Advanced Liquid Cooling R&D

Sreekant Narumanchi
National Renewable Energy Laboratory
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Overview

Timeline
Project Start Date: FY11
Project End Date: FY13
Percent Complete: 80%

Barriers and Targets
• Cost
• Weight
• Specific power
• Power density

Budget
Total Project Funding: $1.6M
DOE Share: $1.6M

Funding Received in FY11 and FY12: $1.2M
Funding for FY13: $400K

Partners
• Interactions/ collaborations
• Project lead: National Renewable Energy Laboratory (NREL)
Relevance/Objective(s)

• Advanced thermal management technologies are critical to enabling higher power densities
  – Resulting in lower weight, size and cost

• Objectives
  – Design and develop light-weight, single-phase liquid-cooled, automotive inverter-scale heat exchanger based on impinging jets and enhanced surfaces.
  – Through thermal management, directly contribute towards the 2015 power electronics targets.
  – Enable use of high-temperature water-ethylene glycol (WEG) coolant for power electronics cooling.

Credit: Mark Mihalic, NREL
<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone or Go/No-Go Decision</th>
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</table>
| September 2011 | Completed finite element analysis (FEA) and computational fluid dynamics (CFD) modeling to design the first prototype heat exchanger.  
**Go/No-Go Decision:** Modeling results showed significant promise for the new design as compared to the baseline channel-flow case; decision was made to proceed with hardware fabrication. |
| February 2012 | Fabricated first jet-based plastic heat exchanger prototype (impingement on plain surface); initiated experimental testing for pressure drop and thermal performance.                                                                                                                                         |
| September 2012 | Completed first study on reliability of the impinging jet configuration on unplated microfinned surfaces.                                                                                                                                                                                                                                             |
| March 2013  | Completed experimental characterization and CFD analysis on the first prototype. Performance benefits with respect to baseline channel-flow case demonstrated; second prototype designed to enable lower pressure drop and easier fabrication/manufacturing.  
**Go/No-Go Decision:** Proceed with fabrication of second prototype (impingement on plain surface) and third prototype (impingement on microfinned surface) heat exchangers. |
| June 2013   | Complete CFD analysis and fabrication of second and third prototype heat exchangers.                                                                                                                                                                                                                                                                   |
| September 2013 | Complete experimental thermal performance and pressure drop characterization on second and third prototype heat exchangers.  
Complete second round of reliability characterization of the impinging jet configuration. |
**Approach/Strategy**

- **Baseline heat exchanger**
- **First prototype new heat exchanger**

- **MicroCool Surface (Wolverine)**
  - Reduce thermal resistance, increase heat transfer rates through WEG jet impingement on enhanced surfaces, and use light-weight material.
  - Characterize thermal performance based on steady-state and transient/realistic loading conditions.
Validation of CFD Modeling for Baseline and Jet-Based Heat Exchanger

<table>
<thead>
<tr>
<th>Flow Rate (x10^-4 m^3/s)</th>
<th>ΔP (Pa)</th>
<th>T_{avg,4diodes} (°C)</th>
<th>R_{th,ja} (°C/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp.</td>
<td>CFD</td>
<td>Exp.</td>
</tr>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.83</td>
<td>5102</td>
<td>5125</td>
<td>84.6</td>
</tr>
<tr>
<td>1.33</td>
<td>12548</td>
<td>12325</td>
<td>84.1</td>
</tr>
<tr>
<td>1.67</td>
<td>19374</td>
<td>17897</td>
<td>83.9</td>
</tr>
<tr>
<td>Jet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.33</td>
<td>--</td>
<td>14214</td>
<td>--</td>
</tr>
<tr>
<td>1.67</td>
<td>24407</td>
<td>20803</td>
<td>82.2</td>
</tr>
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</table>

- 105.3 W dissipated in four diodes in the center power module
- WEG mixture (50–50% by volume of water and ethylene glycol) at 70°C used as coolant
- Junction temperature in the four diodes measured using the transient thermal tester during the steady-state heating
- Solder (jet case) and grease (baseline case) layer resistances adjusted in the model to match with experiments at 1.67x10^-4 m^3/s (10 liters/min) and 105.3 W

12.1% reduction

Credit: Mark Mihalic, NREL
CFD Modeling for Performance at 2.5kW Heat Dissipation

<table>
<thead>
<tr>
<th></th>
<th>Flow Rate ($x10^{-4}$ m$^3$/s)</th>
<th>$\Delta P$ (Pa)</th>
<th>$T_{avg, devices}$ (°C)</th>
<th>$R_{th,ja}$ (°C/W)</th>
<th>$T_{max, devices}$ (°C)</th>
<th>$R_{th,ja}$ (°C/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1.67</td>
<td>17905</td>
<td>117.4</td>
<td>0.0188</td>
<td>121.7</td>
<td>0.0205</td>
</tr>
<tr>
<td>Jet (plain surface)</td>
<td>1.67</td>
<td>20801</td>
<td>111.4</td>
<td>0.0164</td>
<td>114.9</td>
<td>0.0178</td>
</tr>
<tr>
<td>Jet (enhanced surface)</td>
<td>3.34*</td>
<td></td>
<td>101.3</td>
<td>0.0124</td>
<td>104.5</td>
<td>0.0137</td>
</tr>
</tbody>
</table>

*Twice the jet velocity (flow rate) yields nearly equivalent heat transfer as enhanced surfaces

- 2520 W dissipated in 24 IGBTs and 24 Diodes
- WEG mixture at 70°C used as coolant
- 1156 W and 3456 W power levels and heat dissipation ratios of $Q_{IGBT}/Q_{Diode} = 1:1$, 2:1, 3:1 investigated, yielded same thermal resistance
- Jet impingement on plain surface yielded 12.6% reduction in thermal resistance
- Jet impingement on microfinned surface projected to reduce thermal resistance by 33%

Credit: Mark Mihalic, NREL
Impacts on Coefficient of Performance (COP), Power Density, Specific Power and Cost

- Up to 30% increase in COP for 1\textsuperscript{st} generation prototype
- Due to lower pressure drop (fluid power), 2\textsuperscript{nd} generation (plain surface) COP increase projected at >40% and 3\textsuperscript{rd} generation (enhanced surface) increase of >85%
- Up to 51% increase in power density
- Using plastic results in approximately 2.9 kg (6.3 lb) or 50% weight reduction of the heat exchanger - results in up to 84% increase in specific power
- Cost will be competitive/lower with respect to aluminum baseline heat exchanger
Heat Transfer Coefficient (W/m²-K)

- **Baseline**
  - Jets provide localized cooling on devices

- **Jets** (impinging on plain surface)

Jet flow
Temperatures in the Baseline and Jet Cases

- 2520 W (24 IGBT @ 70 W, 24 Diodes @ 35 W)
- WEG mixture at 70°C used as coolant
- For same flow rate, average and maximum device temperature reduced by ~6 to 7°C for the case of jets versus the baseline
Jet Velocity and Pressure

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Pressure (kPa)</th>
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<tbody>
<tr>
<td>3.44</td>
<td>15.0</td>
</tr>
<tr>
<td>3.27</td>
<td>14.5</td>
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<tr>
<td>3.10</td>
<td>14.0</td>
</tr>
<tr>
<td>2.93</td>
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<tr>
<td>2.75</td>
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</tr>
<tr>
<td>2.58</td>
<td>12.5</td>
</tr>
<tr>
<td>2.41</td>
<td>12.0</td>
</tr>
<tr>
<td>2.24</td>
<td>11.5</td>
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<td>2.07</td>
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<td>1.55</td>
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<td>1.38</td>
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<td>1.21</td>
<td>8.5</td>
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<td>1.03</td>
<td>8.0</td>
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<tr>
<td>0.86</td>
<td>7.5</td>
</tr>
<tr>
<td>0.69</td>
<td>7.0</td>
</tr>
<tr>
<td>0.52</td>
<td>6.5</td>
</tr>
<tr>
<td>0.34</td>
<td>6.0</td>
</tr>
<tr>
<td>0.17</td>
<td>5.5</td>
</tr>
<tr>
<td>0.00</td>
<td>5.0</td>
</tr>
</tbody>
</table>

- Jets relatively uniform, with slightly higher velocities on downstream side, reducing thermal resistance
Jet Impingement Reliability Characterization

- Tests with WEG jet impinging on microfinned surface (on 12.5-mm-diameter copper target surface)
- Negligible change in jet nozzle diameter after 12 months of nearly continuous impingement
- Degradation in thermal performance due to oxidation
Jet Impingement Reliability Characterization – Second Round

**8 samples being tested simultaneously**
- 3 DBC substrates
- 3 DBA substrates
- 2 microfinned surfaces (nickel-plated)

**Test Conditions**
- Long-term impingement tests have begun in February, 2013
- Automotive-grade WEG
- 65°C operating temperature
- Submerged jets
  - 5 m/s at the nozzle exit
  - Average nozzle diameter ~1.3 mm
  - ~3 mm distance between nozzle and sample surfaces
Jet Impingement Reliability Characterization – Second Round

- 6 Delphi DBA/DBC samples
  - Periodic testing metrics
    - Scanning Acoustic Microscopy (C-SAM) imaging
    - Thermal Diffusivity
    - Laser profilometry
    - Digital microscope images

- 2 Wolverine microfinned samples (nickel-plated)
  - Periodic testing metrics
    - Digital microscope images
    - Heat transfer coefficients

Credit (all images): Jana Jeffers, NREL
## Collaboration and Coordination

<table>
<thead>
<tr>
<th>Collaborator</th>
<th>Type of Interaction/Collaboration</th>
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</table>
| UQM Technologies Inc. (Industry)                  | • Source for inverter and power modules  
• Source for dynamometer testing of the inverter                                                  |
| Wolverine Tube, Inc. (Industry)                   | • Provided microfinned enhanced surface on copper base plate and blocks                             |
| Delphi Electronics & Safety (Industry)            | • Provided DBC and DBA substrates for reliability characterization of jets                           |
Proposed Future Work (Remainder of FY13)

- Fabrication and characterization of new jet-impingement heat exchanger (second prototype) out of plastic:
  - Will be easier to manufacture using traditional processes,
  - Maintain thermal performance similar to the first prototype,
  - Have less pressure drop, decreasing fluid power, and increasing COP,
  - Potentially reduce volume due to different manifold connections.
Proposed Future Work (Remainder of FY13)

- Characterization of prototype (third) performance based on jet impingement on microfinned surfaces.
- Complete characterization of reliability of jet impingement on DBC/DBA, as well as on nickel-plated microfinned surface.
- Address aspects related to mass-manufacturing as well as cost comparisons of the new heat exchanger with respect to the baseline aluminum heat exchanger.
Summary

DOE Mission Support
• Through thermal management, help make progress towards 2015 power electronics targets
• Enable use of high-temperature WEG coolant

Approach
• Jet impingement on base plate with and without microfinned surface
• Light-weight, low-cost plastic for rest of the heat exchanger
• Demonstration of reliability

Accomplishments
• First experimental prototype of plastic heat exchanger incorporating jet impinging on plain surface shows 12.6% reduction in thermal resistance compared to the baseline case.
• Analysis shows potential for up to 33% reduction in thermal resistance for the case of jets impinging on microfinned surfaces as compared to the baseline
  o Up to 85% increase in COP
  o 51% increase in power density
  o 84% increase in specific power
Summary

Accomplishments

• First round of reliability characterization shows nozzle diameter unaffected by long-term (12 months) near-continuous jet impingement.
  o Some degradation in heat transfer of un-plated microfinned surface due to oxidation of the surface.

Future work

• Complete fabrication and demonstration of performance of simpler prototype heat exchangers incorporating impingement on both plain and microfinned surface.
• Complete comprehensive reliability assessment of the impinging jet configuration.

Collaborations

• UQM Technologies Inc.
• Wolverine Tube Inc.
• Delphi Electronics & Safety
Acknowledgment:
Susan Rogers and Steven Boyd, U.S. Department of Energy

For more information contact:
Principal Investigator
Sreekant Narumanchi
sreekant.narumanchi@nrel.gov
Phone: (303)-275-4062

NREL Team Members:
Scot Waye
Mark Mihalic
Gilbert Moreno
Kevin Bennion
Jana Jeffers

APEEM Task Leader
Sreekant Narumanchi
sreekant.narumanchi@nrel.gov
Phone: (303)-275-4062