TRACTION DRIVE INVERTER COOLING WITH
SUBMERGED LIQUID JET IMPINGEMENT ON
MICROFINNED ENHANCED SURFACES

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SAE 2014 Thermal Management Systems Symposium
September 22–24, 2014
Denver, Colorado
14TMSS-0020
Impacts: Lower cost, volume, and weight

Enabling technology: Enhanced heat transfer/thermal management
Objectives

- Design and develop a light-weight, single-phase, liquid-cooled, automotive inverter-scale heat exchanger based on impinging jets and enhanced surfaces
- Enable use of high-temperature water-ethylene glycol (WEG) coolant for power electronics cooling

Advanced thermal management technologies are critical to enabling higher power densities and meeting DOE targets for specific power, power density, and cost.
Why use a microfinned enhanced surface? Large increase in heat transfer coefficient
Three Configurations Were Tested

**Baseline heat exchanger**
Aluminum channel flow cold plate

**First version heat exchanger prototype**
- Plastic manifold (lower weight)
- Same flow path as baseline
- Submerged jet impingement on plain surfaces
- Submerged jet impingement on microfinned enhanced surfaces

**Second version heat exchanger prototype**
- Plastic manifold (lower weight)
- **Simplified flow path to reduce pressure loss**
- Submerged jet impingement on plain surfaces
- Submerged jet impingement on microfinned enhanced surfaces
Experimentation and Modeling Approach

**Experiments (low power)**
- 50%–50% WEG at 70°C; 5, 8, 10 L/min
- Power 4 diodes (105 W heat)
- Metrics: $R_{th,j-l}$ using T3ster, $\Delta P$

**Modeling (CFD)**
- Validate models at 105-W heat (50%–50% WEG at 70°C; 5, 8, 10 L/min)
- Model 2.5 kW heat (24 IGBTs, 24 diodes)
- Metrics: $R_{th,j-l}$, $\Delta P$

**Experiments (inverter level)**
- 40%–60% WEG at 30°C, 10 L/min
- 40, 60, 80, 100 kW Electrical Power
- Metrics: $\Delta T$ between probes and coolant
Reliability Characterization

12-month testing of free WEG jet impinging on microfinned surface
- 35°C WEG
- 2 m/s jet, 12 m/s jet

Long-term testing of submerged WEG jet on 2 microfinned surfaces (nickel-plated), 3 DBC substrates, and 3 DBA substrates
- 65°C automotive-grade WEG
- 5 m/s jet (1.3-mm nozzle, 3-mm jet distance)

DBA = direct-bond-aluminum
DBC = direct-bond-copper

previous work
Thermal Resistance Map from T3ster (105-W experiment)

Reduction in thermal resistance:

5.1%

10.3%
Performance at 2.5 kW Heat Dissipation (model)

- **9%** (plain) to **32%** (microfinned) reduction in thermal resistance
- **5%** (plain) to **40%** (microfinned) increase in COP \(1/R_{th}[\Delta P \cdot V]\)
- **29%** (plain) to **55%** (microfinned) increase in specific power (kW/kg)
- **6%** (plain) to **28%** (microfinned) increase in power density (kW/L)
- Values from modeling represent idealized limit due to external adiabatic boundaries driving heat into the coolant

Temperature reduction (jets to baseline):
- **5°C – 6°C** (plain)
- **15°C – 16°C** (microfinned)

Jets provide localized cooling on devices

Heat Transfer Coefficient (W/m²-K)
Passive Stack Resistance Dependence

- Decreased convective cooling resistance
- Channel flow cold plate
- Jets on plain surface
- Jets on enhanced surface
- Decreased $R_{th,j-l}$
- Increased heat flux and distribution

4 diodes (105 W)
24 IGBTs / 24 diodes (2520 W)
Inverter Testing on Dynamometer

Thermocouple locations (middle of copper baseplate)

Channel Flow

Jet Impingement

ΔT = TC,avg - Tcoolant, avg

40, 60, 80, 100 kW Electrical Power
0.9, 1.3, 1.6, 2.2 kW heat dissipation (model estimate)
0.9, 1.1, 1.6, 1.9 kW heat dissipation (simple energy balance)
Thermocouple Temperatures

Average thermocouple temperature [°C]

<table>
<thead>
<tr>
<th>Power [kW]</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel, Plain</td>
<td>46.6</td>
<td>52.5</td>
<td>60.2</td>
<td>68.7</td>
</tr>
<tr>
<td>Jet, Plain</td>
<td>N/A</td>
<td>53.5</td>
<td>60.0</td>
<td>67.6</td>
</tr>
<tr>
<td>Jet, Microfined</td>
<td>44.8</td>
<td>50.2</td>
<td>56.1</td>
<td>62.3</td>
</tr>
</tbody>
</table>

Channel Flow, Plain

Jet, Microfinned

Lower temperatures
Less variability
Temperature Difference (Baseplate to Coolant)

\[ \Delta T \propto \text{thermal resistance (} R_{th} = \frac{\Delta T}{Q} \) ]
Full Inverter Thermal Performance

Improvement over baseline

<table>
<thead>
<tr>
<th>Power [kW]</th>
<th>40</th>
<th>60</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet, Plain</td>
<td>-28.5%</td>
<td>-0.8%</td>
<td>1.7%</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Jet, Microfinned</td>
<td>4.8%</td>
<td>14.2%</td>
<td>17.0%</td>
<td><strong>17.4%</strong></td>
</tr>
<tr>
<td>Specific Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet, Plain</td>
<td>15.8%</td>
<td>20.1%</td>
<td>22.5%</td>
<td>21.1%</td>
</tr>
<tr>
<td>Jet, Microfinned</td>
<td>26.4%</td>
<td>33.6%</td>
<td>35.6%</td>
<td><strong>35.9%</strong></td>
</tr>
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<td>Power Density</td>
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<tr>
<td>Jet, Microfinned</td>
<td>4.3%</td>
<td>10.2%</td>
<td>11.9%</td>
<td><strong>12.1%</strong></td>
</tr>
</tbody>
</table>

- Jets with plain surfaces: little improvement
- Jets with microfinned enhanced surfaces: considerable improvement
Inverter-Scale Experimental Thermal Performance Summary

- Full inverter testing (40 – 100 kW) with jets and microfinned surfaces:
  - Reduction in thermal resistance
  - Increase in Coefficient of Performance
  - Increase in power density
  - Increase in specific power (reduction in heat exchanger weight by ~3 kg) compared to channel flow

- Jets with microfinned surfaces provide localized cooling and improved temperature uniformity (5°C less spread) than channel flow case
- Jet reliability is good
Jet and Surface Reliability (First Round Testing)

- Negligible change in jet nozzle diameter after 12 months of nearly continuous impingement
- Degradation in thermal performance of surfaces due to oxidation (no coating, no corrosion inhibitors)

Surface Reliability (Second Round Testing)

- Initial break-in period
- Some degradation on surfaces
- Corrosion inhibitors appear to coat surfaces
## Thermal Performance Summary (Compared to Baseline Channel Flow)

### Jet, Plain

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<thead>
<tr>
<th>Experiment Type</th>
<th>Thermal Resistance</th>
<th>COP</th>
<th>Specific Power</th>
<th>Power Density</th>
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</thead>
<tbody>
<tr>
<td>105 W Experiment</td>
<td>5%</td>
<td>0%</td>
<td>29%</td>
<td>6%</td>
</tr>
<tr>
<td>(70°C 50%-50% WEG)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 kW Model</td>
<td>9%</td>
<td>5%</td>
<td>21%</td>
<td>0%</td>
</tr>
<tr>
<td>(70°C 50%-50% WEG)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~2 kW Experiment</td>
<td>2%</td>
<td>0%</td>
<td>21%</td>
<td>0%</td>
</tr>
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<td>(30°C 40%-60% WEG)</td>
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### Jet, Microfinned

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<tr>
<td>~2 kW Experiment</td>
<td>17%</td>
<td>17%</td>
<td>36%</td>
<td>12%</td>
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- Jets provide localized cooling on devices
- Enhanced surfaces increase jet effectiveness

- • Jets provide localized cooling on devices
- • Enhanced surfaces increase jet effectiveness
Potential for Further Jet Optimization

More aggressive jet cooling strategies can further lower resistance (need to be balanced to not overly increase pressure drop/fluid power)

Previous work illustrating thermal resistances
Conclusions

• Light-weighting with plastics possible with jet impingement because thermal path does not require high conductivity

• Jets provide localized increase in heat transfer (where you need it)

• Enhanced surfaces increase jet heat transfer effectiveness (greater surface area and flow dynamics)