Thermal Management and Safety Concerns for Li-ion Batteries in Electric Mobility and Autonomous Vehicles Applications

Said Al-Hallaj, PhD
CEO, AllCell Technologies, LLC
and
Visiting Research Professor of Chemical Engineering
University of Illinois at Chicago
Overview

- History and future technology roadmap
- Mobility applications
- Key improvements and cost reduction
- Thermal management and safety challenges
- Current solutions
- Passive thermal management with phase change composite
- Case studies
- Concluding remarks
e-Mobility is On the Go!

China is banning traditional auto engines as it aims EV domination

France ban sales of petrol and diesel cars by 2040

Britain ban sales of all diesel and petrol cars and vans by 2040

Germany to deploy 1 million EV by 2020

California lawmakers want to ban gas car sales after 2040

GM will have 20 electric models on the road by 2023

Ford creates “team Edison” to accelerate efforts in battery electric vehicles

Mercedes-Benz plans electric versions of all its models by 2022

BMW to offer 12 full electric car models by 2025

Volvo to go all electric by 2019
Electrification Continuum

Functions
- Start/Stop
- Regen. Breaking
- Power Boost
- Electric Loads

5-15% mpg boost
Autonomous and Electric: UXV Battery Challenges

- Compact
- Lightweight
- Long Lasting

Specific Energy
- ATV, Motorcycle, Scooter, eFoil
- UGV, UUV, Glide aircraft
- Avionics, PHEV, EV, eBoat, VTOL

Specific Power
- Stationary, Material Handling

Safety
Li-ion Battery Cost Reduction is Key for e-Mobility

Solar and energy storage are complementary and both are dropping in cost

Source: Bloomberg
Practical Considerations

- **Interchangeability** – Samsung, Panasonic, LG, Sony, etc. offer virtually identical options.

- **Configurability** – Could you do this with pouches?
- **More assembly time, labor, and material reduces cost and technical benefits**
- **More complex pack electrical design**
- **Fast Charge**
Battery Technology Roadmap

Figure courtesy of H. Iba (Toyota Motor Corporation) and C. Yada (Toyota Motor Europe).
Thermal Management of Li-ion Batteries

- Higher temperatures degrade LIBs more quickly, while low temperatures reduce power and energy capabilities, resulting in cost, reliability, safety, range, or drivability implications.
- Therefore, battery thermal management is needed for xEVs to:
  - Keep the cells in the desired temperature range
  - Minimize cell-to-cell temperature variations
  - Prevent the battery from going above or below acceptable limits
  - Maximize useful energy from cells and pack
  - Use little energy for operation
- However, a battery thermal management systems (BTMS) could:
  - Increase complexity
  - Add cost
  - Reduce reliability
  - Consume energy for operation
  - ...

Kandler, Smith, NREL Milestone report 2008
High Temperatures Dramatically Reduce Battery Life

Figure 15: Example of Li-ion capacity fade and resistance growth for a high-energy 18650 cell (2.9 Ah) with a graphite anode and NCA cathode chemistry. Data shows cycling results under various temperature and peak charge voltage conditions.

Predicting Battery Life is not Easy

Calendar ageing due to SEI Growth

Cycling ageing due to particle fracture

Figure 5. Fitting results for Cell A and Cell B experimental data to semi-empirical models.

\[ \theta_n = \exp \left[ \frac{a_1 F}{R} \left( \frac{1 + a_2 SOC + a_2 SOC^2}{T} - \frac{1 + a_2 SOC_{ref} + a_2 SOC_{ref}^2}{T_{ref}} \right) \right] \]  

Thermal Management Improves Battery Life and Safety

Majority of Auto and Stationary Currently Use Active Systems

Liquid/Refrigerant

- Very effective
- Heavy
- Expensive and Complex
- Concern about Leaks
- Inefficient
- May not stop thermal runaway propagation

Air

- OK for some HEVs:
  - Inadequate heat removal for fully electric vehicles
- Bulky
- Concerns about cold weather
- May not stop thermal runaway propagation

Active Thermal systems can decrease efficiency by up to 20%
Conventional EV Battery Cooling Systems
Thermal Management with Phase Change Composite (PCC)

PCC is a mixture of phase change material (paraffin wax) and graphite

- **Wax**: Wax absorbs heat as it melts
- **Graphite**: Graphite distributes heat evenly

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature With No PCC</th>
<th>Temperature with PCC</th>
<th>Temperature Remains Constant During Melting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Graphs showing:
- Pack temperature with no thermal management
- Pack temperature with AllCell PCC

Images of PCC material and Li-ion cells.
Case Study: 48 V Micro-Hybrid Battery

**Study Parameters:**
- Heat Transfer coupled with a Laminar flow study
- US 06 drive cycle for light hybrid vehicle
- PCM is employed as a Passive thermal management complex.

**Boundary Conditions:**
- Air Ducts as well as PCM Outer surfaces are all Thermally insulated
- Initial Temperature = 30°C

**Battery Specifications (LFP)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>11 (22 peak)</td>
</tr>
<tr>
<td>Energy (Wh)</td>
<td>500</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>7.4</td>
</tr>
<tr>
<td>Volume (L)</td>
<td>5 (.48 x .19 x .8 m)</td>
</tr>
<tr>
<td>Impedance (mOhm)</td>
<td>75</td>
</tr>
<tr>
<td>Thermal management</td>
<td>PCM37 + Air</td>
</tr>
</tbody>
</table>

**Cooling Air:**
- Inflow Velocity = 2 m/s
- Inlet Temperature = 25°C

**PCM Specifications**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Melting Temp (°C)</td>
<td>37</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>925</td>
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<tr>
<td><strong>Latent Heat (J/g)</strong></td>
<td>174</td>
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<tr>
<td>Specific Heat (J/kg.K)</td>
<td>800</td>
</tr>
<tr>
<td>Thermal conductivity (W/m.K)</td>
<td>25 x-y dir 3 z dir</td>
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</table>

Compact | Lightweight | Long Lasting
Initial testing shows temperature uniformity

Hybrid pulse test temperature

Simplified drive cycle – 190 W avg heat gen

Duty Cycle

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Current (A)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>-80</td>
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<tr>
<td>2</td>
<td>-60</td>
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<tr>
<td>4</td>
<td>-40</td>
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<td>6</td>
<td>20</td>
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<tr>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>12</td>
<td>-80</td>
</tr>
</tbody>
</table>

Compact | Lightweight | Long Lasting
US06 Modeling comparison

10 m/s air flow – 0.4 m³/s

Air only

2 m/s air

PCM+Air
Case Study: Commercial Drone Battery

PCC keeps cells cool during high power discharge – 4g of PCC mass per 18650 cell increases runtime by 40%

- Standard battery design, No PCC
- With 8% mass AllCell PCC48

240 Wh/kg cells

Battery Temperature Cutoff

40% run time extension

Time (min)

Battery Temperature (°C)
Case Study: Standby in Hot Environments

A comparison of two battery packs in a hot parking lot (Phoenix, Arizona)

PCC keeps the battery over 15°C cooler than a pack without PCC

Source: AllCell Technologies’ Internal Testing & Simulation
Thermal Management Solutions

<table>
<thead>
<tr>
<th>Items</th>
<th>Performance</th>
<th>Safety</th>
<th>Weight</th>
<th>Size</th>
<th>Reliability</th>
<th>Cost</th>
<th>Energy Consumption</th>
<th>Sum</th>
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<tbody>
<tr>
<td>Weighting factor</td>
<td>x12</td>
<td>x5</td>
<td>x3</td>
<td>x3</td>
<td>x11</td>
<td>x4</td>
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<tr>
<td>Active Air system</td>
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<td>1</td>
<td>3</td>
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<td>3</td>
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<td>Passive Liquid System</td>
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<td>3</td>
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<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
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<td>Combined Liquid System</td>
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<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>90</td>
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<td>Direct Refrigerant System</td>
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<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
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<td>3</td>
<td>2</td>
<td>3</td>
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<td>1</td>
<td>3</td>
<td>93</td>
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<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>77</td>
</tr>
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</table>

Source: http://publications.lib.chalmers.se/records/fulltext/200046/200046.pdf
Safety Concerns are Real
Accelerated Rate Calorimetry (ARC)

- Accelerating Rate Calorimeter (ARC) heats cell (i.e. 5 °C) then waits for stabilization before seeking exothermic behavior. This process is repeated until exothermic behavior is observed. ARC then maintains adiabatic conditions whilst observing cell exothermic and TR behavior.
- Exothermic behavior defined as self-heating >1.5 °C/min
- TR defined as self heating >10 °C/min

ARC Data for Commercial Cylindrical Li-Ion Cells

- Cells exhibit self heating (exothermic) behavior > 130 °C
- Increased cell capacity results in lower self heating initiating temperature
- Cells undergo TR > 160 °C
- TR initiation temperature higher for 2.5 Ah cell compared with 3.2 and 5 Ah cells, which show similar initiation temperature
- Maximum temperature of TR variable among cell repeats

<table>
<thead>
<tr>
<th>Cell capacity</th>
<th>Self heating Onset (Heating rate &gt;1.5°C/min), °C</th>
<th>TR Onset Temperature (Heating rate &gt;10°C/min), °C</th>
<th>Max TR Temperature, °C</th>
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</thead>
<tbody>
<tr>
<td>3.2 Ah (18650)</td>
<td>150</td>
<td>182</td>
<td>552</td>
</tr>
<tr>
<td>3.2 Ah (18650)</td>
<td>149</td>
<td>179</td>
<td>716</td>
</tr>
<tr>
<td>3.5 Ah (18650)</td>
<td>132</td>
<td>166</td>
<td>374</td>
</tr>
<tr>
<td>3.5 Ah (18650)</td>
<td>146</td>
<td>165</td>
<td>523</td>
</tr>
<tr>
<td>5 Ah (21700)</td>
<td>139</td>
<td>169</td>
<td>501</td>
</tr>
<tr>
<td>5 Ah (21700)</td>
<td>138</td>
<td>169</td>
<td>448</td>
</tr>
</tbody>
</table>
Battery Safety Research Overview

- Evaluate what cell packaging materials can prevent the propagation of thermal runaway in a small pack of 18650 style cells.
  - Air
  - Graphite
  - Wax
  - Graphite and Wax (PCC)
- Evaluate the importance of battery configuration and weld strength on thermal runaway propagation
- Nail penetration test
Preventing Thermal Runaway Propagation

No Thermal Management

First cell in thermal runaway
Thermal runaway spreads cell by cell throughout the pack

Cells In a Battery Pack

Cells

Source: U.S. National Renewable Energy Laboratory (NREL)

Thermal Management with PCC

First cell in thermal runaway
PCC absorbs and dissipates heat
Prevents other cells from entering thermal runaway

Cells In a Battery Pack

Cells

Graphite matrix impregnated with PCM

Source: U.S. National Renewable Energy Laboratory (NREL)
Different Material Properties

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Graphite Only</th>
<th>Wax Only</th>
<th>PCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (W/m-K)</td>
<td>0.024</td>
<td>13.77 (in-plane)</td>
<td>0.15</td>
<td>17.21 (in-plane)</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1.23</td>
<td>200</td>
<td>775</td>
<td>935</td>
</tr>
<tr>
<td>Specific Heat (J/kg-K)</td>
<td>1005</td>
<td>725</td>
<td>2384</td>
<td>1837</td>
</tr>
<tr>
<td>Latent Heat (J/g)</td>
<td>N/A</td>
<td>N/A</td>
<td>211</td>
<td>153</td>
</tr>
<tr>
<td>Diffusivity (mm²/s)</td>
<td>19.42</td>
<td>94.96</td>
<td>0.08</td>
<td>10.02</td>
</tr>
</tbody>
</table>
No Thermal Runaway Propagation

Thermal Runaway Propagation

*Pack was sprayed with water after second cell propagated in packs that propagated
Nickel separation during cell venting

Nickel Cladding can separate from venting cell isolating electrical energy available for thermal runway propagation

Not 100% reliable separation. Cells can vent outside of side casing
Spear successfully demonstrated using phase change material to prevent propagation of the 5.0Ah 21700 cell.

Over 20 nail penetrations tests were conducted, including repetitions of the final design to ensure repeatable results.

The test block featured 10 cells connected in parallel. The design incorporates individual cell fusing on the top and bottom of the block.

Images and data are from repeatability test #3 on April 4, 2018.

battery pack supports a directed energy application in an airborne environment
Nail Penetrated Cell
Adjacent Cells

phase change material successfully maintains the temperature of adjacent cells below the onset temperature of thermal runaway.

Nail pen short circuit. Voltage falls and recovers after fuse is blown.
Concluding Remarks

- Li-ion battery is leading the way for powering e-mobility and autonomous vehicles
- Cost of Li-ion battery technology continues to drop and is enabling new applications
- Thermal management and safety concerns are real and may hinder further Li-ion battery deployment
- New battery technology are under development but are at least 5-10 years away from commercialization
Thank You!