Tools for Designing Thermal Management of Batteries in Electric Drive Vehicles

Ahmad Pesaran, Ph.D.
Matt Keyser, Gi-Heon Kim, Shriram Santhanagopalan, Kandler Smith
National Renewable Energy Laboratory
Golden, Colorado

Presented at the
Large Lithium Ion Battery Technology & Application Symposia
Advanced Automotive Battery Conference
Pasadena, CA • February 4-8, 2013

NREL/PR-5400-57747
Battery Temperature in xEVs

• Lithium-ion battery (LIB) technology is expected to be the energy storage of choice for electric drive vehicles (xEVs) in the coming years.

• Temperature has a significant impact on life, performance, safety, and cost of LIBs.

Dictates power capability through cold cranking.

Also limits the electric driving range.
Battery Thermal Management for xEVs

- 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
  - ...
Most in the xEV battery community agree that the value that a BTMS provides in increasing battery life and improving performance outweighs its additional cost and complexity.

However, the BTMS needs to be designed appropriately with the right tools.

The National Renewable Energy Laboratory has been a leader in battery thermal analysis and characterization for aiding industry to design improved BTMSs.

This presentation describes the tools that NREL has used and that we believe are needed to design properly sized BTMSs.
Energy Balance in a Battery

\[
\frac{dE}{dt} = \dot{E}_{\text{gen}} - \dot{E}_{\text{loss}} + \dot{E}_{\text{in}} - \dot{E}_{\text{out}}
\]

Energy Accumulation Rate
Energy Generation Rate
Energy Loss Rate
Input Energy Rate
Output Energy Rate
Heat Transfer in a Battery
(Assumption: isothermal ~ very high thermal conductivity)

\[ mC_p \frac{dT_s}{dt} = Heat_{gen} - hA(T_s - T_a) - e\delta A(T_s^4 - T_a^4) - Q_{Ext\_conduction} \]

Rate of Temp Change | Rate of Internal Heat Generation | Convection Heat Rate | Radiation Heat Rate | Conduction Heat Rate

Heat generated \((Heat_{gen})\) in a battery consists of:
- Electrochemical reactions
- Phase changes
- Mixing effects
- Joule heating

\[ hA(T_s - T_a) + e\delta A(T_s^4 - T_a^4) + Q_{Ext\_conduction} \]

Method of heat rejection/addition for thermal control

\[ T_s = \text{Battery Temp} \]
\[ T_a = \text{Ambient Temp} \]

D. Bernardi, E. Pawlikowski and J. Newman

Assuming uniform battery temperature and the same heat transfer coefficient for three cases.

- **2C Rate (4.45 W/cell) Cp=1019 J/kg/C**
- **C/1 Rate (1.33 W/Cell) Cp = 1019 J/kg/C**
- **2C Rate (4.45 W/Cell) Cp = 707 J/kg/C**

*Fast discharge*

*Slow discharge*
Heat Transfer in a Battery
(Non-isothermal; case and core regions)

**Core region**
\[ \rho C_p \frac{\partial T}{\partial t} = \text{Heat}_{gen} + \nabla \cdot k \nabla T \]

- \( k \): thermal conductivity

**Case or boundary region**
\[ -k_n \frac{\partial T(n)}{\partial n} = h(T_s - T_\infty) + e\delta(T_s^4 - T_\infty^4) + \rho_B C_{p,B} H_B \frac{\partial T_B}{\partial t} \]

- Heat flux from the core
- Convection from various case surfaces
- Radiation from various case surfaces
- Heat accumulation in the case

Johnsee Lee, K. W. Choi, N. P. Yao and C. C. Christianson

Case + Core Example: T Distribution in a Module

Air-cooled
5 W/cell
h = 18 W/Km²

Max. Cell Temperature [°C]

Time [min]

What Information is Needed to Design a BTMS?

- **Acceptable temperature range** for cell components at all times, i.e., active material, binders, separators, electrolyte, etc.
- **Acceptable temperature difference** within cells and from cell to cell, depending on the chemistry and management system
- **Maximum and minimum temperature limits** for life specifications, performance ratings, and safety considerations
- **Thermo-physical properties** of cells or components (density, specific heat, directional thermal conductivities)
- **Heat generation rate** under average and aggressive drive profiles and loads for the specific electric drive
- **Heat rejection rate** depending on thermal management strategy
  - Fluid heat transfer coefficients or sink conductance
  - Cooling fluid flow rate and sink temperature
- **Configurations and dimensions** of cells and proposed BTMS
- **Parasitic power** needed to push fluids/cooling through BTMS
Tools for Designing BTMS

• **Experimental Tools**
  - Isothermal calorimeters and battery testers
  - Infrared thermal imaging
  - Thermal conductivity meters
  - Heat transfer characterization setup
  - Battery thermal testing loop

• **Modeling Tools**
  - First-order/lumped capacitance thermal and fluid models
  - 1-D and 2-D thermal and fluid-flow performance models
  - 1-D vehicle integrated thermal-flow models
  - 3-D electro-thermal models
  - 3-D electrochemical-thermal model
  - Computer-aided engineering software
Isothermal Battery Calorimeters

- We use a single-ended (one test chamber) conduction calorimeter to measure **specific heat** and **heat generation** at various current rates, temperatures, and states of charge (SOCs).

Initially fabricated by Calorimetry Sciences Corporation; later **improved** by NREL.
NREL’s First Isothermal Battery Calorimeter

- Heat flux measured between the sample and a heat sink using heat flux gauges
- The heat sink is kept at a constant temperature with a precise isothermal bath

- Max module that could be tested: 21 cm x 20 cm x 32 cm
- Heat rate detection: 0.015 W to 100 W
- Minimum detectable heat effect: 15 J (at 25°C)
- Baseline stability: ±10 mW
- Temperature range: -30°C to 60°C (±0.001°C)
- Accuracy of better than ±3%

Calorimeter response

Total heat generation = Area under each curve

Calorimeter

Calorimeter Cavity

Photo Credits: David Parson & Matt Keyser, NREL
Example Heat Generation Data for CC Discharge
(from max to min allowable capacity-SOC)

22-Ah Li-Ion Cell

Heat Generation (Watts)

RMS Discharge Current (Amps)

Initial Temp = -15°C
Initial Temp = 0°C
Initial Temp = 30°C
Specific Heat (Heat Capacity)

- Can be estimated from constituents of cell/module
  \[ C_{p,ave} = \frac{\sum (C_{p,i} \cdot m_i)}{\sum m_i} \]

- Can be estimated using a calorimeter by measuring heat lost/gained (Q) from the battery going from \( T_{\text{initial}} \) to \( T_{\text{final}} \)
  - Heat capacity is calculated by
    \[ C_{p,ave} = \frac{Q}{(m_{\text{total}} \cdot (T_{\text{initial}} - T_{\text{final}}))} \]

---

### Table: Thermal Characteristics of Selected EV and HEV Batteries

<table>
<thead>
<tr>
<th>Cell/Module</th>
<th>( T_{\text{average}} ) (°C)</th>
<th>Heat Capacity J/kg/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiMH – 18 Ah</td>
<td>33.2</td>
<td>677</td>
</tr>
<tr>
<td>Li-Ion 18650</td>
<td>33.1</td>
<td>1,105</td>
</tr>
<tr>
<td>Li-Ion Pouch – 4 Ah</td>
<td>18</td>
<td>1,012</td>
</tr>
<tr>
<td>VRLA – 16.5 Ah</td>
<td>32</td>
<td>660</td>
</tr>
<tr>
<td>Ni Zn – 22 Ah</td>
<td>20</td>
<td>1,167</td>
</tr>
</tbody>
</table>

_Thermal Characteristics of Selected EV and HEV Batteries, A. Pesaran, M. Keyser. Presented at the 16th Annual Battery Conference; Long Beach California, January 2001_
NREL’s Large Volume Battery Calorimeter

- Single chamber, conduction, isothermal
- Includes several patent-pending concepts
- Test chamber submerged
- Capability to test liquid-cooled batteries
- Safety features in case of events
- Test chamber 6 times larger than the NREL module calorimeter
  - 2 ft x 2 ft x 4 ft
- Heat Rate: 0.05 W to 4 kW
- Accuracy of heat meas. ±3%

Photo Credits: Dennis Schroder & Ahmad Pesaran, NREL

Completed System with Heating/Cooling Unit

Test Chamber

Flux Gauges in Test Chamber

Test Chamber in Isothermal Bath
NREL’s New Isothermal Cell Calorimeter

- Single chamber, conduction, isothermal
- Test chamber submerged under isothermal bath
- Testing chamber: 15 cm W x 10 cm L x 6 cm H
- Heat detection limit: 1 mW and 10 J
- Initial testing shows excellent baseline stability and an error of less than ±1.6%
- CRADA and license agreement signed with NETZSCH to commercialize NREL’s battery calorimeter design


Photo Credits: Dennis Schroder & Dirk Long, NREL
Infrared Thermal Imaging

- Quickly finds thermal signature of the whole cell under electrical loads
- Helps understand thermal behavior, creates diagnostics, and improves designs
- Could be used as a validation of thermal models
- Thermal signature depends on several factors
  - Geometry, thermal conductivity of case and core, location of terminals, design of interconnects, current density, current profile, chemistry, environment
- *We spray a thin layer of boron nitride on all the surfaces of the face that needs to be imaged*
- *We minimize reflections from other objects by placing the cells in a non-reflective environment*
- *We usually test three cells to see the impact of power cable connected to the two end cells*

Thermal image of a 6.5-Ah NiMH module from a MY 2002 Prius under 100A CC discharge

Photo Credits: Matt Keyser, NREL
Examples of Battery Infrared Thermal Imaging

25°C

45°C

http://www.nrel.gov/vehiclesandfuels/energystorage/publications.html

Photo Credits: Matt Keyser & Dirk Long, NREL
Thermal Conductivity Estimation & Measurement

- Usually case and core of a cell are considered two different regions with different thermal conductivity.

- The core material (electrochemically active part) is assumed to consist of a homogenous material with average properties for resistivity and thermal conductivity, but with different properties in different directions (orthotropic xyz or rθZ).

Can use finite element analysis to calculate the effective thermal conductivity in each direction:

\[ k_x = \frac{q \cdot \Delta x}{\Delta T} \]
\[ k_y = \frac{q \cdot \Delta y}{\Delta T} \]

or

\[ k_z = \frac{q \cdot \Delta z}{\Delta T} \]
\[ k_r = \frac{q \cdot \Delta r}{\Delta T} \]

Measurement Techniques

Provided by Peter Ralbovsky - Netzsch Instruments
Measuring Thermal Conductivity of LIB Components

Flash Diffusivity Method:

- Thermal diffusivity ($\alpha$) is a measure of how quickly a material can change its temperature when heat is applied.
- The temperature rise on the rear surface is measured in time using an infrared detector.

\[ K(T) = \alpha(T) \cdot c_p(T) \cdot \rho(T) \]

Measurements have shown that generally the thermal conductivity of LIB is much lower in-plane than cross-plane:

- Cross plane ~ 0.8 to 1.1 W/m/K
- In plane ~ 28 to 35 W/m/K

Photo Credit: John Ireland, NREL
Battery Thermal Testing Loops

- Measuring heat transfer coefficients or conductance

Air → [Diagram of battery thermal testing loops]

Photo Credits: Ahmad Pesaran

- Hardware in the loop thermal testing

Photo Credits: Kandler Smith, NREL

Temp dist. in a USABC module

Photo Credits: Kandler Smith, NREL
Process for Battery Thermal Modeling

**Module Cooling Strategy**
- Coolant Type: Air/Liquid
- Direct Contact/Jacket Cooling
- Serial/Parallel Cooling
- Terminal/Side Cooling
- Module Shape/Dimensions
- Coolant Path inside a Module
- Coolant Flow Rate
- Passive with phase change
- etc.

**Cell Characteristics**
- Shape and size: Prismatic/Cylinder/Oval, etc.
- Materials/Chemistries
- Voltage/current & heat gen data
- Thermal/Current Paths inside a Cell

**Battery Thermal Responses**
- Temperature History Cells/Module/Pack
- Temperature Distribution in a Cell
- Cell-to-Cell Temperature Imbalance in a Module
- Battery Performance Prediction
- Pressure Prop and Parasitic Power
- etc.

**Operating Conditions**
- Vehicle Driving Cycles
- Control Strategy
- Ambient Temperature
- etc.

**Design Process**
- 3D Component Analysis
- System Analysis

**Software Tools**
- ANSYS
- FLUENT
- MATLAB

**Temperature History**
- Temperature distribution in cells/
- Module/Pack

**Temperature Distribution**
- in a Cell

**Cell-to-Cell Temperature Imbalance**
- in a Module

**Battery Performance Prediction**
- Pressure Prop and Parasitic Power
- etc.
Lumped Capacitance Thermal Model for Vehicle Simulations

- For vehicle simulation, the thermal model needs to be linked to the battery model for temperature dependency
- A 2-node lumped thermal model (case + homogenous core) with simple heat convection is developed for ADVISOR vehicle simulator

\[
Q_{\text{ess\_case}} = \frac{T_{\text{ess}} - T_{\text{air}}}{R_{\text{eff}}}
\]

\[
R_{\text{eff}} = \frac{1}{hA} + \frac{t}{kA}
\]

where

\[
h = \begin{cases} 
  h_{\text{forced}} = a \left( \frac{\dot{m}}{\rho A} \right)^b, & T_{\text{ess}} > \text{ess\_set\_tmp} \\
  h_{\text{natl}} = 4, & T_{\text{ess}} \leq \text{ess\_set\_tmp}
\end{cases}
\]

\[
T_{\text{air}} = T_{\text{amb}} + \frac{0.5Q_{\text{ess\_case}}}{\dot{m}_{\text{air}} c_{p,\text{air}}}
\]

\[
T_{\text{ess}} = \int_0^t \frac{Q_{\text{ess\_gen}} - Q_{\text{ess\_case}}}{m_{\text{ess}} c_{p,\text{ess}}} \, dt
\]

Example of 2-D Module Thermal Modeling

Case 1. No holes and no air flow between cells

\[ T_{\text{max}} = 53^\circ\text{C} \]
\[ \text{Delta } T_{\text{core}} = 13^\circ\text{C} \]

Case 2. With holes and air flow between cells

\[ T_{\text{max}} = 44^\circ\text{C} \]
\[ \text{Delta } T_{\text{core}} = 9^\circ\text{C} \]

Photo Credits: David Parsons, NREL
Electro-Thermal Analysis Approach

- Capture details of a cell including non-electrochemical hardware with finite element analysis
- Estimate component resistances using geometry and materials
- Apply voltage drop to calculate current density in components
- Estimate resistive heating ($I^2R$) in each component
- Apply electrochemical heat of reactions in the core (active parts)
- Apply heat transfer boundary conditions on cell exterior
- Predict temperature distribution in the cell from current density and related heat generation distribution
Example of 3-D Electro-Thermal Modeling

**Design A**
Terminals on each side

**Design B**
Terminals on the same side

**16 Ah Power Cell**


<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Cell Design A</th>
<th>Cell Design B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current</strong></td>
<td>110 Amps</td>
<td>166 Amps</td>
</tr>
<tr>
<td>Maximum Hardware</td>
<td>60</td>
<td>93</td>
</tr>
<tr>
<td>Maximum Winding</td>
<td>43</td>
<td>53</td>
</tr>
<tr>
<td>Average Winding</td>
<td>~ 41</td>
<td>~ 49</td>
</tr>
</tbody>
</table>

Under 110 A RMS load

- The overall resistance of Cell Design B is less than Cell Design A
- Under the same current profile, Cell Design B generates less heat and thus performs better thermally

Photo Credit: Ahmad Pesaran
Combined 3D Electrochemical-Thermal Models

Comparison of two 40-Ah Li-ion prismatic cell designs

2 min 5C discharge

- Larger over-potential promotes faster discharge reaction
- Converging current causes higher potential drop along the collectors

Electrochemical current production

- High temperature promotes faster electrochemical reaction
- Higher localized reaction causes more heat generation

Working potential

- This cell is cycled more uniformly, can therefore use less active material ($) and has longer life.

Current Collector (Cu)

Current Collector (Al)

Negative Electrode

Separator

Positive Electrode
Computer-Aided Engineering of Batteries (CAEBAT)

- U.S. Department of Energy is supporting development of electrochemical-thermal models and software design.
- The objective is to shorten time and reduce cost for design and development of battery systems, including the design and analysis of BTMSs.
- Other software design and analysis tools dealing with other physics may be incorporated in CAEBAT.

![Diagram](Image)

**Physics of Li-Ion Battery Systems in Different Length Scales**

- **Particle Scale**
  - Li diffusion in solid phase
  - Interface physics
  - Particle deformation & stability

- **Atomic Scale**
  - Thermodynamic properties
  - Lattice stability
  - Material-level kinetic barrier
  - Transport properties

- **Electrode Scale**
  - Charge balance and transport
  - Electrical network in composite electrodes
  - Li transport in electrolyte phase

- **Cell Scale**
  - Electronic potential & current distribution
  - Heat generation and transfer
  - Electrolyte wetting
  - Pressure distribution

- **Module Scale**
  - Thermal/electrical inter-cell configuration
  - Thermal management
  - Safety control

- **System Scale**
  - System operating conditions
  - Environmental conditions
  - Control strategy

**CAEBAT Overall Program**

- **Element 1**
  - Electrode/Component Level Modules (Continued Activity)
  - GM
  - ANSYS
  - CD-adapco
  - Johnson Controls
  - Johnson Controls

- **Element 2**
  - Cell Level Modules (Continued Activity)
  - A123 Systems
  - Ford
  - EC Power

- **Element 3**
  - Battery Pack Level Modules (Continued Activity)
  - NREL
  - Johnson Controls

- **Element 4**
  - Open Architecture Software (New Activity)

**Thermal-electrochemical response of a pack**

Courtesy of Christian Shaffer, EC Power-CAEBAT
Summary

• Battery thermal management needed for xEVs
• Battery thermal management system needs to be optimized with right tools for lowest cost
• NREL has state-of-the-art experimental and analytical tools for analysis and design of battery thermal management systems
• Experimental tools, such as the isothermal calorimeter, are essential for obtaining data for generating input to design tools and eventually verifying the performance of the battery thermal management system
• Computer-aided engineering tools for the design of battery electrical and thermal management systems are now accessible to automotive and battery engineers
Acknowledgments

• Support provided by the DOE Vehicle Technologies Program
  o Dave Howell, Hybrid and Electric Systems Team Lead
  o Brian Cunningham, Energy Storage Technology Manager

• Feedback from CAEBAT Subcontract Technical Leads
  o Taeyoung Han (General Motors)
  o Steve Hartridge (CD-adapco)
  o Christian Shaffer (EC Power)

• Support from NREL Staff
  o John Ireland
  o Dirk Long
  o Mark Mihalic
  o Marissa Rusinek

Contact Information:
Ahmad Pesaran
ahmad.pesaran@nrel.gov
303-275-4441

nrel.gov/vehiclesandfuels/energystorage