Integrated Traction Drive Thermal Management

Keystone Project 3

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National Renewable Energy Laboratory (NREL)
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DOE Vehicle Technologies Program
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Project ID # elt217

Overview

Timeline

- Project start date: 10/01/2018
- Project end date: 09/30/2023
- Percent complete: 30%

Budget

- Total project funding: $500K (FY 2019 and FY 2020)
  - DOE share: $500K
- Funding for FY 2019: $250K
- Funding for FY 2020: $250K

Barriers

- Barriers addressed
  - Cost
  - Power density of a traction drive/system
  - Reliability and lifetime

Partners

- Industry
  - Automotive original equipment manufacturers (OEMs)
  - Driveline fluid manufacturers
- Research institutions
  - Oak Ridge National Laboratory (ORNL)
  - University of Wisconsin-Madison

Relevance

Objectives:

- Research and evaluate motor-integrated power electronics packaging technologies and thermal management approaches
- For selected driveline fluids, measure convective cooling heat-transfer characteristics and electrical properties.

Project Impact:

- Identify pathways enabling high-performance, compact, and reliable integrated electric drives:
    - Help achieve DOE 2025 target of 33 kW/L system power density for an electric traction drive.

Milestones

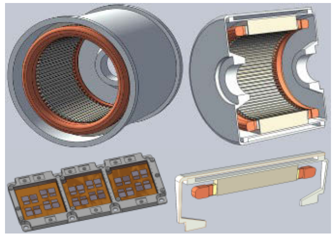
FY 2019 Targets

Description	End Date	Status
• Traction drive fluid thermal and electrical evaluation (literature review). Determine if thermal, electrical, and mechanical fluid properties align with driveline fluid performance requirements for the integration methods proposed for the electric motor and power electronics.	06/30/2019	Met
• Perform jet impingement heat-transfer coefficient characterization for one automatic transmission fluid (ATF) type based on already-identified parameters.	09/30/2019	Met
• Submit manuscript based on jet impingement heat-transfer coefficient characterization results for ATF.	09/30/2019	Met

FY 2020 Targets

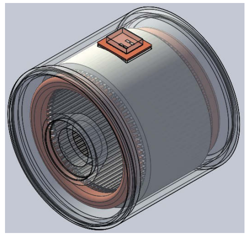
Description	End Date	Status
• Perform thermal management simulations for up to two integration approaches.	12/31/2019	Met
• Submit manuscript based on thermal simulations for integrated traction drive thermal management approaches (cross-comparison of integration topologies).	09/30/2020	On Track
• Perform jet impingement heat-transfer coefficient characterization for one automatic transmission fluid (ATF) type for extended parameters (impingement angle, nozzle distance).	6/30/2021	On Track

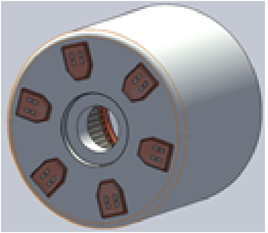
Approach



Geometries of state-of-the-art components

- Inner- or outer-rotor electric machines
- Wide bandgap (WBG) power electronics (PE)/devices



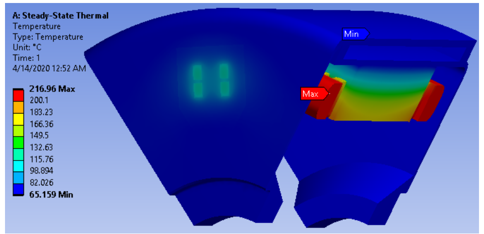


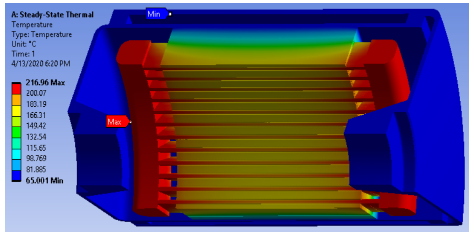
Motor + PE integration approaches / CAD => FEA models

- Separate motor and PE enclosures
- PE distributed/mounted radially on the motor casing
- PE integrated axially in the motor front/back plate

Experimental heat transfer characterization

- ATF currently used in automotive transmissions
- Select dielectric driveline fluids suitable for direct electric motor and PE cooling





Evaluate cooling solutions with numerical modeling

- Comparison of thermal management approaches (radial, axial)
- Modeling jet impingement cooling solutions (orifice jet, fan jet)

Clarification of terms:

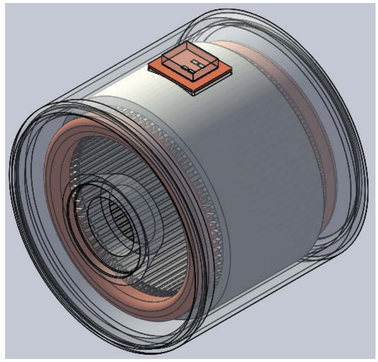
ATF – automatic transmission fluid: used for lubrication and cooling in vehicle transmissions
CAD – computer-aided design
FEA – finite element analysis

PE – power electronics: used for control of electric traction drives
WBG – wide bandgap electronics: emerging semiconductor technology in power electronics

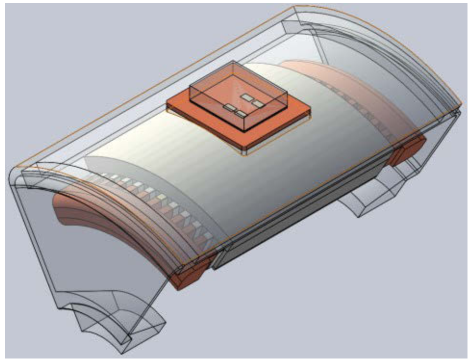
Figure and photo credits: Bidzina Kekelia, NREL

Technical Accomplishments and Progress: Integrated Traction Drive – Integration Approaches

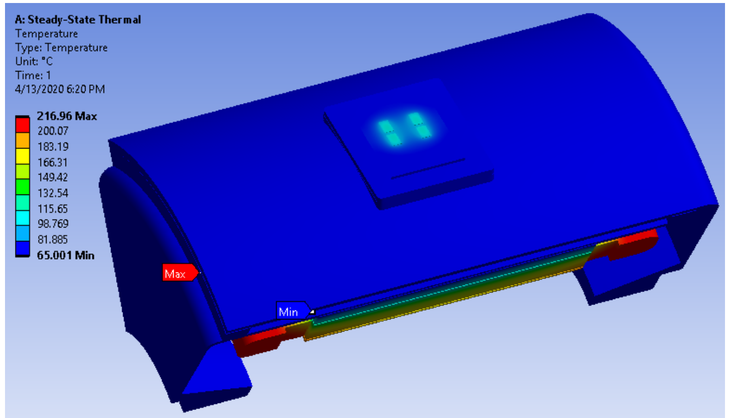
- Computer-aided design (CAD) model for **radially integrated** solution was developed based on:
  - BMW i3 traction motor
  - Power electronics using Cree **SiC** power MOSFET CPM3-0900-0010A dies
- Initial FEA thermal simulations in Ansys were carried out using thermal load estimates (losses) from ORNL:
  - Motor: DC/AC losses at 11,000 rpm for BMW i3 traction motor
  - Power module: 1,770 W / 6 phases (4 Cree 900-V SiC device per phase) = 295 W/phase

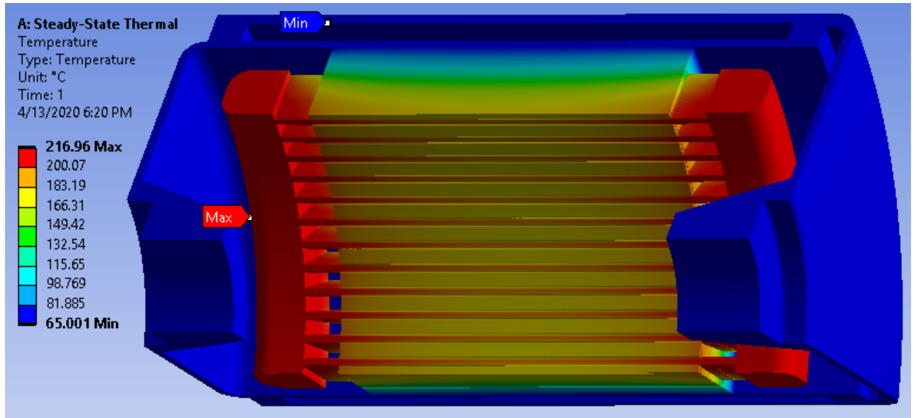


CAD model of radially integrated power electronics with a traction motor (shared cooling jacket)



1-phase module with 1/6 of the motor





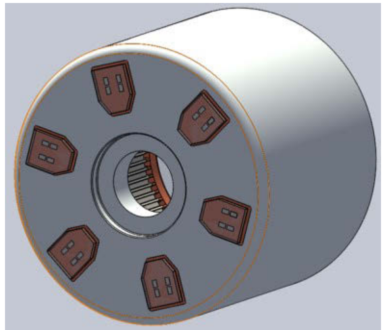
FEA simulations of radially integrated traction drive model in Ansys

Figures by Bidzina Kekelia, NREL

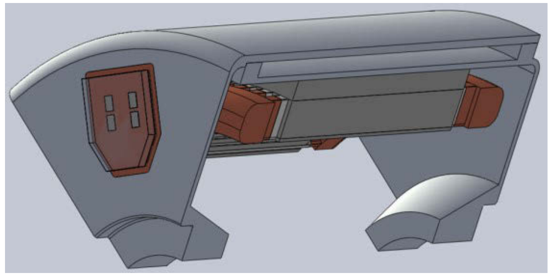
MOSFET: metal–oxide–semiconductor field-effect transistor
SiC: silicon carbide

Technical Accomplishments and Progress: Integrated Traction Drive – Integration Approaches

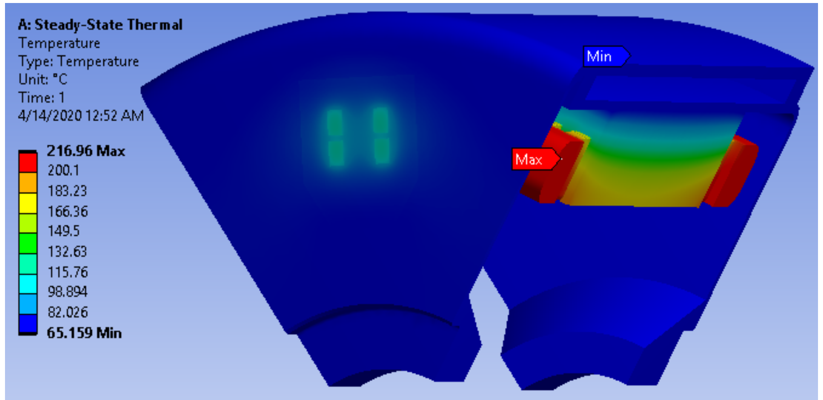
- Computer-aided-design (CAD) model for **axially integrated** solution was developed based on:
  - BMW i3 traction motor
  - Power electronics using Cree **SiC** power MOSFET CPM3-0900-0010A dies
- Initial FEA thermal simulations in Ansys were carried out using thermal load estimates (losses) from ORNL:
  - Motor: DC/AC losses at 11,000 rpm for BMW i3 traction motor
  - Power module: 1,770 W / 6 phases (4 Cree 900-V SiC device per phase) = 295 W/phase

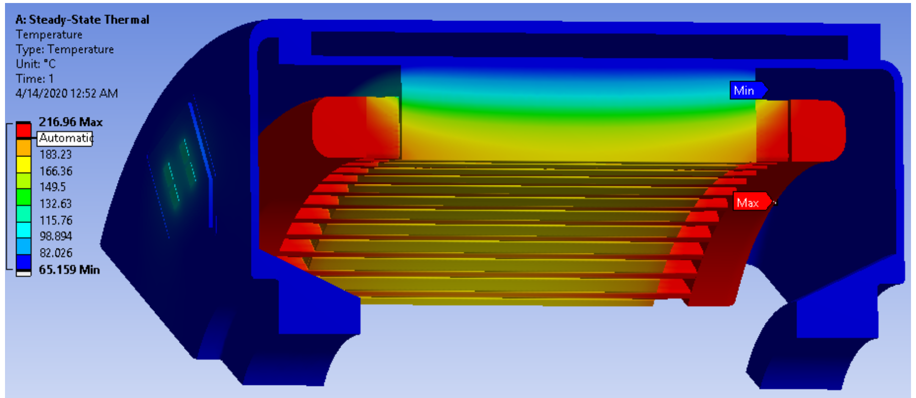


CAD model of axially integrated power electronics with a traction motor



1-phase power module with 1/6 of the motor



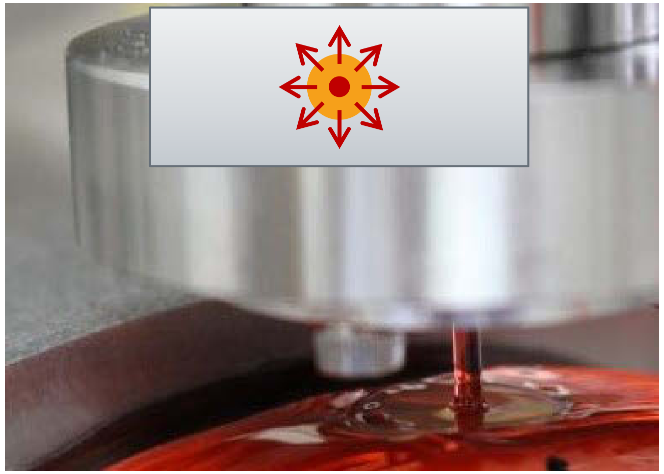


FEA simulations of axially integrated traction drive model in Ansys

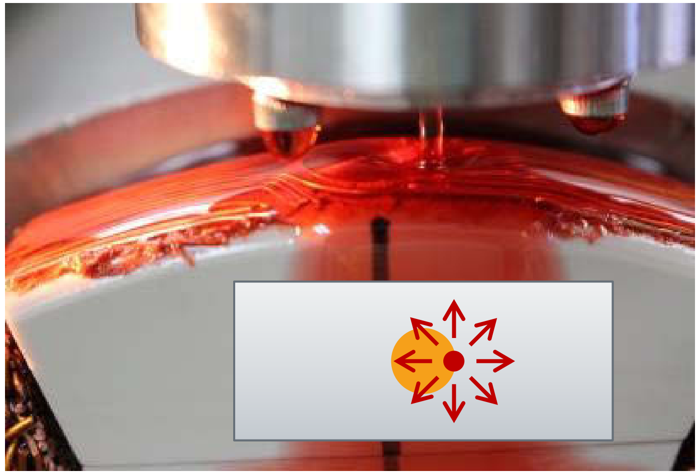
Figures by Bidzina Kekelia, NREL

Technical Accomplishments and Progress: Experimental Characterization of ATF Jet Impingement Heat Transfer

- FY 2019 experimental work: characterization of ATF jet impingement cooling on target center and edge



Orifice jet center impingement



Orifice jet edge impingement

Photo credits: Bidzina Kekelia, NREL

Front View

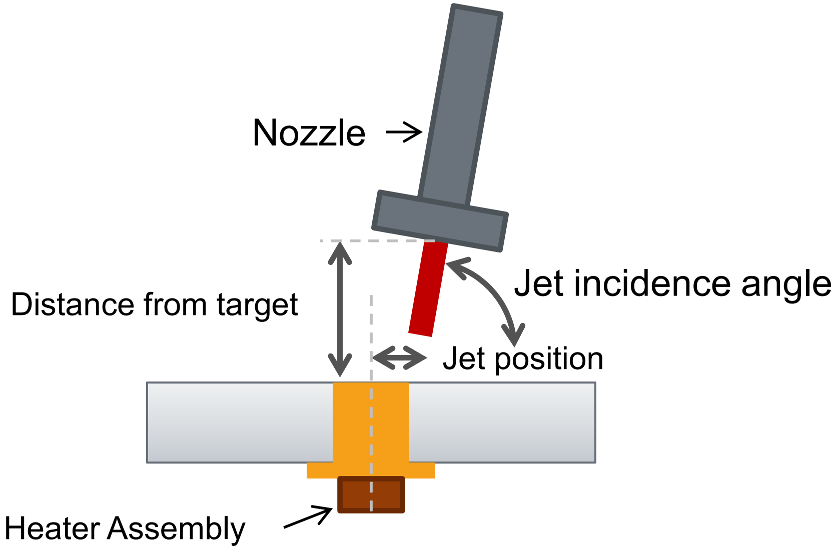
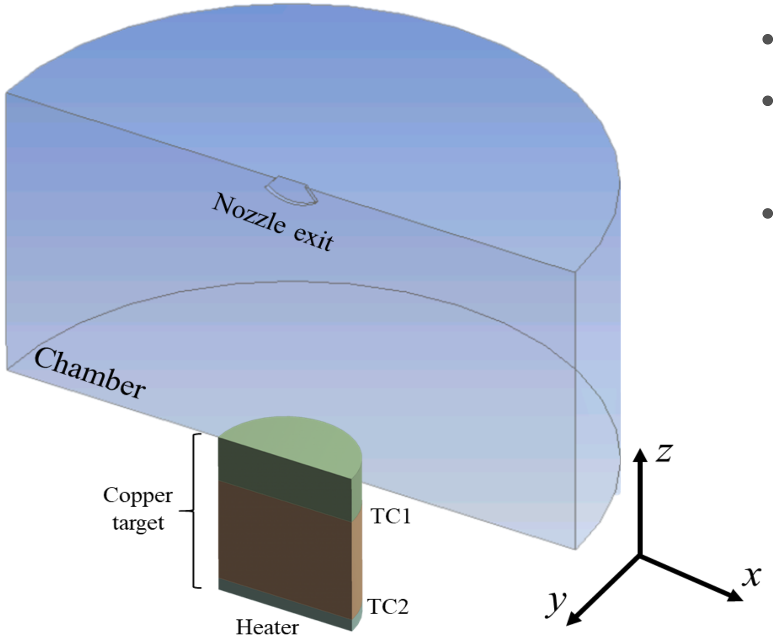


Figure credit: Kevin Bennion, NREL

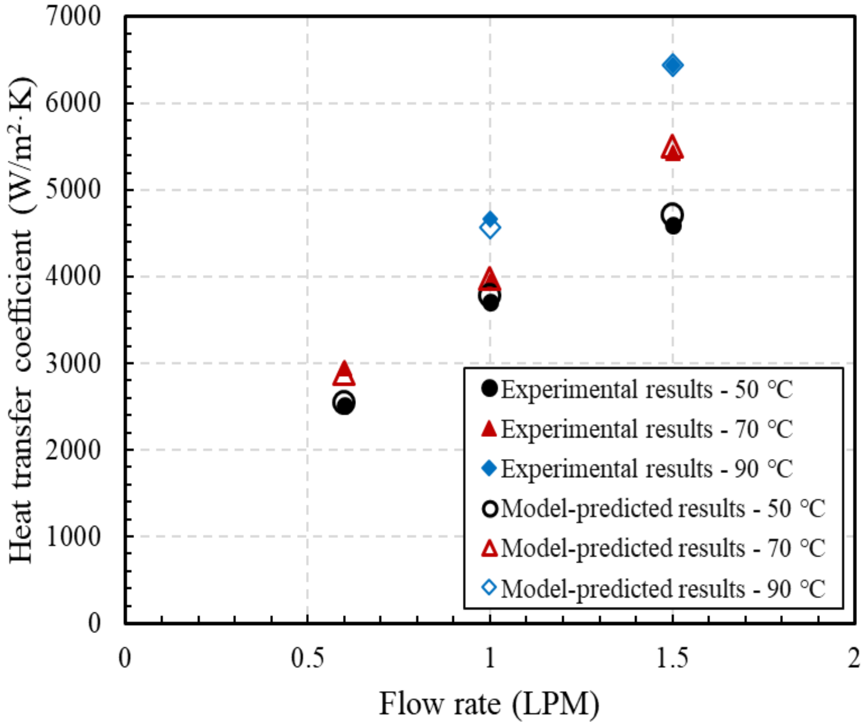
- FY 2020 experimental work (planned for Q4): extend characterization of ATF jet impingement cooling by investigating the impact of jet incidence angles, as well as the distance between the nozzle and the target surface

Parameters	Values
Fluid temperature (T_f)	50°C, 70°C, 90°C
Surface temperature (T_s)	90°C, 100°C, 110°C, 120°C
Jet incidence location	center, edge
Jet incidence angle	90°, 60°, 45°
Nozzle distance from target	5 mm, 10 mm, 15 mm

Technical Accomplishments and Progress: CFD Modeling of ATF Fan Jet Impingement



- Only the fluid in test chamber was simulated using Ansys Fluent
- Cylindrical copper target with attached heat source is shown with locations of thermocouples (TC1 and TC2)
- Only half or a quarter of entire domain is simulated due to geometrical symmetry



- Flow rates are 0.6, 1.0, and 1.5 LPM and fluid temperatures are 50°C, 70°C, and 90°C
- CFD-predicted results show excellent agreement with experimental results, validating the CFD model of fan jet
- Increasing flow rate leads to increasing heat-transfer coefficients, and so does increasing the fluid temperature

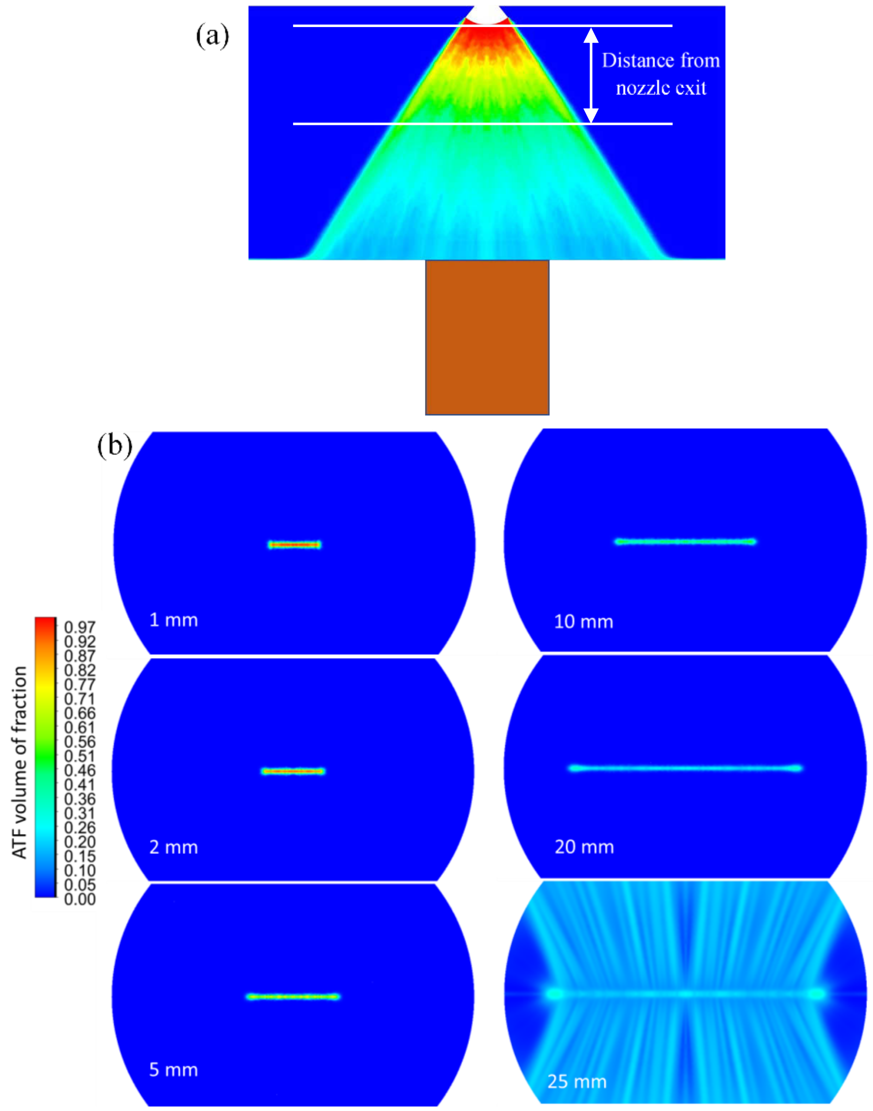
CFD: computational fluid dynamics
LPM: liters per minute

Figures by Xuhui Feng, NREL

Technical Accomplishments and Progress: CFD Modeling of ATF Fan Jet Impingement

Fan Jet Development After Leaving Nozzle

- Cross-sectional contours of the fan jet at various distances from nozzle are shown
- Development of fan jet sheet thickness shows conservation of momentum inside jet core region
- Strong surface tension between fluid and air causes thicker edges on both ends

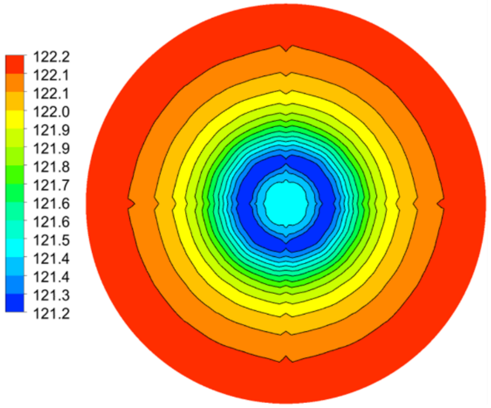


Figures by Xuhui Feng, NREL

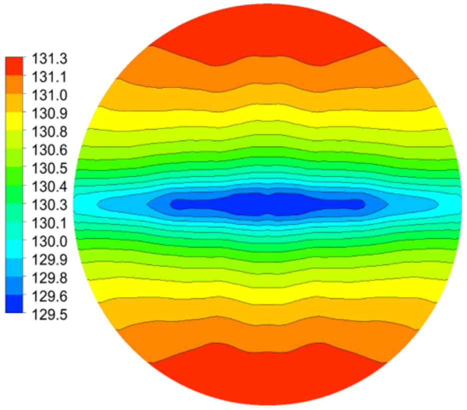
Technical Accomplishments and Progress: CFD Modeling of ATF Fan Jet Impingement

Comparison of Fan Jet to Circular Jet

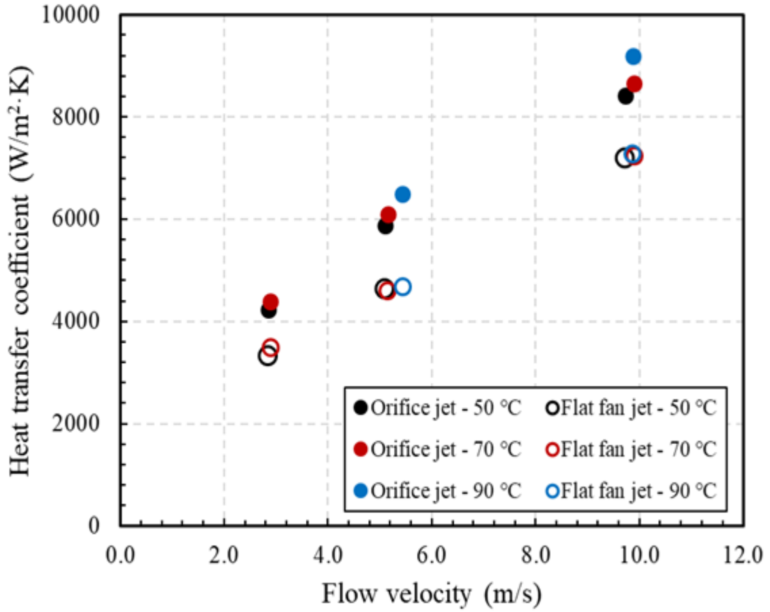
- Fan and circular jets were compared with the same nozzle-to-target distance of 10 mm, same flow rates and temperatures
- In all cases, circular jet presents higher heat-transfer coefficients and more even temperature distribution on impinged surface than fan jet
- The possible reason is that while circular jet impinges on the center of target, fan jet spreads beyond target surface with considerable amount of fluid missing the target
- In case of cooling motor windings, fan jet provides much larger surface coverage and may have better overall cooling effect compared to circular jet



Circular nozzle: 1LPM, 70°C



Fan nozzle: 1LPM, 70°C

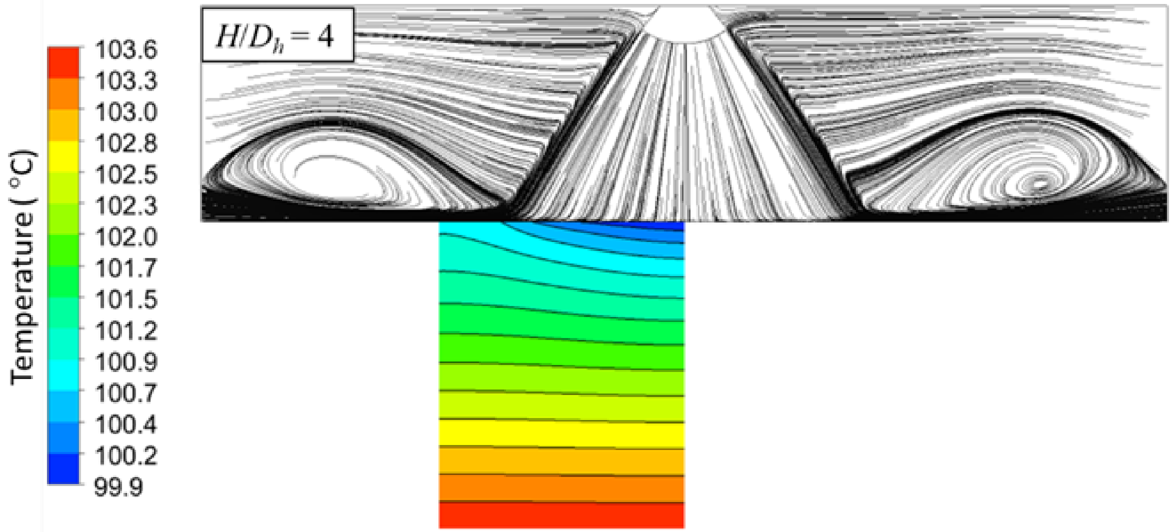


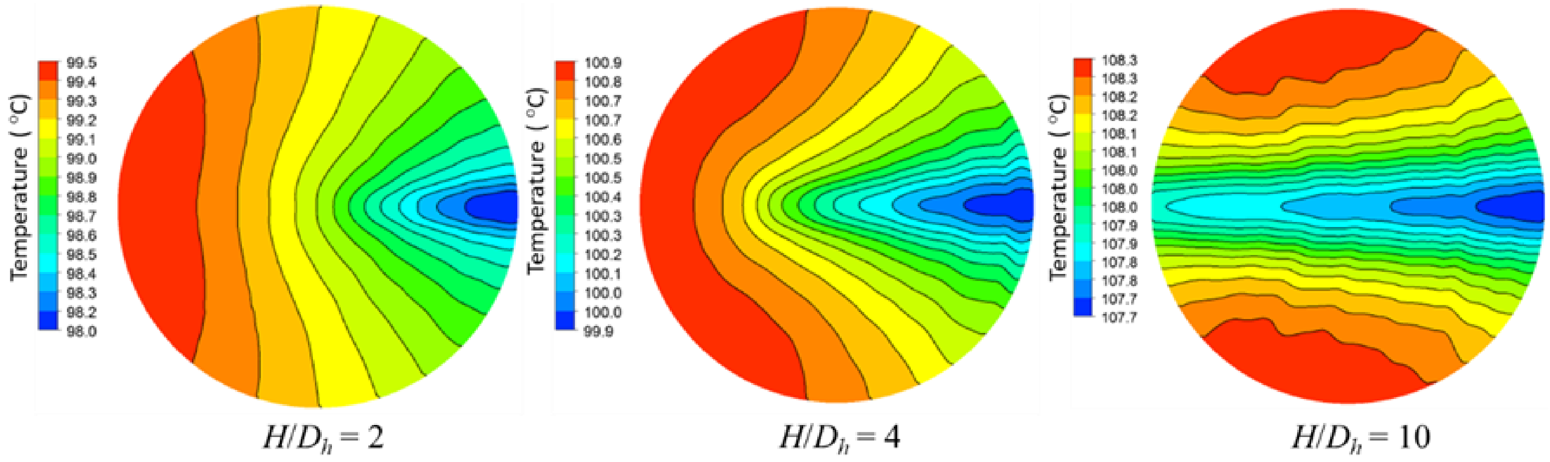
Figures by Xuhui Feng, NREL

Technical Accomplishments and Progress: CFD Modeling of ATF Fan Jet Impingement

Off-Center Fan Jet Impingement

- Fan jet is positioned off-center
- Surface temperature contours show strong elongations with larger separations



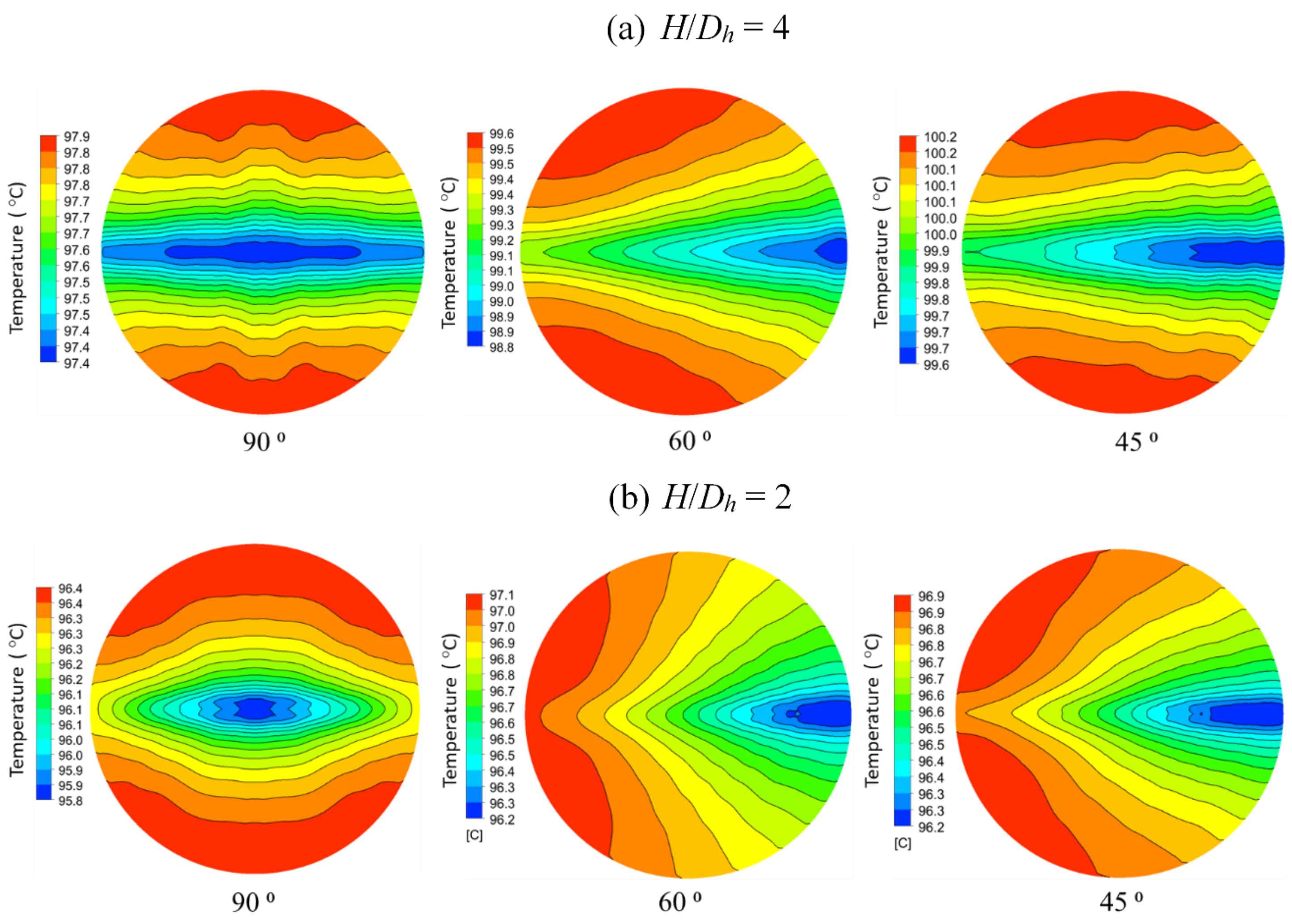


Figures by Xuhui Feng, NREL

Technical Accomplishments and Progress: CFD Modeling of ATF Fan Jet Impingement

Oblique Fan Jet Impingement

- Incidence angle is varied
- At a large separation distance, obliqueness reduces the heat-transfer efficiency
- At a smaller separation distance, obliqueness shows less-significant impact on heat transfer



Figures by Xuhui Feng, NREL

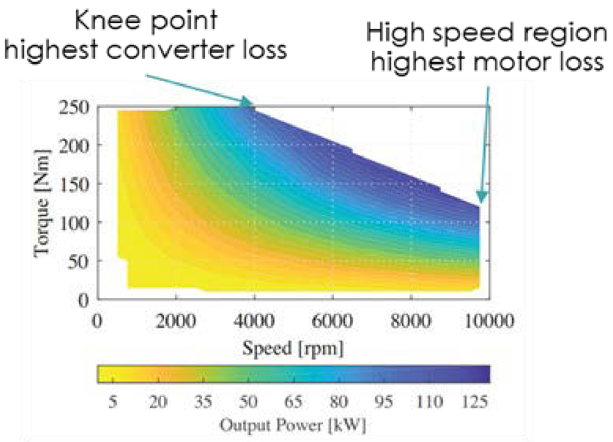
Responses to Previous Year Reviewers' Comments

- This reviewer noted good results from testing that show impact of some jet design parameters on the heat-transfer coefficient. It would have been good to see a reference heat-transfer coefficient for the typical cooling jacket design. It is not obvious how much better the jet impingement heat-transfer coefficient is compared to current state of the art.
  - As the planned work on characterization of jet impingement cooling is not complete, it is the researchers' intention to identify relevant ranges of heat-transfer coefficients for corresponding cooling techniques/methods (including values for single-phase forced convective cooling typical of cooling jacket design) on the compiled plots. Detailed cross-comparison and analysis will be presented in forthcoming papers planned to be published in FY 2020 and FY 2021.
- The reviewer said the jet impingent experiments results are interesting—as the surface temperature increases the convection coefficient increases. From a practical standpoint, how could you take advantage of that in the electric motor?
  - The phenomenon is most likely confined to fluids with strong temperature-dependent viscosity (ATF, Alpha 6, or other driveline and thermal management fluids with similar properties). The NREL-compiled database of heat transfer coefficient (HTC) values measured for a number of cooled surface temperatures will aid automotive original equipment manufacturers and electric machine manufacturers, as well as the broader research and development community, in the design and development of compact, high-performance, and reliable machines. Namely, knowing surface temperature-dependent HTC values helps in applying correct values at higher temperatures/thermal loads during modeling and design tasks.
- This reviewer said it is a good approach to continue on to methods of integrating the impingement cooling into a motor design. It is not clear how much testing is needed versus analysis. The reviewer asked how much more testing is really needed if the jet impingement analysis agreed well with the testing. One place more work might be needed is on the impact of cross flow of coolant on impingement, once you put more than one jet next to each other. Analysis or testing in this area should be considered.
  - Suggested expansion of cross flow or multiple jet effect on cooling performance is a logical continuation of this research. We are planning to explore thermal management implications associated with multiple jet impingement starting with finite element analysis (FEA) and computational fluid dynamics (CFD) modeling. Potentially expanding experimental capabilities in this direction in future as well. Compiling experimental data for off-center and number of jet impingement incidence angles, planned for FY 2020 and FY 2021, is a step in this direction.
- The reviewer said ATF-based cooling technology, if demonstrated by example, could be very useful for industries in niche applications that require simplification of vehicle architecture.
  - Researchers agree with the reviewer's viewpoint: one of the main goals of ATF jet impingement cooling characterization is providing HTC data to electric drive designers, enabling future single-fluid electric vehicle applications, eliminating the need of multiple fluid systems on a vehicle.

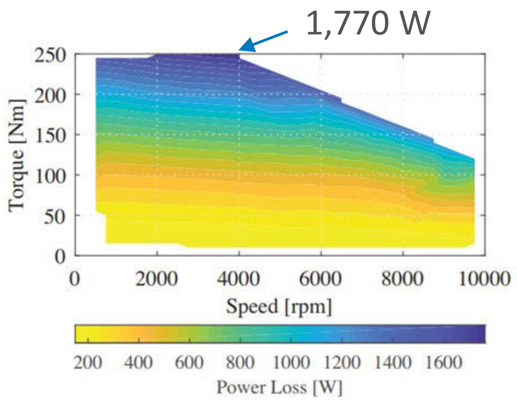
Any proposed future work is subject to change based on funding levels.

Collaboration and Coordination

- Oak Ridge National Laboratory provided input data for FEA thermal simulations
  - Thermal loads/losses for BMW i3 motor (Tsarafidy Raminosoa)
  - Thermal loads/losses for SiC–based power electronics module (Shajjad Chowdhury)



Power map of BMW i3 traction dive



Inverter loss map

Figures by Shajjad Chowdhury, ORNL

- University of Wisconsin-Madison
  - Initiated discussion on thermal management support from NREL for the U Wisconsin's integrated electric drive design (Thomas Jahns and Bulent Sarlioglu)
- Automotive OEMs – defining priorities and focus areas

Remaining Challenges and Barriers

- Gathering technical data and information on proprietary motor-integrated power electronics and thermal management solutions (not readily available or open source) for evaluation and comparison
- Identifying and obtaining driveline fluids suitable for direct cooling of electric machines or high-voltage (800–1,200 V) power electronics
- Potential need for quantifying electrical (dielectric) properties at high voltages for selected candidate fluids => requiring development of additional in-house fluid characterization capabilities or identifying external providers of similar services.

Proposed Future Research

FY 2020

- Complete FEA thermal simulations for identified integrated traction drive packaging geometries (baseline, radial, and axial integration) and cooling concepts
- Perform ATF jet impingement experiments for extended parameters (impingement angles, distances from the target)
- Identify (and obtain, if available) candidate dielectric driveline fluids suitable for direct cooling of electric machine components and power electronics for thermal characterization.

Beyond FY 2020

- Extend effort of characterizing jet impingement cooling with ATF to other driveline fluids
- If needed, quantify thermal and/or electrical (dielectric) properties of identified driveline fluids (building a test bench in house or via commercial testing service providers)
- Identify promising fluid jet delivery arrangements to motor windings (external jets: top, side; internal jets: upwards, side, bottom)
- Carry out CFD thermal modeling for comparison of different integrated thermal management approaches.

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

Summary

Relevance

- Effective thermal management is essential for high-performance, compact (power-dense), and reliable integrated electric traction drives to achieve the 2025 DOE system power density target of 33 kW/L

Approach/Strategy

- Research state-of-the-art thermal management solutions for integrated electric traction drives
- Identify component geometries based on publicly accessible scientific literature, published OEM materials, interactions with automotive industry, and collaboration with other research labs
- Experimentally quantify heat-transfer coefficients for direct jet impingement cooling with ATF and other driveline fluids
- Apply measured heat-transfer coefficients in finite element analysis thermal modeling for comparison of various integrated thermal management approaches

Technical Accomplishments

- Developed CAD and FEA models of radially and axially integrated power electronics in traction drive casing
- Performed initial FEA thermal simulations of radially and axially integrated traction drive concepts in Ansys
- Performed CFD modeling for ATF fan jet impingement cooling
- Published one paper on ATF jet impingement HTC at InterPACK 2019
- Two more paper publications on integrated-drive FEA thermal management modeling and fan jet CFD modeling are underway

Collaborations

- Industry: Automotive OEMs, driveline fluid manufacturers
- Research institutions: Oak Ridge National Laboratory, University of Wisconsin-Madison

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