Relevance – Why Motor Cooling

- Current Density
- Magnet Cost
  - Price variability
  - Rare-earth materials
- Material Costs
- Reliability
- Efficiency
- Temperature Distribution
Passive and Active Cooling

Passive Thermal Design
- Motor geometry
- Material thermal properties
- Thermal interfaces

Active Convective Cooling
- Available coolant
- Cooling location
- Parasitic power
- Heat transfer coefficients
Passive Thermal Design

- Thermal Contact Resistance
- Slot Windings
- Slot Paper
- Stator Laminations

Measure
- Material thermal properties
- Thermal interfaces

Force Applied

Test apparatus built in accordance with ASTM D5470-12 steady state technique
Thermal Contact Resistance

Interlamination Thermal Contact Resistance \( (R_c) \) [mm²-K/W]

<table>
<thead>
<tr>
<th>Clamping Pressure [kPa]</th>
<th>M19 29 Gauge</th>
<th>M19 26 Gauge</th>
<th>HF10</th>
<th>Arnon 7</th>
<th>Ridged Average</th>
<th>Smooth Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>138</td>
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</tbody>
</table>

Photo Credit: Emily Cousineau

Full technical report available at: www.nrel.gov/publications/
Lamination Thermal Conductivity

- Thinner laminations have more contacts per unit length
- Higher pressure lowers contact resistance
- Error bars represent 95% confidence interval

\[ k_{\text{effective}} = \frac{t}{R_C + R_L} \]

- \( k_{\text{effective}} \) = effective thermal conductivity
- \( t \) = thickness of one lamination
- \( R_C \) = thermal contact resistance
- \( R_L \) = thermal resistance of one lamination

Full technical report available at: www.nrel.gov/publications/
Slot Materials and Interfaces

Slot Winding (paper bonded)

Slot Winding (paper removed)

Slot Paper

Photo Credit: Emily Cousineau, NREL
Slot Materials and Interfaces

• Preliminary results indicate substantial thermal resistance present between slot winding and paper
  • Preliminary results measured to be 1,800 mm²-K/W
  • As large as or larger than the slot liner paper alone (1,676 mm²-K/W)
  • More tests are necessary to confirm results and reduce measurement uncertainty
• Contact resistance between paper and stator may also be significant
Active Convective Cooling

**Direct impingement on target surfaces**

Measure heat transfer coefficients for ATF cooling of end windings

**Impingement on motor end-windings**

**Average Heat Transfer Coefficients**
- Establish credibility of experiment and data with comparison of flat target surface results to existing correlations in literature
- Produce new data for textured surfaces representative of end-winding wires

**Spatial Mapping of Convective Heat Transfer Coefficient**
- Jet local convective heat transfer
- Large-scale end-winding convective heat transfer mapping

ATF: automatic transmission fluid
Average Heat Transfer Coefficients

<table>
<thead>
<tr>
<th>$D$ (mm)</th>
<th>$d$ (mm)</th>
<th>$S$ (mm)</th>
<th>$S/d$</th>
<th>$D/d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.7</td>
<td>2.06</td>
<td>10</td>
<td>5</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Oil impingement test section schematic (left). Photo during operation (right).
ATF Impingement Target Surfaces

- ATF impingement baseline target is flat polished copper with 600-grit sandpaper
- Additional targets mimic wire bundles with insulation (18, 22, and 26 AWG)

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>18 AWG</th>
<th>22 AWG</th>
<th>26 AWG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (wire and insulation), mm</td>
<td>N/A</td>
<td>0.547</td>
<td>0.351</td>
<td>0.226</td>
</tr>
<tr>
<td>Total wetted surface area, mm²</td>
<td>126.7</td>
<td>148.2</td>
<td>143.3</td>
<td>139.2</td>
</tr>
</tbody>
</table>

AWG = American wire gauge
Comparison to Plain Surface Correlations

ATF fluid properties provided by Ford.
Heat transfer coefficients of all target surfaces at 50°C inlet temperature

- At lower impingement velocities, all samples achieve similar heat transfer
- Average heat transfer coefficients increase with larger wetted areas based on wire size

Note: Heat transfer coefficient calculated from the base projected area (not wetted area).
ATF Heat Transfer Coefficients

- Fluid splatter observed at higher velocities for 70°C and 90°C inlet liquid temperatures
- Splatter at 90°C occurred at lower velocity than at 70°C
- As temperature increases, it is expected that the fluid splatter will occur at lower velocities

18 AWG sample data for all inlet temperatures

ATF flowing over surface

ATF deflecting off surface

Note: ATF viscosity decreases as temperature increases.
Spatial Mapping of Heat Transfer

• Not all motor end-winding surfaces are directly impacted by ATF jets

• It is important to map the spatial distribution of the heat transfer coefficients to know the overall cooling effect

Photo Credit: Kevin Bennion, NREL
Local Convective Heat Transfer

Spatial mapping of local heat transfer with ATF jet impingement:

- Jet impingement heat transfer coefficients are not uniform over the entire cooled surface.
- The rate of decrease in the heat transfer coefficient is unknown.

Experimental velocity profile of jet impingement showing variation in velocity at target surface. Measured using particle image velocimetry (PIV) at NREL.
Local Convective Heat Transfer

Built test apparatus to spatially map local heat transfer coefficients with ATF jet impingement.

TLC: thermochromic liquid crystals

Photo Credits: Gilbert Moreno, NREL
Large-Scale Heat Transfer

Spatial mapping of large-scale end-winding convective heat transfer with direct ATF cooling

Stator winding removed for sensor package

3D drawing of stator with sensor packages installed

Photo Credit: Kevin Bennion, NREL
Sensor Design

Sensor Package

Targets

Flat  18 AWG  20 AWG

Exploded View
Spatial Mapping of Heat Transfer

1. Fluid Jet Geometry
   - Location and orientation of ATF fluid jets
   - Nozzle type/geometry
   - System flow rate
   - Jet velocity
   - Parasitic power

2. Relative position between measured heat transfer and jet location
   - Impact of gravity and free fluid flow
   - Fluid interactions between jets
Motor Thermal Management

- Cast aluminum cooling jacket pressed around the stator
- Water-ethylene glycol (WEG) circulated through three cooling channels within the cooling jacket

View of the cooling channels showing the WEG flow path
Motor Thermal Management

Use computational fluid dynamics and finite element analysis

- Validate the models using experimental results
Electric Motor Thermal Management

![Graph showing thermal resistance vs. flow rate for end winding side 1, end winding side 2, and stator middle. Solid lines represent experiment data, while symbols represent model data.](image)
Electric Motor Thermal Management

Lpm: liters per minute
Conclusion

Relevance
• Supports transition to more electric-drive vehicles with higher continuous power requirements.

Approach/Strategy
• Engage in collaborations with motor design experts within industry, national laboratories, and universities.
• Perform in-house thermal characterization of materials, interface thermal properties, and cooling techniques.

Summary
• Published results for lamination stack thermal tests.
• Published results for ATF convective heat transfer measurements.
• Built experimental apparatus to measure variation in local convective heat transfer coefficients.
• Developed design and initiated construction of test equipment and sensors to map large-scale convective heat transfer coefficients on motor end-windings with ATF direct cooling.
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