



Electric Motor Thermal Management R&D

Annual Report

Kevin Bennion

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy
Laboratory (NREL) at www.nrel.gov/publications.

Management Report
NREL/MP-5400-64944
April 2016

Contract No. DE-AC36-08GO28308



Electric Motor Thermal Management R&D

Annual Report

Kevin Bennion

Prepared under Task No. VTP2.7401

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

Management Report
NREL/MP-5400-64944
April 2016

Contract No. DE-AC36-08GO28308

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

NREL prints on paper that contains recycled content.

Electric Motor Thermal Management R&D

Principal Investigator : Kevin Bennion

National Renewable Energy Laboratory (NREL)
Transportation and Hydrogen Systems Center
15013 Denver West Parkway
Golden, CO 80401
Phone: 303-275-4447
E-mail: kevin.bennion@nrel.gov

DOE Technology Development Manager: Susan A. Rogers

U.S. Department of Energy
1000 Independence Ave. SW EE-3V
Washington, DC 20585
Phone: 202-586-8997
E-mail: susan.rogers@ee.doe.gov

NREL Task Leader: Sreekant Narumanchi

Phone: 303-275-4062
Email: sreekant.narumanchi@nrel.gov

Abstract/Executive Summary

With the push to reduce component volumes, lower costs, and reduce weight without sacrificing performance or reliability, the challenges associated with thermal management increase for power electronics and electric motors. Thermal management for electric motors will become more important as the automotive industry continues the transition to more electrically dominant vehicle propulsion systems. The transition to more electrically dominant propulsion systems leads to higher-power duty cycles for electric drive systems. Thermal constraints place significant limitations on how electric motors ultimately perform, and as thermal management improves, there will be a direct trade-off between motor performance, efficiency, cost, and the sizing of electric motors to operate within the thermal constraints.

The goal of this research project is to support broad industry demand for data, analysis methods, and experimental techniques to improve and better understand motor thermal management. Work in FY15 focused on two areas related to motor thermal management: passive thermal performance and active convective cooling. Passive thermal performance emphasized the thermal impact of materials and thermal interfaces among materials within an assembled motor. The research tasks supported the publication of test methods and data for thermal contact resistances and direction-dependent thermal conductivity within an electric motor. Active convective cooling focused on measuring convective heat-transfer coefficients using automatic transmission fluid (ATF). Data for average convective heat transfer coefficients for direct impingement of ATF jets was published. Also, experimental hardware for mapping local-scale and stator-scale convective heat transfer coefficients for ATF jet impingement were developed.

Accomplishments

- Completed and published data for average convective heat transfer coefficients of ATF jets on target surfaces representative of motor end-winding wire bundle surfaces. The published results were presented at conferences and shared with motor industry representatives.
- Published a detailed technical report on lamination materials to share the unique test approach developed at the National Renewable Energy Laboratory (NREL) to measure through-stack motor lamination thermal conductivity and lamination interface thermal contact resistances for motor lamination stacks.
- Collaborated with Oak Ridge National Laboratory (ORNL) to measure thermal properties of motor slot windings and slot winding materials.

- Fabricated experimental components to spatially map convective heat transfer coefficients due to ATF fluid jets impinging on motor end windings.
- Shared data and experimental techniques with industry, leading to improved technology transfer and progress towards developing improved electric drive technologies supporting DOE program goals.



Introduction

Thermal management for electric motors is important as the automotive industry continues to transition to more electrically dominant vehicle propulsion systems. With the push to reduce component size, lower costs, and reduce weight without sacrificing performance or reliability, the challenges associated with thermal management for power electronics and electric motors increase. The transition to more electrically dominant propulsion systems leads to higher-power duty cycles for electric drive systems. Thermal constraints place significant limitations on how electric motors ultimately perform. As summarized by Thomas Lipo, “[a]n optimized thermal design can help increase machine rated power substantially, almost without any increase of its manufacturing costs.” [1]. The performance limitations caused by motor heating are highlighted in Figure I-1. The motor's ability to increase running time at higher power levels within electrical operating limits is directly related to the ability to remove heat from critical components. As thermal management improves, there will be a direct trade-off among motor performance, efficiency, cost, and the sizing of electric motors to operate within the thermal constraints.

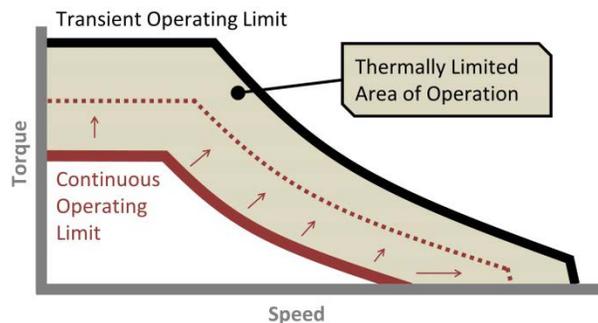


Figure I-1: Thermal management impact on motor performance to support increased power

Image Source: NREL

Thermal management of electric motors is a complex challenge because of the multiple heat transfer paths within the motor and the multiple materials and thermal interfaces through which the heat must pass to be removed. The technical challenges to motor thermal management are summarized by Hendershot and Miller as follows: “Heat transfer is as important as electromagnetic and mechanical design. The analysis of heat transfer and fluid flow in motors is actually more complex, more nonlinear, and more difficult than the electromagnetic behavior” [2]. Figure I-2 provides a cut cross-section view illustrating heat transfer and cooling paths for automotive traction drive applications. The heat generated by the electric motor is distributed throughout multiple components within the electric motor. For example, heat is generated due to losses within the stator slot-windings, stator end-windings, stator laminations, rotor laminations, and rotor magnets or conductors. The distribution of the generated heat within the components is dependent on the motor type and the operating condition (torque/speed) of the motor. The selected cooling approach for the motor impacts the path of heat flow through the motor and the temperature distribution of components. For example, as shown in Figure I-2, a motor cooled with a stator cooling jacket will require heat generated within the slot windings to pass through multiple material layers and material interfaces before the heat is extracted through the cooling jacket. The thermal properties of the materials and the thermal contact resistances due to the material interfaces impact the temperature distribution inside the motor as heat flows into the cooling jacket. Alternatively, direct cooling of the windings with oil or ATF reduces the heat transfer path from the motor windings to the coolant. However, heat from the stator must pass through several interfaces. The resulting changes in the temperature distribution within the motor lead to hot spots within the motor that could be difficult to measure.

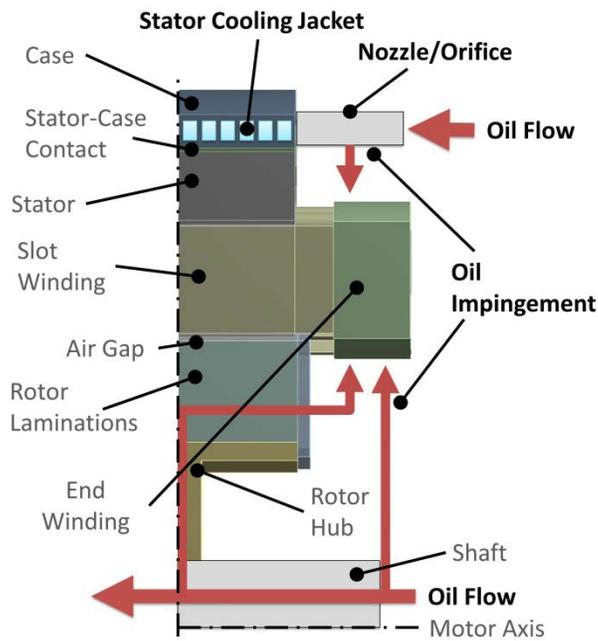


Figure I-2: Heat must pass through several layers within the motor to be extracted through active cooling such as through a cooling jacket or spray cooling with oil such as ATF.

Image Source: NREL

Thermal management of the motor is not only important for the reliability of the motor, but the temperatures of the components within the motor affect material properties that directly relate to the torque production, control, and efficiency of the motor. For this reason, motor designers need accurate thermal models of the electric motor during the design and control development of the motor. Critical to the ability to accurately model the thermal behavior of the motor is access to data describing critical thermal characteristics of the motor. Such data include direction-dependent thermal conductivity measurements of nonuniform motor components such as lamination stacks and windings. It also includes data to quantify thermal contact resistances between components in the motor. Finally, it also includes data to support the modeling and design of active cooling of the motor and the convective heat transfer coefficients possible from alternative cooling approaches.

Approach

The ability to remove heat from an electric motor depends on the passive stack thermal resistance within the motor and the convective cooling performance of the selected cooling technology. For this reason, the approach for the research project splits the efforts for motor thermal management within these two categories as illustrated by Figure I-3.

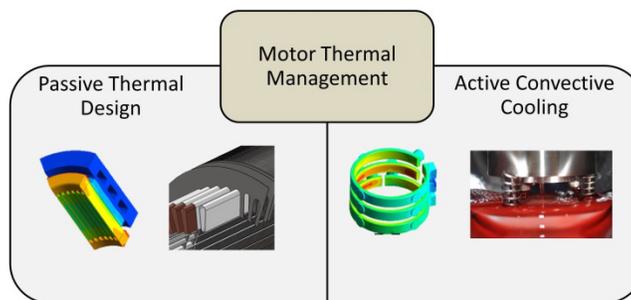


Figure I-3: Approach to motor thermal management divided between passive thermal design and active convective cooling

Photo Credit: Jana Jeffers, NREL

The passive thermal design refers to the geometrical layout, material selection, and thermal interfaces that affect the heat-spreading capabilities within the motor. The ability for heat to spread through the motor affects the thermal temperature gradients within the motor. The active convective cooling technology is the cooling mechanism that ultimately removes the heat from the motor and transfers the heat to another location to reject the heat to the ambient environment.

Active cooling

The two common approaches highlighted in Figure I-3 for active cooling include: 1) directly cooling the motor with ATF, and 2) cooling the motor with a cooling jacket surrounding the stator. The advantages of either cooling approach depend on the application's coolant availability, the motor geometry, and the motor loss distribution. The advantage of cooling using ATF is it is possible to directly cool the motor windings or rotor. Past work focused on measurement of average convection coefficients of ATF jets directly impinging on target surfaces representative of motor end windings. In the area of active cooling, the focus during FY15 emphasized spatial mapping of the heat transfer coefficients at the local scale and stator scale.

The heat transfer coefficients of jet impingement at the local scale (around the jet impingement zone) are not uniform, and the magnitude of the variation is unknown for ATF jets applied to motor cooling. Figure I-4 shows the fluid velocity profile of a fluid jet impinging on a flat target surface. The velocity profile was experimentally obtained at NREL using equipment for particle image velocimetry. The fluid velocity variation from the centerline stagnation point along the wall through the turbulence transition point impacts the local convective heat transfer along the wall or target boundary. During FY15, experimental hardware was redesigned and built to begin efforts to experimentally measure the local variation in the convective heat transfer coefficient around the jet impingement region. The experimental equipment that was designed and built for the measurements is briefly described below. The measurements are part of ongoing work.

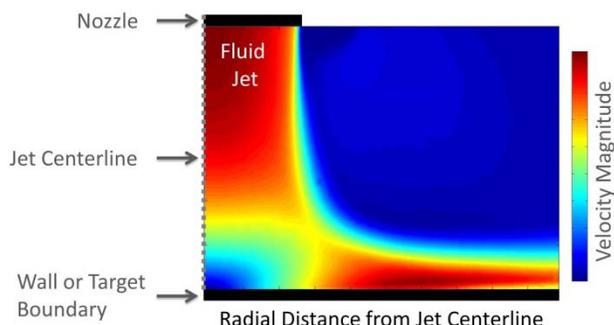


Figure I-4: Experimental velocity profile of jet impingement showing variation in velocity at the target or wall boundary. Data measured using particle image velocimetry equipment at NREL.

Image Source: NREL

In addition to the variation in the local-scale heat transfer coefficient, the heat transfer coefficient will also vary along the larger-scale stator end-winding illustrated in Figure I-5. As seen in Figure I-5, the discrete placement of a limited number of ATF jets produces nonuniform cooling of the end-winding. Also, as the ATF flows over the end-winding, the heat transfer will be different than around the impingement zone of the jet. The irregular surface caused by the wire bundles also complicates the fluid flow paths and the heat transfer. During FY15, NREL built an experimental setup with customized heat transfer sensors to measure the heat transfer variation on the motor end-winding. The initial experiments exclude the irregular surfaces caused by the wire bundles seen in Figure I-5, but additional end-winding geometry complexity can be incorporated in future experiments using the same experimental setup. The following sections summarize the design and construction of the experimental equipment, and the experiments are part of ongoing work.

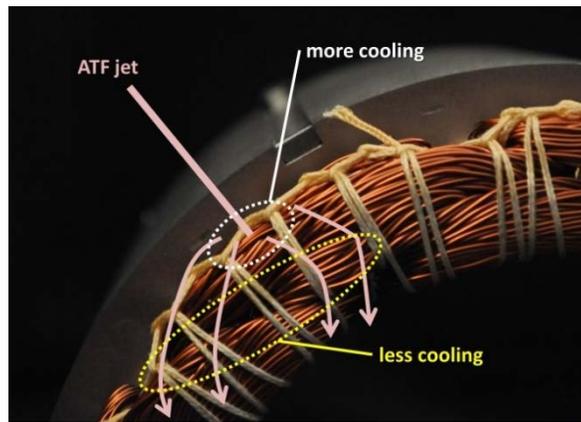


Figure I-5: Heat transfer due to ATF jet impingement will vary over the end-winding surface.

Photo Credit: Kevin Bennion, NREL

Passive Thermal Design

The passive thermal stack elements illustrated in Figure I-2 and Figure I-6 are critical to designing effective thermal management systems for electric motors. The work supports improved thermal models for motor design, but it also enables analysis to compare the potential impacts of new materials, fabrication methods, or material processing on motor heat transfer. Figure I-6 illustrates a few of the critical elements that influence the passive cooling of the motor or the ability of heat to flow through the motor. A few of the items highlighted in Figure I-6 include the stator-to-case thermal contact resistance, lamination through-stack and in-plane thermal conductivity, winding cross-slot thermal properties and thermal interface resistance between ground insulation materials and the respective motor elements in contact with the slot liner or ground insulation. Efforts continued in FY15 to measure passive stack elements within the motor as highlighted above in collaboration with industry, universities, and ORNL.

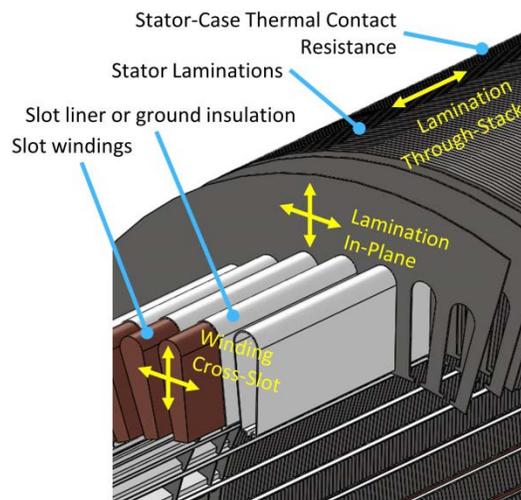


Figure I-6: Passive stack thermal properties and terminology.

Image Source: NREL

Results and Discussion

The discussion included below is separated into the two main focus areas described above. The first section summarizes the progress for active cooling with emphasis on using ATF for cooling electric motors. The second section focuses on the passive cooling of the electric motor. The sections also highlight published reports prepared during FY15 that can be referenced for additional details beyond what can be included in this report.

Active cooling

Work on active convective cooling during FY15 focused on using ATF for cooling electric motors. Past work measured the average convective heat transfer coefficients of ATF jets directly impinging on stationary target surfaces with surface features representative of motor end-windings. The results of the average heat transfer data were published and presented during FY15. Detailed descriptions of the experimental results and data are available in a published paper [3].

Hardware for measuring the local-scale convective heat transfer around the ATF jet impingement zone was redesigned and constructed during FY15. The experimental design is shown in Figure I-7. The approach uses a thin metal foil that is heated by passing an electric current through the foil. The top surface of the foil is exposed to the ATF fluid jet while the bottom side of the metal foil is coated with encapsulated thermochromic liquid crystals (TLCs). The TLC's color hue changes in response to a change in temperature. The TLCs can be used to provide a local temperature measurement along the heated foil that is cooled with the ATF jet. The knowledge of the surface temperature, ATF fluid temperature, and the imposed heat flux are used to spatially map the heat transfer coefficients over the jet stagnation zone through the wall jet region. A camera is placed below the test article as shown in Figure I-7 and captures images of the TLC-coated surface. The foil surface between the bus bars is 12.7 mm by 12.7 mm.

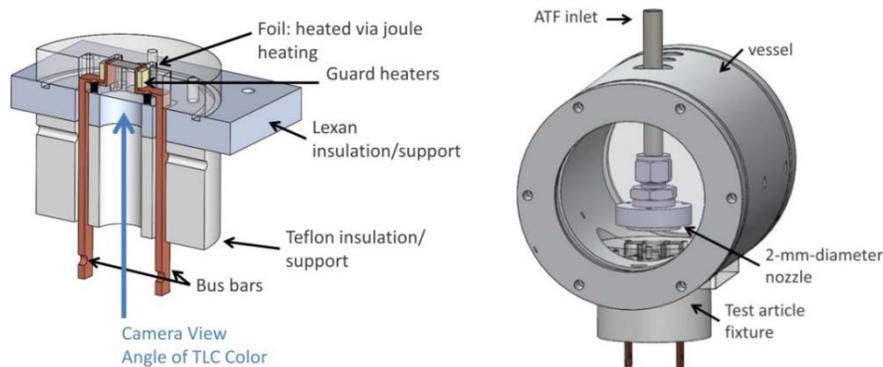


Figure I-7: Cross-sectional view of TLC test article (left). Test article with nozzle assembly (right).

Image Source: NREL

The assembled test article for the TLC measurements is shown in Figure I-8. The image on the left shows the test article with the metalized foil sealed into the fixture to prevent ATF from leaking out of the test vessel. The article was redesigned during FY15 to facilitate the removal of the metalized foil after testing to make it easier to reuse or change the TLC-coated foil. The image on the right shows light emitting diodes (LEDs) that were incorporated into the design to illuminate the TLC surface to improve the lighting of captured images from the camera.

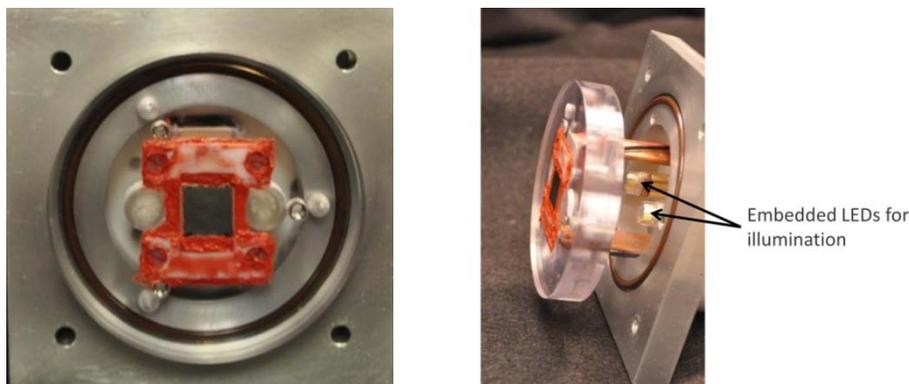


Figure I-8: Assembled test article showing impingement surface (left), Assembled test article showing embedded LEDs to illuminate the TLC surface (right).

Photo Credit: Gilbert Moreno, NREL

The test apparatus installed within the test vessel is shown in Figure I-9. The image on the left shows the test article with the TLC-coated foil installed. The orifice nozzle for the fluid jet is installed within the test vessel and is located above the metal foil. The image also shows the lighting provided by the LEDs to illuminate the TLC surface. The image on the right shows the view from the camera view angle looking up at the TLC-coated surface illuminated by the LEDs. Work is currently in progress to calibrate the TLCs response to temperature after they are coated onto the metalized foil and placed within the test apparatus.

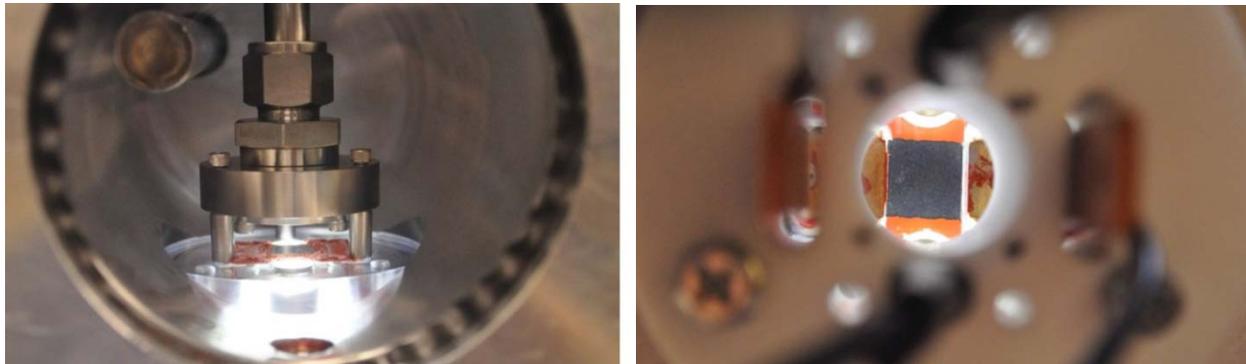


Figure I-9: Test article and nozzle assembly (left), assembled test article showing camera view of illuminated TLC surface (right)

Photo Credit: Gilbert Moreno, NREL

The objective of the stator-scale ATF thermal measurements on motor end-windings is to map the spatial distribution of the heat transfer coefficients over the motor end-winding surface. The image on the left of Figure I-10 illustrates the goals of the experimental setup. The experiment was designed to enable the measurement of heat transfer on multiple surfaces of the motor end winding while allowing for the relative position between the heat transfer sensor and fluid jet impingement zone to change. Unlike prior measurements, the fluid jet is not constrained to be in a fixed location relative to the heat transfer sensor location. The experimental setup allows for the study of nozzle location, nozzle type, jet interactions, flow rates, gravity, and alternative cooling designs along the inner diameter, outside diameter, and outside edge of the motor end winding. The drawing on the right of Figure I-10 illustrates the heat transfer sensor package installed in two locations to measure the heat transfer on the outside diameter and outside edge of the motor end winding.

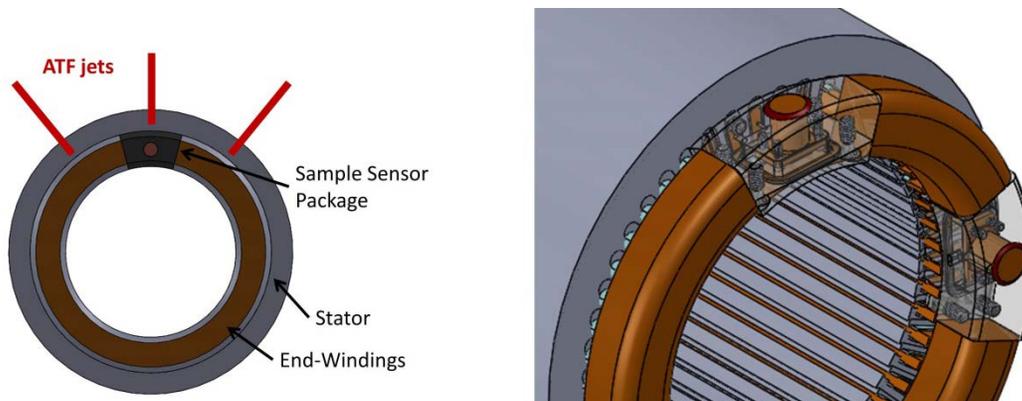


Figure I-10: Illustration of sensor package installed in end winding (left), three-dimensional drawing of stator end winding with sensor package installed for convective heat transfer measurements (right)

Image Source: NREL

The details of the heat transfer sensor package are shown in Figure I-11. The drawings on the left show the construction of the sensor package. The outside surface of the sensor package simplifies the structure of the end winding with a flat surface in comparison to the irregular shape of the wire bundles. However, the outside of the sensor package was designed to allow for wires to be attached to the outside surface to simulate the wire bundle surface. The package can incorporate alternative target surfaces representative of different wire

surfaces. The flat target surface is included to perform baseline measurements to compare against prior measurement data. The bottom of the copper target is in contact with a heater, and the copper target is also instrumented with thermocouples.

The sensor package was designed using a three-dimensional thermal finite element analysis model. The parametric model was used to evaluate alternative design parameters to minimize the experimental error of the test apparatus. The model replicated the sensor locations for the measurement data and the equations to calculate the surface heat flux and surface heat transfer coefficient. The modeling and analysis improved the experimental robustness of the heat transfer coefficient calculation to measurement uncertainty. The analysis incorporated the systematic measurement uncertainties of the sensors to quantify the impact of the uncertainties on the calculated heat transfer coefficient. The image on the right of Figure I-11 shows a sample result of the finite element analysis thermal model. The example shows the temperature profiles from the heater through the target surface. The result shows the locations of temperature sensors and the uniform temperature gradient within the target for calculating the heat flux through the surface of the part.

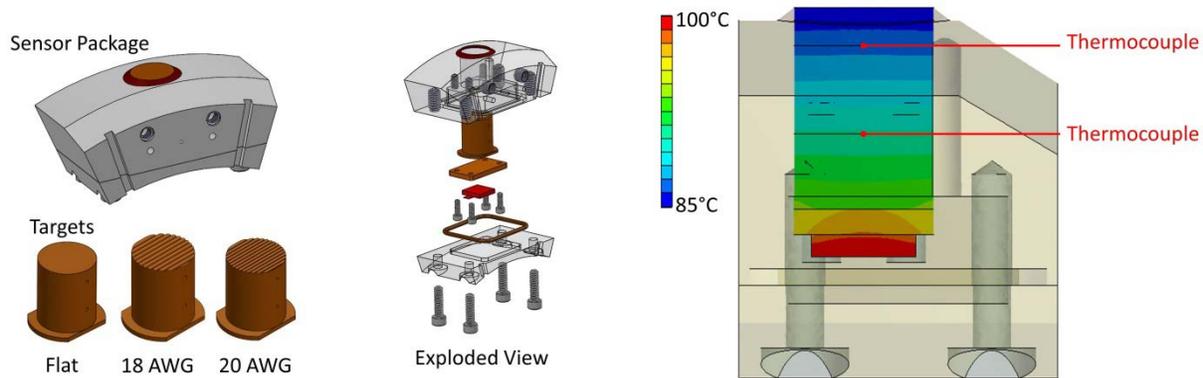


Figure I-11: Design of sensor package showing assembled components and ability to change target surfaces (left), thermal finite element model of sensor package design (right).

Image Source: NREL

The fabricated sensor packages are shown in the left image of Figure I-12. The top sensor package is designed to measure the heat transfer coefficient on the outside diameter of the end winding. The sensor package on the bottom is designed to measure the outside end surface of the end-winding surface. The sensor package replaces a small section of the end winding in the stator as shown in the image on the right of Figure I-12.



Figure I-12: Assembled sensor packages for outer diameter surface measurement and end surface measurement (left), stator winding removed for sensor package (right)

Photo credits: Emily Cousineau, NREL (left); Kevin Bennion, NREL (right)

Passive Thermal Design

The work focusing on characterizing and improving the passive thermal stack in an electric motor is summarized below. During FY15, experimental data for lamination materials and interface thermal contact resistances were published as part of an NREL technical report [4] and presented [5], [6] at conferences. The

NREL technical report provides details of the experimental approach and data related to lamination materials [4]. The report also provides equations that can be used to interpret or apply the data. The published report and testing capability developed at NREL have led to increased interactions with industry interested in applying the data to their motor designs or taking advantage of NREL's developed testing capability.

During FY15, NREL worked in collaboration with ORNL to focus more closely on the winding materials within the electric motor. Figure I-13 shows examples of the motor winding materials. The irregular shape of the motor end winding makes the process of extracting measurement samples for testing a challenge. However, future work will continue to investigate methods to quantify the direction-dependent thermal properties of the motor end winding. The focus during FY15 in collaboration with ORNL was on the slot winding of the motor.

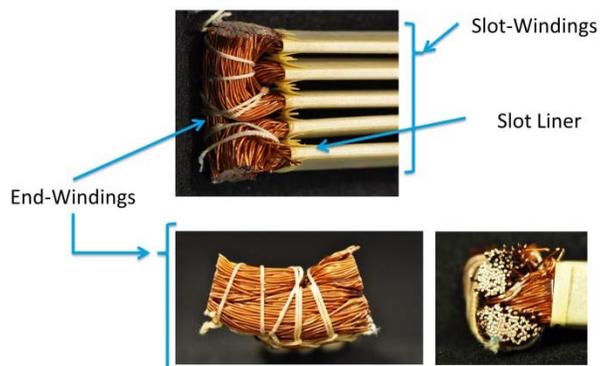


Figure I-13: Images of sample slot-winding and end-winding motor components

Photo credit: Kevin Bennion, NREL

Examples of the tested slot materials are shown in Figure I-14. The images on the left show examples of tested materials that include the slot winding with and without the slot liner or ground insulation bonded to the wire bundle of the slot. The image on the right of Figure I-14 shows sample slot winding materials being tested. In the provided example, tests were performed to measure the cross-slot thermal conductivity of the slot winding wire bundle. Measurements were also taken for the slot liner and for the thermal resistance between the slot liner and the slot winding.

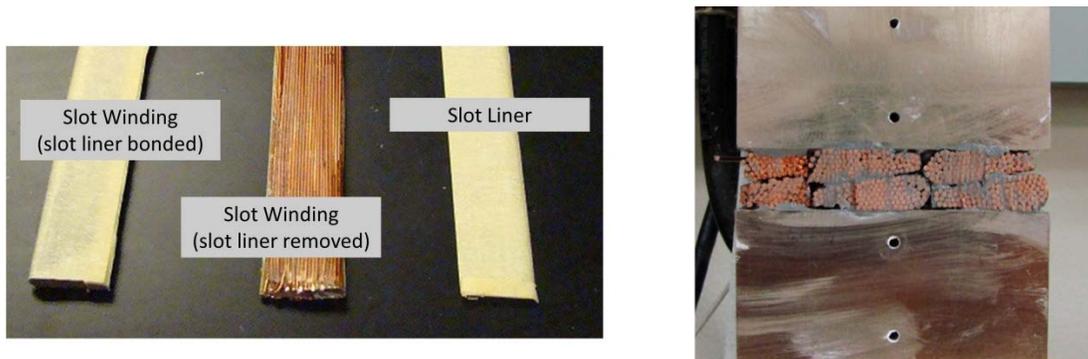


Figure I-14: Images of sample slot-winding materials (left), sample slot winding under test for measuring cross-slot thermal conductivity (right)

Photo credits: Emily Cousineau, NREL

The measurement data are summarized in Table I-1. The cross-slot thermal conductivity measurements are summarized within the first row of the table. The copper fill factor of the wire bundle was measured to be approximately 75%, which excludes the area occupied by the slot liner and only includes the wire bundle portion of the slot. The tested cross-slot thermal conductivity was 0.88 W/m-K with 95% confidence uncertainty limits (U95) of ± 11 W/m-K. In comparison, the estimated thermal conductivity from modeling the slot bundle was 0.99 W/m-K. More testing is needed, but the model and experimental results appear to agree.

The measurements of the slot liner insulation are summarized in row two of Table I-1. The measured thermal conductivity was 0.175 W/m-K, which corresponds to a thermal resistance of 1,676 mm²-K/W for the

measured material thickness. The results compare favorably to available literature data of 0.144 W/m-K [7] and 0.139 W/m-K for 10-mil Nomex [8].

Table I-1: Summary of the measurement results on the slot winding materials^a

	Thermal conductivity [W/m-K]	Thickness [mm]	Thermal Resistance [mm ² -K/W]
Slot winding cross-slot	0.88 ± 0.11	NA	NA
Slot liner	0.175	0.294	1,676
Slot-liner to slot-winding interface	NA	NA	1,800 ^a

^a Preliminary measurements; more experiments are necessary.

A key measurement to highlight is the slot-liner to slot-winding interface thermal resistance. The preliminary measurements of this interface thermal resistance were approximately 1,800 mm²-K/W. The measured thermal resistance was higher than initially expected and is as significant as the slot-liner insulation thermal resistance alone. The measured thermal interface is equivalent to a 0.1-mm to 0.3-mm solid varnish layer between the slot-winding and the slot-liner insulation. While not measured, it is thought that the thermal interface between the slot-liner insulation and the stator lamination could be a comparable thermal resistance. Future work is proposed to measure this interface resistance.

The measurements provide valuable data when trying to develop a motor thermal model from the component level up to the full motor system. The measured material properties were applied to the thermal benchmarking efforts to model motor thermal resistance, and the modeling results matched the experimental results. The results provided by the thermal benchmarking performed at NREL provided confirmation of the experimental techniques and data for material and interface thermal measurements that have been measured to date.

These results were shared with industry and ORNL. Efforts are continuing to further characterize the thermal resistances within the slot winding. As part of the motor research collaboration between NREL and ORNL, ORNL prepared wire bundle samples for testing. ORNL prepared blocks of the wire bundle samples as shown in the left image of Figure I-15. The blocks were then cut by ORNL into 50-mm by 50-mm (2-in. by 2-in.) blocks of various thicknesses to allow testing at NREL of the directional thermal conductivity of the wire bundle blocks. The samples allow for testing the cross-wire thermal conductivity and the along-wire thermal conductivity as shown in the images on the right of Figure I-15. The measurements results performed in collaboration with ORNL will look at alternative measurement techniques and compare the impact of wire gauge and copper fill factor for samples of various thicknesses.



Figure I-15: Winding sample blocks prepared by ORNL for thermal property measurements (left), cut samples prepared by ORNL and sent to NREL for directional thermal property measurements (right)

Photo credits: Andrew Wereszczak, ORNL (left); Emily Cousineau, NREL (right)

During FY15, NREL continued industry collaborations in the area of case-to-stator thermal contact resistance measurements. An experimental setup for measuring the case-to-stator thermal contact resistance is shown in Figure I-16. The experimental approach makes use of hardware and past experience for measuring interface resistances at NREL. The experimental approach developed enables measurement of the case-to-stator thermal measurements along with the in-plane lamination stack thermal conductivity at high pressures representative of the interference fit between the stator and case. During FY15, the experimental setup was utilized to support an industry-led project that provided confirmation of the experimental approach.

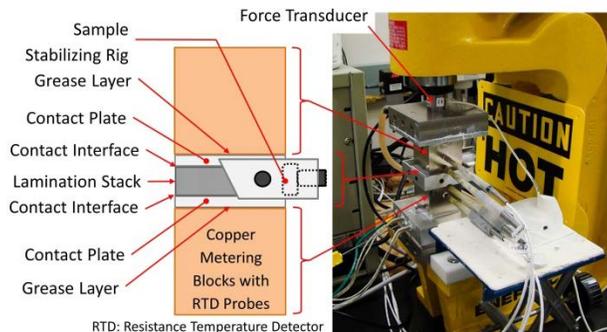


Figure I-16: Experimental setup for measuring stator-to-case thermal contact resistance and lamination in-plane thermal conductivity under high pressure

Photo credits: Emily Cousineau, NREL

Conclusions and Future Directions

Past work in the area of active convective cooling provided data on the average convective heat transfer coefficients of ATF jets impinging on stationary targets intended to represent the wire bundle surface of the motor end-winding. This work was completed during FY15, and the results were shared through publications and conference papers. The work during FY16 will transition to spatially map the convective heat transfer coefficients at local scale and stator scale over a motor end winding. Experimental hardware was built for the spatial mapping heat transfer experiments. Future work will focus on obtaining experimental data from tests using the developed hardware.

The area of passive thermal design saw the completion of past work to develop experimental approaches and obtain data for lamination stack thermal properties and interface contact thermal resistances. During FY15, the experimental approach and data were published as an NREL technical report and shared with industry, university, and other research partners. The publication of the report has led to increased industry interactions at NREL in the area of motor thermal management. During FY15, in collaboration with ORNL, NREL focused on the measurement of wire-bundles and materials for motor slot windings. The work in collaboration with ORNL will support test methods to characterize the thermal properties of the materials and interface thermal resistances. The data will enable motor thermal models based on component level and thermal interface data. Future efforts will continue with ORNL to complete thermal property measurements of sample materials provided by ORNL.

FY 2015 Presentations/Publications/Patents

- [1] K. Bennion, J. E. Cousineau, X. Feng, C. King, and G. Moreno. "Electric Motor Thermal Management R&D." presented at the IEEE Power & Energy Society General Meeting, Denver, CO, July 26-30, 2015.
- [2] J. E. Cousineau, K. Bennion, D. DeVoto, and S. Narumanchi. "Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines." Presented at the ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems and ASME 2015 12th International Conference on Nanochannels, Microchannels, and Minichannels, San Francisco, CA, United States, July 6-9, 2015.

- [3] K. Bennion and G. Moreno. “Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets with Implications for Electric Machine Thermal Management.” in ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems and ASME 2015 12th International Conference on Nanochannels, Microchannels, and Minichannels, San Francisco, CA, United States, July 2015.
- [4] E. Cousineau, K. Bennion, D. DeVoto, M. Mihalic, and S. Narumanchi. “Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines.” NREL Technical Report NREL/TP-5400-63887, June 2015.
- [5] K. Bennion. “Electric Motor Thermal Management R&D.” 2015 DOE Vehicle Technologies Office (VTO) Annual Merit Review, June 2015.
- [6] K. Bennion, E. Cousineau, C. King, G. Moreno, and C. Stack. “Electric Motor Thermal Management R&D.” Electric Drive Technologies FY15 Kickoff Meeting, DOE Vehicle Technologies Office, Oak Ridge, TN, November 2014.

Acknowledgements

The author would like to acknowledge the support provided by Susan Rogers and Steven Boyd, Technology Development Managers for the Electric Drive Technologies Program, Vehicle Technologies Office, U.S. Department of Energy Office of Energy Efficiency and Renewable Energy.

The significant contributions from Emily Cousineau, Xuhui Feng, Charlie King, Gilbert Moreno, Caitlin Stack, and Adam Stokes (NREL) to the project are acknowledged. The support, collaboration, and sample motor materials provided by Andrew Wereszczak and Tim Burress (ORNL) are also acknowledged.

References

- [1] T. A. Lipo, Introduction to AC Machine Design, 3rd ed. Wisconsin Power Electronics Research Center, University of Wisconsin, 2007.
- [2] J. R. Hendershot and T. J. E. Miller, Design of Brushless Permanent-Magnet Motors. Oxford, UK: Magna Physics Publishing, 1994.
- [3] K. Bennion and G. Moreno, “Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets with Implications for Electric Machine Thermal Management,” in ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems and ASME 2015 12th International Conference on Nanochannels, Microchannels, and Minichannels, San Francisco, CA, United States, 2015.
- [4] E. Cousineau, K. Bennion, D. DeVoto, M. Mihalic, and S. Narumanchi, “Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines.” NREL Technical Report NREL/TP-5400-63887, Jun-2015.
- [5] J. E. Cousineau, K. Bennion, D. DeVoto, and S. Narumanchi, “Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines,” presented at the ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems and ASME 2015 12th International Conference on Nanochannels, Microchannels, and Minichannels, San Francisco, CA, United States, July 9, 2015.
- [6] K. Bennion, J. E. Cousineau, X. Feng, C. King, and G. Moreno, “Electric Motor Thermal Management R&D,” presented at the IEEE Power & Energy Society General Meeting, Denver, CO, July 26, 2015.
- [7] E. Jih, K. Chen, T. Abraham, and V. Siddapureddy, “Thermal Management for the HEV Liquid-Cooled Electric Machine,” in Vehicle Thermal Management Systems Conference & Exposition, Nashville, TN, 2001, vol. 2001-01-1713.
- [8] “DuPont™ Nomex® 410 Paper, 10 mil Nominal Thickness.” [Online]. Available: <http://www.matweb.com/search/datasheet.aspx?matguid=389ac8bf734e4aa1980022397e6b5016&ckck=1>. [Accessed: 15-Sep-2015].