Outline

• Battery thermal management using CFD
  – WB (DM, WB mesher, CFD, CFD-post, DX)

• Battery system thermal management using Foster network approach
  – Fluent (or CFX) + Simpler

• Battery electric circuit model
  – Simpler + Fluent (for thermal part)

• Battery single cell thermal model
  – Fluent + Simpler (for discharge curve)

• Battery electrochemistry
  – Simpler

• Battery thermal management with bus bar heating using CFD
  – WB tools
WorkBench – An Integrated Solution for Battery CFD Analysis

DM: Geometry tool with full parametric capability

Project page: Defines the work flow

WB: Mesher: Quality meshing with automation

CFD post: Takes advantage of CFX post-processing capability
Build-in What-if Study in WB

- More uniform temperature across cells with smaller gap due to higher velocity at the same mass flow rate inlet.

- First and last cells have higher temperature due to lower velocity without the blockage effect.
HEV Battery Thermal Management

- Thermal Well
- Thermistor in a Well
- Air Flow Gaps Between Modules
HEV Battery Thermal Management

- Input with Variations
  - Gap Thickness
  - Cell Resistance
  - Flow Rate
  - Six input parameters:
    - $\mu_{t_{\text{gap}}}$
    - $\sigma_{t_{\text{gap}}}$
    - $\mu_{R}$
    - $\sigma_{R}$
    - $\mu_{\text{Frate}}$
    - $\sigma_{\text{Frate}}$
HEV Battery Thermal Management

- Outputs – variation
  - Max temperature
  - Differential temperature
  - Pressure drop
- Six output parameters:
  - μTmax
  - μdT
  - μdP
  - σTmax
  - σdT
  - σdP
- Three Upper Specification Limits (USL)
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Battery System Thermal Management

- CFD as a general battery thermal analysis tool is accurate but expensive
  - Not suitable for large system level CFD analysis
  - Not suitable for coupling with battery electrical circuit for large system analysis

- Seek alternatives suitable for system analysis but without compromise of accuracy
  - Thermal network
    - Compromised accuracy
    - Needs careful calibration and calculation of thermal resistance, capacitance, and heat transfer coefficients
  - LTI characterization (reduced order method, Foster network)
    - Can be as accurate as CFD or testing depending on the nature of the system and how the system is characterized
    - No need to calculate thermal resistance, capacitance, or htc.
Automated Process in Simplorer 8.1

1. Create step responses
   - From CFD / Test

2. Generate .simplinfo file

3. Extract equivalent thermal model
   - Use Simplorer

4. Simulate inside Simplorer
Inputs: heat source to each battery
Outputs: battery volume average temperature
Some cross heating elements have negligible contribution (less than 0.1% compared with self heating) and thus no Foster network.
- Reduce the computational effort.
• Foster network and Fluent give identical solution under arbitrary sinusoidal power inputs
  • While CFD calculation takes a few hours on one single CPU, Foster network in Simpler takes approximately 10 to 20 seconds.
Foster Network Approach for Flowrate Change of 100%

- Power inputs are sinusoidal functions.
- Flow rate changes at time of 1000 seconds.
- Results are excellent for the entire duration. A small difference is seen during transition period.
Foster Network  Model of a General Motors  Example Using ANSYS WB + Simpleror

State space model gives the same results as CFD

State space model runs in less than 30 seconds while the CFD runs 2 hours on one single CPU
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Electrical Circuit Model
Motivation

• Simple enough for system level analysis
  – Models based on detailed electrochemistry or detailed CFD analysis is too complex and/or too time consuming for system level analysis

• Accurate enough for virtual prototyping
  – Non-linear circuit voltage as a function of SOC
  – Transient I-V performance
  – Runtime prediction
  – Discharge rate dependent capacity
  – Temperature effect
  – Accurate transient temperature prediction
Battery Cell Electrical Model

Ref: Chen et al*

- Accounts for non-linear open-circuit voltage
- Capable of predicting runtime
  - Error less than 0.4%
- Capable of predicting transient I-V performance
  - Error less than 30-mV
- Can be implemented easily in circuit simulator
  - Implemented in Simplorer®

Experimental Observation

Ref: Gao et al*

- Chen’s model works OK compared with testing data.
  - Under constant temperature and discharge rate

- Rate effect and temperature effect are important to consider

- The discharge history is sensitized to rate of discharge and temperature through rate factor ($\alpha$) and temperature factor ($\beta$)
  - State of Charge:
    $$SOC = 1 - \frac{1}{Q} \int_0^t \alpha[i(t)] \cdot \beta[T(t)] \cdot i(t) \cdot dt$$

Three node cell thermal network model

- Two temperature nodes for the battery
- Separate temperature node for Positive Temperature Coefficient (PTC)
  - PTC has higher temperature under high load condition
- CFD can be used to provide heat transfer coefficient
Electrical + Thermal Network

Ref: Gao et al*

- Electrical circuit and thermal circuit are coupled
  - Includes Positive Temperature Coefficient (PTC)

Electrical + Foster Network Model

- Comments about thermal network
  - It needs expertise to build
  - It is not very accurate due to limited number of thermal nodes
  - It is complex with many nodes
  - It is easy to use once built
- LTI approach can replace the thermal network to be coupled with electric circuit model
- There are two LTI approaches inside Simplorer
  - The Foster network LTI
  - State space LTI

\[ V = I \cdot \sum R_t \cdot \left(1 - e^{-t/\tau_t}\right) \]

\[ \dot{x} = Ax + Bu \]
\[ y = Cx + Du \]

State space

<table>
<thead>
<tr>
<th>Foster Network</th>
<th>LTI Approach</th>
<th>Power</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery1 Power</td>
<td>Battery2 Power</td>
<td>Battery3 Power</td>
<td>Temperature1</td>
</tr>
</tbody>
</table>
Example: A Battery Module Analysis

- Thermal model is represented by a LTI Foster network
  - RC values are derived from CFD results
- System level response from LTI Foster network is equivalent to the detailed CFD analysis
  - LTI Foster network executes significantly faster

Results from the Foster network are identical to Fluent
System Level Circuit Model
Li-ion Battery

- 60 Cells connected in matrix pack
- Packs are connected in matrix to final configuration

- Peak voltage: 16 V (4 cells in series)
- Peak current: ~3.25 Amp (15 cells in parallel)
  - 0.4 Amp for single battery case
  - And yet runtime is ~doubled
  - Estimated life: 0.4/(3.25/15)x8000 sec without rate factor consideration
Battery in Control System with Motor Controller

- Solid-state driver chips
- Solid-state Controller
- Perm. Mag. Motor
- Alternator/inverter
- Multi-disc clutch
- Torque limiter
- Linear Coupling
- Drive shafts

Battery Performance
- Command
- Motor Performance
- Battery Voltage
- Battery Current
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  – Simploter
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The model is based on the work of:

- Newman & Tidemann (1993);
- Gu (1983);

\[ \nabla \cdot (\sigma \nabla \phi) = J \quad \text{Transfer current} \]

\[ J = Y (\phi_p - \phi_n - U) f(T) \]

U and Y are derived from experimentally obtained polarization curve, dependent on Depth of Discharge (DOD) & Temperature.

\[ U = a_0 + a_1(DOD) + a_2(DOD)^2 + a_3(DOD)^3 \]

\[ Y = a_4 + a_5(DOD) + a_6(DOD)^2 \]
Results of a Prismatic Lithium-Ion Cell

Geometry & Mesh

Temperature

Current Density

2 Ah Prismatic Cell Discharge Curve

- 0.5C
- 1C
- 2C

DOD

Cell Voltage [V]

Discharge Time [min]
Case Setup

Integrated battery cell thermal setup panels
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Newman’s 1d Electrochemistry Model in Simplorer

- Electrochemical Kinetics
- Solid-State Li Transport
- Electrolytic Li Transport
- Charge Conservation/Transport
- (Thermal) Energy Conservation

\[ \eta = \phi_e - \phi_x - U \]
\[ i_0 = k(c_e)^{\alpha_z}(c_{s,\text{max}} - c_{s,e})^{\alpha_z}(c_{s,e})^{\alpha_z} \]
\[ \frac{\partial(e_c c_e)}{\partial t} = \nabla \cdot (D_e \nabla c_e) + \frac{1-t^+}{F} j^{Li} \]
\[ j^{Li} = a_s i_o \left\{ \exp \left[ \frac{\alpha_a F}{RT} \eta \right] - \exp \left[ - \frac{\alpha_a F}{RT} \eta \right] \right\} \]

Results from Simplorer

Results from Newman

Newman assumed constant diffusivity inside particles. In the current model, such an assumption is not used and the particle diffusion equations are solved numerically and thus allow for non-constant diffusivity. This makes the model really 2d rather than 1d. This model is also called pseudo-2d in literature.

Sample Results in Simplover

Discharge Curve

- It takes less than two days for an engineer to implement the model in Simplover compared to months using in-house methods
- Run time is a couple of minutes for a complete discharge curve of 100,000 seconds

Particle Concentration

Electrolyte Concentration
Single Insertion Comparison

Simplorer’s Results

Newman’s Results

Dual Insertion Comparison

Simplorer’s Results

Newman’s Results

Dual Insertion Comparison

Simplorer’s Results

White’s Results

Dual Insertion Comparison

- Simpler’s Results
- White’s Results

Dual Insertion Thermal Results

Concentration profiles at the same time and discharge rate but for different temperature

Discharge curves at the same discharge but for different temperature

Li concentration in electrodes during discharge
3D Electrochemistry Modeling

Cell potential vs SOC

Axial distribution of Li$^+$ concentration
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Bus Bar Heating for Battery

- For steady (or low frequency) currents under temperature dependent conductivity

\[
\nabla \cdot (\sigma \nabla \Phi) = 0
\]
\[
\sigma = f(T)
\]
\[
\text{Ohmic Loss} = \frac{|\mathbf{J}|^2}{\sigma}
\]

User Defined Scalar:

\[
\text{Fluent Energy Solver}
\]

Temperature dependent conductivity

Ohmic loss for energy solver
Validation – Maxwell vs Fluent

Maxwell Results:
\[ \Phi_{\text{max}} = 0.0247 \text{ V} \]
\[ \Phi_{\text{min}} = -0.00410 \text{ V} \]

Fluent Results:
\[ \Phi_{\text{max}} = 0.0247 \text{ V} \]
\[ \Phi_{\text{min}} = -0.00411 \text{ V} \]

Property:
\[ \sigma_{\text{copper}} = 5.95 \times 10^7 \text{ sm}^{-1} \]

Boundary Conditions:
- 7 current boundaries
- 2 voltage boundaries

Constant conductivity used for comparison
Coupled Simulation in Fluent

Temperature Distribution

Conductivity Distribution

Current Density Magnitude Distribution

Fluent Results:
Φmax changes from 0.0247 V to 0.0270 V due to temperature impact

Property:
\[ \sigma_{copper} = \frac{1}{1.68 \times 10^{-8} \left[ 1.0 + \alpha (T - T_{ref}) \right]} \text{ sm}^{-1} \]
\[ \alpha = 0.004 \]
What if Only One-Way Coupling

One way coupling means that Ohmic loss from constant conductivity is mapped to thermal solver without update of temperature from thermal solver.

With only one-way coupling, the max temperature increase is 25K compared with that of 29K using two-way coupling, a difference of 15%.

Two-way coupling is necessary.
Validation and Coupled Simulation in CFX

• Same coupled analysis can be done in CFX with the same results.
Conclusion

• ANSYS is uniquely ready with full range engineering simulation solutions for the entire range of battery applications - from detailed electrochemistry to system level thermal management

ANSYS technology provides the most comprehensive state-of-the-art battery solutions in the industry
Note how the new geometry avoided the high temperature for the first and last battery cell.
Examination of Constant Density Assumption

• For a temperature change of 140K, the error due to constant density assumption is less than 10%. For a typical temperature variation of a few degrees in battery application, the constant density assumption is certain valid.
What is an LTI system?

- A LTI system is a **Linear Time Invariant (LTI)** system
  - Output of such a system is completely characterized by its impulse (or step) response in that the output of the system under any input is simply the convolution of the impulse response and the input.

- Battery cooling problem can be treated like a system, in which the inputs are the power generated by individual batteries and the outputs are temperatures at user specified locations
  - Impulse response is the temperature history of a battery given a unit amount of heat source at time zero.