Electric Motor Thermal Management R&D

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Overview

Timeline

- Project Start Date: FY2014
- Project End Date: FY2017
- Percent Complete: 38%

Budget

- Total Project Funding:
  - DOE Share: $1,075K
- Funding for FY2015: $575K

Barriers

- Cost
- Performance (Power Density)
- Life

Partners

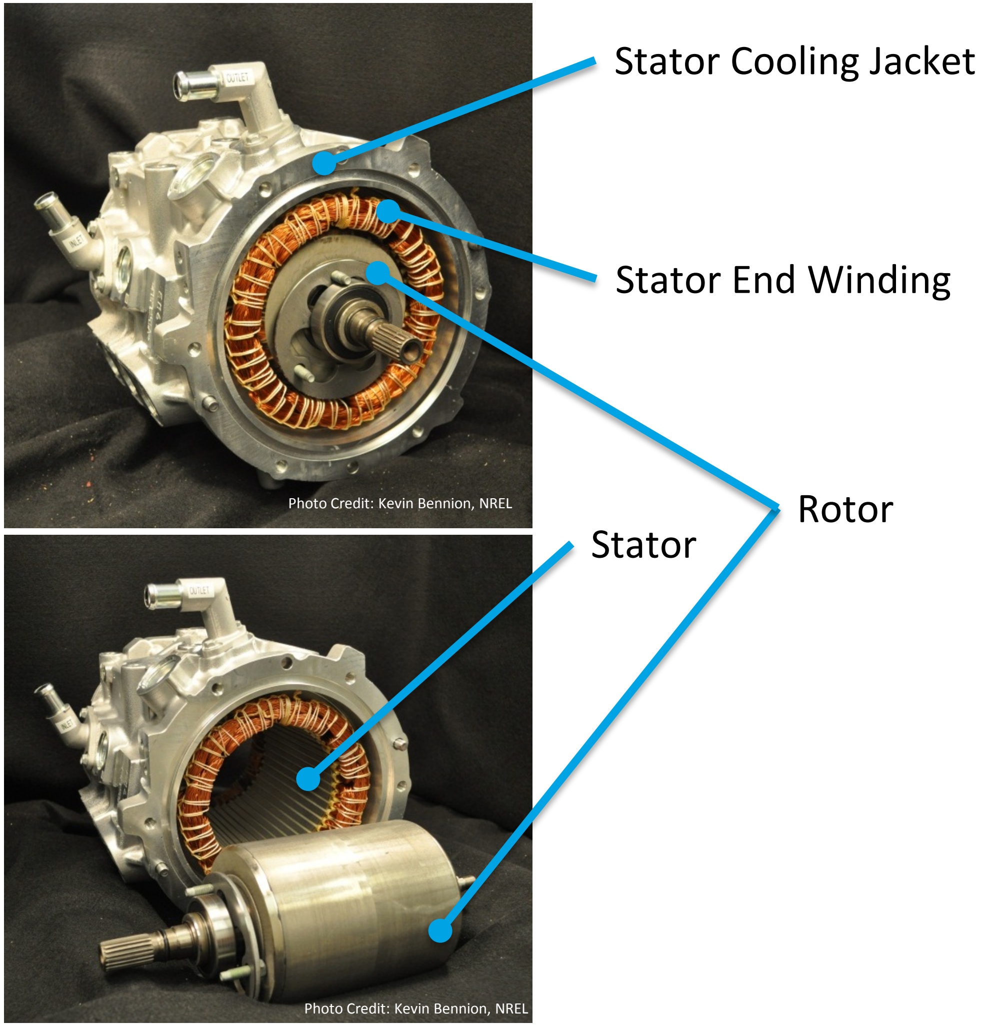
(Interactions/Collaborations)

- Motor Industry – R&D Input and Application of Research Results
  - Suppliers, end users, and researchers
- Oak Ridge National Laboratory (ORNL) – Motor R&D Lead
  - Tim Burress (ORNL)
  - Andy Wereszczak (ORNL)
- National Renewable Energy Laboratory (NREL) – Thermal Project Lead

Relevance – Why Motor Cooling?

Thermal management enables more efficient and cost-effective motors.

- **Current Density**
  - Size
  - Weight
  - Cost
- **Material Cost**
  - Magnets
  - Price variability
  - Rare-earth materials
- **Reliability**
- **Efficiency**



Relevance – Research Objective

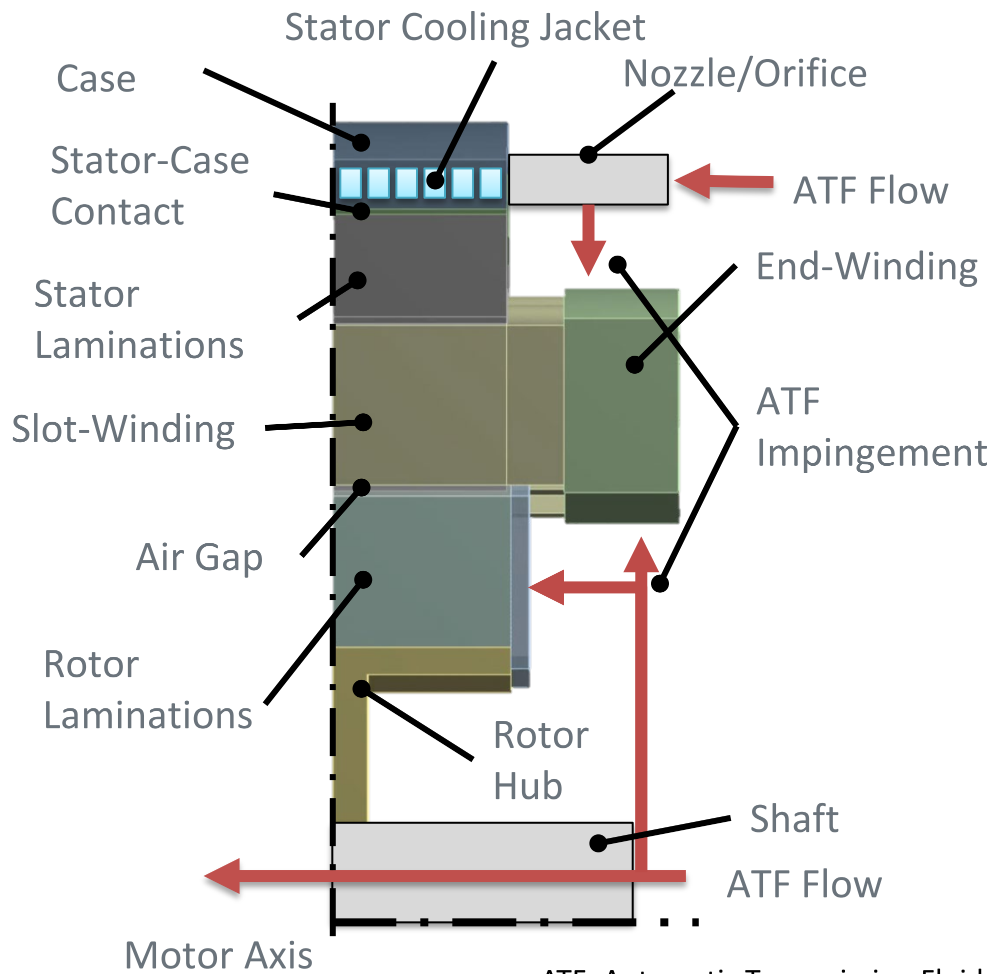
Problem

Core Thermal Capabilities and Research Tasks

Objective

Support broad industry demand for data, analysis methods, and experimental techniques to improve and better understand motor thermal management.

Motor Cooling Section View



ATF: Automatic Transmission Fluid

Milestones

Date	Description
December 2013	Go/No-Go • Measured orthotropic thermal conductivity of ORNL laminations and winding samples. • Continued collaboration with ORNL on thermal property measurements.
January 2014	Milestone • Completed lamination thermal tests.
February 2014	Go/No-Go • Received automatic transmission fluid (ATF) property data from Ford Motor Company.
September 2014	Milestone Report • Submitted project summary report for FY14.
December 2014	Milestone • Design test bench setup for measurement of ATF jet impingement on representative motor end-windings.
March 2015	Milestone • Perform thermal measurements on passive thermal materials in collaboration with ORNL.
June 2015	Go/No-Go • Select potting material for bench-level testing on representative motor components in collaboration with ORNL. • Select focus for future material tests.
September 2015	Milestone • Publish end-winding jet impingement heat transfer data and share with industry.

Approach/Strategy – Problem

Problem

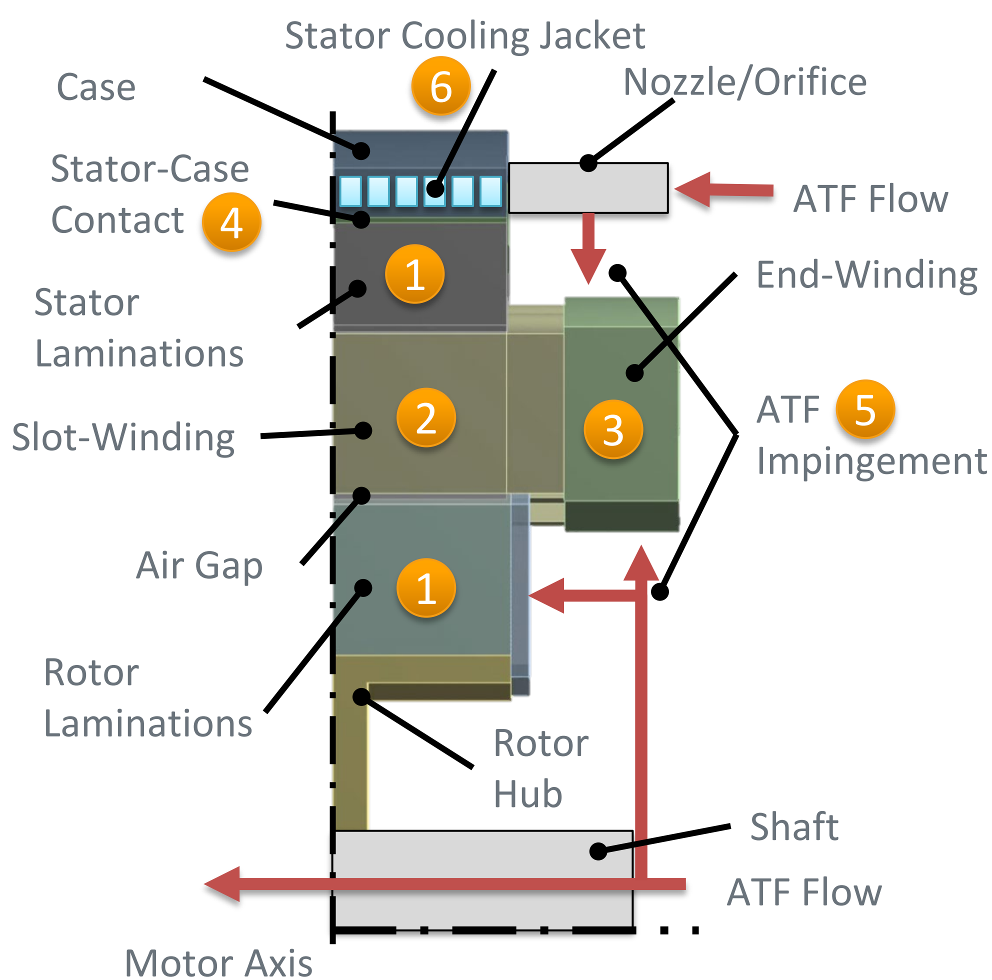
- Multiple factors impacting heat transfer are not well quantified.

Contributing Factors

1. Orthotropic (direction dependent) thermal conductivity of lamination stacks
2. Orthotropic thermal conductivity of slot-windings
3. Orthotropic thermal conductivity of end-windings
4. Thermal contact resistances (stator-case contact, slot-winding interfaces)
5. Convective heat transfer coefficients for ATF cooling
6. Cooling jacket performance

ATF: Automatic Transmission Fluid

Motor Cooling Section View



Approach/Strategy – Focus

Core Capabilities

Apply core thermal experimental and modeling capabilities.

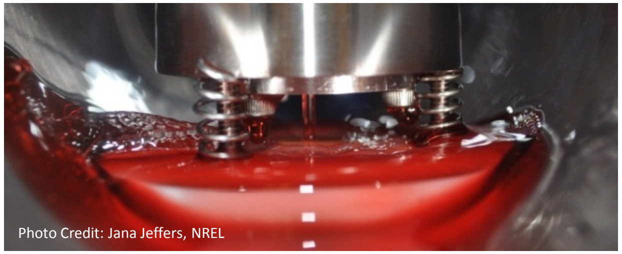
Tasks

- Measure convective heat transfer coefficients for ATF cooling of end-windings.
- Measure interface thermal resistances and orthotropic thermal conductivity of materials.

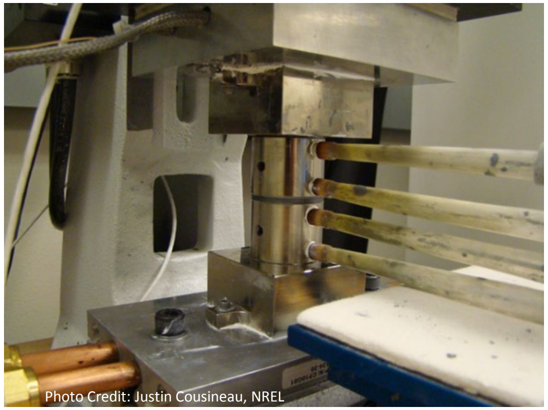
Objective

Support broad industry demand for data to improve and better understand motor thermal management.

Automatic Transmission Fluid Heat Transfer



Material and Thermal Interface Testing



Approach/Strategy – Plan

2014 Oct	Nov	Dec	2015 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

Build redesigned test setup to measure local heat transfer coefficients using ATF impingement.

Measure local ATF jet heat transfer coefficients.

Milestone Annual Report

Design test bench setup for measurement of ATF jet impingement on representative motor end-windings.

Refine and build experimental setup for heat transfer experiments on end-winding surfaces.

Measure end-winding heat transfer coefficients.

Perform thermal measurements on passive thermal materials in collaboration with ORNL.

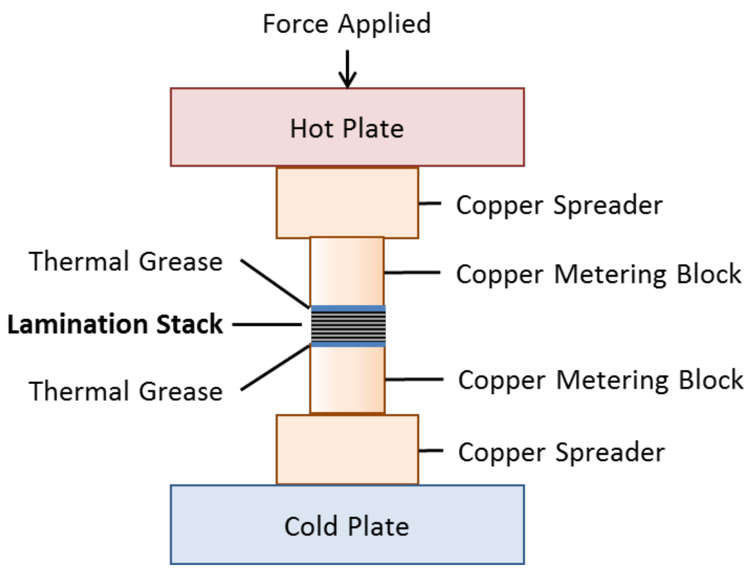
Support ORNL; select potting material for testing.

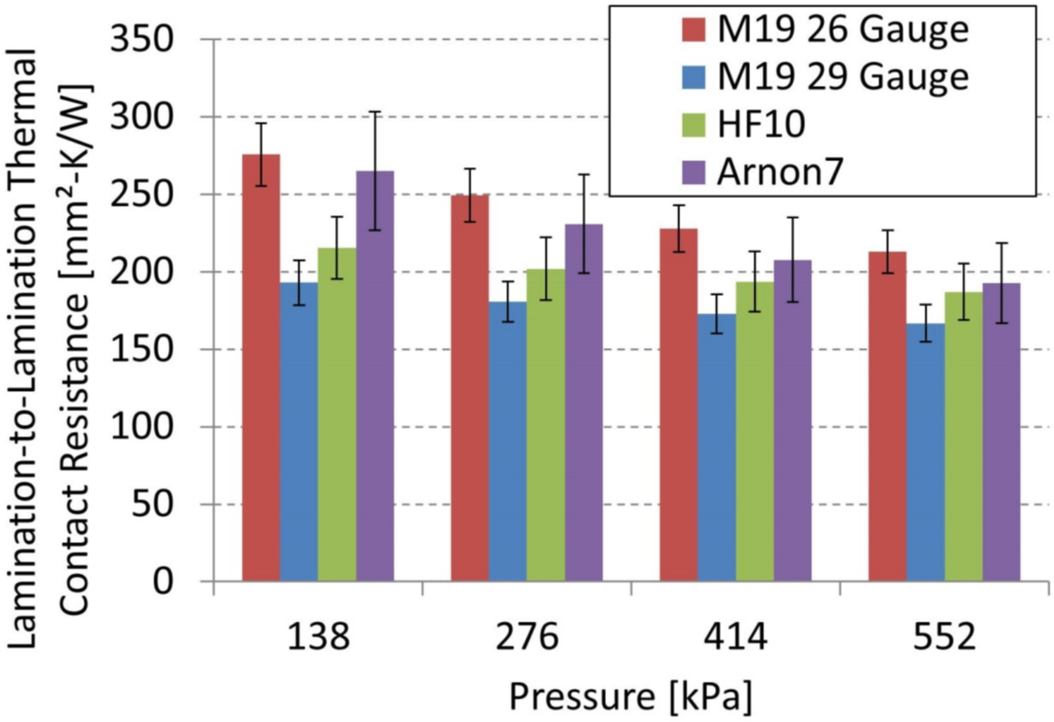
Go/ No-Go

Select focus for material thermal measurements.

Technical Accomplishments

Prepared publication on lamination-to-lamination thermal contact resistance for estimating through-stack thermal conductivity to share with industry.





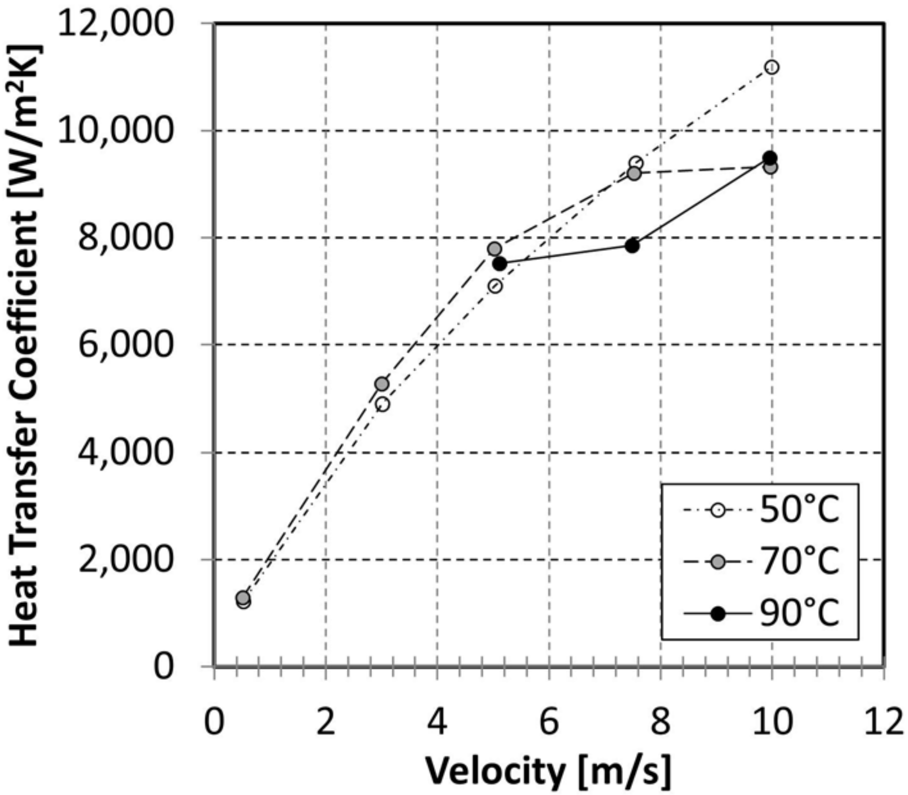
Error bars represent 95% confidence level.

Note: Data measured during FY2014.

Technical Accomplishments

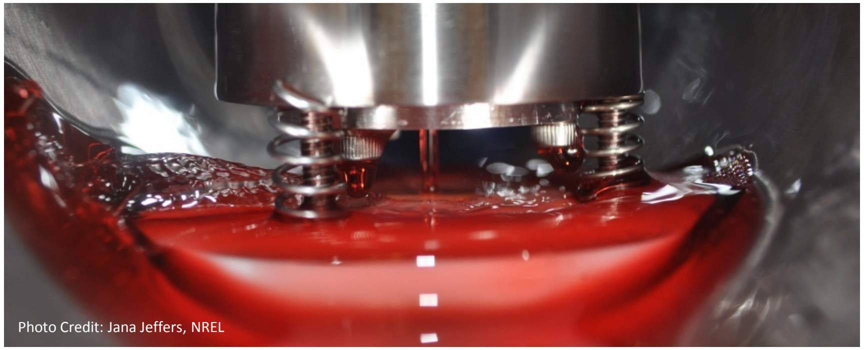
Prepared publication on ATF jet impingement convective heat transfer data to share with industry.

18 AWG sample data for all inlet temperatures

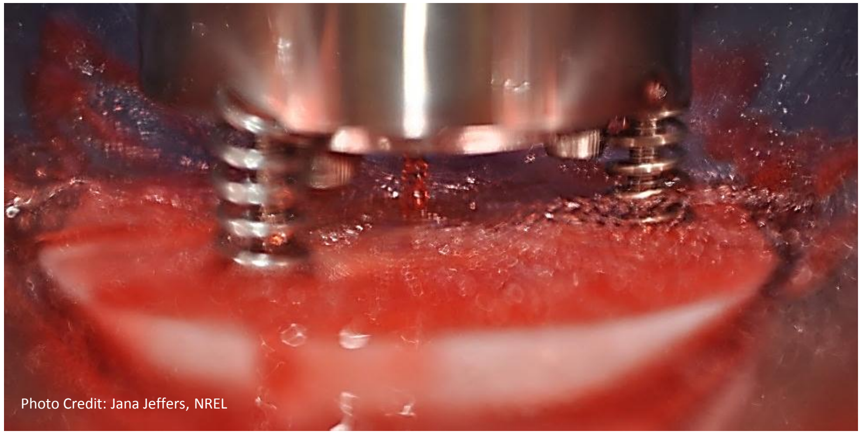


Notes: ATF viscosity decreases as temperature increases.
Data measured during FY2014.

ATF flowing over surface



ATF deflecting off surface

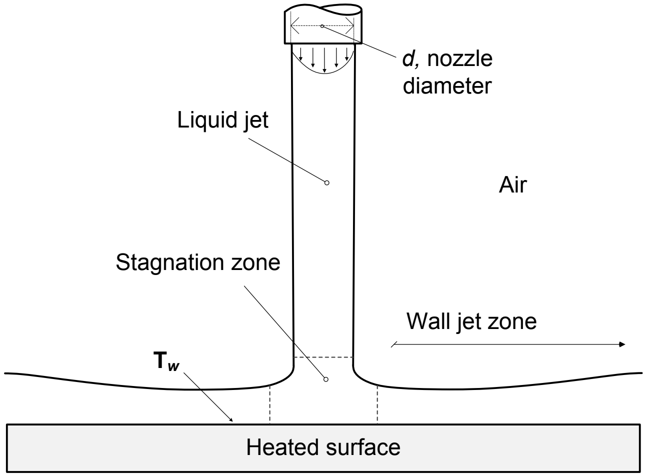


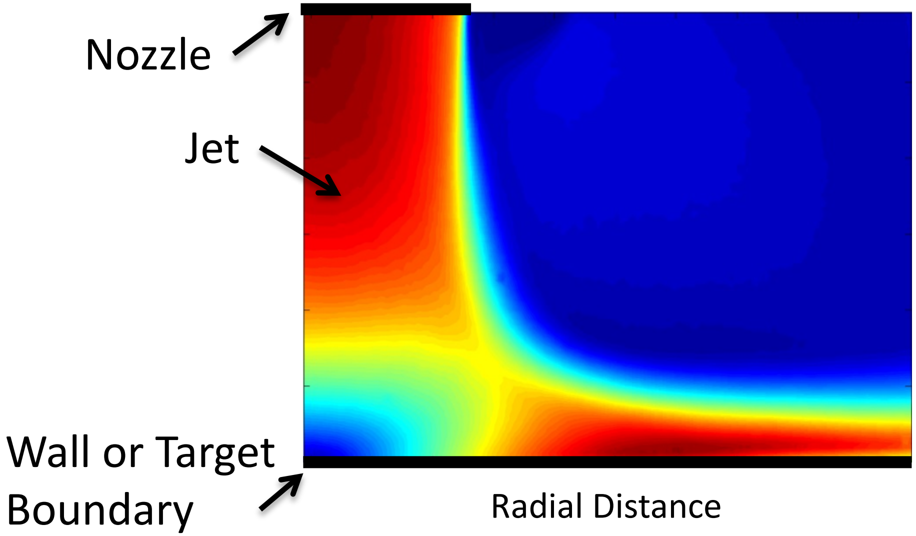
AWG: American Wire Gauge.

Technical Accomplishments

Spatial mapping of local heat transfer with ATF jet impingement:

- Jet impingement heat transfer coefficients are not uniform over the entire cooled surface.
- The highest heat transfer coefficients occur at the jet impact zone.
- The rate of decrease in the heat transfer coefficient is unknown.



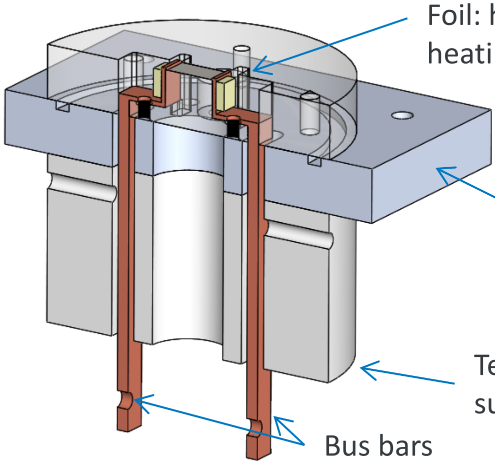


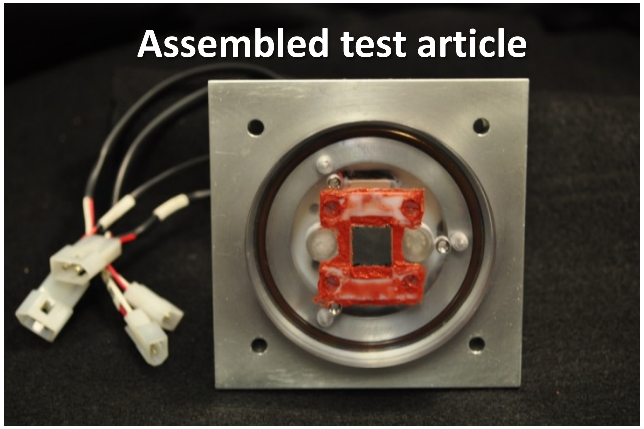
Experimental velocity profile of jet impingement showing variation in velocity at target surface. Measured using particle image velocimetry (PIV) at NREL.

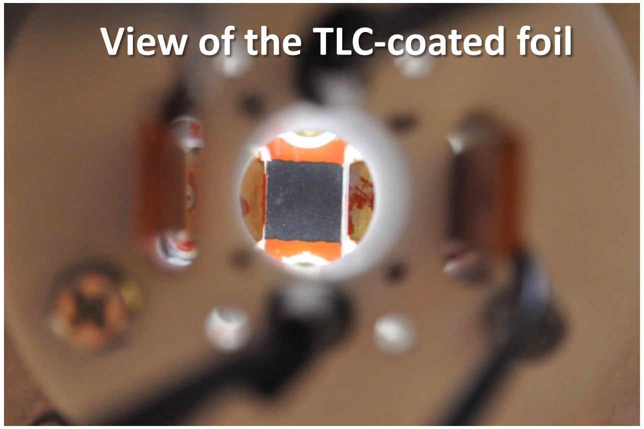
Technical Accomplishments

Redesigned and built test apparatus to spatially map local heat transfer coefficients with ATF jet impingement.

Test article cross-sectional view





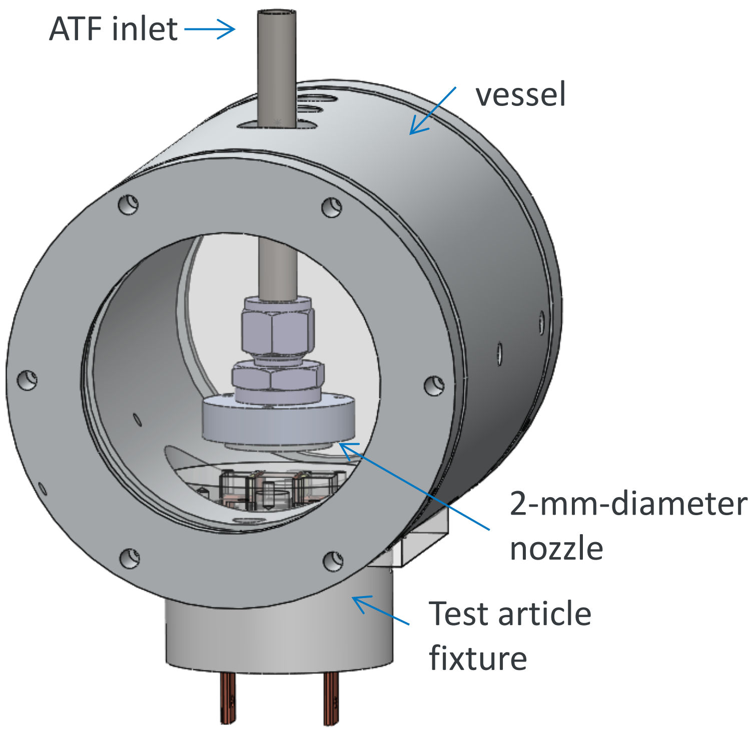


LED: Light-Emitting Diode, TLC: Thermochromic Liquid Crystals.

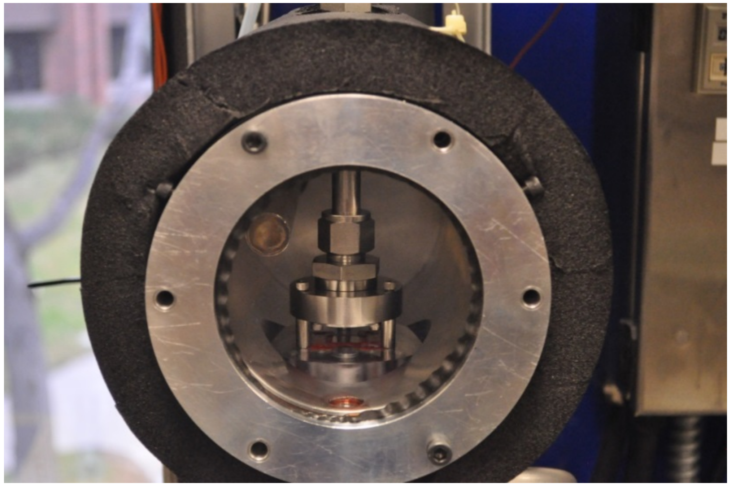
Photo Credits: Gilbert Moreno, NREL

Technical Accomplishments

Integrated assembled test fixture with ATF test bench.



Test article within the vessel



Test article with nozzle assembly

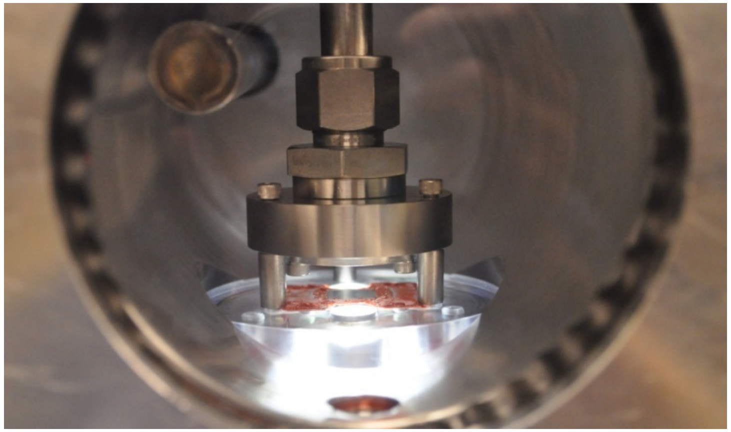


Photo Credits: Gilbert Moreno, NREL

Technical Accomplishments

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

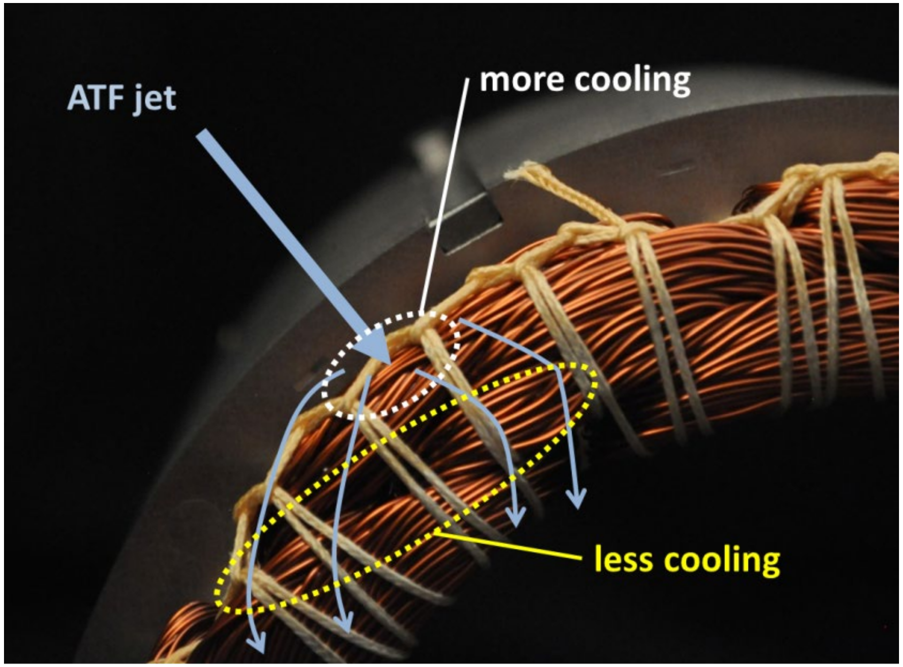


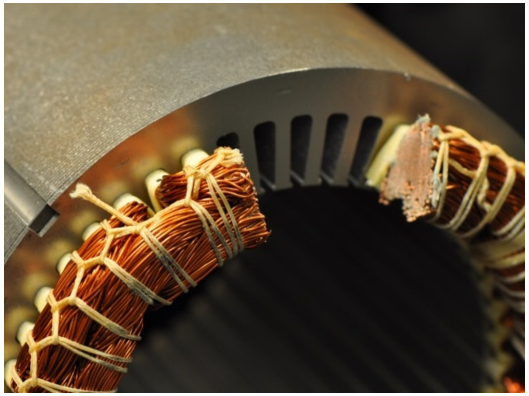
Photo Credit: Kevin Bennion, NREL

- Map the large-scale spatial distribution of the heat transfer coefficients over motor end windings.
- Study effects of:
  - Oil jet placement
  - ATF free flow over end-winding surfaces
  - Jet interactions
- Assumptions:
  - Flat surface with texture of wires

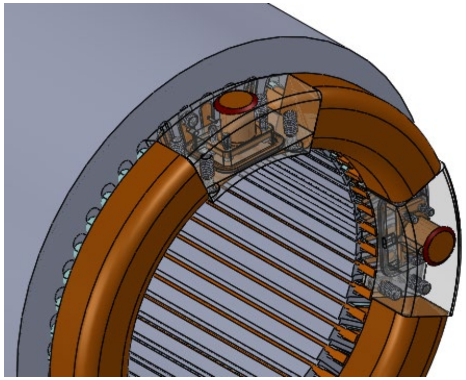
Technical Accomplishments

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



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

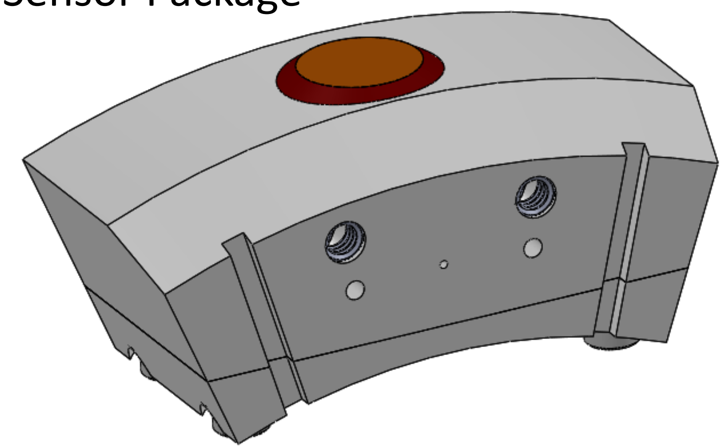
Note: Initial focus is on measurement of heat transfer coefficients from stationary nozzles on the end surface and outer diameter. Future work will incorporate measurements on the inside diameter of the end-windings as we incorporate the rotation of the rotor.

Photo Credits: Kevin Bennion, NREL

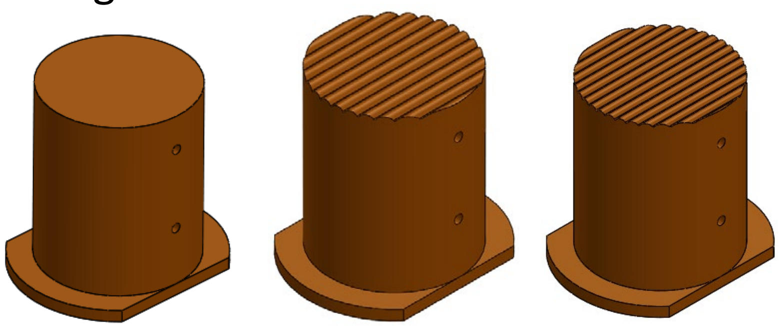
Technical Accomplishments

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

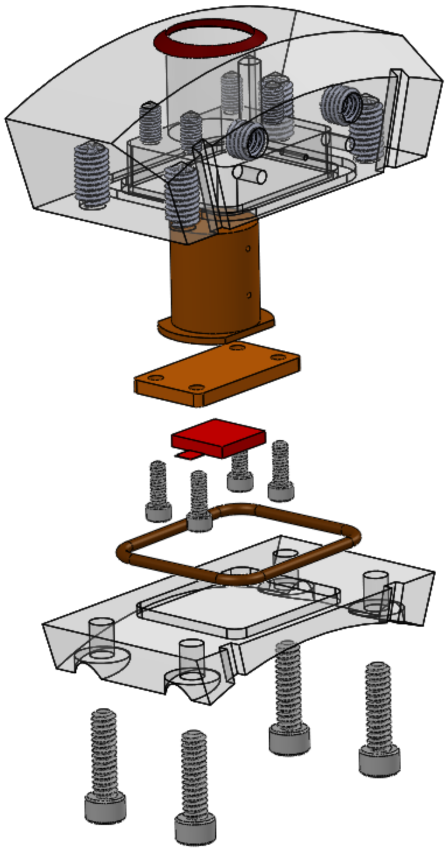
Sensor Package



Targets



Flat | 18 AWG | 20 AWG

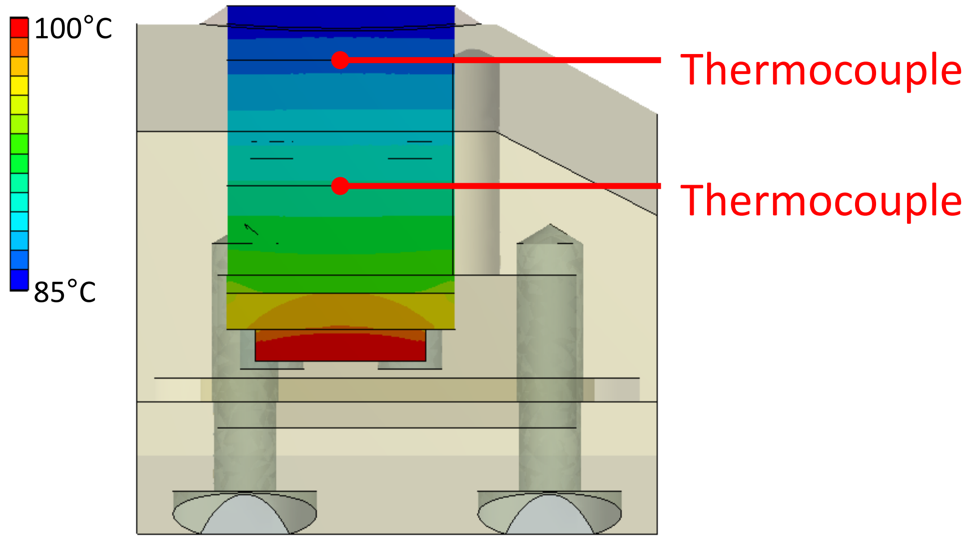


Exploded View

Technical Accomplishments

Created design to minimize experimental error by developing a 3D parametric thermal model of test apparatus.

- Replicated sensor locations for measurement data and equations to calculate heat flux.
- Incorporated systematic measurement uncertainties to improve experimental robustness to measurement uncertainty.



Technical Accomplishments

Performing thermal analysis on passive thermal materials.

Winding sample blocks prepared by ORNL for thermal property measurements (2 x 2 x 2 inch blocks)

- ORNL preparing slot winding samples with variations for:
  - wire size
  - copper fill factor
  - sample thickness
- Collaborating with ORNL on comparison of thermal conductivity measurement techniques in the context of motor slot windings
- Investigating thermal conductivity for motor end-windings
- Measuring slot winding materials

Photo Credit: Andrew Wereszczak, ORNL

Technical Accomplishments

Performing thermal analysis on passive thermal materials.

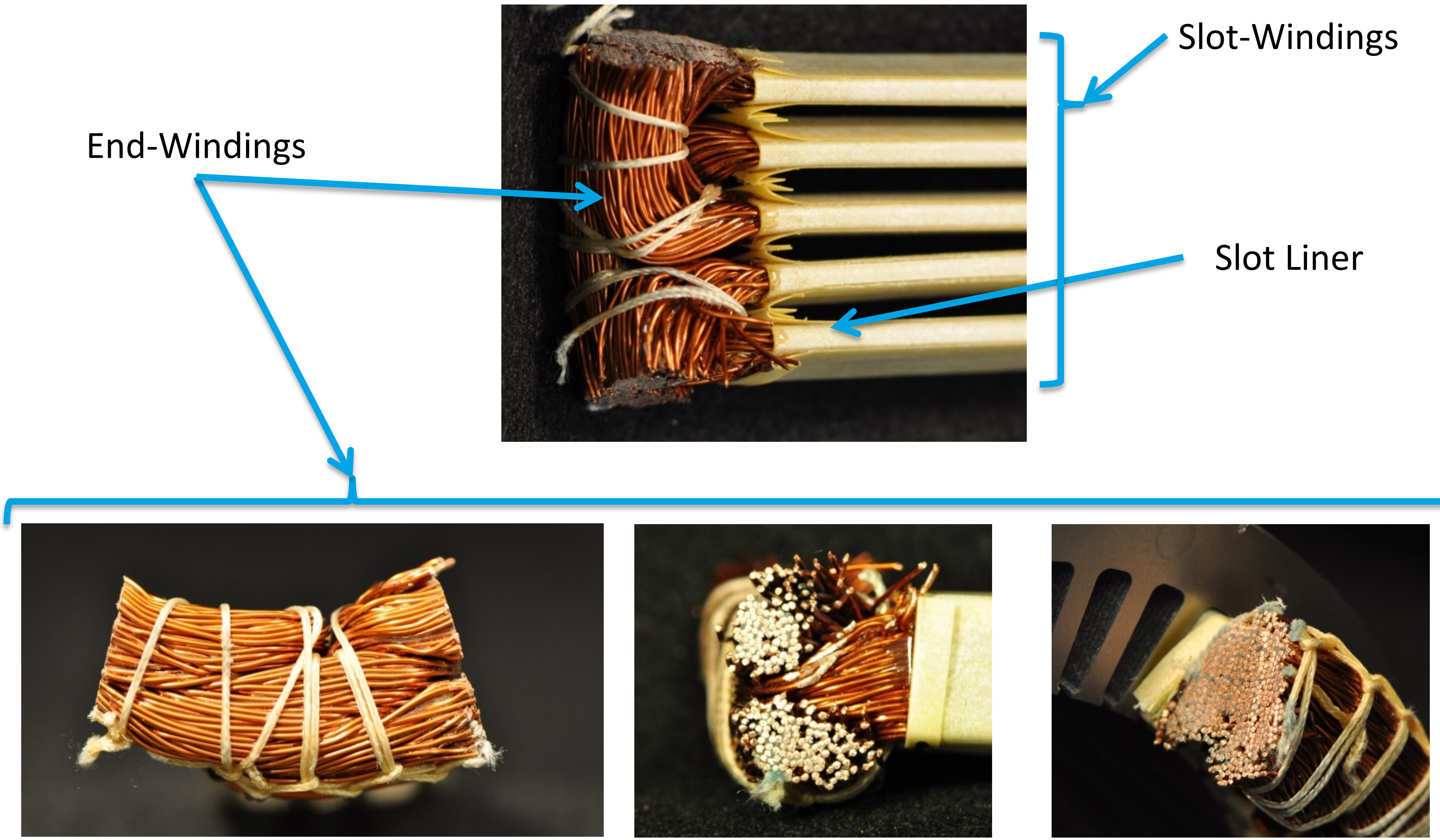


Photo Credits: Kevin Bennion, NREL

Response to Previous Year Reviewers' Comments

- **Previous reviewers mentioned that thermal management was a key technology for improving power/torque density and reliability of electric machines.**
  - *Based on this input and similar comments from other sources we are continuing efforts to better characterize factors impacting thermal management of motors in electric traction drive applications.*

- **It was mentioned of past work that the focus was on the stator system to be applicable to as many machine types as possible, and it was noted that additional attention would be useful in the area of active rotor thermal management and methods to predict rotor temperatures.**
  - *This is useful input and matches comments received at other meetings in which the research was presented. Efforts to incorporate rotor thermal management are being proposed for future work in this area.*

- **Prior reviewer comments appreciated the rigorous test methods for measuring convection and directional properties of materials.**
  - *We have tried to publish the test results and methods to make the information more accessible, and we have tried to include more details of the test methods in this update.*

Collaboration and Coordination with Other Institutions

Industry

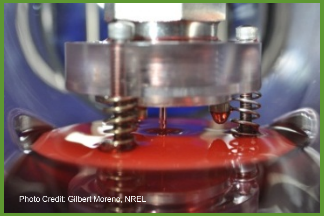
- Motor industry suppliers, end users, and researchers
  - Sharing of experimental data, modeling results, and analysis methods
  - Companies providing research comments, requesting data, or supplying data or motor material information include: Ford, FCA, GM, Tesla, UQM Technologies, GE Global Research, Remy, John Deere, Oshkosh

Other Government Laboratories

- ORNL
  - Support from benchmarking activities
  - Collaboration on motor designs to reduce or eliminate rare-earth materials
  - Collaboration on materials with improved thermal properties
    - Potting materials for end-windings for improved heat transfer
    - Slot-winding materials

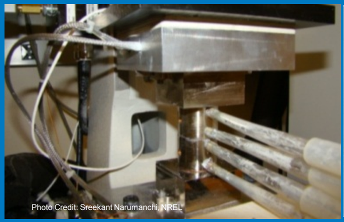
Remaining Challenges and Barriers

Cooling Technology Development



- Heat transfer coefficients of ATF impingement on irregular surfaces of motor end-windings
- Impact of alternative winding configurations that would change the end-winding form factor or geometry leading to different fluid flow and heat transfer (bar windings, concentrated windings)

Passive Thermal Stack and Reliability



- Thermal tests of interfaces between slot insulation and laminations and slot insulation and slot-windings
- Irregular structure of certain end-windings present a challenge to measure thermal conductivity

Proposed Future Work

FY2015

- Continue ongoing collaboration with ORNL material developments and motor research.
- Measure passive stack thermal interfaces and orthotropic thermal properties of materials (windings and potting materials) in collaboration with ORNL.
- Measure local and large-scale variation in ATF impingement heat transfer coefficients.

FY2016

- Incorporate motor rotor cooling and effects on cooling end-windings.
- Measure convective cooling of alternative ATF flow arrangements on round wires.
- Expand convective heat transfer analysis from round wire to include bar wound windings.

Summary

Relevance

- Supports transition to more electric-drive vehicles with higher continuous power requirements.
- Enables improved performance of motors using non-rare earth metals and supports lower cost through reduction of rare earth materials used to meet temperature requirements (dysprosium).

Approach/Strategy

- Engage in collaborations with motor design experts within industry.
- Collaborate with ORNL to provide motor thermal analysis support on related motor research at ORNL.
- Perform in-house thermal characterization of materials, interface thermal properties, and cooling techniques.

Technical Accomplishments

- Published results for lamination stack thermal tests to share with industry.
- Published results for ATF convective heat transfer measurements to share with industry.
- 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.
- Collaborating with ORNL on measurement techniques to quantify thermal properties of passive stack materials within motor stators.

Collaborations

- Motor industry representatives: manufacturers, researchers, and end users (light-duty and medium/heavy-duty applications)
- Oak Ridge National Laboratory.

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Acknowledgments:

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Team Members:

Emily Cousineau (NREL)
Xuhui Feng (NREL)
Charlie King (NREL)
Gilbert Moreno (NREL)
Tim Burress (ORNL)
Andy Wereszczak (ORNL)

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Technical Back-Up Slides

Reviewer-Only Slides

Publications and Presentations

Past Presentations

- K. Bennion, J. E. Cousineau, J. Jeffers, C. King, and G. Moreno, “Convective Cooling and Passive Stack Improvements in Motors,” Advanced Power Electronics and Electric Motors FY14 Kickoff Meeting, DOE Vehicle Technologies Program, Oak Ridge, TN, November 2013.
- K. Bennion, J. E. Cousineau, J. Jeffers, C. King, and G. Moreno, “Convective Cooling and Passive Stack Improvements in Motors,” Advanced Power Electronics and Electric Motors FY14 Annual Merit Review Meeting, DOE Vehicle Technologies Program, Washington DC, June 2014.
- K. Bennion, J. E. Cousineau, C. King, G. Moreno, and C. Stack, “Electric Motor Thermal Management R&D,” Advanced Power Electronics and Electric Motors FY15 Kickoff Meeting, DOE Vehicle Technologies Program, Oak Ridge, TN, November 2014.

Future Planned Publications

- J. E. Cousineau, K. Bennion, and D. DeVoto, “Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines,” NREL Technical Report, 2015.
- K. Bennion and G. Moreno, “Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets with Implications for Electric Machine Thermal Management,” full paper and presentation at ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems, San Francisco, CA, 2015.
- J. E. Cousineau, K. Bennion, D. DeVoto, and S. Narumanchi, “Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines,” presentation at ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems, San Francisco, CA, 2015.

Critical Assumptions and Issues

- The wide variation in motor types and designs presents a challenge. The analysis and thermal management technologies should be applicable to as many motor configurations as possible.
  - For this reason we are collaborating with research partners with expertise in electric motor design.
  - Our work is applicable to various motor configurations.
- The variation in thermal loads in terms of location and magnitude for different operating conditions presents a challenge.
  - The variation in heat magnitude and location based on the operating conditions of the motor will require the ability to evaluate the impact of thermal management technologies under multiple operating conditions.
- Proprietary thermal performance data and technologies will require methods for interacting with original equipment manufacturers and suppliers with interests specific to product applications.
  - We will work to overcome this challenge to support broad industry demand for data, analysis methods, and experimental techniques to improve and better understand motor thermal management that can be applied within industry to support product specific needs.