Cooling and Preheating of Batteries in Hybrid Electric Vehicles

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Outline

- Background
- Battery Thermal Management
- Cooling
- Preheating
  - Finite Element Analysis
  - Experiments
- Concluding Remarks
Background

- Hybrid electric vehicles (HEV) entering the market
  - Engine
  - Battery-powered motor

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

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

Battery temperature affects vehicle performance, reliability, safety, and life cycle cost
Consumers expect satisfactory performance from hybrid vehicles at all climates.

Generally, as battery temperature increases:
- Power and energy capability of battery increase
- Calendar and cycle life decrease

At very cold temperatures batteries could not deliver the needed power and energy.
Impact of Temperature on Battery Discharge Power

Panasonic 6.5 Ah NiMH prismatic Module (7.2 Volts) and 55% SOC (based on 18 sec discharge pulses)

General trend in life

Based on experiments at NREL
Why Battery Thermal Management?

- Regulate battery to operate in the desired temperature range for optimum performance and life.
- Reduce uneven temperature distribution in a pack batteries to avoid unbalanced modules/pack and thus, avoid reduced performance.

- **Cooling** in hot climates, mostly for avoiding premature degradation and improving safety.
  - Battery internal heating is dominant due to resistive heating.

- **Preheating** in very cold climates, to overcome poor performance.
Cooling using Air Ventilation

Passive cooling- Outside Air Ventilation

Outside Air → Battery Pack → Exhaust

Passive cooling/heating- Cabin Air Ventilation

Outside Air → Cabin Air → Battery Pack → Exhaust

Vehicle heater and evaporator cores

Active cooling/heating- Outside or Cabin Air

Outside Air → Battery Pack → Exhaust

Auxiliary or Vehicle heater and evaporator cores
Cooling using Liquid Circulation

Passive Cooling

Active moderate cooling/heating

Active cooling/heating
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
Preheating Study

- Sources of energy for on-board preheating
  - Heat from engine
  - Electricity from battery
  - Electricity from generator/inverter

- Identify the most effective preheating technique
  - External heating techniques:
    - Electrically heated thermal jackets
    - A sealed enclosure with an internal heating element
    - Circulating a fluid heated from the engine
  - Internal heating techniques:
    - Resistive heating elements embedded within the batteries
    - Apply current to the battery terminal

- Perform FEA thermal analysis for a rectangular module
- Perform feasibility tests.
Internal Core Heating using Battery Resistance

- Geometry: rectangular modules consisting of six cells
- Heat transfer by conduction from core to exterior
- Half FEA model

Small convection losses to surroundings from case

\[ h = 1-3 \text{ W/m}^2/\text{°C} \]
Case 1

Transient Volumetric Heat Generation Applied

- Heat generated in the core from battery resistive heating (decreases as temperature increases)

Volumetric Heat Generation Versus Time for Various Values of Input Power

<table>
<thead>
<tr>
<th>Input Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.09 Whr</td>
</tr>
<tr>
<td>2.90 Whr</td>
</tr>
<tr>
<td>4.71 Whr</td>
</tr>
<tr>
<td>6.53 Whr</td>
</tr>
</tbody>
</table>

Total energy input in ¼ of a module over 10 minutes
Maximum Temperature versus time for Internal Core Heating

- Temperature increases with time and amount of internal heating energy.
- After 2 minutes, the slope of temperature rise decreases because the heating rate decreases.

Total energy input in ¼ of module over 10 minutes:
- 1.09 Whr
- 2.90 Whr
- 4.71 Whr
- 6.53 Whr

National Renewable Energy Laboratory
Case 2

External Electric Jacket Heating around Module

- Geometry: rectangular modules consisting of six cells
  - Jacket heater: 0.0625 inch thick with additional 0.0625 insulation
- Half FEA Model

Heat transfer is by conduction from heater to core of module.

Small convection losses to surroundings from the heater insulation.
Internal Electric Jacket Heating around Cells

- **Geometry**: rectangular modules consisting of six cells
  - Jacket heater: 0.0625” thick with additional 0.0625” insulation
Internal Heating Using Fluid between each Cell

- **Geometry:** rectangular modules consisting of six cells
  - Air gap between each cell: 3.1 mm

- **Heat Transfer Coefficients:**
  - $h_{\text{side}} = 25 \text{ W/m}^2/\text{°C}$
  - $h_{\text{horizontal}} = 2-5 \text{ W/m}^2/\text{°C}$
Comparison of Four Heating Cases

- The most uniform heating was with internal core heating (Case 1)
Average Core Temperature at 2 minutes for various Heating Methods

Average Core Temperature at 2 min versus Input Power for various heating methods

- Internal heating using battery energy
- External heating using electric heaters
- Internal heating using electric heaters
- Internal Airflow Heating 100% Efficiency
- Internal Airflow Heating 20% Efficiency

Uniform Input Heat over 2 minutes (Whr)
Effect of aspect ratio studied to see if it has any impact on heating effectiveness

L/W = 17.2
6-cell Mass = 2.12 kg
Heat input = 6.62 Wh/kg core

L/W = 2.0
6-cell Mass = 1.56 kg
Heat input = 6.62 Wh/kg core
Comparison of Heating Effectiveness for the same Whr heat/kg

Average Core Temperature Versus Time

- Core Heating
- Jacket Heating

Case 1
Thermal Analysis Observations

- Electric heating raises the battery temperature faster than heating with fluids.
- The most uniform temperature distribution was with internal core heating.
- With the same heat input, average core temperature was raised faster with core heating.
- These observations not changed for batteries with different aspect ratios.
How much Energy and Power for Preheating a Battery?

To raise the temperature of a 40 kg battery pack from -30°C to 0°C in 2 min, 9.76 kW of power (or about 325 Wh of heat energy) is required for a 100% efficient process.
How to apply the more effective core heating method?

- At low temperatures battery resistance is high
- Charging/discharging heats the battery (I²R)
- DC currents could damage batteries
- Applying high frequency alternating currents (AC) may heat up the battery without too much energy loss and battery damage
- Initial feasibility work done in collaboration with University of Toledo
  - 60 Hz AC heating on lead acid and NiMH batteries
  - High frequency (10-20 kHz) AC heating to a NiMH pack
**Applying 60 Hz AC Power is Effective in Warming Batteries**

- Measured pulse DC resistance (pulse power capability) of a lead acid module at very cold temperatures before and after applying 60 Hz AC heating

<table>
<thead>
<tr>
<th>AC Heating</th>
<th>Internal R (mil Ohm)</th>
<th>Peak current (A)</th>
<th>Estimated T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>108</td>
<td>100</td>
<td>-40</td>
</tr>
<tr>
<td>3 min</td>
<td>19.6</td>
<td>210</td>
<td>-4</td>
</tr>
<tr>
<td>6 min</td>
<td>14.7</td>
<td>250</td>
<td>+6</td>
</tr>
<tr>
<td>9 min</td>
<td>13.5</td>
<td>270</td>
<td>+9</td>
</tr>
</tbody>
</table>

- 60 Hz AC (off-board) more suitable for electric vehicles
High Frequency AC Heating Evaluation

- Higher frequencies reduce size of power electronics for potential on-board hardware.
- Applied 10-20 kHz current to a Panasonic NiMH battery pack (16-module, 115.2 V, 6.5 Ah) using a special heater circuit.
- Measured resistance and peak power before and after applying high frequency current

\[ I_{AC}, I_{B1}, I_{B2}, I_1 = \text{RMS value of 10-20 kHz current.} \]
\[ I_{DC} = \text{DC current.} \]
Obtained Battery Internal Resistance for various Temp and State of Charge

![Graph showing the relationship between Battery Internal Resistance ($R_B$) and Temperature ($T_{bat}$). The graph includes data for different State of Charges (SOC): 55%, 25%, and 75%. The x-axis represents temperature in degrees Celsius, and the y-axis represents resistance in ohms. The data points are shown as different markers for each SOC level.](image-url)
High Frequency AC Heating on the NiMH Pack

Rbat of (16) module Panasonic 6.5 Ah NiMH pack vs. time with High Frequency (10 kHz)

-20°C Resistance calculated over 25 A discharge pulse for 2 seconds.

AC heating current : 65 Arms

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>R (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>1.024</td>
</tr>
<tr>
<td>-10</td>
<td>0.614</td>
</tr>
<tr>
<td>0</td>
<td>0.410</td>
</tr>
<tr>
<td>10</td>
<td>0.333</td>
</tr>
<tr>
<td>25</td>
<td>0.205</td>
</tr>
<tr>
<td>35</td>
<td>0.179</td>
</tr>
</tbody>
</table>

1. Pack SOC = 55%.
2. Temp = -20°C.
3. IAC = 60 A.rms / 10 kHz.
4. Rbat = 0.21 Ω @ 25°C.
5. Soak time > 7 hrs.
6. Pack Voltage = 130 Vdc
Impact of Higher Current Amplitudes

Frequency = 10 kHz

![Graph showing temperature change over time for different current amplitudes (80 Arms, 70 Arms, 60 Arms).]
Battery Capacity Improves with AC Heating

Discharge Tests at -30 deg.C

SOC=25%  SOC=55%  SOC=75%

<table>
<thead>
<tr>
<th>RT</th>
<th>No AC</th>
<th>w/AC</th>
<th>Ampere Hours (AH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>1.25</td>
<td>0.3</td>
<td>0.95</td>
</tr>
<tr>
<td>RT</td>
<td>3.28</td>
<td>0.5</td>
<td>2.59</td>
</tr>
<tr>
<td>RT</td>
<td>4.38</td>
<td>0.75</td>
<td>3.58</td>
</tr>
</tbody>
</table>

Frequency = 10 kHz
Concluding Remarks

- Battery thermal management necessary in HEVs
- Analysis showed that core heating is the most effective method to preheat batteries
  - Uses least amount of energy for the same Temp rise
  - More uniform temperature distribution
- Testing showed that core heating is feasible through applying AC power through battery terminals
- Further analysis, testing, hardware evaluation, and trade off analysis under way for on-board vehicle applications.