Electric Motor Thermal Management

Kevin Bennion
National Renewable Energy Laboratory
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DOE Vehicle Technologies Program
2021 Annual Merit Review and Peer Evaluation Meeting

Project ID: ELT214

Overview

Timeline

- Project start date: October 2018
- Project end date: September 2023
- Percent complete: 50%

Budget

- Total project funding: $750,000
  - DOE share: $750,000
- Funding for FY 2020: $250,000
- Funding for FY 2021: $250,000

Barriers

- Cost
- Power density
- Lifetime

Partners

- National Renewable Energy Laboratory (NREL)
  - Lead for thermal and reliability research
- Oak Ridge National Laboratory (ORNL)
  - Motor development, modeling, and material research
- Ames Laboratory
  - Motor material research
- Sandia National Laboratories (SNL)
  - Motor and materials research
- Georgia Institute of Technology (Georgia Tech)
  - Motor thermal management technologies
- University of Wisconsin Madison
  - Motor thermal management technologies.

Relevance

- This project is part of the Electric Drive Technologies (EDT) Consortium and focuses on NREL's role under Keystone 2

Keystone 1

- Power Electronics

Keystone 2

- Electric Motors

Keystone 3

- Traction Drive System

- Research enabling compact, reliable, and efficient electric machines
  - Motor 10x power density increase (2025 versus 2015 targets) [1]
  - Motor 2x increase in lifetime [1]
  - Motor 53% cost reduction (2025 versus 2015 targets) [1]

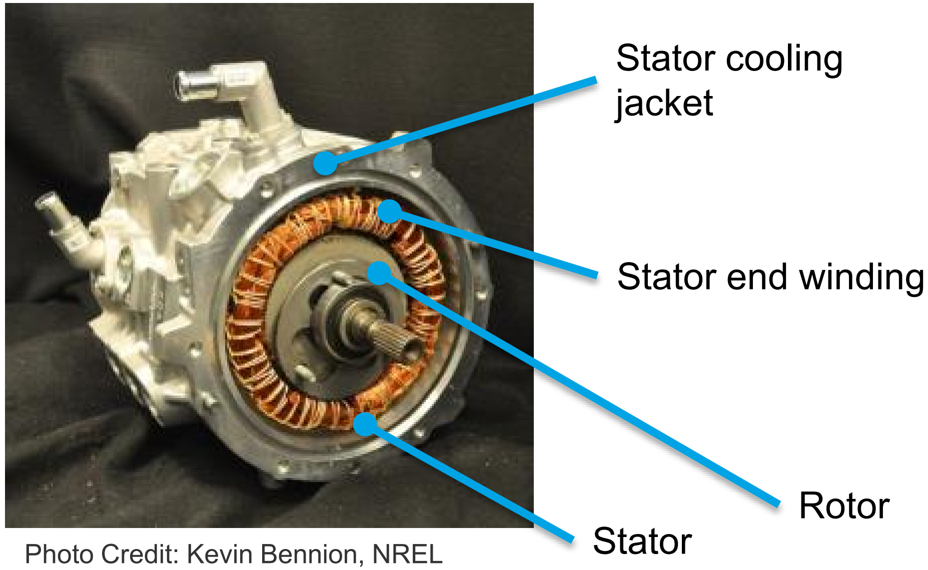
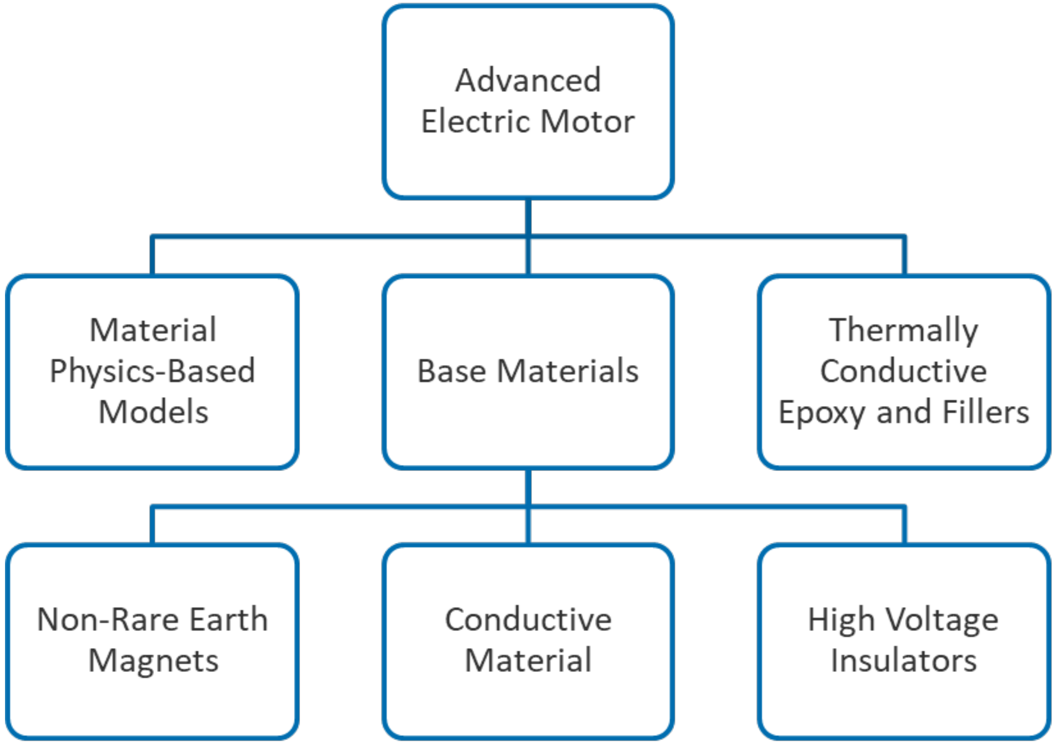


Photo Credit: Kevin Bennion, NREL

[1] U.S. DRIVE. 2017. *Electrical and Electronics Technical Team Roadmap*. https://www.energy.gov/sites/default/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf.

Relevance



Electric Drive Motor R&D Areas

- Material conductivity thermally drives the amount of material necessary to create the required magnetic field to create mechanical power
- Material performance characterization techniques are not well known or identified in the literature
- It is important to reduce the thermal resistance of the motor packaging stack-up to help increase the power density.

U.S. DRIVE. 2017. *Electrical and Electronics Technical Team Roadmap*. https://www.energy.gov/sites/default/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf.

Milestones

Date	Description
December 2020 (Complete)	Prepare experimental setup for motor subcomponent (motorette) thermal measurements
March 2021 (Complete)	Complete measurements of SNL-provided motor material samples
June 2021 (Complete)	Prepare and thermally characterize motorette structures for thermal performance characterization in support of motor thermal management efforts with consortium collaborators
September 2021 (In Progress)	Prepare report on research results.

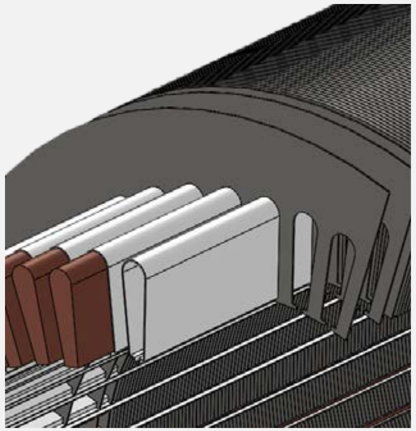
Approach

Electric Drive Technologies Consortium Team Members

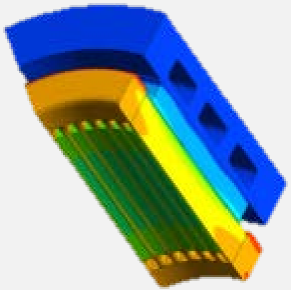
NREL-Led Thermal Management Research

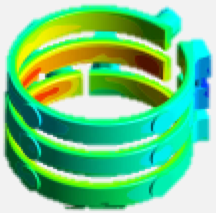
Material and Interface Thermal and Mechanical Characterization

a



Motor System Thermal Analysis Support





b

Photo Credits:
a: Doug DeVoto, NREL
b: Kevin Bennion, NREL

Approach

Material and Interface Thermal and Mechanical Characterization

Setup for material and interface characterization up to 200°C

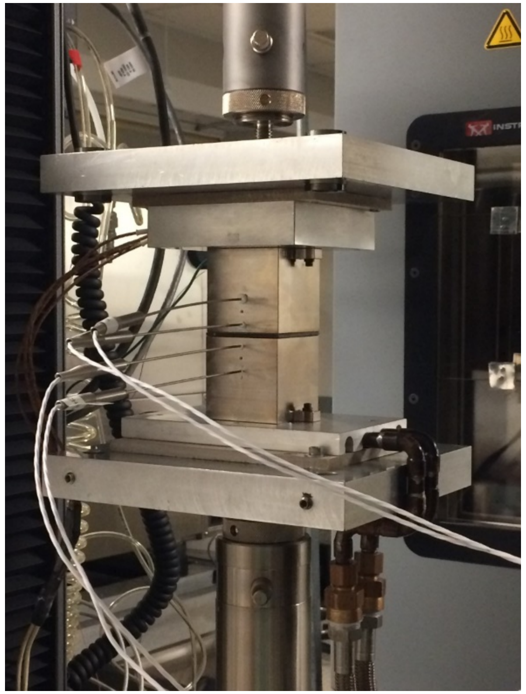
Photo Credit: Emily Cousineau, NREL

- Collaboration with Sandia National Laboratories (ELT216)
  - Support mechanical and thermal measurements of new motor materials
- Collaboration with Ames Laboratory (ELT215, ELT234)
  - Support thermal analysis of electric machines enabled by material innovations
- NREL Motor Material and Interface Characterization
  - Bulk property measurements of slot-liner materials (50°C–200°C)
  - Thermal contact resistance measurements between unbonded interfaces (50°C–200°C)

Technical Accomplishments and Progress

Collaboration with Sandia National Laboratories (ELT216)

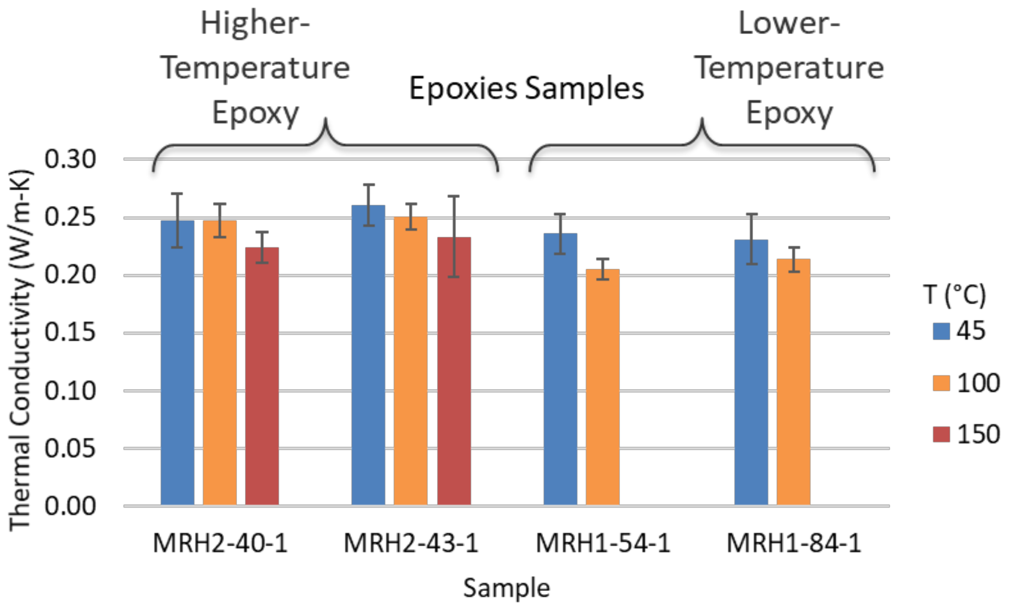
- Support mechanical and thermal measurements of new motor materials

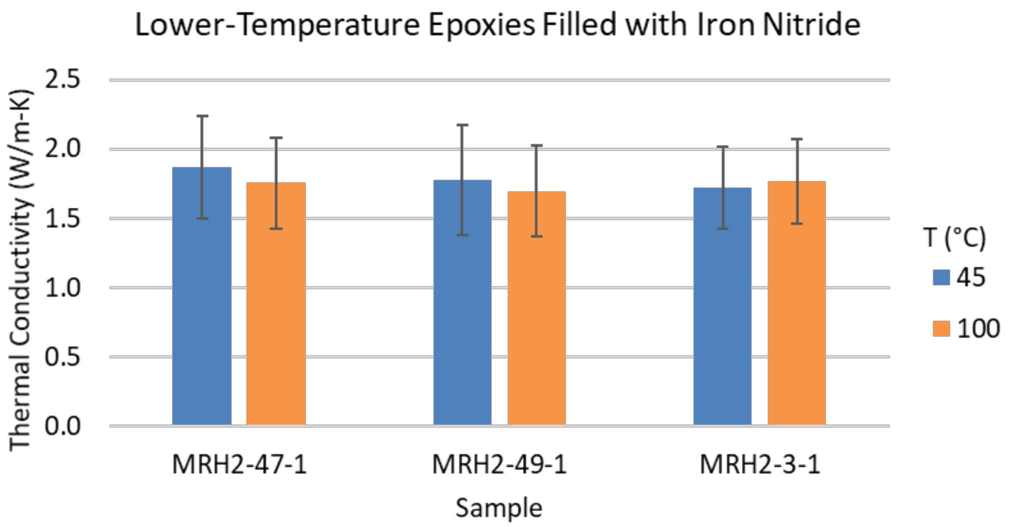


Sample from SNL undergoing testing.

Photo Credit: Emily Cousineau, NREL

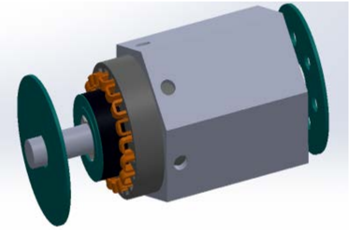
Iron nitride-filled samples show ~7.5x higher thermal conductivity at ~45°C relative to unfilled base epoxy samples.



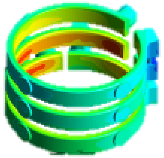


Approach

Motor System Thermal Analysis Support



- Collaboration with University of Wisconsin (ELT243)
  - NREL providing technical support, thermal data, and material information to support integrated cooling of motor and power electronics.



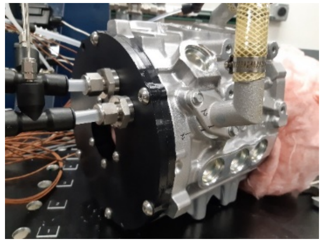
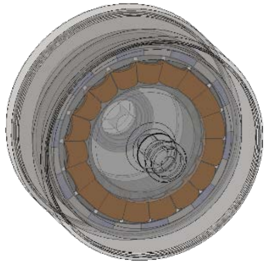
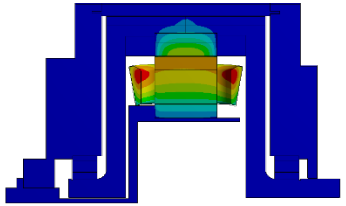


Photo Credit: Sebastien Sequeira, Georgia Tech and NREL

- Collaboration with Georgia Tech to support research efforts at Georgia Tech for advanced convective heat-transfer technologies for electric machines (ELT251)
  - NREL providing technical support, geometry data, thermal modeling data, and experimental data to support evaluations of advanced cooling impacts
  - NREL and Georgia Tech completed experiments of motor subcomponent (motorette) thermal characterization





- Collaboration with ORNL to support motor thermal analysis and thermal design of advanced machine design led by ORNL (ELT212)
  - Providing thermal design support to support iterative electric machine design process led by ORNL
- Collaboration with Keystone 3 project areas at ORNL (ELT221) and NREL (ELT217).

Technical Accomplishments and Progress

Georgia Institute of Technology
Motor Research
(ELT251)

Collaboration with Georgia Tech

1. NREL providing technical support, geometry data, thermal modeling data, and experimental data to support evaluations of advanced cooling impacts
2. Experiments of motor subcomponent (motorette) thermal characterization performed with Georgia Tech at NREL.

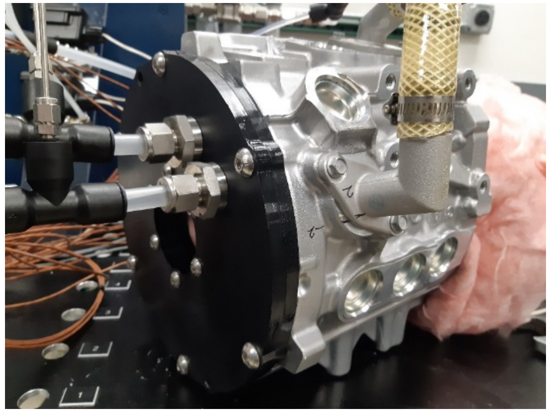
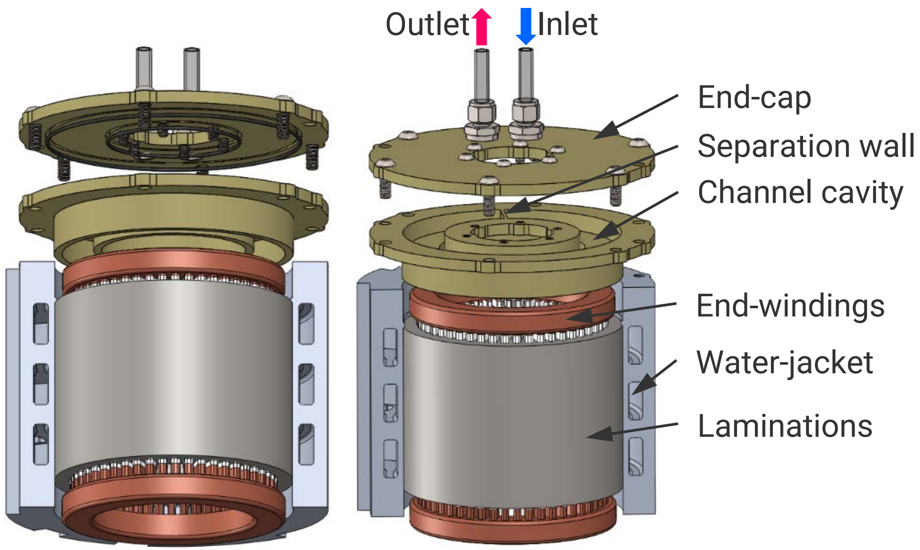


Photo Credit: Sebastien Sequeira, Georgia Tech and NREL

Technical Accomplishments and Progress



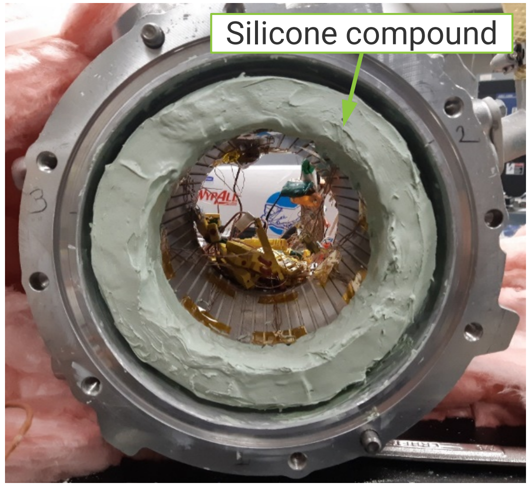
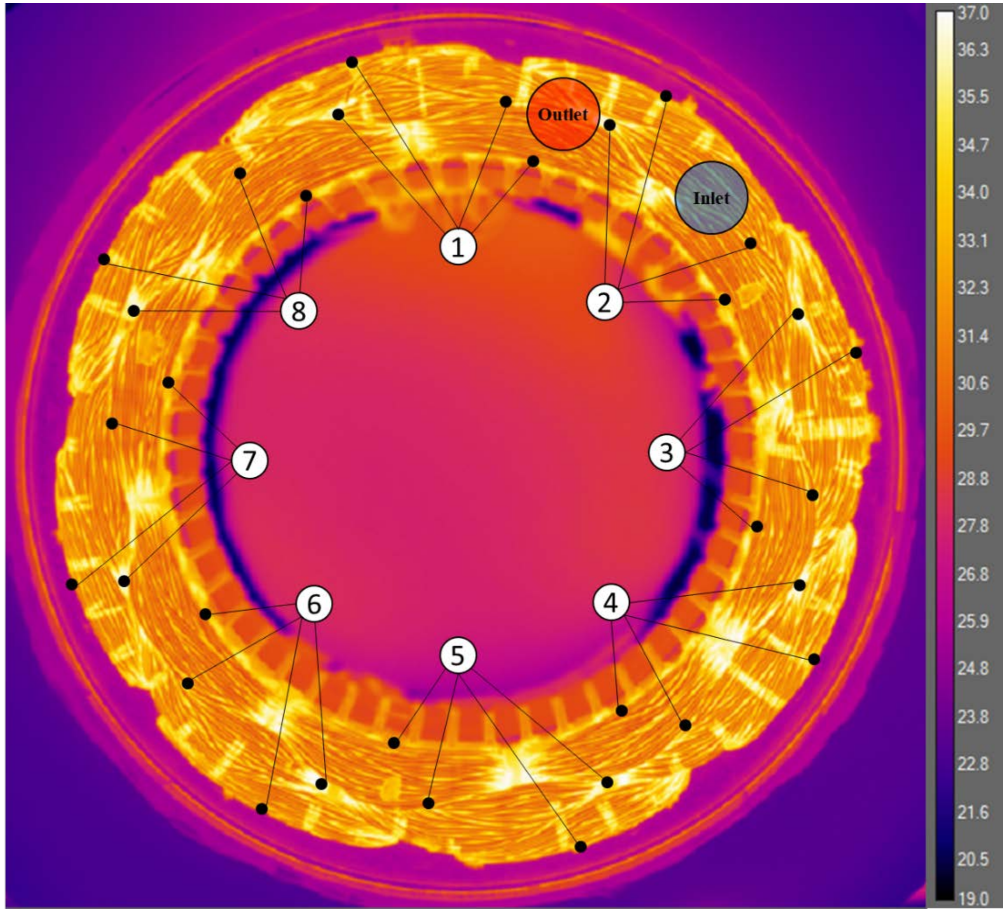


Photo Credit: Sebastien Sequeira, Georgia Tech and NREL

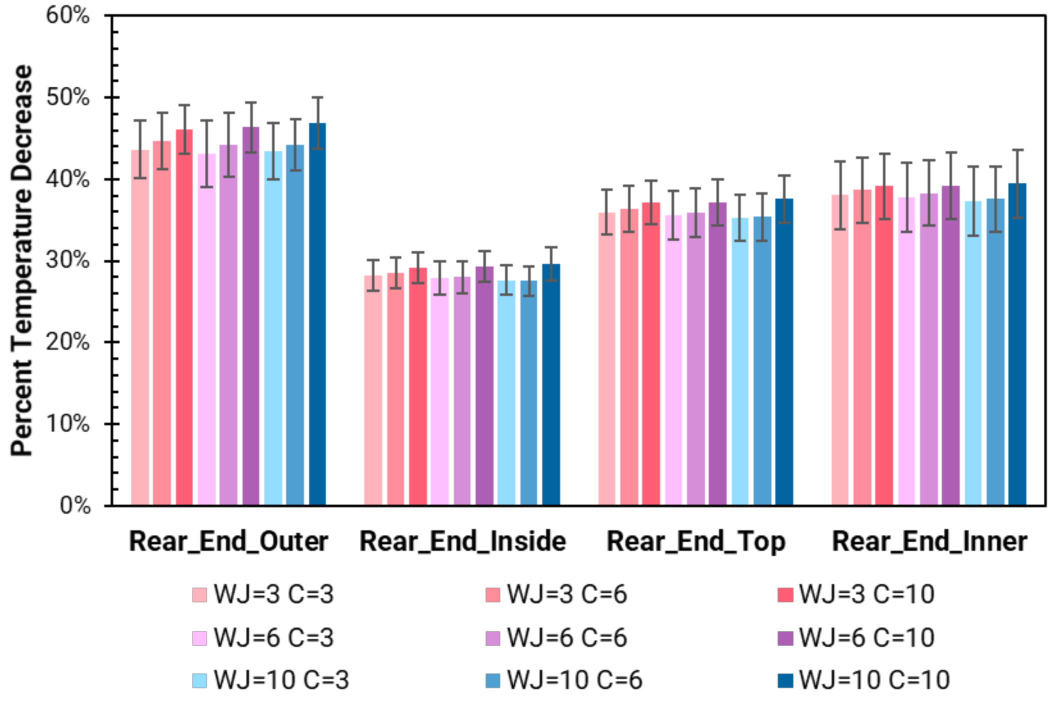
Collaboration with Georgia Tech

- Reference motor
  - Nissan Leaf motor
- Design
  - U-shape end-winding channel in two parts fixed to the housing
- Manufacturing
  - 3D-printing process at NREL
- Material
  - ULTEM 9085
  - Maximum operating temperature: 153°C
  - Thermal conductivity at 100°C: 0.25 W/m·K
- Silicone compound to improve thermal contact between channel and end winding
  - Thermal conductivity: 3.5 W/m·K

Technical Accomplishments and Progress



Thermocouple locations on end winding



Percent decrease in temperature relative to baseline stator cooling jacket at each flow rate (L/min) in the stator water jacket ("WJ") and the end-winding cooler ("C").

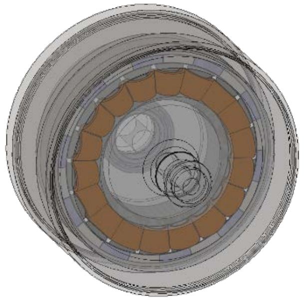
Photo Credit: Sebastien Sequeira, Georgia Tech and NREL

Technical Accomplishments and Progress

ORNL

Non-Heavy-Rare-Earth High-Speed Motors

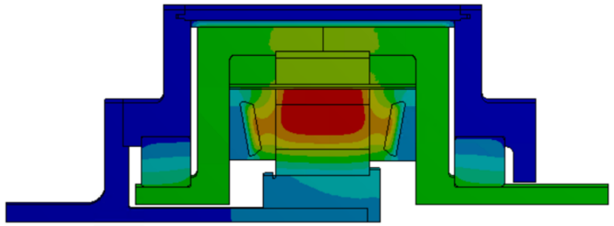
ELT212



Materials, Geometry, Heat Loads, and Temperature Limits

Motor Thermal Analysis and Design (NREL)

1. Quantify impacts and trade-offs of alternative material selections
   - Potting materials
   - Lamination materials
2. Quantify active cooling performance requirements to mitigate critical hot spots and operating conditions
   - Cooling location
   - Heat transfer coefficient
3. Quantify impacts and trade-offs of alternative motor geometry
   - Winding and stator geometry.



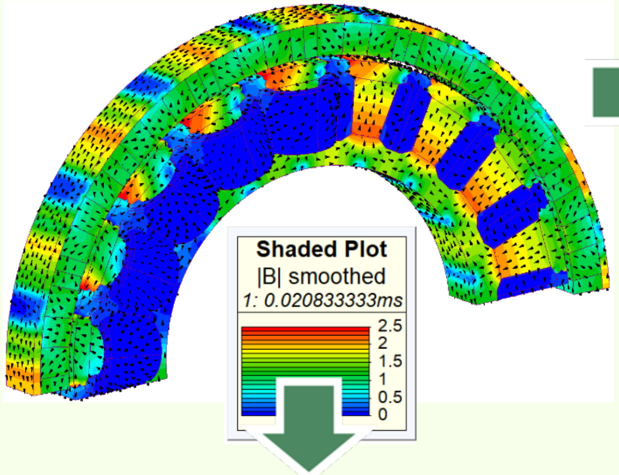
Thermal analysis trade-off studies

Technical Accomplishments and Progress

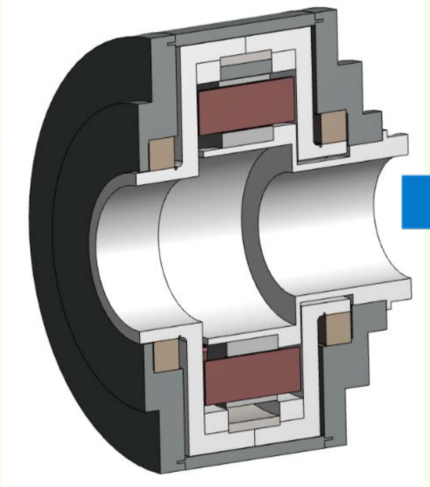
Electromagnetic, Mechanical, and Thermal Design

ELT212 ORNL

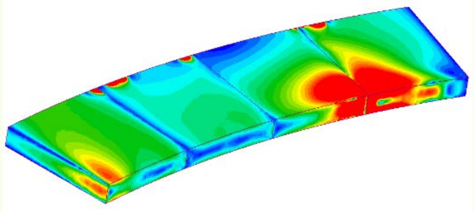
Electromagnetic design



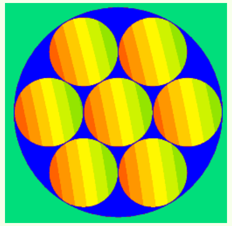
Mechanical assembly design



Loss evaluation



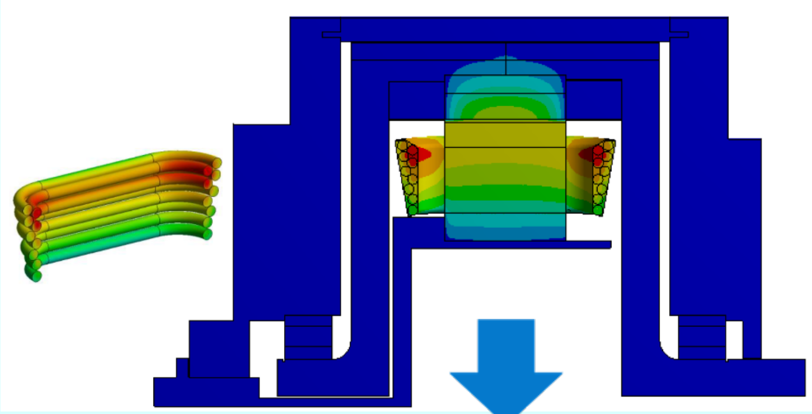
Permanent magnet eddy current loss



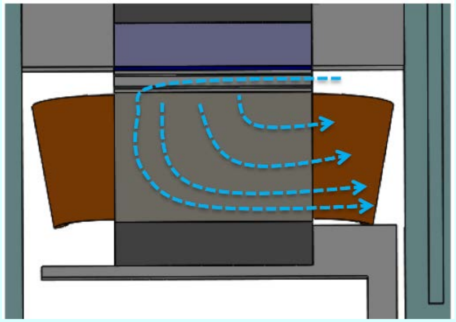
AC loss in Litz wire winding

ELT214 NREL

Thermal modeling



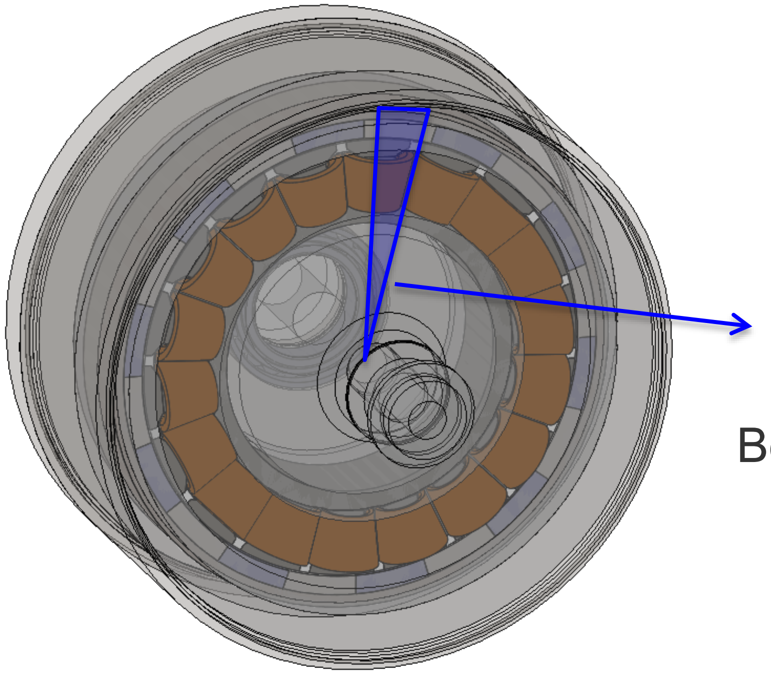
Cooling design

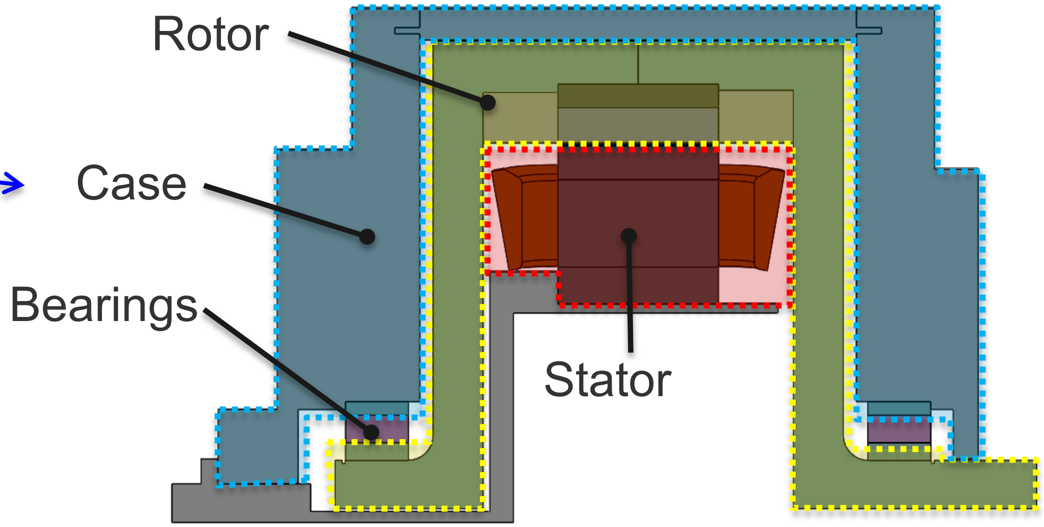


Slot heat exchanger

Technical Accomplishments and Progress

Outer Rotor Motor Description

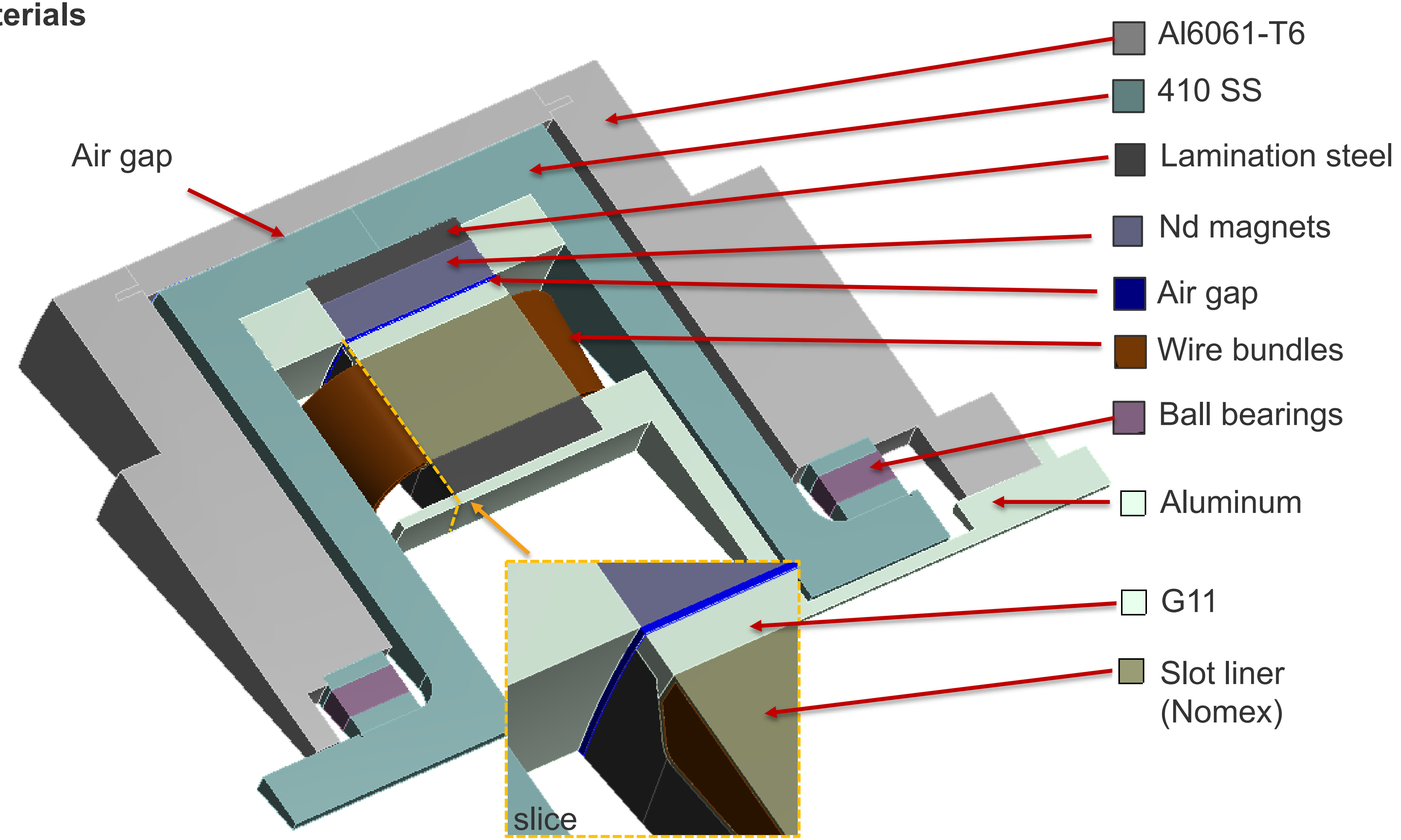




- Design led by ORNL
- Maximum rated speed 20,000 rpm
  - 55-kW continuous power
  - 100-kW peak power
- NREL supporting thermal analysis and design research.

Technical Accomplishments and Progress

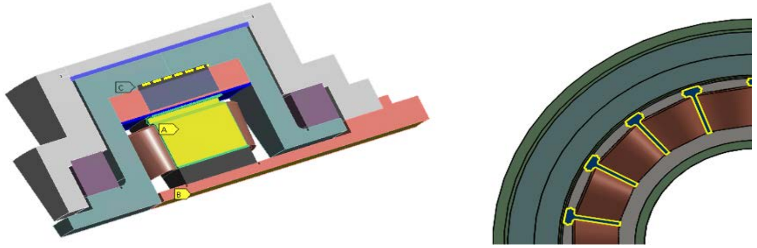
Model Materials



Technical Accomplishments and Progress

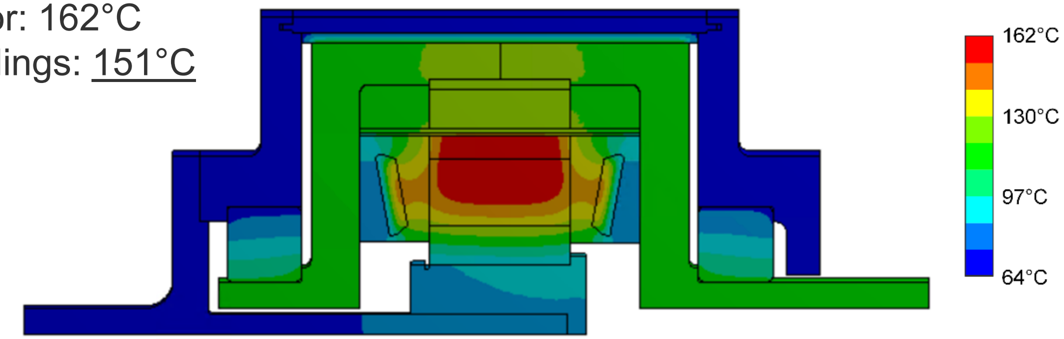
Cooling Approach

- Multiple approaches for machine cooling
  - Interior cooling of the stator
  - In-slot cooling for winding and stator teeth
  - High-performance potting compound
  - Extended slot heat exchanger

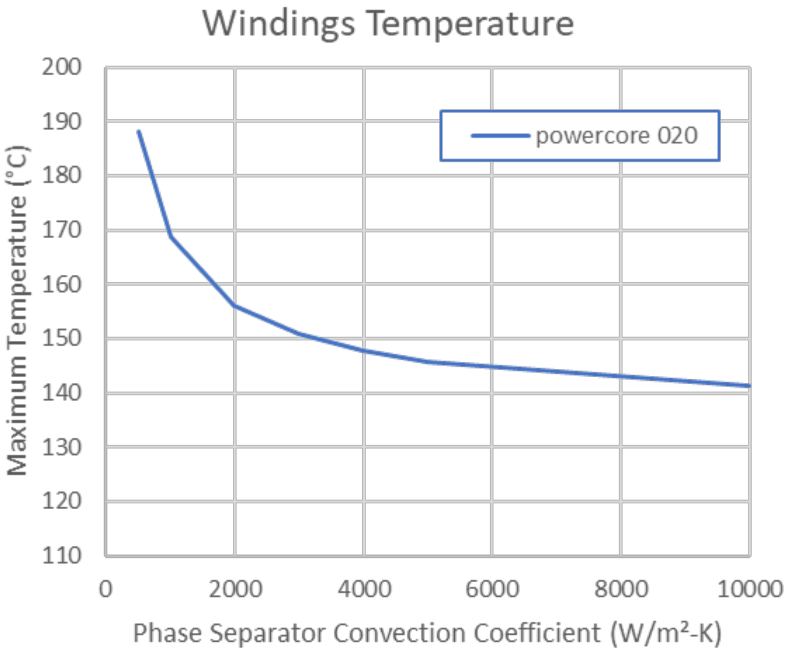


ORNL motor cooling approaches.

Maximum Temperatures
- Magnets: 122°C
- Stator: 162°C
- Windings: 151°C



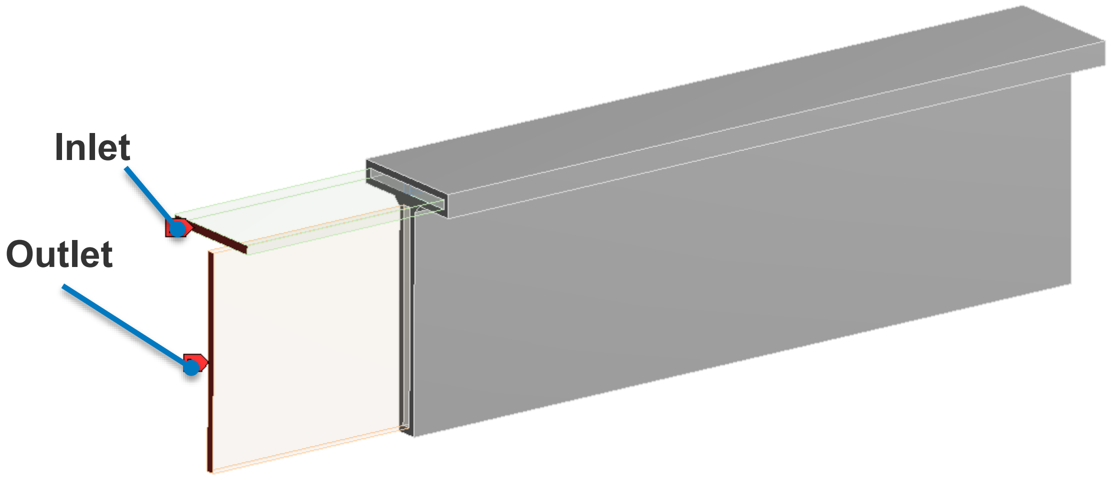
ORNL motor temperatures with Powercore020 laminations and expanded slot heat exchanger.



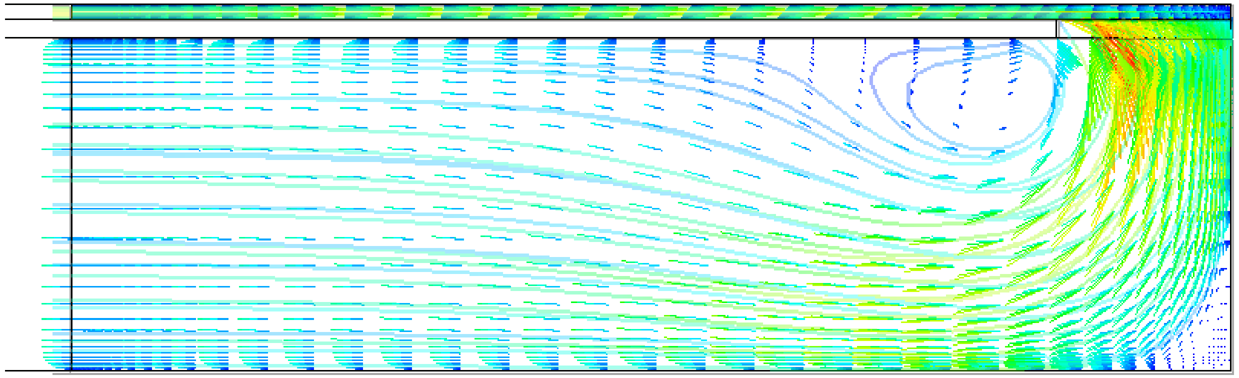
ORNL motor winding temperature versus heat transfer coefficient.

Technical Accomplishments and Progress

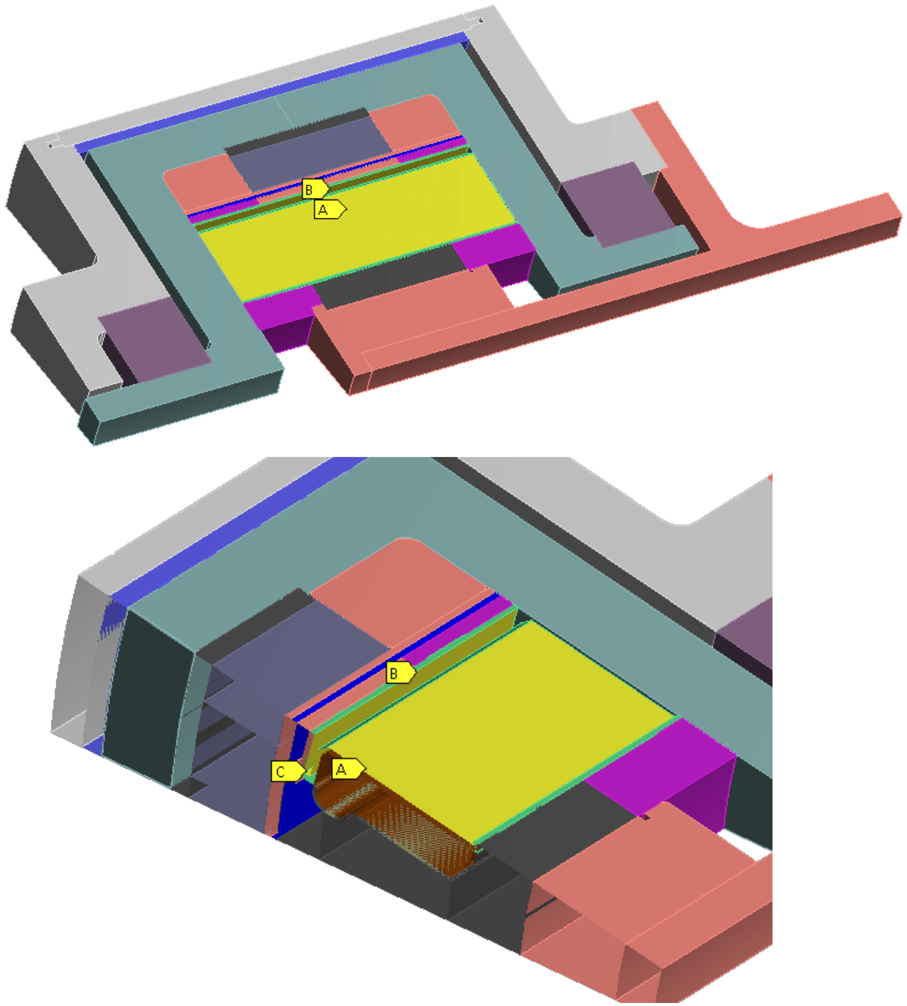
Slot Cooling Analysis



In-slot heat exchanger with inlet/outlet region (for development of flow profile)



Preliminary computational fluid dynamics (CFD) simulation showing areas for improved fluid flow.



Heat exchanger boundary conditions separated into three sections (A, B, and C) based on heat loads into each area.

Responses to Previous Year Reviewers' Comments

- One prior reviewer comment mentioned it is not clear that there are significant new technologies or approaches proposed
  - *We included more information specific to work with project collaborators in the presentation materials for this year.*

- One prior reviewer mentioned the novelty of the work done—especially in comparison to the state of the art—needs to be emphasized and clarified
  - *We included some results of experimental data compared against a baseline water jacket cooled system for one of the technologies with Georgia Tech.*

- One reviewer previously pointed out that the aims of the project are timely, needed, and well defined. The project has a strong collaboration with external partners.

Collaboration and Coordination

- Other Government Laboratories
  - ORNL
    - NREL collaborating on electric motor design efforts led by ORNL
    - NREL supporting thermal modeling and simulation analysis for motor and material performance trade-off studies
  - SNL
    - NREL supporting material thermal and mechanical property measurements for material research efforts led by SNL
  - Ames Laboratory
    - NREL continuing discussions with Ames to support material characterization efforts led by Ames Laboratory and potential impacts related to motor thermal management
- Universities
  - Georgia Institute of Technology
    - NREL collaborating with Georgia Tech to support research efforts for advanced convective heat transfer technologies for electric machines
    - NREL providing technical support, geometry data, thermal modeling data, and experimental data to support evaluations of advanced cooling impacts
    - NREL and Georgia Tech completed experiments of motor subcomponent (motorette) thermal characterization
  - University of Wisconsin Madison
    - NREL providing technical support, thermal data, and material information to support integrated cooling of motor and power electronics.

Remaining Challenges and Barriers

Electric Drive Technologies Consortium Team Members

NREL-Led Thermal Management Research

Material and Interface Thermal and Mechanical Characterization	Motor System Thermal Analysis Support
• Methods to quantify thermal interfaces and materials with reduced uncertainty • Reliability measurements of interfaces to support increased lifetime targets	• Experimental validation of cooling approaches to support hot-spot cooling within electric motor design with ORNL

Proposed Future Research

- FY21
  - In support of ORNL, complete CFD analysis of proposed heat exchanger design and prepare design for experimental characterization.
  - In support of SNL:
    - Explore methods to reduce uncertainty in thermal conductivity measurements of filled-epoxy samples
    - Prepare for mechanical property tests of additional SNL material samples.
  - Continue discussions with Ames Laboratory and other consortium partners to support material characterization efforts led by Ames Laboratory and potential impacts related to motor thermal management.
  - Support Georgia Tech in efforts to publish motor thermal management research results.
  - Continue meetings and discussions with University of Wisconsin Madison to provide technical support, thermal data, and material information to support integrated cooling of motor and power electronics.

Any proposed future work is subject to change based on funding levels.

Proposed Future Research

- FY22
  - In collaboration with ORNL, build cooling prototype to verify expected cooling performance in relation to the Non-Heavy-Rare-Earth High-Speed Motors research effort led by ORNL
  - Continue support with laboratory partners (SNL and Ames) to support material characterization efforts led by Ames Laboratory and potential impacts related to motor thermal management
  - Continue thermal analysis support for university-led research efforts at Georgia Tech and the University of Wisconsin
  - Support motor material and interface thermal and reliability characterization efforts
    - —Bonded interface thermal contact resistance (50°C–200°C)
    - —Bulk property measurements of slot-liner materials (50°C–200°C)
    - —Thermal contact resistance measurements between unbonded interfaces (50°C–200°C)

Any proposed future work is subject to change based on funding levels.

Summary

Relevance

- Supports research enabling compact, reliable, low-cost, and efficient electric machines aligned with Roadmap research areas

Approach/Strategy

- Engage in collaborations with motor design experts and component suppliers within industry
- Collaborate with ORNL, Ames, and SNL to provide motor thermal analysis support, reliability evaluation, and material measurements on related motor research at national laboratories
- Collaborate with university partners including Georgia Tech and University of Wisconsin Madison to support university-led motor thermal management research efforts
- Develop and document thermal and mechanical characterization methods of material and interface properties

Technical Accomplishments

- NREL collaborating with SNL to support mechanical and thermal measurements of new motor materials
- NREL providing thermal design support for iterative electric machine design process led by ORNL
- NREL completed motor subcomponent (motorette) experimental evaluations at NREL in collaboration with Georgia Tech

Collaborations

- Oak Ridge National Laboratory
- Ames Laboratory
- Sandia National Laboratories
- Georgia Institute of Technology
- University of Wisconsin

Acknowledgments

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Thank You

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Reviewer-Only Slides

Publications and Presentations

- K. Bennion, “Electric Motor Thermal Management,” 2020 DOE VTO Annual Report.
- T. Raminosoa, R. Wiles, J. E. Cousineau, K. Bennion, and J. Wilkins, “A High-Speed High-Power-Density Non-Heavy Rare-Earth Permanent Magnet Traction Motor,” in 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Oct. 2020.
- S. Sequeira et al., “Validation and Parametric Investigations Using a Lumped Thermal Parameter Model of an Internal Permanent Magnet Motor,” presented at the ASME 2020 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems, Dec. 2020.
- X. Feng, E. Cousineau, K. Bennion, G. Moreno, B. Kekelia, and S. Narumanchi, “Experimental and numerical study of heat transfer characteristics of single-phase free-surface fan jet impingement with automatic transmission fluid,” *International Journal of Heat and Mass Transfer*, vol. 166, Feb. 2021.

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.