG) inside center of winding and two outside the case of the cell (20 AWG).
- Steady-state, one-dimensional heat conduction for cylindrical objects:

\[
\dot{Q} = \frac{2\pi k_{\text{eff}} L (T_1 - T_2)}{\ln\left(\frac{R_2}{R_1}\right)}
\]
Experimental Setup (18650 Cell)
Experimental Setup (22650 Cell)

- **DC Power Supply**
- **22650 Cell**
- **Data Logger for Thermocouples**
- **Insulation**
- **Multimeter to Measure Voltage across Nichrome Wire**
18650 Cell Experiments

- Conducted only on cells with spindles (dark green plastic covers): Cells 12 and 13
- Nichrome wire and thermocouples inside spindle (used conductive paste)
- No spindle; nichrome wire and thermocouples inside gap at center of winding
  - Give more accurate measurements because according to model, thermal resistance between spindle and winding is quite high
- Combinations of spindle/no spindle, green plastic cover, and case of cell
### 18650 Cell Experimental Data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>0.34</td>
<td>9.8</td>
<td>32.5</td>
<td>0.21 ± 0.04</td>
</tr>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>0.66</td>
<td>16.6</td>
<td>39.3</td>
<td>0.24 ± 0.03</td>
</tr>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>0.70</td>
<td>22.2</td>
<td>43.2</td>
<td>0.19 ± 0.02</td>
</tr>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>0.93</td>
<td>28.4</td>
<td>49.4</td>
<td>0.20 ± 0.01</td>
</tr>
<tr>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>0.35</td>
<td>4.0</td>
<td>30.0</td>
<td>0.52 ± 0.14</td>
</tr>
<tr>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>0.59</td>
<td>7.6</td>
<td>35.8</td>
<td>0.47 ± 0.08</td>
</tr>
<tr>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>0.91</td>
<td>13.7</td>
<td>42.0</td>
<td>0.40 ± 0.06</td>
</tr>
<tr>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>1.4</td>
<td>19.3</td>
<td>50.6</td>
<td>0.42 ± 0.05</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>0.60</td>
<td>10.2</td>
<td>38.7</td>
<td>0.35 ± 0.09</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>0.93</td>
<td>11.3</td>
<td>44.7</td>
<td>0.50 ± 0.10</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>0.77</td>
<td>21.3</td>
<td>44.8</td>
<td>0.22 ± 0.02</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>0.85</td>
<td>17.4</td>
<td>41.1</td>
<td>0.29 ± 0.05</td>
</tr>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>0.36</td>
<td>6.9</td>
<td>32.6</td>
<td>0.31 ± 0.05</td>
</tr>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>0.67</td>
<td>12.6</td>
<td>38.0</td>
<td>0.32 ± 0.04</td>
</tr>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>0.80</td>
<td>14.7</td>
<td>41.6</td>
<td>0.33 ± 0.03</td>
</tr>
<tr>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>0.73</td>
<td>11.2</td>
<td>39.7</td>
<td>0.39 ± 0.09</td>
</tr>
<tr>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>1.0</td>
<td>14.8</td>
<td>42.8</td>
<td>0.41 ± 0.05</td>
</tr>
<tr>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>1.5</td>
<td>21.7</td>
<td>51.7</td>
<td>0.41 ± 0.03</td>
</tr>
<tr>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>0.59</td>
<td>12.6</td>
<td>39.1</td>
<td>0.28 ± 0.04</td>
</tr>
<tr>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>0.92</td>
<td>20.4</td>
<td>48.0</td>
<td>0.27 ± 0.03</td>
</tr>
</tbody>
</table>

Uncertainty calculations were computed using a root-sum-square method.
• Cells do not contain spindle, so nichrome wire and thermocouples were put inside gap at center of winding
• Cardboard cover slides off easily
• Only Cells 8 and 15
Uncertainty calculations were computed using a root-sum-square method.
Discussion

18650 Cells:
• Thermal resistance btw. spindle and winding is high, so experiments with NO spindles are preferred
• Last two trials from Battery 12 were ignored: 1) In event of thermal runaway propagation, heat would conduct through all parts of cell; 2) Bad thermocouple placement
• Averaging the values in red: $0.43 \pm 0.07 \text{ W/m-K}$

22650 Cells:
• Experiments with highest power input give most accurate measurements (higher temp. difference)
• Averaging the values in red: $0.20 \pm 0.04 \text{ W/m-K}$
Comparisons with Prior Work

2016 NASA Model (Rickman, et al.)

- Winding
  - Radial k = 1 W/m-K

  Contact Coefficient
  - Prof. Marconnett, Purdue value $h=670$ W/m$^2$-C
  - Correlated value in use was much lower, 50 W/m$^2$-C, to match model with Li-ion cell propagation test data

Caltech Study 2017

- Winding
  - Radial k = 0.43 W/m-K

  Plastic Layer
  - 12X thicker than separator

  Contact Coefficient
  - Gaitonde, et al. value: $h=670$ W/m$^2$-C
  - Thick layer (0.15 mm) of plastic surrounds winding
  - Effective contact coefficient including plastic layer and the reduced winding conductivity yields $h_{\text{eff}} = 36$ W/m$^2$-C in reasonable agreement with the correlated value
For 18650 cell, we experimentally measured an effective thermal conductivity of $0.43 \pm 0.07$ W/m-K. For 22650 cell, we got a thermal conductivity of $0.20 \pm 0.04$ W/m-K.

Our values are greater than measured by Drake et al. so 18650 and 22650 cells can conduct heat better than previously thought.

Our model’s predicted value for 22650 cell (0.22 W/m-K) is close to measured value. Predicted value for 18650 cell (0.27 W/m-K) isn’t too close. One reason: contact resistance between cathode and plastic separator is greater than predicted.
Acknowledgements

Many thanks to:

My mentors: Professor Melany Hunt and Dr. Bruce Drolen

Caltech SFP Office

The Tyson Family