Virtual Vehicle Application:
Battery Cooling Network Study
Key Takeaways

- Battery cooling network design requires component level analysis and tests within a full-vehicle simulation.
- Integrating fluid, thermal, electrical, and mechanical domains is key to assessing system-level performance.
- Rapid simulations covering a wide range of drive cycles and ambient conditions are needed to evaluate design criteria.
Agenda

- Importance of Battery Cooling
- Exploring Battery Cooling Network Designs
- Integration in Vehicle Model
- Evaluation of Design in Full Vehicle Tests
Why Explore Battery Cooling?

- Electrification is a cross-industry market driver
  - Power, heating, transportation
  - Shift to electric and hybrid powertrains
- Key to success: efficiency and safety

- **Battery State of Health**
  - Too Hot: Efficiency Reduced By 50%
  - Too Cold: Output Reduced By 80%

- **Voltage vs. Charge**

- **EV Sales and Market Share**

- **Safety Concerns**
  - Thermal Runaway Leads to Explosion
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Design Challenge: Battery Cooling Network

- **Requirements**
  - Cell temperature range: 20-40 °C
  - Cell temperature max delta: 8 °C

- **Evaluation**
  - Hot and cold environments
  - Driving conditions (FTP75, US06, WOT, etc.)
  - Charge cycle

- **Two options considered**
  - One-pass
  - Two-pass
Design Process for Battery Cooling Network

1. Explore designs
Design Process for Battery Cooling Network

1. Explore designs
2. Integrate in vehicle model
Design Process for Battery Cooling Network

1. Explore designs
2. Integrate in vehicle model
3. Perform full vehicle tests
Design Challenge: Battery Cooling Network
Modeling and Simulation Options

CFD and FEA
- Accurate, but computation intensive

Spreadsheet
- Accessible, but limited scalability
- Limited options for integrating other models

Lumped parameter physical networks
- Less accurate than CFD, but scalable
- Appropriate for system-level analysis
- Integrates well with other domains including control algorithms

Computational Time vs. Model Complexity

- CFD and FEA
- Lumped Parameter Network
- Spreadsheet
Simscape: Build Accurate Models Quickly

- Simply connect the components you need
- The more complex the system, the more value you get from Simscape
- Resulting model is intuitive, easy to modify, and easy for others to understand

\[
\begin{align*}
F_{\text{Spring}} &= k_{\text{Spring}} \cdot (x_{\text{Mass}}) \\
F_{\text{Damper}} &= b_{\text{Damper}} \cdot (\frac{dx_{\text{Mass}}}{dt}) \\
\frac{d^2 x_{\text{Mass}}}{dt^2} &= -\frac{F_{\text{Spring}} + F_{\text{Damper}}}{m_{\text{Mass}}}
\end{align*}
\]
Physical Modeling Within Simulink

- Simulink is best known for signal-based modeling
  - Causal, or input/output
- Simscape enables bidirectional flow of energy between components
- System level equations:
  - Formulated automatically
  - Solved simultaneously
  - Cover multiple domains

**Simulink: Input/Output**

**Simscape: Physical Networks**
Battery Model

- Modeled using Simscape
  - 60 kWh total capacity (4 sections)
  - Equivalent circuit captures transient dynamics
  - Lookup tables: nonlinear and thermal effects
  - Battery aging can be included

Resistors, capacitor, and voltage source depend upon SOC, DOC, and temperature
Battery Pack

- Create test to compare the cooling network designs

- Lumped thermal model
  - Divided into four sections along flow path

- Heat transferred to different portions of the cooling channel
Battery Cooling Network

- Physical connections in the Simscape model match architecture of design

One-Pass

Two-Pass
Battery Cooling Network

- Simplify testing using Variant Subsystems
  - Swap in different cooling designs
  - Interactive or automated using MATLAB commands

- Same model, settings, and test set up
  - Input vectors
  - Results analysis
Cooling Network Test

- Fast charge (cooling critical)
  1. From 2% to 99% in 1 hour
  2. Range of coolant flow rates

![Graph showing State of Charge and Charging Current over time](image)

1. From 2% to 99% in 1 hour
2. Range of coolant flow rates
Cooling Network Test

- Fast charge (cooling critical)
- Performance criteria
  a. Maximum temperature
  b. Temperature gradients
  c. Pump power consumption

Section Temperature

- Graph showing temperature (degC) over time (s)
  - Section 1
  - Section 2
  - Section 3
  - Section 4

Diagram showing:
- Two_Pass Cooling
- Pump
- Battery
- Temperature range: 20°C < < 40°C
- Maximum temperature ≤ 8°C
Component Level Analysis

- Criteria 1: Temperature Range
  - For same flow rate, Two-Pass has lower maximum temperature
  - Acceptable range for either design
Component Level Analysis

- **Criteria 1: Temperature Range**
  - For same flow rate, Two-Pass has lower maximum temperature
  - Acceptable range for either design

- **Criteria 2: Temperature Gradient**
  - Both designs acceptable
  - Two-pass has very low temperature difference between sections

![Maximum Temperature vs. Flow Rate Graph](image-url)
Component Level Analysis

- **Criteria 3: Pump Power**
  - One Pass requires less pump power than Two Pass for the same flow rate
    - Two Pass has smaller pipe diameter and longer channel
Component Level Analysis

- Criteria 3: Pump Power
  - One Pass requires less pump power than Two Pass for the same flow rate
    - Two Pass has smaller pipe diameter and longer channel

- Test shows advantages of designs
- Now test system in vehicle
  - Control system, rest of physical system
  - See which criteria is most important
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Electric Vehicle Model
Electric Vehicle Model

- Battery Electric vehicle
- 3-Motor Architecture
  - Rear: 40 kW Motor (2x)
  - Front: 60 kW Motor
Full Vehicle Test

- Integrate into Reference Application from Powertrain Blockset
  - Baseline model provides architecture
  - Extend to 3 motor system

- Use Model-Based Design to
  - Assess performance including fuel economy and acceleration
  - Develop control algorithms
  - Deploy to hardware
Powertrain Blockset

Library of blocks

- Energy Storage and Auxiliary Drive
- Drivetrain
- Propulsion
- Transmission
- Vehicle Dynamics
- Vehicle Scenario Builder

Pre-built reference applications

- Conventional Vehicle Reference Application
- Hybrid Electric Vehicle Multimode Reference Application
- Hybrid Electric Vehicle Input Power-Split Reference Application
- Hybrid Electric Vehicle (HEV) P2 Reference Application
- Electric Vehicle Reference Application
- CI Engine Dynamometer Reference Application
- SI Engine Dynamometer Reference Application
Agenda

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Scenario Testing

- 342 simulations:
  - 2 cooling networks
  - 57 drive cycles
  - 3 temperatures: 0/20/40 °C

- Criteria
  - Temperature range: 20-40 °C
  - Temperature gradient: <8 °C
  - Total cooling energy

- Accelerate testing
  - Parallel Computing Toolbox
Summary of Results

- Observations from 342 tests
  - Two Pass has lower temperature difference
    Less cell imbalance, better battery life
  - One Pass has lower energy consumption:
    Better fuel economy for same maximum temperature
Key Takeaways

- Battery cooling network design requires component level analysis and tests within a full-vehicle simulation.

- Integrating fluid, thermal, electrical, and mechanical domains is key to assessing system-level performance.

- Rapid simulations covering a wide range of drive cycles and ambient conditions are needed to evaluate design criteria.
Products Used

- Battery Cooling Network  Simscape, Simscape Fluids
- Electrical Network      Simscape Electrical
                          Simscape Driveline
- Vehicle and Environment Powertrain Blockset
- Testing                Simulink Test
                          Parallel Computing Toolbox
Q&A

Which tasks shown in this presentation are most interesting to you?

- [ ] a Battery Modeling
- [ ] b Cooling System Modeling
- [ ] c Electrical Network Modeling
- [ ] d Full Vehicle Simulation
- [ ] e Parameter Sweeps and Results Analysis

Please contact us with questions

smiller@mathworks.com