Development and Application of Liquid-cooled Lithium-ion Battery Pack Thermal Model

Model based approach by using GT-SUITE

Yifan (Flora) Zhou
DEP

Meng Li
DEP

Fan He
Optimal

Wei Tao
FCA US LLC

Xinran Tao
Optimal

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Motivation: Battery Thermal Modeling

- Battery cell temperature and hot spots can have a critical impact on cell, pack and battery system performance.
- Proper thermal management prevents:
  - Thermal runaway
  - Low fuel economy
  - Reduced battery life
  - Poor performance
- High-fidelity battery pack and cooling system model is important for accurate control and proper thermal management.

Battery Cooling system
- Pump sizing
- Flow, heater and AC control
- Warm-up strategy
- ...
Single Cell Modeling Concept

- Diagram: Battery pack and cooling system
- Every single cell GT model includes electrical and thermal sub-models
- This model is for an indirect liquid-cooling battery thermal system

**Diagram: Battery pack and cooling system**

- **Vehicle speed**
  - **Power demand**
    - **Battery: Electrical**
    - **Battery: Thermal**
      - **Heat generation**
        - **Cell temperature**
          - **Heat removal by cooling system**
To resolve current, heat generation and temperature non-uniformity within one cell, a detailed electrical model consisting of cathode, anode and sub-cell electrical networks is required.

- A Single cell model consisting of 3 sub-cells (in 1x3 configuration) is shown below.

Rci: electrical resistances on cathode current collector

Rin: internal resistance of sub-cell

OCV: open circuit voltage of sub-cell

H: Cell height

W: Cell width
Battery Cell Thermal Modeling

- **A battery cell thermal model** template has been developed.

- **Battery thermal behavior prediction**
  Battery cell model offers transient thermal behavior prediction, given variable charging/discharging cycles and different coolant flow rates and temperatures.

- **Battery temperature distribution prediction**
  Battery pack Max/Min temperature prediction, as well as coolant temperature change can be achieved, by using simulation from knowledge of specific boundary conditions.
System Model Integration

- Assembly from previous slide battery cell model is packaged as a GT compound template.
- The battery cell temperature, coolant temperature and SOC can directly link to ICOS for system level co-simulation.
Heat Transfer Coefficient

• Heat transfer coefficient (HTC) at cooling pad on the coolant side is calculated through Dittus-Boelter Correlation.

Dittus-Boelter Correlation:

\[ h = 0.23 \left( \frac{k}{d} \right)^{0.8} \left( \frac{j * d}{\mu} \right)^{0.8} \left( \frac{\mu * c_p}{k} \right)^{0.33} \]

• Effective convection thermal resistance of cooling plate derived from HTC as a transient function of coolant flow rate

\[ R_{plate} = \frac{1}{h} A_{plate} \]
Simulation Assumptions

• By neglecting electric work done in the electrolyte and the reversible entropic loss, which can be neutralized during charging/discharging reaction, heat generation in one battery cell can be considered to be mainly contributed by Joule losses calculated as

\[ Q = R I^2 \text{ [watt]} \]

In which, I: Current, R: Internal resistance, Q: Heat generation rate

• Coolant inlet temperature and ambient temperature are set to be 18°C
• Battery cell divided into 3 uniform thermal masses. Inside each mass the heat generation is estimated as a function of local current density and equivalent resistance, arranged as shown with bottom part connected to cooling pad

• Different coolant volume flow rates are investigated
• Define the transient current profile
• Convective heat transfer coefficient between battery and air is 5W/m²K
## Simulation Cases Boundary Conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Current Profile</th>
<th>Coolant Flow Rate (L/min)</th>
<th>Coolant Inlet T (°C)</th>
<th>Ambient T (°C)</th>
<th>Battery Cell Initial T (°C)</th>
<th>Initial SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>shown as</em></td>
<td><strong>Constant Flow</strong></td>
<td>18</td>
<td>25</td>
<td>25</td>
<td>0.9</td>
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<tr>
<td>2</td>
<td>Current Profile 1C</td>
<td><em>Profile shown as Coolant Flow</em></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

![Current Profile 1C Graph](image1)

![Coolant Flow Graph](image2)
Battery Pack Results Correlation

- Constant coolant mass flow rate applied for battery temperature stabilization
- Input electric current drops to 0A at 6,000s, without heat generation, the temperature decreases very fast
- A good correlation between test data and GT simulation results achieved with an error smaller than 1%

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Heat generation from battery charge & discharge

Convection cooling & Cooling system effect
Battery Pack Results Correlation

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<td>Coolant Flow 3</td>
<td>18</td>
<td>25</td>
<td>25</td>
<td>0.9</td>
</tr>
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- For the first 6000s, with no coolant flow applied, cell temperature increases.
- Cell temperature drops slowly due to air convection without heat generation (current is 0A) during 6,000-8,000 sec of the simulation.
- Coolant started flowing after 8,000 sec, the battery temperature decreases dramatically.

Heat generation from battery charge & discharge

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Convection cooling

Convection cooling & Cooling system effect

Test max T
GT max T
Test coolant T
GT coolant T

Max T @6000s (°C)
Coolant outlet T @10,000s (°C)

Error
1.1%
Summary

• GT battery cell model template was applied to a battery thermal model for transient heat generation rate calculation, battery cell temperature distribution prediction and overall cooling system performance evaluation

• Integrated battery pack thermal model, developed with proposed single cell model offers accurate estimation of hottest individual cell temperature as well as battery pack coolant temperature change at outlet

• Proposed GT template-based battery pack model provided a fast simulation of thermal behavior and is convenient for integration into the whole vehicle level simulation

• Future work includes model based thermal management control strategy development and experimental validation for improved simulation accuracy
Acknowledgement

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