Outline

- Battery thermal management using CFD
- Battery system thermal management using Foster network approach
- Battery electric circuit model
- Battery single cell thermal model
- Battery electrochemistry
- Battery thermal management using co-simulation
- Battery thermal management with bus bar heating using CFD
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
• 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

- Input with Variations
  - Gap Thickness
  - Cell Resistance
  - Flow Rate
- Outputs with variations
  - Max temperature
  - Differential temperature
  - Pressure drop
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Motivation of Using Model Order Reduction

- CFD as a general thermal analysis tool is accurate but
  - Can be expensive for large system level repeated transient CFD analysis
  - Can be cumbersome to couple with electrical circuit model for large system analysis
Motivation of Using Model Order Reduction

• Seek reduced order models for system level transient analysis
  – Thermal network (use thermal resistors and capacitors, etc)
    • Compromised accuracy
    • Needs careful calibration and calculation of thermal resistance, capacitance
  – LTI method (Foster network, state space)
    • Can be as accurate as CFD or even testing
    • No need to calculate thermal resistance, capacitance
    • Rely on linearity and time invariance
1. Create step responses
   - From CFD / Test
2. Generate .simpinfo file
3. Extract equivalent thermal model
   - Use Simplorer
4. Simulate inside Simplorer
Six Cell Test Case
Geometry/Mesh

- Inputs: heat source to each battery
- Outputs: battery volume average temperature
Foster Network for the Battery Module in Simpleror

This Foster network can be automatically generated by Simpleror!!

- 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 CFD give identical solution under arbitrary sinusoidal power inputs
  - Systems represented by impulse response, Foster network, and the original thermal system are all equivalent systems.
LTI Approach for Flow Rate Change of 100%

- Power inputs are sinusoidal functions
- Flow rate changes at time of 1000 second.
- Results are excellent for the entire duration. A small difference is seen during transition period.
Non-linear CFD: Ideal gas law plus temperature dependent properties are used. Full Navier-Stokes equations are solved.

LTI: Assumes the system is linear and time invariant.

A speed-up factor of 10,000 is observed. Huge time saving if the error, which is about 2%, is acceptable.
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.

A Novel Thermal Model for HEV/EV Battery Modeling Based on CFD Calculation

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Abstract -- Battery thermal management for high power applications such as electrical/hybrid vehicles is crucial. Modeling is an indispensable tool to help engineers design better battery cooling systems. An accurate battery thermal model using Foster network is proposed. The parameters in the Foster network including capacitance and resistance are extracted from Computational Fluid Dynamics (CFD) results. The Foster network model is then shown to provide identical results as those from CFD under any transient power inputs. The model can be readily coupled with battery electrical circuit model to form a complete battery system circuit model capable of predicting accurate battery temperature and the impact of temperature on battery electrical transient performance.

Index Terms—Battery thermal management, HEV, EV, LTI, CFD, electrical battery model, ANSYS, SIMPLER, Fluent.

I. INTRODUCTION

A State Space Thermal Model for HEV/EV Battery Modeling

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Abstract -- Battery thermal management for high power applications such as electrical/hybrid vehicles is crucial. Modeling is an indispensable tool to help engineers design better battery cooling systems. While Computational Fluid Dynamics (CFD) has been used quite successfully for battery thermal management, CFD models can be too large and too slow for repeated transient thermal analysis especially for a battery module or pack. An accurate but much smaller battery thermal model using a state space representation is proposed. The parameters in the state space model are extracted from CFD results. The state space model is then shown to provide identical results as those from CFD under transient power inputs. While a CFD model may take hours to run depending on the size of the problem, the corresponding state space model runs in seconds.

Index Terms—Battery thermal management, HEV, EV, LTI, CFD, state space, ANSYS, Simpler, Fluent.

I. INTRODUCTION

The Lithium-ion battery is a preferred candidate as a power source for Hybrid Electric Vehicle (HEV) and Electric approach has been used by electronics industry [5][6]. And recently, Hu et al. [7] have applied this method to battery thermal system. In such a Foster network model, a number of capacitors and resistors are used to represent the transfer function of the battery thermal system. Note that the capacitors and resistors used in a Foster network do not have the same meaning as the thermal capacitors and thermal resistors used in the thermal network model. In the thermal network approach, the RCs are connected corresponding to physical arrangement of the battery cells, and their numerical values are extracted through physical argument, calculation, or testing. For the Foster network, however, the RC connection is fixed regardless of the physical arrangement of the battery cells. And the numerical values for the resistors and capacitors are extracted through matching the step responses of the Foster network to those of the battery system calculated by using CFD. It was shown by Hu[7] that the Foster network gives identical solution as CFD. In the current paper, a state space model will be proposed. This

Separate training material exists for LTI method.
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Electrical Circuit Model Motivation

• Simple enough for system level analysis
  – Models based on detailed electrochemistry can be 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:
    \[
    SOC = 1 - \frac{1}{Q} \int_0^t \alpha[i(t)] \cdot \beta[T(t)] \cdot i(t) \cdot dt
    \]

Thermal Network Model for Li-ion Battery: 1 Cell

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)

Complete Circuit Model for Li-ion Battery: 1 Module

- Electrical circuit and Foster network are coupled
- Electrical circuit provides power to Foster network
- Foster network provides temperature to electrical circuit

![Diagram of Complete Circuit Model for Li-ion Battery: 1 Module]
Example: A Battery Module Coupled Analysis

\[ \text{Voc} = 1.031 \times \exp(-35 \times (\text{abs} (I_{\text{Batt}}.V/V_{\text{init}}))) + 3.685 + 0.2156 \times (\text{abs} (I_{\text{Batt}}.V/V_{\text{init}})) - 0.1178 \times (\text{abs} (I_{\text{Batt}}.V/V_{\text{init}}))^2 + 0.3201 \times (\text{abs} (I_{\text{Batt}}.V/V_{\text{init}}))^3 + 0.3/30.0 \times (U1.\text{Temp}_\text{block}1-273) \]
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
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The model is based on the work of:

- Newman & Tidemann (1993);
- Gu (1983);
- Kim et al (2008)*

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

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

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

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Case Setup

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

Lithium Ion Batteries

\[
\begin{align*}
\text{Li}^+ & \quad \text{Jump} \quad \text{Li}^+ \\
Li_xC_6 & \quad \text{Li}_x\text{Metal-oxide} \\
\text{Li}(1-x)\text{CoO}_2 + \text{Li}_x\text{C} & \quad \text{LiCoO}_2 + \text{C}
\end{align*}
\]

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

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 Simplorer

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

Discharge Curve

Electrolyte Concentration

Particle Concentration
Newman 1d Model – Single Insertion

Simplorer’s Results

Newman’s Results

Newman 1d Model – Dual Insertion

Simplorer’s Results

Newman’s Results

Newman 1d Model – Quantitative Comparison

Simplorer’s Results

White’s Results

Newman 1d Model - Quantitative Comparison

Simplorer’s Results

White’s Results

Concentration profiles due to different temperatures

Discharge curves due to different temperatures

Energy Equation

- Energy Equation + Heat Source
  
  - Energy Equation (Default)
    
    \[
    \frac{\partial (\rho c_p T)}{\partial t} = \nabla \cdot \lambda \nabla T + q
    \]

  - Heat Source (Source Term/reaction heat + joule heating)
    
    \[
    q = a_{sj} i_{nj} \left( \phi_s - \phi_e - U_j + T \frac{\partial U_j}{\partial T} \right)
    \]
    
    \[
    + \sigma^{\text{eff}} \nabla \phi_s \cdot \nabla \phi_s + \left( \kappa^{\text{eff}} \nabla \phi_e \cdot \nabla \phi_e + \kappa_D^{\text{eff}} \nabla \ln c_e \cdot \nabla \phi_e \right)
    \]

Newman 1d Model - Energy

3D Electrochemistry Modeling

Li concentration in electrodes during discharge
Concentration of $\text{Li}^+$

- Discharge 20\[A\]
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Introduction

• CFD as a battery thermal management tool needs heat generation as input and can produce temperature as output

• Battery electrical circuit model and electrochemistry model can produce heat generation but they themselves need temperature as input

• Coupling of electrical circuit model or electrochemistry model with CFD is the solution
Simplorer FLUENT Co-Simulation

Simplorer Battery Circuit Model

Heat Dissipated

Temperature

FLUENT Battery CFD Model

Cell 1
Cell 2
Cell 3
Cell 4
Cell 5
Cell 6
Simplorer FLUENT Co-Simulation

Heat dissipation

Discharge curve

Heat Dissipated

Temperature

Simpler Battery Circuit Model

Temperature

FLUENT Battery CFD Model
Quasi-Steady CFD vs Transient CFD

- The previous CFD model uses quasi-steady assumption because thermal time scale is much smaller than electrical time scale
  - Transient Simplorer coupled with steady state CFD
  - Transient Simplorer coupled with transient CFD is also possible
Comparison of Two Coupling Strategies

The battery circuit model is the same for both approaches. The difference is on the modeling of the thermal side.
ROM (LTI) vs Co-Simulation

ROM Using LTI

- Faster
- Easier to use

Co-Simulation

- Can provide more detailed temperature information
  - temperature field, max temperature, temperature gradient, etc.
- Can have non-linearity and non-constant flow rate

**Recommendation:**
- If temperature field is not needed, use LTI approach.
- If non-linearity is strong, use co-simulation.
- If flow rate changes constantly, use co-simulation
Simplorer Electrochemistry Model and FLUENT CFD Model Co-Simulation

**Simplorer Battery Electrochemistry Model**

**FLUENT Battery CFD Model**

Heat Dissipated

Temperature

Contours of Static Temperature (K)

Mar 04, 2011

ANSYS FLUENT 13.0 (3d, dp, pbn, lam)
Simplorer Electrochemistry Model and FLUENT CFD Model Co-Simulation

An Array of Simplorer Battery Electrochemistry Models

Heat Dissipated

Temperature

FLUENT Battery CFD Model
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Bus Bar Heating for Battery

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

\[ \nabla \cdot (\sigma \nabla \Phi) = 0 \]

\[ \sigma = f(T) \]

\[ \text{Ohmic Loss} = \left| \frac{\vec{J}}{\sigma} \right|^2 \]

User Defined Scalar for potential

Temperature dependent conductivity

Ohmic loss for energy solver

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

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

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

Boundary Conditions:
7 current boundaries
2 voltage boundaries

Constant conductivity used for comparison
Temperature Distribution

Current Density Magnitude Distribution

Conductivity Distribution

Fluent Results:
\[ \Phi_{\text{max}} \text{ changes from 0.0247 } V \text{ to 0.0270 } V \]
due to temperature impact

Property:
\[ \sigma_{\text{copper}} = \frac{1}{(1.68 \times 10^{-8} [1.0 + \alpha (T - T_{\text{ref}})])} \text{ } \text{sm}^{-1} \]

\[ \alpha = 0.004 \]
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
• 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
Thank You