Battery Thermal Management in EVs and HEVs: Issues and Solutions

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www.ctts.nrel.gov/BTM

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Presentation Outline

- **Background**
- **Attributes of a thermal management system**
- **Thermal characteristics/behavior of batteries**
- **Discussion**
  - active vs. passive
  - cooling vs. cooling/heating
  - series vs. parallel flow
  - liquid vs. air
  - VRLA, NiMH, Li-Ion
- **Concluding Remarks**
Background

- Electric and hybrid electric vehicles in the market

- EV and HEV success depends on battery performance, life, and cost
Battery Temperature is Important

- Temperature affects battery:
  - Operation of the electrochemical system
  - Round trip efficiency and charge acceptance
  - Power and energy
  - Safety and reliability
  - Life and life cycle cost

Battery temperature affects vehicle performance, reliability, safety, and life cycle cost
Battery Pack Thermal Management Is Needed

- Regulate pack to operate in the desired temperature range for optimum performance/life

- Reduce uneven temperature distribution in a pack to avoid unbalanced modules/pack and thus, avoid reduced performance

- Eliminate potential hazards related to uncontrolled temperature
Trend in Battery Thermal Management

For high temperature batteries such as ZEBRA and lithium metal polymer has always been considered.

For room temperature batteries:
- From desirable to must by both vehicle OEMs and battery manufacturers
- From simple to complex/effective
  - active rather than passive
  - parallel rather series air cooling
  - use of liquid as cooling medium
- From pack thermal design to module thermal design
Battery Thermal Management System

- Desired attributes
  - Small temperature variation within a module and within a pack
  - Optimum temperature range for all modules

- Requirements
  - Compact, lightweight, and easily packaged
  - Reliable and serviceable
  - Low-cost and low parasitic power
Thermal Control using Air Ventilation

Passive cooling- Outside Air Ventilation

Outside Air → Battery Pack → Exhaust

Passive heating/cooling- Cabin Air Ventilation

Outside Air → Cabin Air (Vehicle heater and evaporator cores) → Battery Pack → Exhaust

Active heating/cooling- Outside or Cabin Air

Outside Air → Battery Pack → Exhaust

Auxiliary or Vehicle heater and evaporator cores → Battery Pack → Exhaust

Prius & Insight

Vehicle heater and evaporator cores

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Thermal Control using Liquid Circulation

**Passive Cooling**

1. Liquid
2. Battery Pack
3. Outside Air
4. Fan
5. Liquid/air heat exchanger
6. Liquid/direct contact or jacketed

**Active moderate cooling/heating**

1. Liquid
2. Battery Pack
3. Vehicle engine coolant
4. Liquid/liquid heat exchanger
5. Liquid/direct contact or jacketed

**Active cooling/heating**

1. Liquid
2. Battery Pack
3. Vehicle engine coolant
4. Liquid/liquid heat exchanger
5. Liquid/direct contact or jacketed
6. AC Heat Exchanger
7. Air from Evaporator or Refrigerant from Condenser

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NREL has used various tools in working with vehicle and battery manufacturers on BTM

- Thermal analysis (CAD) for proper design, evaluation, and packaging
- Thermal imaging for evaluation and diagnostics
- Fluid and heat transfer experiments for uniform temperature distribution and low parasitic power designs
- Thermal characterization for heat generation and heat capacity
- Battery modeling for vehicle simulation
- Battery Pack and Vehicle Testing
A Systematic Approach for Designing BTMS

- Define BTMS design objectives and constraints
- Obtain module heat generation and heat capacity
- Perform a first order BTMS evaluation
- Predict battery module and pack behavior
- Design a preliminary BTMS
- Build and test the BTMS
- Refine and optimize BTMS

Good pack thermal design starts with good module thermal design.
Heat Generation Rate and Heat Capacity Impacts Module Temperature Rise

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

**Graph:**
- Time (seconds) on the x-axis
- Temperature Rise (Degree C) on the y-axis
- Three curves representing different heat generation rates and heat capacities.
Battery Calorimeter for Thermal Characterization

- We use a single-ended, large conduction calorimeter to measure **heat generation** at various rates, Temp, and SOC and **heat capacity**

- Cavity dimensions: 21 cm x 20 cm x 39 cm (WxHxL)
- 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)
## Typical Heat Capacity of EV/HEV Batteries

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Application</th>
<th>Average Temp (°C)</th>
<th>Heat Capacity J/kg/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiMH - P</td>
<td>HEV</td>
<td>33.2</td>
<td>677.4</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>HEV</td>
<td>33.1</td>
<td>795</td>
</tr>
<tr>
<td>Li-Ion Polymer</td>
<td>EV</td>
<td>18</td>
<td>1011.8</td>
</tr>
<tr>
<td>NiMH</td>
<td>EV</td>
<td>33.9</td>
<td>787.5</td>
</tr>
<tr>
<td>NiMH - C</td>
<td>HEV</td>
<td>19</td>
<td>810</td>
</tr>
<tr>
<td>VRLA</td>
<td>HEV</td>
<td>32</td>
<td>660</td>
</tr>
<tr>
<td>Ni-Zn</td>
<td>EV</td>
<td>19.95</td>
<td>1167</td>
</tr>
</tbody>
</table>
Heat Generation Rate Depends on SOC

Heat generation increases with higher rates.

Heat generation increases with lower temperature.

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Cycle</th>
<th>Heat Generation (W/Cell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRLA, 16.5 Ah</td>
<td>C/I Discharge, 100% to 0% State of Charge</td>
<td>1.21</td>
</tr>
<tr>
<td>VRLA, 16.5 Ah</td>
<td>5C Discharge, 100% to 0% State of Charge</td>
<td>16.07</td>
</tr>
<tr>
<td>NiMH, 20 Ah</td>
<td>C/I Discharge, 70% to 35% State of Charge</td>
<td>-</td>
</tr>
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<td>NiMH, 20 Ah</td>
<td>5C Discharge, 70% to 35% State of Charge</td>
<td>-</td>
</tr>
<tr>
<td>Li-Ion, 6 Ah</td>
<td>C/I Discharge, 80% to 50% State of Charge</td>
<td>0.6</td>
</tr>
<tr>
<td>Li-Ion, 6 Ah</td>
<td>5C Discharge, 80% to 50% State of Charge</td>
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Heat generation increases with higher rates. Heat generation increases with lower temperature.

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<th>Heat Generation (W)/Cell</th>
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<tr>
<td></td>
<td></td>
<td>0°C</td>
</tr>
<tr>
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Discharge Heat Generation at Elevated Temperatures for three HEV Batteries

- Lithium Ion @ 50C
- NiMH @40C
- Lead Acid @ 45C
Discharge Energy Efficiency at Room Temperature

![Graph showing the discharge energy efficiency for Li-Ion, VRLA, and NiMH batteries at Room Temperature. The graph plots Efficiency (%) against Current (A). The data points for each battery type are indicated with different markers and colors.](image-url)
Temperature Distribution is Dictated by Module/Cell Design

Factors: aspect ratio, # of cells, geometry, thermal conductivity, location of terminals, current density

Case 1

Case 2

Only 2°C Difference
<table>
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<th>Air</th>
<th>Liquid</th>
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<td>Ducting air</td>
<td>Piping liquid</td>
</tr>
<tr>
<td>Direct contact</td>
<td>Direct contact - oils</td>
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<tr>
<td>Simple designs</td>
<td>Indirect contact - water/glycol</td>
</tr>
<tr>
<td>Less effective heat transfer</td>
<td>Higher heat transfer rate</td>
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Air Cooling vs. Liquid Cooling - VRLA Module

Air cooled
\[ h = 18 \text{ W/Km}^2 \]

Liquid cooled
\[ h = 28 \text{ W/Km}^2 \]

Based on the same parasitic power

Liquid cooling more effective

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## Air Cooling vs. Liquid Cooling

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<tr>
<td>– Less effective heat transfer</td>
<td>– Higher heat transfer rate</td>
</tr>
<tr>
<td>– Lower volume efficiency</td>
<td>– Compact design</td>
</tr>
<tr>
<td>– Lower cost</td>
<td>– More parts</td>
</tr>
<tr>
<td>– Easier maintenance</td>
<td>– Higher maintenance</td>
</tr>
<tr>
<td>– Not easily sealed from environment</td>
<td>– Higher cost</td>
</tr>
<tr>
<td>– Location sensitive</td>
<td>– Could be sealed easier</td>
</tr>
<tr>
<td></td>
<td>– Location insensitive</td>
</tr>
<tr>
<td></td>
<td>– High viscosity and thermal mass at cold temperatures</td>
</tr>
</tbody>
</table>
Liquid Cooled Modules

Integrated liquid cooling in a module provide an opportunity to reduce temperature distribution in addition to lowering the overall temperature for large modules, good for electrical balancing.
Active vs. Passive Systems

- Passive systems less complicated
- Passive systems have lower cost and lower number of components
- Passive systems consume less energy
- Passive systems not adequate at all climates
- With maturing of HEVs, more battery thermal management systems will use active systems
Cooling only vs. Cooling/Heating Systems

- Cooling only systems work fine for moderate climates such as California.
- Utilizing engine coolant can provide some cooling for warm days and heating for cool days, but has limitations.
- HEVs and EVs operating for all climates (-30 to 60°C) need both active battery heating and cooling.
- Cooling can be provided by vehicle/auxiliary Air Conditioner components.
- For cold starts, a heating source may not be available so the battery may need to be used for self heating.
- Use of active systems can reduce fuel economy.
Series vs. Parallel Air Distribution

Series flow
In this case, modules on side airflow across

Parallel flow
In this case, modules upright airflow up

Balancing pressure drops with proper manifold
Parallel flows provides a better temperature distribution

Series air flow  Parallel air flow

Japan Prius and Insight  New Prius

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Thermal Management of VRLA, NiMH, and Li-Ion

- Factors that determine magnitude of thermal management system
  - Heat generation rate
  - Energy efficiency
  - Sensitivity to temperature
  - Cold and hot performance and life

- NiMH less efficient and generates more heat and appear to be more sensitive to temperature variation. So NIMH needs a more elaborate thermal management system.

- Li-Ion generates more heat in a smaller volume and is more sensitive to extreme cold and hot, so also need a complete battery management system
Concluding Remarks

- Thermal management of HEV batteries are becoming more sophisticated.
- Liquid cooling more effective, but more complex.
- Air cooling for power-assist HEVs is sufficient.
- Liquid cooling may be needed for EV and series HEVs.
- Parallel air flow distribution more desirable.
- NiMH requires more elaborate thermal management, than Li-Ion than VRLA.
- Location of pack has a strong impact on type of cooling system (air vs. liquid).
- Active systems will be required, and heating will be a challenge.
Acknowledgments

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