Thermal Management of Batteries in Advanced Vehicles Using Phase-Change Materials

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Outline

Using Phase-Change Material for Automotive Battery Thermal Management

- Background & Motivation
- Approach
- Analysis
  - Use in Intermittent Discharge Application
  - Use in HEV application
  - Use in PHEV application
- Summary
Background & Motivation

- **Temperature** is one of the most significant factors impacting both the performance and life of a battery.
- More effective, simpler, and less expensive thermal management would assist in the further development of affordable battery packs and increase market penetration of HEVs and PHEVs.
- Battery thermal management using phase-change material (PCM) has potential to bring benefits, such as passively buffering against life-reducing high battery operating temperatures.
- *PCM technology should be assessed to determine whether it would improve upon existing vehicle battery thermal management technologies.*
Prototype Technology

PCM-absorbed Carbon Matrix - AllCell®

Description: 18650 Li-Ion cells are surrounded by a high-conductivity graphite ‘sponge’ that is saturated by a phase-change material (‘wax’). The matrix holds the PCM in direct contact with the cells, and the latent heat capacity to melt the PCM is intended to absorb the waste heat rejected by the cells during periods of intensive use.

NOTE: This module is not a optimized design for readily use in HEV/PHEV
Perceived Advantages & Disadvantages of Using PCM for Vehicle Battery Thermal Management

- **Possible Advantages**
  - Reduced peak temperatures
  - Better temperature uniformity
  - Reduced system volume

- **Possible Disadvantages**
  - Heat accumulation
  - Additional weight
  - Undesirable thermal inertia
Approach

**Acquired Product/Material Samples from AllCell®**

**TEST:** Property/Performance Measurement & Validation

**MODEL:** Module/System Level Analysis

Evaluation for use in HEV/PHEV

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**Cell Characteristics**
- Q? Calorimeter Test
- $R_{int}$ / Efficiency

**PCM Module Design**
- Matrix Dimensions
- PCM Amount
- Melting Temperature
- Cell Array Config.
- Additional Cooling

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**Operation Scenario**
- Standard Driving Profile
- Real World Survey

Vehicle Selection
- Control Strategy
- Component Sizing
- Grade

Vehicle Simulation
- Vehicle Drive Data

Battery Power Profile in Vehicles (HEV,PHEV)

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**THERMAL RESPONSES OF SYSTEM**
- Battery Temperature History
- Frequency/Duration of Exposure to High Temperatures
Prototype Module Test

- Evaluate thermal management performance of PCM matrix in the prototype module
- Provide data for model validation and improvement
- Instrument for voltage(4), current(1) and temperature(21) distribution;
  - K-type calibrated thermocouples
  - ±0.35°C uncertainty
- Connect to battery cycler and place in environmental chamber
Model Description

**Thermally Lumped System Model**

System level analysis: temporal variation of battery system thermal responses

- Assume fast internal heat transfer
- Reasonable for the prototype module, where the system Biot number is roughly 0.005 (<<0.1).

\[
M_{sys} \left( C_{p_{sys}} + D \lambda_{sys} \right) \frac{dT}{dt} = h A_{surf} (T_{amb} - T) + Q_{gen}
\]

\[
D = \frac{e^{-(T - T_{melt})^2 / \delta T^2}}{\sqrt{\pi \delta T^2}}
\]

**Multi-dimensional Model**

Multi-dimensional analysis: spatial temperature imbalance in a module

- Developed with finite volume method (FVM)
- Address thermal distributions through a module
- Ignore fluid motion of melted PCM in a porous carbon

\[
\rho \bar{c}_p \frac{dT}{dt} = \nabla (k \nabla T) + q'''
\]

\[
\bar{c}_p = (c_p + D \lambda)
\]
Analysis & Evaluation

1. Analysis of Intermittent Discharge Application
2. Analysis of Aggressive HEV Application
3. Analysis of PHEV10 Cycling Application
Analysis & Evaluation

1. Analysis of **Intermittent Discharge** Application
2. Analysis of Aggressive HEV Application
3. Analysis of PHEV10 Cycling Application
Single Discharge

- Limited duration of heat release
- Finite heat generation
  - Possible to quantify maximum heat for PCM
- Usually long rest period between uses
  - No need for fast heat removal from the system

- Model shows good agreements with experiments in general
- Module temperature stays below the PCM melting temperature (55°C) under 30°C ambient temperature discharge event
Thermal Performance Comparison under Different Ambient Conditions

– 40A single discharge for 9 minutes

at 25°C ambient → no phase change

at 40°C ambient → phase change

- Peak temperatures at PCM module and Air-cooled module were comparable under room temperature discharge case
- PCM latent heat limits the peak temperature of module under high temperature environment use
Temporal & Spatial Temperature Variations
40A Single Discharge at 40°C Ambient
- PCM Phase Change Limits the Cell Temperature Increase

Average Temperatures of Cells and Matrix
Concluding Remarks on Use in Intermittent Discharge Application

- PCM effectively prevents the exposure to battery damaging high temperatures especially for high rate discharge under high temperature ambient condition.

- Fast heat transfer through highly conductive carbon matrix keeps the temperatures of cells in a module fairly uniform.

- Passive thermal management using the PCM technology would show excellent performance in intermittent discharge applications.
Analysis & Evaluation

1. Analysis of Intermittent Discharge Application
2. Analysis of Aggressive HEV Application
3. Analysis of PHEV10 Cycling Application
Prototype Module Test Profile for Mid-size Sedan HEV: US06

- Prototype P/E ~ 10 kW/kWh
  - Underpowered pack for HEV
  - Oversized in energy content
- Developed electrical test profile using vehicle simulations
- Profile was clipped with continuous charge/discharge limits

Model Validation for HEV Cycle

2hr cycle at 30°C

4hr cycle at 45°C
Continuous Cycling

Model Investigation: Periodic Steady State

- Continuous cycling
  → Continuous heat
- Heat rejection rate
  → Equilibrium system T

Initial T=30, Air T=30

Q=45 W/module
Q=9.2 W/module
Real World ‘HEV’ Drive

- 2 hour mountain drive
  - Start from mountain
  - To the suburb of Denver
- “Prius” drive with stock NiMH pack
  - Collected data during the drive

Altitude

Vehicle Speed

Battery Power
Thermal Performance with a Virtual Li-Ion Pack in Real World ‘HEV’ Drive

**Virtual Module**
- Identical electrical response
- 12 26650 cells (6p 2s)
- 3mm spacing with 4x3
- 94% efficiency
- Replace 1 stock module

<table>
<thead>
<tr>
<th></th>
<th>Prius Stock NIMH Module</th>
<th>Virtual Li-Ion Module</th>
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<tr>
<td>P/E</td>
<td>28</td>
<td>27</td>
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<tr>
<td>Specific Power (W/kg)</td>
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<td>Specific Energy (Wh/kg)</td>
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<td>67</td>
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<tr>
<td>Mass Density (kg/m³)</td>
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<td>~2000</td>
</tr>
<tr>
<td>Specific Heat (J/kg.K)</td>
<td>~850</td>
<td>~850</td>
</tr>
</tbody>
</table>

**Battery Temperatures**

**Heat Rejection Rate**
- $h = 10 \text{ W/m}^2\text{K}$
- $\bar{Q} = 9.9 \text{ W/module}$

- PCM only
- PCM + Air
- Air only
Evaluation of Use in HEV Application

Thermal Responses with a **Large Cell Pack** in Real World ‘HEV’ Drive

**Battery Temperatures**

- PCM
- PCM + AIR
- AIR ONLY
- PCM + AIR with extended surface

**Battery Temperatures**

- $h_{0n,0n}=10 \text{ W/m}^2\text{K}$
- $h_{0n,0n}=15 \text{ W/m}^2\text{K}$
Thermal Responses with a **Large Power Cell Pack** in Real World ‘HEV’ Drive

- A more advanced battery would have fewer cells to meet the vehicle power requirements
  - Higher power cells could cause higher volumetric heat
- **Brief Investigation**
  - Doubling Power Rate
  - Efficiency Increase, 94% → 96%
Concluding Remarks on Use in HEV application

Evaluation of Use in HEV Application

Rate of Heat Generation

System Maximum Heat Generation Rate

Rate of Heat Removal

Design Decision for Heat Removal Rate

+ Phase-Change Material
Analysis & Evaluation

1. Analysis of Intermittent Discharge Application
2. Analysis of Aggressive HEV Application
3. Analysis of PHEV10 Cycling Application
Prototype Module Test for Mid-size PHEV10 - US06 Cycle

- Typical PHEV drive =
  - Initial EV drive (Charge Depleting) + Flowing HEV drive (Charge Sustaining)
  - Thermally Aggressive Operation + Thermally Moderate Operation
PHEV10 Battery Temperature Response at high ambient temperature (45°C)

$h=10 \text{ W/m}^2\text{K}$

- Initial thermally aggressive Charge Depleting drive causes temperature excursion to over 60°C in air-cooling battery
Methods for Limiting Temperature Excursion during EV Drive

- If available,
  - Use the thermally regulated cabin air (30°C) for battery cooling
- If not,
  - Incorporate a high heat transfer coefficient (40W/m²K) design
  - Limit EV drive at high battery temperatures
  - Combine PCM with moderate heat transfer coefficient (20W/m²K) design
Concluding Remarks on Use in PHEV application

- In short EV range PHEVs, combining PCM for addressing aggressive initial EV drive can minimize the size of air cooling systems.

- In large EV range PHEVs, the batteries may have enough thermal mass by themselves to provide a buffer against intermittent temperature spikes.
Impact of “PCM/Graphite Matrix” on Thermal Runaway Propagation in a Module
(Results from G.-H. Kim et al., 212th ECS, Washington, DC, Oct, 2007)

If one cell goes into thermal runaway, will it propagate to other cells and how?

Rather than air, highly conductive PCM/Graphite Matrix filled the space between the cells in the module.
Multi-Dimensional Analysis
Thermal Abuse Reaction Model

Temperature

Reaction Heat from SEI decomposition
Summary

- Battery thermal management using PCM shows excellent performance in limiting peak temperatures at short period extensive battery use.

- Using PCM without convective cooling methods may not applicable in HEV/PHEV applications.

- Combining PCM method would allow smaller air cooling system and less need to limit battery power output in high-temperature conditions.

- Vehicle designers will need to weigh the potential increase in mass and cost associated with adding PCM against the anticipated benefits.
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