Thermal Control of Power Electronics of Electric Vehicles with Small Channel Coolant Boiling

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Sponsored by L. Slezak and D. Anderson (Vehicle Systems)

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Overview

**Timeline**
- Project start date – FY14
- Project end date – FY15
- Percent complete – 75%

**Barriers**
- **Weight** – eliminate the second radiator for hybrid electric vehicles (HEVs)
- **Performance and lifetime of electronic components** – temperature
- **Efficiency** – junction temperature control
- **Applications** – cooling of high power electronic modules for HEVs & electric vehicles (EVs)

**Budget**
- Total project funding (to date): $355K
- Funding received prior to FY15: $150K
- Funding for FY15: $205K

**Partners**
- Interactions/collaborations
  - Advanced Power Electronics & Electrical Machines (APEEM)
  - Oak Ridge National Laboratory (ORNL)
  - Dana Corporation
  - Bergstrom
  - Eaton Corporation
- Project lead
  - Argonne National Laboratory
Relevance

- Elimination of a low temperature cooling system
- Power electronic modules can operate at high powers or conversely have smaller footprints
- Reduction in size & weight of power electronics package => reduced costs
  - current costs ~$30/kWh, target is $8/kWh by 2020
- Secondary benefits of the technology
  - improved efficiency and reliability of power electronics at higher operating conditions
    - smaller inverters delivering same level of power to motor
  - increased lifetimes of the power electronic components ($$ savings)
Objectives

Use subcooled boiling in the cooling channel to enhance the cooling of vehicle power electronics for hybrid and all-electric vehicles

Objectives:
- Explore the potential of subcooled boiling for vehicle power electronics cooling
- Conduct numerical heat transfer simulations
- Experimentally investigate subcooled boiling heat transfer

Targets Addressed:
- Eliminating the low-temperature cooling system for HEVs -- reduce the cost and weight
  - Reduced pumping power and parasitic losses
- Using subcooled boiling to increase heat removal capacity
- Controlling junction temperature -- improve the efficiency and lifetime of electronic components
- Applying to high power density electronics
  - Wideband gap semiconductors based power electronics -- heat flux: 200-250 W/cm²
- Simple cooling system configuration
  - Integrated into the main engine cooling system
**Approach/Strategy**

- **Heat transfer simulations**
  - Analyze benefits of subcooled boiling over currently used convective heat transfer
  - Investigate various parameter effects on subcooled boiling
    - Thermal conductivity of thermal interface material (TIM)
    - Flow velocity
    - Inlet flow temperature
    - Heat flux

- **Experimental measurements**
  - Modify the heat transfer test facility to connect with the cooling module of power electronics
  - Measure subcooled flow boiling heat transfer coefficients under vehicle power electronics cooling conditions and compare with simulation results
  - Develop predictive models for the subcooled boiling heat transfer coefficient for power electronics geometry cooling systems

Demonstrate the applicability of subcooled nucleated boiling cooling technology for power electronics for HEVs and EVs
## Approach - Milestones

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-Go Decision</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep./2014</td>
<td>Milestone</td>
<td>Numerical heat transfer simulations (COMSOL) to establish the advantages of subcooled nucleated boiling for power electronics cooling</td>
<td>Completed</td>
</tr>
<tr>
<td>Dec./2014</td>
<td>Milestone</td>
<td>Numerical simulations on selected power electronics cold plate</td>
<td>Completed</td>
</tr>
<tr>
<td>Mar./2015</td>
<td>Milestone</td>
<td>Design &amp; modify the current subcooled boiling test loop to integrate a power electronic module (inverter) heat sink for tests</td>
<td>Completed</td>
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<tr>
<td>July/2015</td>
<td>Milestone</td>
<td>Measure subcooled boiling heat transfer coefficients for a typical power electronic module cooling channel and compare the data with the simulations</td>
<td>On going</td>
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<tr>
<td>Sep./2015</td>
<td>Milestone</td>
<td>Develop predictive models for the subcooled boiling heat transfer coefficient based on the experimental data for power electronics geometry cooling systems</td>
<td>Will be done</td>
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</table>
Key Conditions of Subcooled Boiling Simulations

- Use of conventional engine coolant -- 50/50 ethylene glycol/water (EG/W) mixture
- Coolant fluid inlet temperature of 105 C -- using engine cooling pumping system
- Coolant under 2 atmosphere pressure -- same as engine cooling system pressure
- Flow velocity around 0.16 m/s (laminar flow)
  - Lower pressure drops and pumping power requirements
- Coolant fluid outlet temperature below the saturation point -- no vapor in rest of the system
- Cooling channel wall temperature of 10-30° C above the saturation point (~129° C under 2 atm)
Previous Accomplishments -- FY14
Effects of Various Parameters on Subcooled Boiling

1. TIM Thermal Conductivity Effects
   - Double-sided cooling without fin for a 100-W/cm² heat flux
   - Modeling Geometry (Toyota Lexus):
     (a) With fins
     (b) Without fins

2. Coolant Flow Velocity Effects on Subcooled Boiling
   - Double-sided cooling with a 7.5-W/m·K TIM for a 100-W/cm² heat flux
   - Coolant flow velocity range: 0.05 m/s - 0.4 m/s (100 W/cm² heat flux with fins)

3. Coolant Inlet Temperature Effects on Subcooled Boiling
   - Subcooled boiling with a 7.5 W/m·K TIM can control the junction temperature under 175°C
   - Fins can be eliminated in double-sided subcooled boiling cooling
Comparison of Convective and Subcooled Boiling Heat Transfer Simulations for Toyota Lexus Power Electronics Package

- TIM - 7.5 W/m·K

<table>
<thead>
<tr>
<th></th>
<th>Subcooled boiling cooling system</th>
<th>Laminar flow cooling system *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant inlet temperature (ºC)</td>
<td>105 105 105 105 70 70</td>
<td>70 70</td>
</tr>
<tr>
<td>Total heat flux on IGBT and Diode surfaces (W/cm²)</td>
<td>100 125 100 250 127 100</td>
<td>127 100</td>
</tr>
<tr>
<td>Coolant flow velocity (m/s)</td>
<td>0.16 0.16 0.16 0.16 0.24 0.24</td>
<td>0.24 0.24</td>
</tr>
<tr>
<td>Fins in the channel</td>
<td>No Yes Yes Yes Yes Yes</td>
<td>Yes Yes</td>
</tr>
<tr>
<td>Junction temperature (ºC)</td>
<td>175 175 160 175 150 175</td>
<td>150 175</td>
</tr>
</tbody>
</table>

* Literature base case: Bennion, K. et al., 2009 simulation results

- Without fins, double-sided subcooled boiling can cool current systems
- With fins, subcooled boiling can increase the cooling rate by 25% or reduce the junction temperature
- With fins, double-sided subcooled boiling can cool wideband gap semiconductors up to 250 W/cm²
Technical Accomplishments -- FY15
Toyota Prius Power Electronics Package (Modeling Geometry COMSOL)

(a) Cold plate
(b) Cooling channels
(c) Cooling channel modeling geometry (unit in mm)
(d) Cooling channels used for power electronics cooling
(e) Power electronics module
(f) Final modeling geometry for power electronics module
**Technical Accomplishments -- FY15**

**Materials and Dimensions of Each Component**

<table>
<thead>
<tr>
<th>Materials</th>
<th>x (mm)</th>
<th>y (mm)</th>
<th>z (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon IGBT</td>
<td>13.0</td>
<td>9.0</td>
<td>0.51</td>
</tr>
<tr>
<td>Silicon diode</td>
<td>6.5</td>
<td>6.0</td>
<td>0.32</td>
</tr>
<tr>
<td>Copper layer</td>
<td>32</td>
<td>21.5</td>
<td>0.41</td>
</tr>
<tr>
<td>AlN layer</td>
<td>32</td>
<td>21.5</td>
<td>0.64</td>
</tr>
<tr>
<td>Copper base plate</td>
<td>73</td>
<td>225</td>
<td>3.0</td>
</tr>
<tr>
<td>Solder layer</td>
<td>32</td>
<td>21.5</td>
<td>0.1</td>
</tr>
<tr>
<td>TIM: Thermal grease</td>
<td>73</td>
<td>225</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Aluminum cooling channel (10 channels per set):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{ch}$</td>
<td>14</td>
</tr>
<tr>
<td>$H_b$</td>
<td>5</td>
</tr>
<tr>
<td>$H_t$</td>
<td>6</td>
</tr>
<tr>
<td>$W_{ch}$</td>
<td>1.75</td>
</tr>
<tr>
<td>$W_w$</td>
<td>1.75</td>
</tr>
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</table>
Technical Accomplishments -- FY15
Toyota Prius Heat Sink Simulation Results

Current technology -- Single phase laminar flow:
- Heat flux: 100 W/cm²
- Coolant inlet temperature: 70°C
- Coolant flow velocity: 0.16 m/s
- TIM: 1.5 W/m K
- Junction temperature: < 175°C

Single phase laminar flow:
- Heat flux: 100 W/cm²
- Coolant inlet temperature: 105°C
- Coolant flow velocity: 0.16 m/s
- TIM: 1.5 W/m K
- Junction temperature: 186°C

Single phase convective heat transfer will not work at coolant temperatures of 105°C.
Technical Accomplishments -- FY15
Toyota Prius Heat Sink Simulation Results

Subcooled boiling cooling system:
- Heat flux: 100 W/cm²
- Coolant inlet temperature: 105°C
- Coolant flow velocity: 0.16 m/s
- TIM: 1.5 W/m K
- Junction temperature: 154°C

Subcooled boiling cooling system:
- Heat flux: 114 W/cm²
- Coolant inlet temperature: 105°C
- Coolant flow velocity: 0.16 m/s
- TIM: 1.5 W/m K
- Junction temperature: 161°C

- With subcooled boiling, the coolant inlet temperature can be increased to 105°C
- With subcooled boiling, the heat flux for Prius power electronics can be increased to 114 W/cm² compared to the single phase convective cooling
Subcooled boiling technology for Toyota Prius power electronics cooling provides:

- Increased coolant inlet temperature of 105°C
  - Elimination of the second low temperature cooling system
- Control of Junction temperature <175°C
- Low flow velocity
  - Low pressure drop and pumping power requirement
- Increased cooling rate by 14% compared to the current technology based on convective heat transfer
  - The heat flux is limited by the temperature rise of the coolant
    - Constraint to keep coolant outlet temperature below the saturation point
  - The heat flux can go higher if the cooling channel is altered from series to parallel channels
Experimental Design

Heating wire to supply heat fluxes (simulating IGBT and diode on the cold plate):

- Nichrome 80
- Diameter: 0.072”
- Electrical resistance: 0.1254 Ohms/ft nominal
- Wire spacing: 3/16”
- Total heating wire length: ~40”

(a) Heating wire, TCs and pressure transducers setup on the heat sink

(b) Heat input from heating wire equivalent to 100 W/cm² heat flux on IGBT and diode pairs

(c) Heating wire attached on the cold plate
Technical Accomplishments -- FY15

Modified Experimental Subcooled Boiling Test Loop

Pressurized system
Technical Accomplishments -- FY15
Heat Sink Test Section Assembled and Incorporated on the Test Loop

Heat sink integrated on to the test section loop

• Experiment test conditions:
  ✓ Coolant: 50/50 EG/W mixture
  ✓ Coolant inlet temp: 70-125 C
  ✓ Flow velocity: 0.05-1.0 m/s
  ✓ Max power input: up to 1500 W
  ✓ Pressure: ~2 atm
Heat Loss Calibration

• No flow heat loss tests
  ✓ Applied five power inputs to bring its wall temperature to selected levels
    ➢ Corresponding heat loss = applied power
• Heat loss characteristics
  ✓ Heat loss due to the high thermal conductivity of aluminum
    ✓ Predicted well with the fitting equation
    ➢ Linearly depended on the driving temperature
  ✓ Incorporated into the data reduction procedures
    ➢ For single-phase and boiling heat transfer tests

Heat loss is well characterized
Technical Accomplishments -- FY15

Preliminary test for laminar flow in the cooling channel

- Experiment test conditions
  - Coolant: 50/50 EG/W mixture
  - Flow velocity: 0.04 m/s

Coolant flow average temperature, $T_f$:
1 - 68.9 C
2 - 74.0 C
3 - 81.3 C

Simulation predictions agree with the measurement results for single phase laminar flow in the Toyota Prius power electronics cooling channel.
Collaborations/Interests

• APEEM/ORNL
  ✓ For information exchange of power electronics cooling
  ✓ For power electronics cooling system module
  ✓ For next step testing of coolant subcooled boiling cooling of power electronics in HEVs or EVs

• Dana Corporation
  ✓ Initial discussions on heavy-duty markets, light-duty markets, and thermal management

• Bergstrom

• Eaton Corporation
  ✓ Waste heat recovery for heavy-duty engines
Future Work

• Rest of FY15
  ✓ Measure the subcooled boiling heat transfer coefficients in the cooling channel under various steady state conditions:
    ➢ Various heat flux
    ➢ Flow velocity
    ➢ Coolant inlet temperature
    ➢ High pressure (~2 atm)
  ✓ Develop predictive models for subcooled boiling heat transfer coefficients based on experimental data
  ✓ Compare and refine the simulation results

Demonstrate the technology on an actual power electronics cold plate under steady state conditions

• Beyond FY15:
  ✓ Investigate the applicability of the technology under transient conditions (motor/inverter) to simulate vehicle drive cycles
Summary

• Relevance
  ✓ Use subcooled boiling in the cooling channel to enhance the cooling of vehicle power electronics for HEVs and EVs
  ✓ Eliminate the second cooling system
  ✓ Apply to high power density electronics -- 200-250 W/cm² heat flux

• Approach
  ✓ Perform numerical heat transfer modeling and simulations
  ✓ Conduct experimental measurements

• Technical Accomplishments
  ✓ Analyzed benefits of subcooled boiling over currently used convective heat transfer
  ✓ Investigated effects of various parameters (flow velocities, coolant inlet temperatures, heat fluxes, etc.) on subcooled boiling of 50/50 EG/W coolant
  ✓ Modified the heat transfer test facility and integrated the power electronics heat sink module into the test loop for evaluating the performance of subcooled boiling heat transfer
  ✓ Preliminary experiments data collected
Summary (cont.)

• **Collaborations**
  ✓ Ongoing efforts with APEEM team & ORNL for power electronics cooling system module

• **Future Work**
  ✓ Measure the subcooled boiling heat transfer coefficients
  ✓ Compare and refine the simulation results
  ✓ Develop predictive models for subcooled boiling heat transfer coefficients based on test data
  ✓ Demonstrate the subcooled boiling technology for power electronics cooling in HEVs to eliminate the low temperature radiator
  ✓ Investigate the applicability of the technology under transient conditions to simulate vehicle drive cycles
Technical Back-Up Slides
Background: Current research and technologies for power electronics cooling system

- Liquid-cooled heat sinks with fin structure *(Bennion, K., Kelly, K., NREL 2009)*
  - Use of fins in the cooling channel to remove the heat
  - Need for second radiator to reduce the coolant inlet temperature

- Single-phase or two-phase jet impingement *(Narumanchi, S. et al., NREL 2005, 2008; Garimella, S.V. et al., Purdue University 2013)*
  - Removal of large, concentrated heat fluxes
  - Hardware for impingement
  - High flow velocity required
  - Stress concentration in the impingement zone

- Two-phase spray cooling *(Bharathan, D. et al., NREL 2005, 2008)*
  - Removal of large amount of heat flux
  - Need for a condenser to condense the vapor
  - Need for a pump to pressurize the liquid to form the spray

- Immersion pool boiling *(Moreno et al., NREL 2011)*
  - Need for separate pumping system for condensing vapor
Background: Current research and technologies for power electronics cooling system

- Single-phase jet impingement (*Narumanchi, S. et al., NREL 2005*)

<table>
<thead>
<tr>
<th></th>
<th>Glycol-water mixture</th>
<th></th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90 W/cm²</td>
<td>200 W/cm²</td>
<td>90 W/cm²</td>
</tr>
<tr>
<td>Jet velocity, m/s</td>
<td>8</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>$T_{\text{inlet}}, ^\circ \text{C}$</td>
<td>105</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>$T_{\text{max}}, ^\circ \text{C}$</td>
<td>125</td>
<td>135</td>
<td>119</td>
</tr>
<tr>
<td>$h_{\text{copper}}, \text{W/m}^2\text{K}$</td>
<td>39,000</td>
<td>75,700</td>
<td>74,200</td>
</tr>
<tr>
<td>$h_{\text{aluminum}}, \text{W/m}^2\text{K}$</td>
<td>19,800</td>
<td>40,500</td>
<td>37,100</td>
</tr>
</tbody>
</table>
Heat Transfer Coefficient Model for Simulations

Subcooled Boiling Heat Transfer Coefficients

- **Shah Correlation (1977):**

\[
h_b = \frac{\dot{q}''}{(T_w - T_f)} = \frac{\dot{q}''}{[(T_w - T_{sat}) + (T_{sat} - T_f)]} = \frac{\dot{q}''}{(\Delta T_{sat} + \Delta T_{sub})}
\]

\[
\Delta T_{sat} = \frac{\dot{q}''}{(\psi h_i)}
\]

\[
h_i = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} (k / d)
\]

\[
\psi = \begin{cases} 
\psi_o & \text{low_subcooling_region} \\
\psi_o + \frac{\Delta T_{sub}}{\Delta T_{sat}} & \text{high_subcooling_region}
\end{cases}
\]

\[
\psi_o = \begin{cases} 
1 + 46Bo^{0.5} & Bo < 3 \times 10^{-5} \\
230Bo^{0.5} & Bo > 3 \times 10^{-5}
\end{cases}
\]

Here, \( Bo \) is the boiling number

\[
Bo = \frac{\dot{q}''}{Gh_{fg}}
\]
Challenges and Barriers

- High coolant temperature, 105 C -- eliminate the second radiator for HEVs
  ✔ Reduce the weight and cost of the vehicles

- Junction temperature control ≤ 175 C
  ✔ Improve the efficiency and lifetime of electronic components

- Applications of high power density electronics
  ✔ Wideband-gap semiconductor based power electronics (heat flux: 200-250 W/cm²)

- Coolant outlet temperature below the saturation point
  ✔ No vapor in the rest of the system
  ✔ Simple cooling system configuration