Tutorial – Electric Motor and Integrated Traction Drive Thermal Management

Bidzina Kekelia and Xuhui Feng
Advanced Power Electronics and Electric Machines
Center for Integrated Mobility Sciences
National Renewable Energy Laboratory

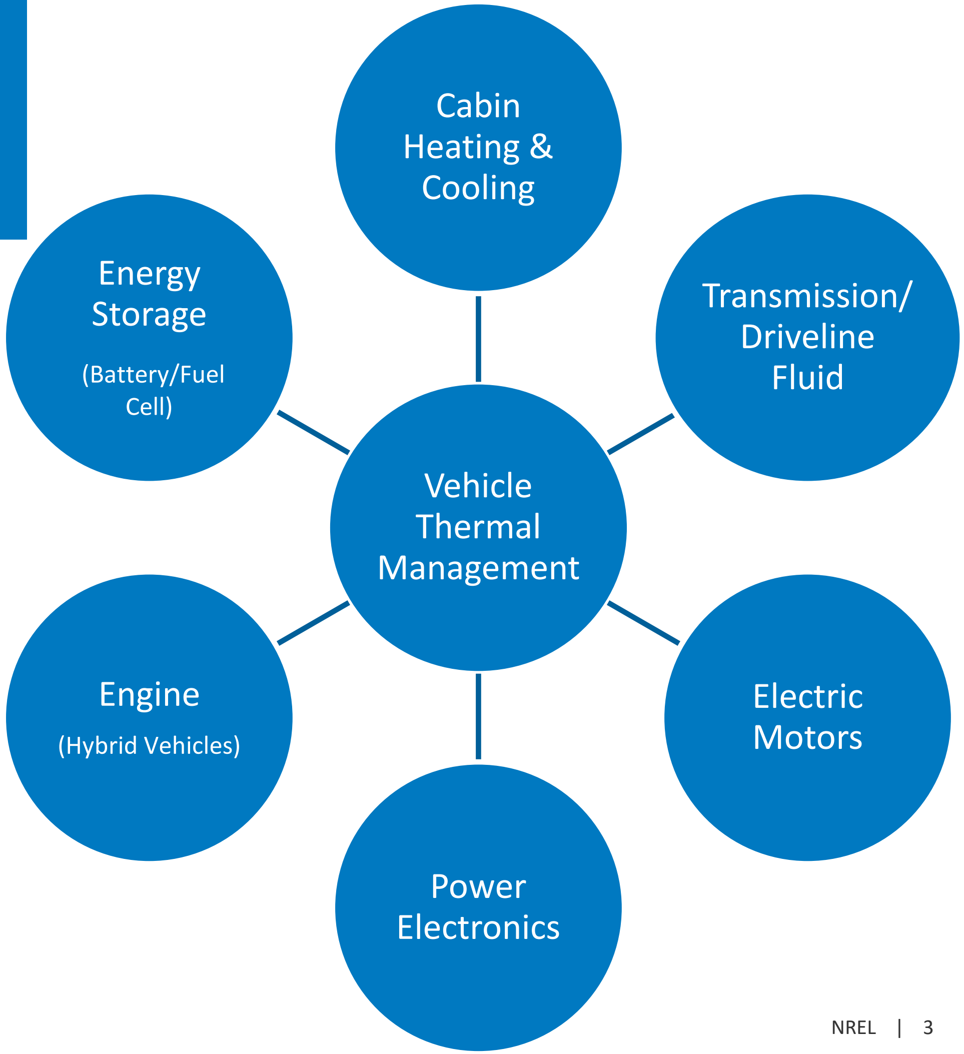
ASME InterPACK 2023
San Diego, CA
October 26, 2023

Tutorial Outline

1. Vehicle Thermal Management Systems
2. Power Electronics and Electric Motor Components
3. Integrated Traction Drive and Integration Techniques
4. Review of Integration and Cooling Approaches
5. Thermal Management System Design Workflow (CFD and FEA)
6. Experimental Characterization of Materials and Coolant HTCs
7. Challenges and Summary

Electric-Drive Vehicle Thermal Systems

- Multiple separate thermal management systems to manage temperature constraints for different vehicle subsystems.



Power Electronics and Electric Machines

Power electronics (inverters, converters, chargers) and electric machines (motors) are critical to controlling the power flow through electric-drive vehicles across a range of applications (hybrid, battery electric, fuel cell).

Photo credits: NREL 40146, NREL 22791

Motor Components Requiring Cooling

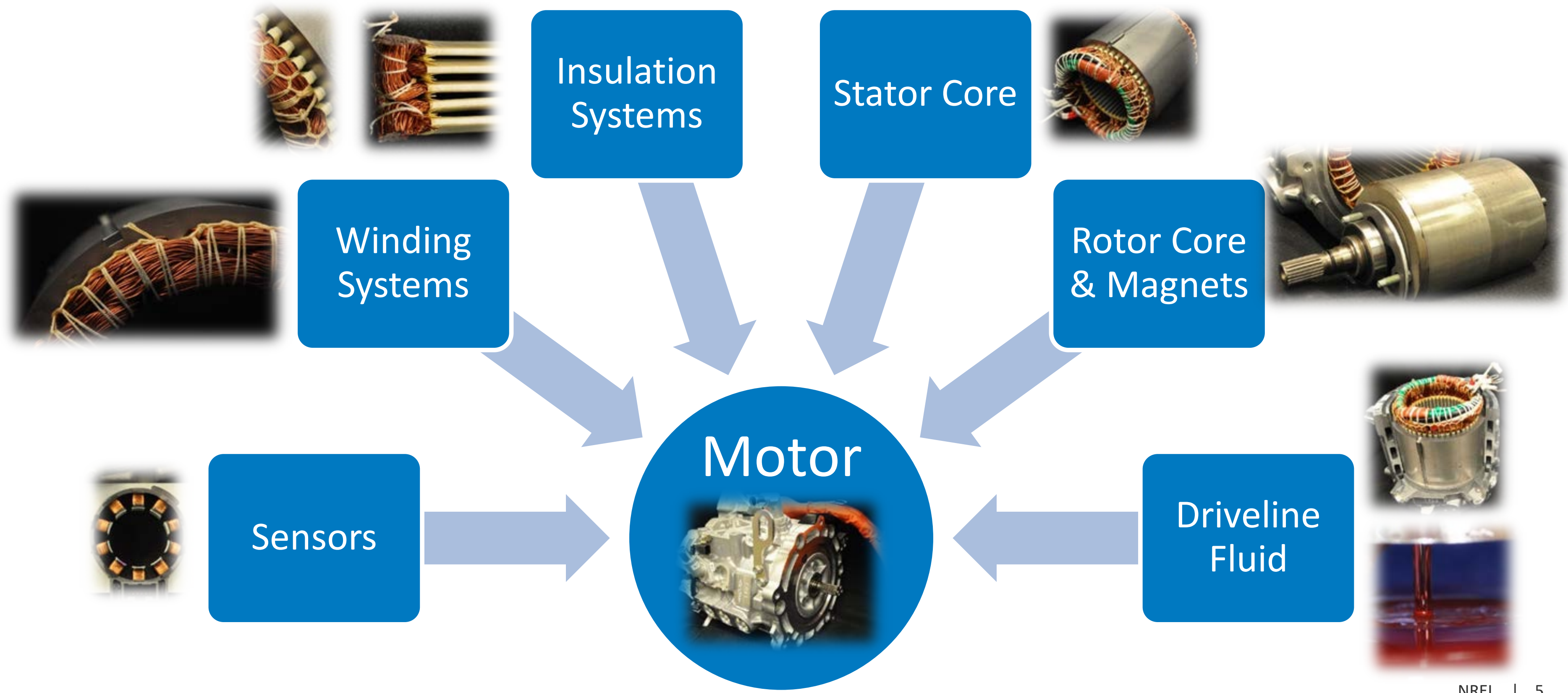


Photo credits: Kevin Bennion and Bidzina Kekelia, NREL

Inverter Components Requiring Cooling

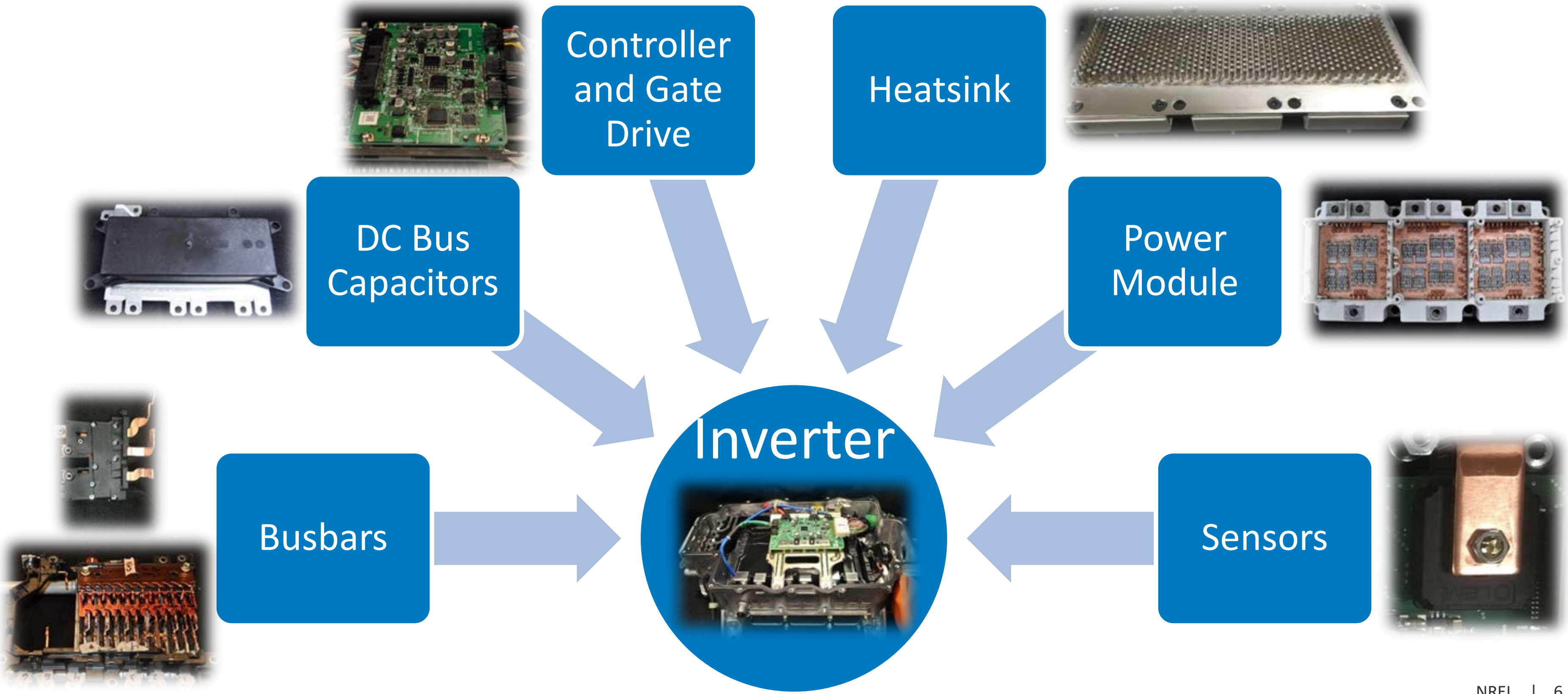


Photo credits: Gilbert Moreno and Xuhui Feng, NREL

Power Electronics and Electric Machines

Integrated Drive Unit: (Motor + Inverter) & Transmission

→

- Reduced Components
- Improved Power Density
- Reduced System Cost

Photo credits: NREL 40146, NREL 22791

U.S. Department of Energy (DOE) Vehicle Technologies Office
Electric Drive Technologies Research Pathway for Vehicle Electrification

Current electric vehicle (EV) platform (GM's 2017 Chevrolet Bolt battery-electric vehicle chassis with electric powertrain)

Future skateboard platform design concept (GM's flat skateboard chassis containing electric powertrain)

U.S. DRIVE 2025 Targets for Electric Traction Drive System	
Cost	**$6/kW (50% reduction)**
Power density	**33 kW/L (850% increase)**
Power level	**100 kW**
Reliability/lifetime	**300,000 miles (100% increase)**

Volumetric power density!

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

DOE ARPA-E Aviation Electric-Drive Efforts

Single-aisle (narrow-body) airplanes with 100–200 passengers

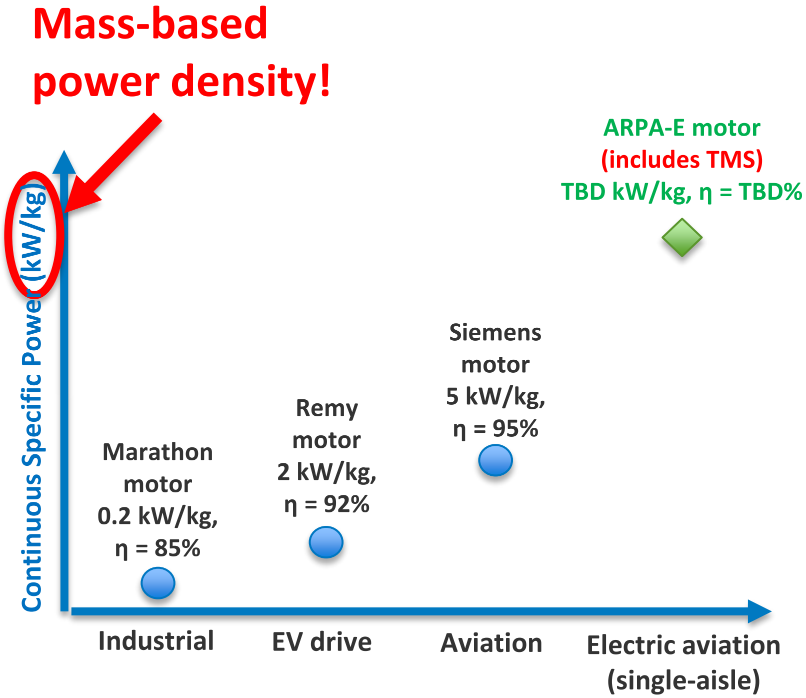
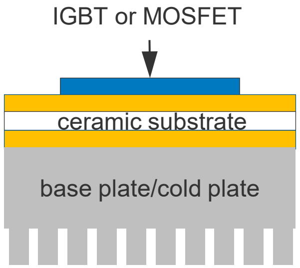


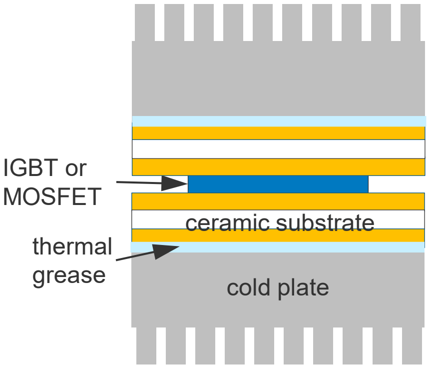
Photo credit: Dennis Schroeder, NREL

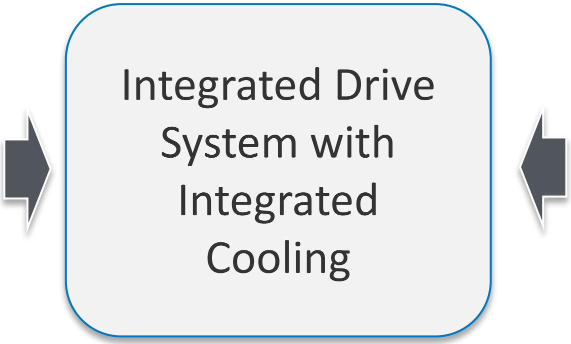
Source: Based on overview presentation by Dr. Michael Ohadi at the Advanced Research Projects Agency – Energy (ARPA-E) Workshop on Electrified Aviation, August 2019, Arlington, VA.

Integrated Electric Traction Drive

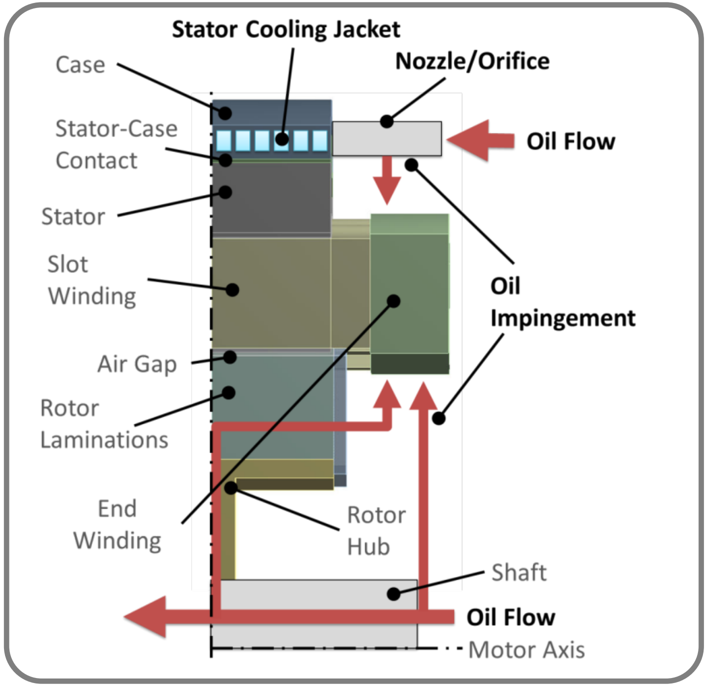
Power Electronics







Electric Motor

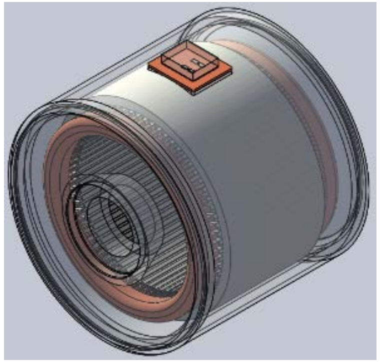


IGBT: insulated-gate bipolar transistor
MOSFET: metal–oxide–semiconductor field-effect transistor

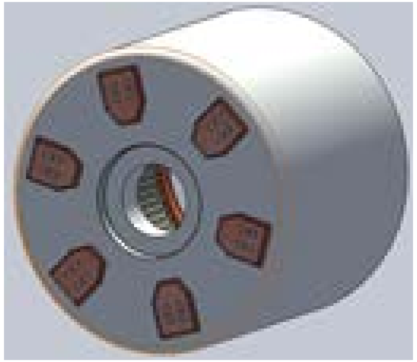
Integration Techniques

- Current industry trend: highly integrated, compact, traction drive unit.
- Different integration techniques.
- Various cooling strategies—preferably a single system/fluid approach.

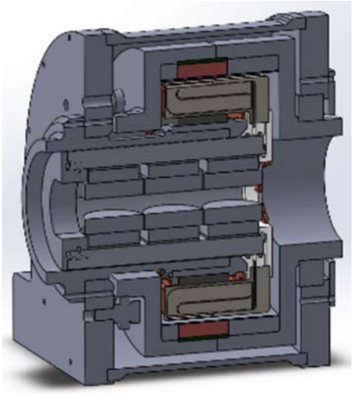
Separate enclosures



Radial integration

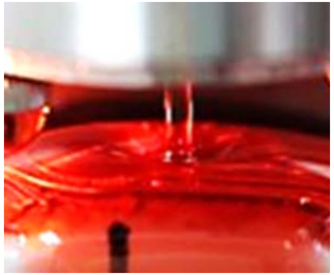


Axial integration



Inside motor

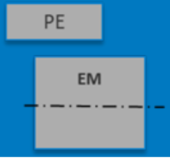
Available Choice of Coolants



- Water-ethylene/propylene glycol: 65°C
- Driveline fluids:
  - Oil or automatic transmission fluid (ATF): 80°C–90°C.
- EV-specific dielectric fluids:
  - Originally for battery thermal management: AC100, Alpha 6.
  - Mobil EV family of fluids.
  - Under development or proprietary formulations.
- Refrigerants for two-phase cooling:
  - Not yet widely adopted in current automotive power electronics applications.

Integration Approaches by Different Manufacturers and Research Teams

Power electronics and electric motor integration techniques and respective cooling approaches



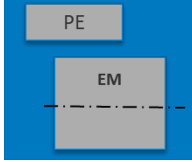
BMW i3

	Comments
Configuration	Motor and inverter separate
Coolant	Water/glycol
Other Comments	

Cooling Location	NA	Oil	Water Glycol
Stator housing			Y
Stator end winding	NA		
Stator slot winding	NA		
Rotor end plates	NA		
Rotor shaft	NA		
Inverter			Y
Motor/inverter lead cooling			N

Photos by NREL

Data source: Munro & Associates Inc. 2020. "Tearing Down Tesla Segment 8: Comparing the Cooling Strategy / Housings of Motors for Tesla Model 3 vs BMW i3." https://leandesign.com/wp/2020/03/10/tearing-down-tesla-segment-8-comparing-the-cooling-strategy-housings-of-motors-for-tesla-model-3-vs-bmw-i3/.

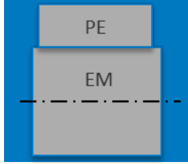


GM Chevy Bolt

	Comments
Configuration	Motor and inverter separate/remote
Coolant	Hybrid (oil and water/glycol)
Other Comments	Integrated oil-glycol heat exchanger

Cooling Location	NA	Oil	Water Glycol
Stator housing	NA		
Stator end winding		Y	
Stator slot winding	NA		
Rotor end plates		Y	
Rotor shaft	NA		
Inverter			Y
Motor/inverter lead cooling	NA		

Source: Steven Loveday. 2018. “Check Out The Chevy Bolt EV High Voltage Components In Detail.” *InsideEVs*, Dec. 6, 2018. https://insideevs.com/news/341420/check-out-the-chevy-bolt-ev-high-voltage-components-in-detail/.

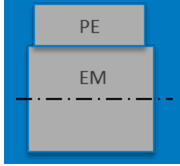


Nissan Leaf (2013)

	Comments
Configuration	Inverter radial mount on one side of motor
Coolant	Water/glycol
Other Comments	

Cooling Location	NA	Oil	Water Glycol
Stator housing			Y
Stator end winding	NA		
Stator slot winding	NA		
Rotor end plates	NA		
Rotor shaft	NA		
Inverter			Y
Motor/inverter lead cooling			Y

Source: H. Shimizu, T. Okubo, I. Hirano, S. Ishikawa, and M. Abe. 2013. “Development of an Integrated Electrified Powertrain for a Newly Developed Electric Vehicle.” SAE Technical Paper 2013-01–1759. http://papers.sae.org/2013-01-1759/.

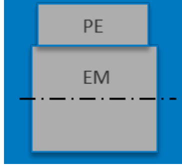


Audi e-Tron

	Comments
Configuration	Inverter radial mount on one side of motor
Coolant	Water/glycol
Other Comments	

Cooling Location	NA	Oil	Water Glycol	Air
Stator housing			Y	
Stator end winding	NA			
Stator slot winding	NA			
Rotor end plates	NA		Y (indirect)	Y
Rotor shaft	NA		Y	
Inverter			Y	
Motor/inverter lead cooling			N?	

Source: The Wheel Network. 2019. “Audi e-tron Electrical Components.” YouTube, Oct. 8, 2019. https://www.youtube.com/watch?v=sicWHkG6g8c.



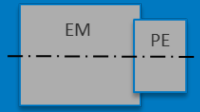
Lucid Air

	Comments
Configuration	Inverter radial mount on one side of motor
Coolant	Hybrid
Other Comments	Oil jet cooled with water-ethylene-glycol (WEG) heat exchanger

Cooling Location	NA	Oil	Water Glycol
Stator housing		?	
Stator end winding		Y	
Stator slot winding	NA		
Rotor end plates		?	
Rotor shaft		?	
Inverter			Y
Motor/inverter lead cooling			?

Sources:

1. https://www.greencarcongress.com/2020/09/20200903-lucid.html
2. https://www.topspeed.com/cars/car-news/lucid-s-drivetrain-technology-makes-the-air-the-flash-of-the-ev-world-ar189518/pictures.html#933889
3. https://www.lucidmotors.com/media-room/lucid-motors-proprietary-electric-drivetrain-technology-powers-record-setting-performance
4. Lucid Air | Performance (lucidmotors.com)
5. https://www.youtube.com/watch?v=nGan_iPPdqk



Tesla Model 3

	Comments
Configuration	Inverter axial mount over motor
Coolant	Oil (ATF 9)
Other Comments	Oil cooled with WEG heat exchanger

Cooling Location	NA	Oil	Water Glycol
Stator housing	NA	Y	
Stator end winding		?	
Stator slot winding	NA		
Rotor end plates		?	
Rotor shaft		?	
Inverter			Y
Motor/inverter lead cooling			?

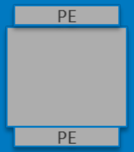
Sources:
1. Weber State University's YouTube Auto Channel:
Weber Auto, Tesla Model 3 and Y Modular Motors, (Jul. 03, 2021). Accessed: Jun. 23, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=SRUrB7ruh-8
2. All EV Canada, Tesla Model 3 Motor Tear Down - ALL EV, (Jun. 15, 2020). Accessed: Jun. 23, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=oVge8I6kxPY

American Axle & Manufacturing (AAM) Gen 5.0 3-In-1 EDU

	Comments
Configuration	Inverter axial mount
Coolant	Oil
Other Comments	Oil cooled with WEG heat exchanger

Cooling Location	NA	Oil	Water Glycol
Stator housing		Y	
Stator end winding		Y	
Stator slot winding	NA		
Rotor end plates		?	
Rotor shaft		Y	
Inverter		Y	
Motor/inverter lead cooling		?	

Source:
DOE Vehicle Technologies Office 2022 Annual Merit Review, Low Cost, High-Performance, HRE-Free 3-In-1 Electric Drive Unit, presentation by AAM, https://www1.eere.energy.gov/vehiclesandfuels/downloads/2022_AMR/elt179_crecelius_2022_o_5-1_1108am_ML.pdf



University of Wisconsin-Madison’s Integrated Traction Drive

	Comments
Configuration	CSI Power Electronics radial mount
Coolant	Water/glycol
Other Comments	Rotor cooled with air

Cooling Location	NA	Air	Water Glycol
Stator housing			Y
Stator end winding		Y	
Stator slot winding	NA		
Rotor end plates		Y	
Rotor shaft		Y	
Inverter			Y
Motor/inverter lead cooling			?

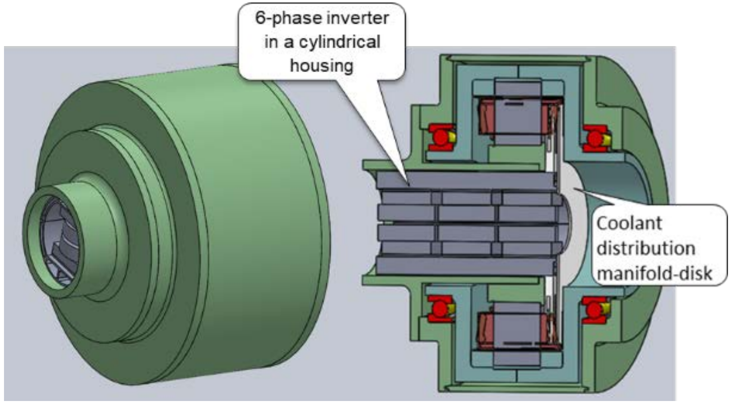
Source:
DOE Vehicle Technologies Office 2022 Annual Merit Review, Integrated Motor and Drive for Traction Applications, presentation by University of Wisconsin, https://www1.eere.energy.gov/vehiclesandfuels/downloads/2022_AMR/elt243_sarlioglu_2022_p%20-%20Bulent%20Sarlioglu_5.4_237pm_LS.pdf

PE

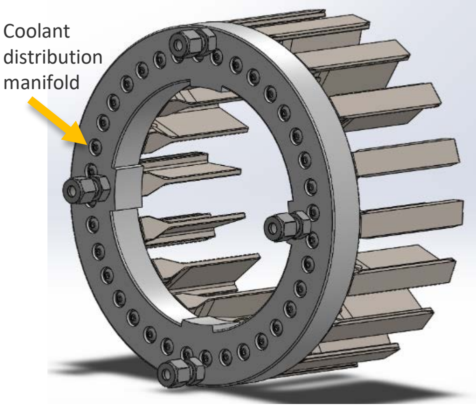
Outer-Rotor Motor With Integrated Inverter

Oak Ridge National Laboratory's (ORNL's) integrated traction drive features:

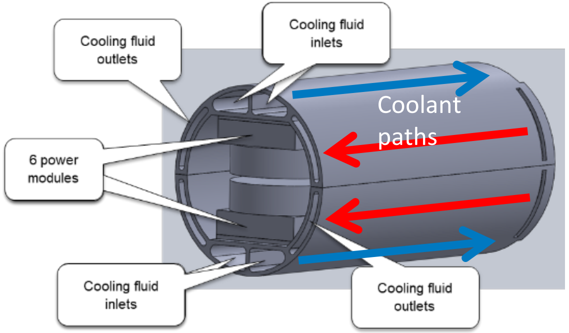
- Single WEG cooling loop approach.
- Cylindrical housing for a six-phase inverter with internal channels for a coolant flow.
- In-slot ceramic heat exchangers embedded between stator windings.[1]



Design concept of ORNL's integrated traction drive with inverter in central cavity. Computer-aided design (CAD) by ORNL and NREL.



Stator cooling assembly with 18 T-shape heat exchangers attached to coolant distribution manifold



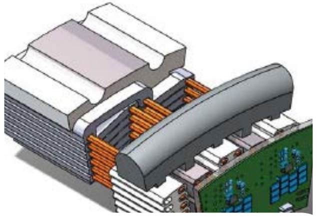
Design concept of a cylindrical inverter housing with cooling fluid channels in the walls. CAD by Bidzina Kekelia, NREL

[1] W. Sixel, M. Liu, G. Nellis, and B. Sarlioglu. 2021. "Ceramic 3-D Printed Direct Winding Heat Exchangers for Thermal Management of Concentrated Winding Electric Machines." *IEEE Transactions on Industry Applications* 57 (6): 5829–5840. doi: 10.1109/TIA.2021.3104273.

Thermal Management System Design Workflow

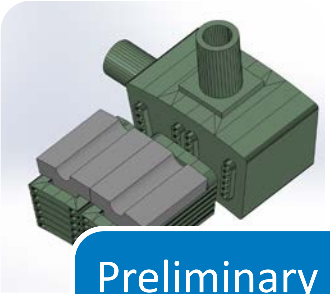
Thermal CFD and FEA modeling informing thermal management system design

Design and Analysis Process



Questions

- Cooling requirements
- Thermal path from heat source to ambient
- Possible cooling methods



b

Preliminary study

- Overall cooling capacity/goals
- Size of thermal management system (TMS)
- Coolant flow rate and temperature
- Heat sink details

Model

- 3D numerical models
- Temperature profile/heat dissipation
- Iteration and optimization with test results
- Test and validation

Questions To Start Design

- How much heat?
  - From the electromagnetic (EM) analysis
  - From MotorCAD design tool
  - From testing
- Temperatures?
  - Motor temperature limit
  - Coolant temperature
  - Ambient temperature
- System configuration?
  - All-in-one
  - Separate pump
  - Closed/open
  - Intermediate loop/direct cooling
- Spatial constraint?
  - Integrated
  - Stand-alone
- Which cooling method or coolant?
  - Air
  - Liquid (water, WEG, engine oil, lubricant…)
  - Hybrid

Preliminary Estimate

- Preliminary study is needed before detailed model-based design
  - Analytical method or empirical correlation
  - Estimate TMS size, heat sink geometry
  - Evaluate flow condition: temperature, flow rate, etc.

- It helps to narrow down the range of heat transfer coefficient(s) (HTCs), required surface area based on anticipated working and sink temperatures.

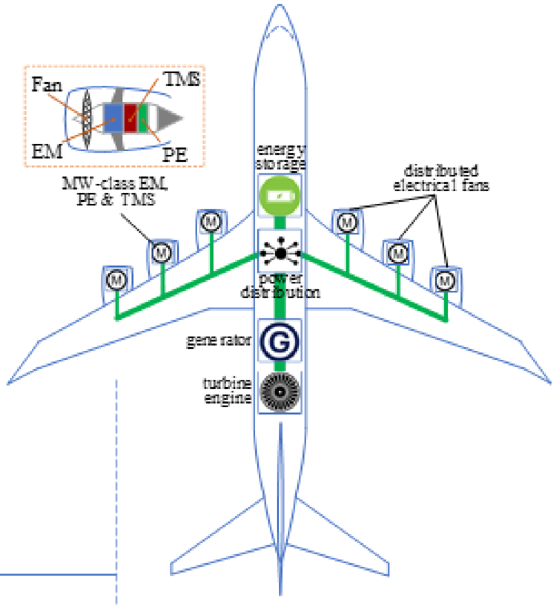
- It provides overall estimate of cooling capacity and helps with downselection of cooling methods.

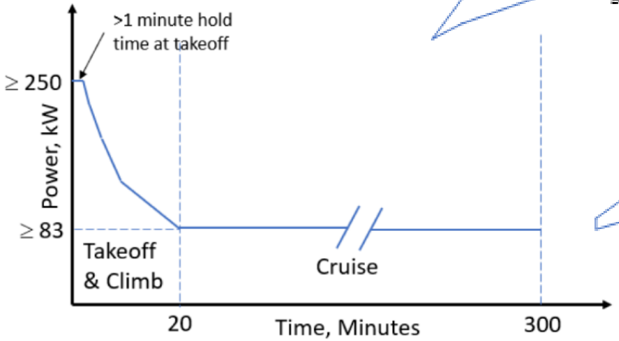
Modeling and Validation

- 1D thermal network
  - Hard to develop
  - Fast calculation
- 3D numerical tools
  - Thermal finite element analysis (FEA)
  - Computational fluid dynamics (CFD)
- Validation and iterations with aid of motor test results
- Model results can be fed back to EM design/optimization.

Case Study: Electric Propulsion System for Commercial Aircraft

- Thermal management system for an aircraft propulsion electric machine.
- Highly integrated drivetrain that consists of machine, power electronics, and TMS.
- Design metrics
  - Power
  - Power density
  - Temperature
  - Steady-state and transient performance.





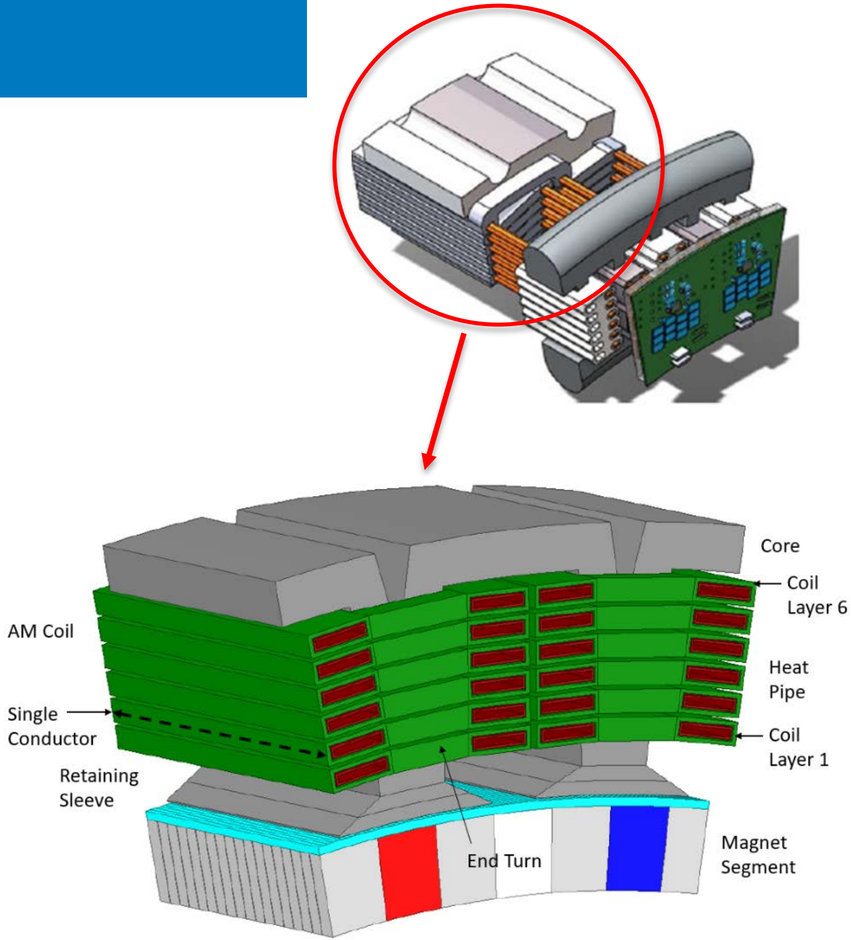
Design Specifications and Parameters

Item	Value
Machine specific power	20 kW/kg
Machine efficiency	>95%
System specific power	>12 kW/kg
Peak power	250 kW
Continuous power	83 kW

Source: T. Chowdhury *et al.*, "Thermal Management System for an Electric Machine with Additively Manufactured Hollow Conductors with Integrated Heat Pipes," *2022 International Conference on Electrical Machines (ICEM)*, Valencia, Spain, 2022, pp. 1920-1926, doi: 10.1109/ICEM51905.2022.9910918.

Estimate Cooling Needs and Conditions

- Due to structural symmetry, 1/18 of electric machine (motor) was extracted for analysis.
- It lays the foundation of TMS
  - Size TMS with machine
  - Match the cooling capacity with heat loss
    - Heat pipe Q_{max}
    - Heat exchanger
    - Path to ambient
  - Optimize overall machine geometry.

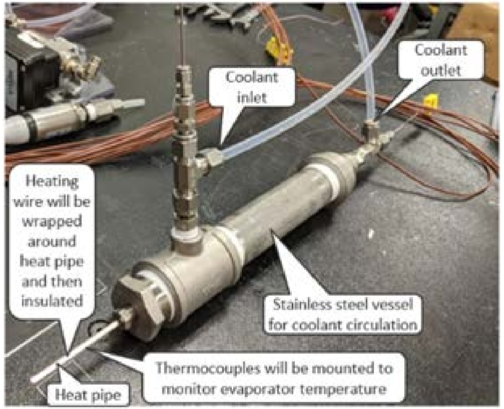


LOSS BREAKDOWN IN 1/18 OF THE MACHINE

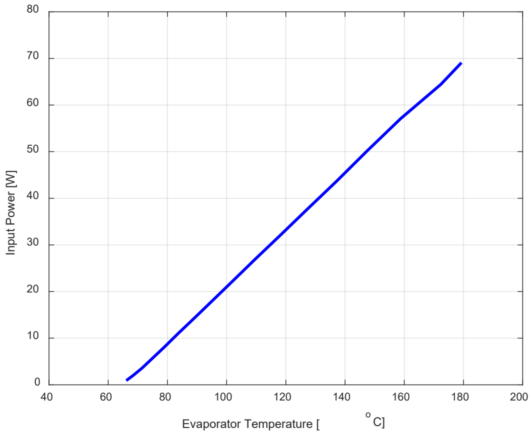
Loss Component	Loss [W]
AM coil	794
Stator core	277
Heat pipes	94.5
Magnets	36.7
Friction and windage	68

Preliminary Tests

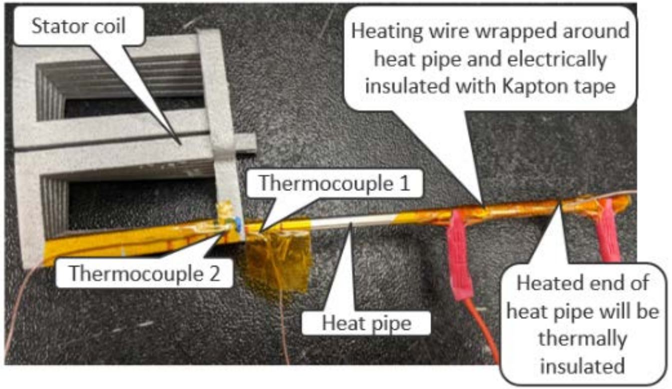
- In this design, additively manufactured coil with embedded heat pipe is the essential part of TMS.
- Characterization of heat pipe is critical
  - Heat pipe diameter affects the AM coil geometry and hence the heat loss.
  - Measure Q_{max} at various operating temperature
  - Evaluate thermal contact resistance
    - Thermal paste
    - Boron nitride coating.



Heat pipe Q_{max} test setup



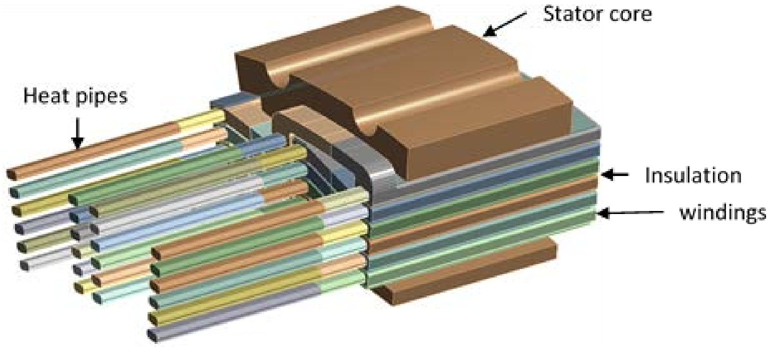
Flattened 6-mm heat pipe test



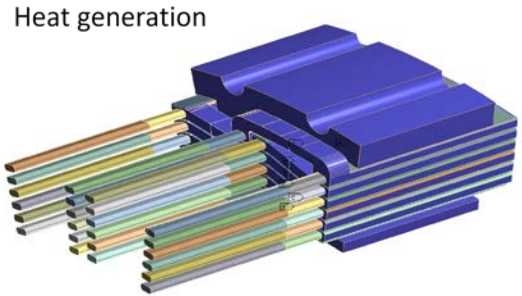
Heat pipe contact resistance measurement setup

Numerical Simulations

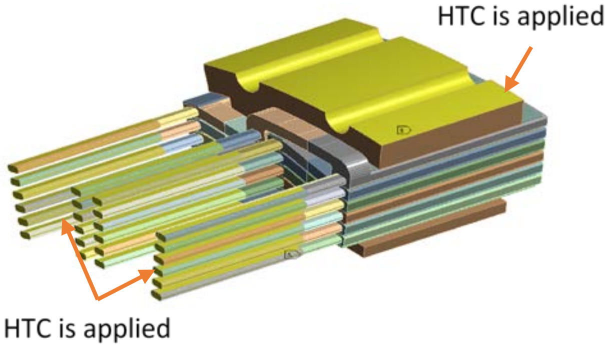
- 3D thermal FEA model is developed based on machine configuration and geometry
  - Include potting and insulation layers
  - Material properties (density, thermal conductivity, etc.)
  - Uniform or nonuniform heat loss
  - Steady-state or transient
  - Boundary conditions
    - Analytical calculation
    - Model prediction.



3D thermal model



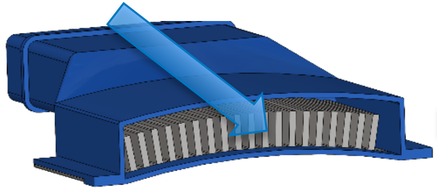
3D thermal model: heat sources



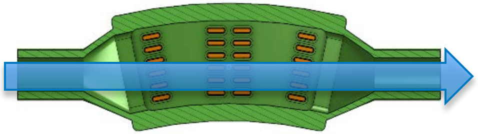
3D thermal model: cooled surfaces with HTC applied

Boundary Conditions

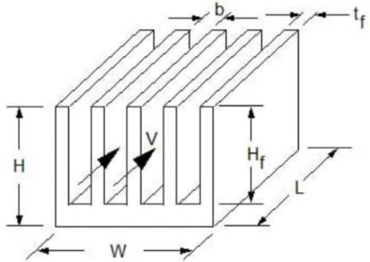
- Analytical method
  - Empirical correlation
  - Quick but often lacks accuracy



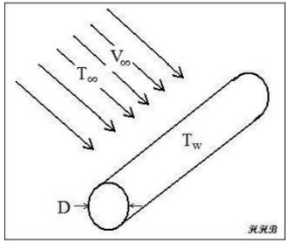
Air flow over fins



WEG over heat pipes



Parallel plate fin heat sink

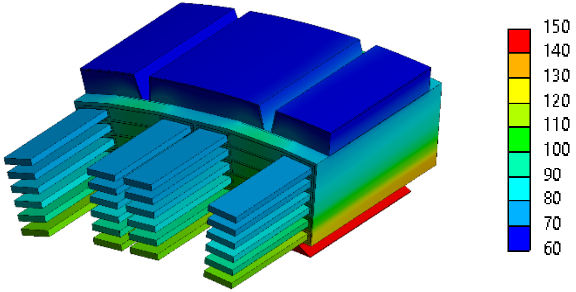


Cross flow over a circular cylinder

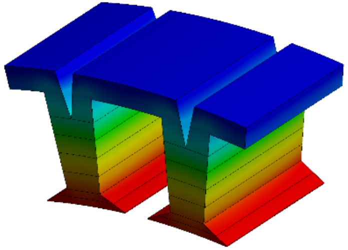
- Numerical method
  - CFD tool
  - More time to develop
  - Require knowledge for model parameters/setting
  - Higher accuracy
  - Derive location-wise information
    - Temperature
    - HTC
    - Heat flux.

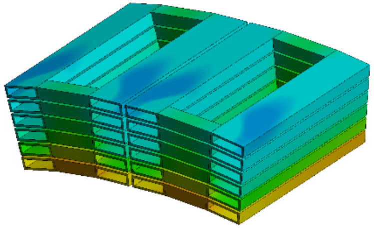
Modeling Results and Iterations

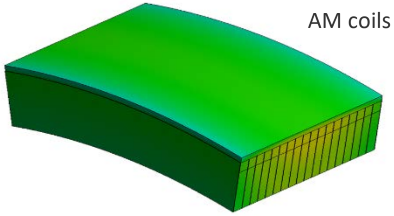
- Boundary condition from either empirical calculation or CFD predication.
- Temperature profile is obtained.
- Temperature in each layer can be fed back into EM for tuning the heat losses.
- Motor test can be used to validate numerical model.
- Validated model is used for design optimization.



Overall temperature profile


Stator core


AM coils

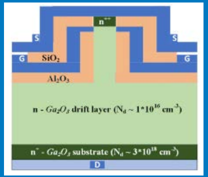

Magnets

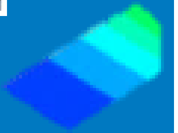
Experimental Characterization of Material Stack-Up Thermal Resistances and Coolant HTCs

NREL's experimental research

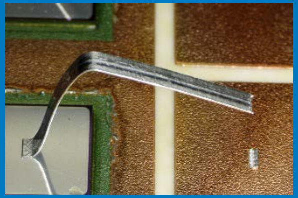
NREL APEEM Group Research Focus Areas

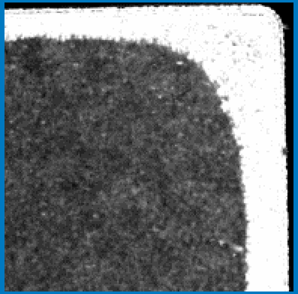
Power Electronics



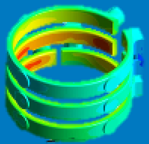


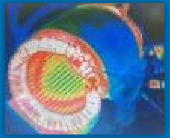
Advanced Packaging Reliability

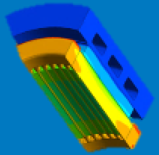




Electric Motor







Electric Motor Research

- Understand and evaluate material and interface properties as a function of temperature.
- Develop and evaluate advanced fluid-based cooling strategies.
- Modeling to guide advanced motor design and development.

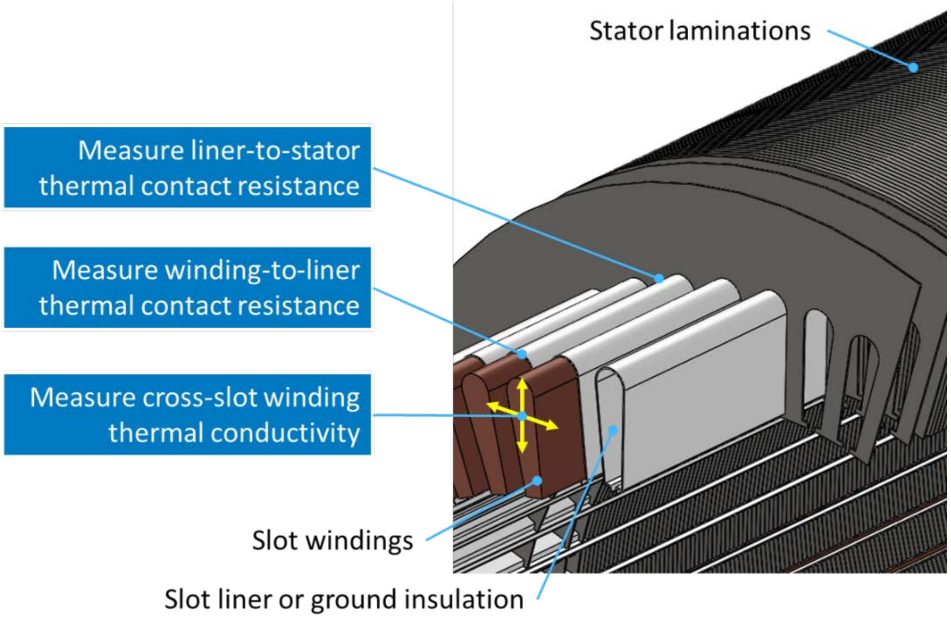
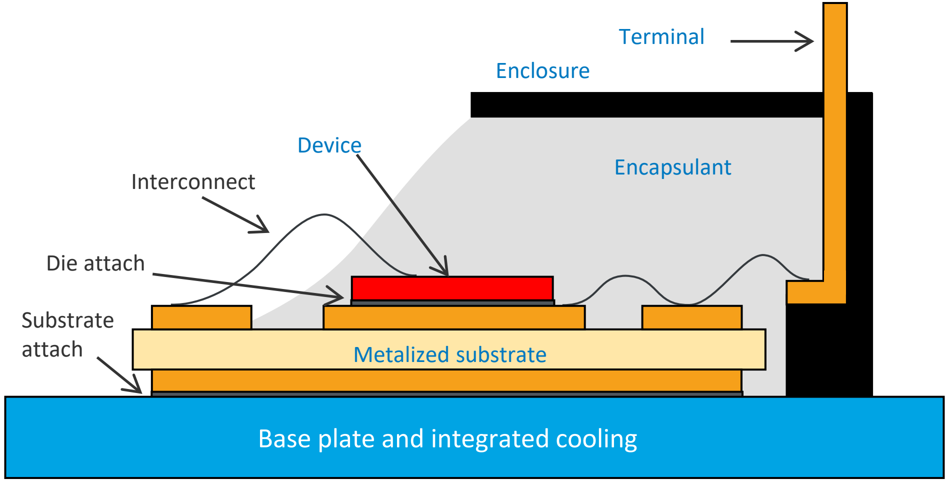


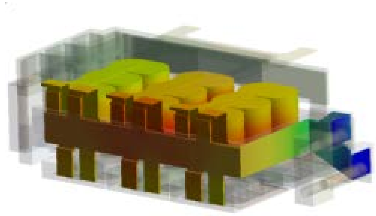
Image by Emily Cousineau, NREL

Power Electronics Thermal-Fluids Research

- Compact, power-dense, wide-bandgap-device-based power electronics
  - Higher-temperature-rated devices, components and materials.
  - Advanced heat transfer technologies.
  - System-level thermal management.



Advanced cooling

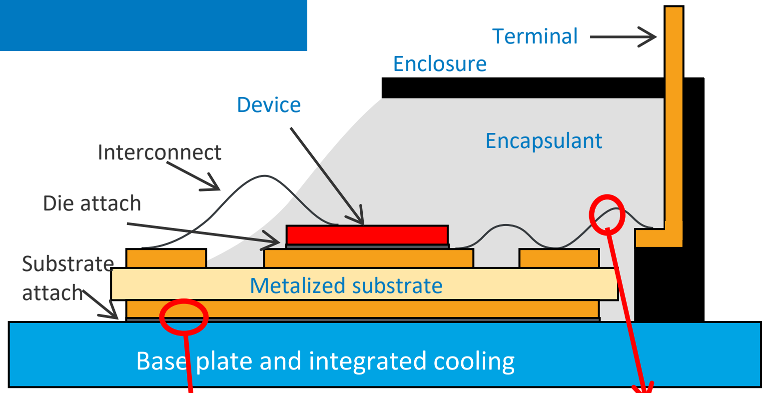


Component-level and system-level heat transfer

Images by Gilbert Moreno, NREL

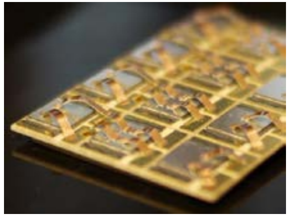
Power Electronics Reliability

- Improve reliability
- Develop predictive and remaining lifetime models
- State-of-health estimation
- Package parametric modeling.

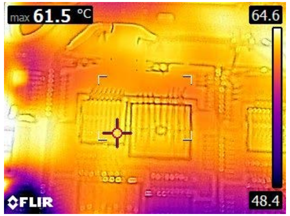


Bonded interface

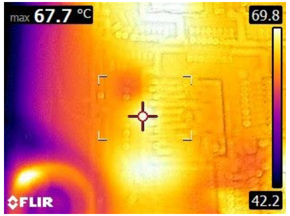
Electrical interconnects



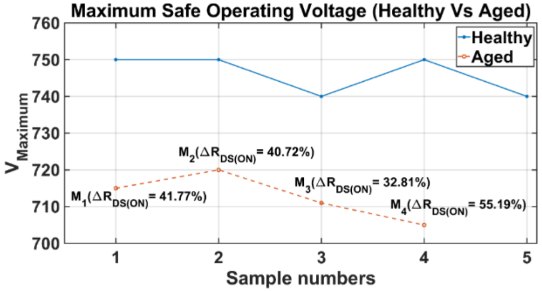
Destructive test results



Healthy device



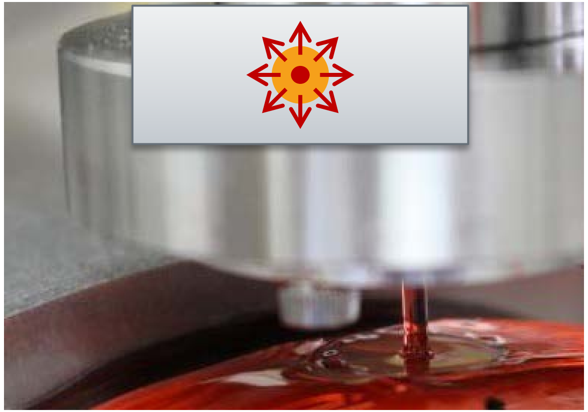
Aged device (hot spot is formed)



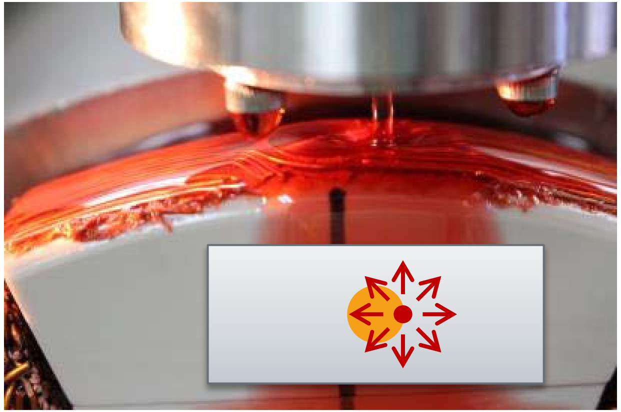
(Safe operating voltage goes down with aging)

ATF Cooling of Windings

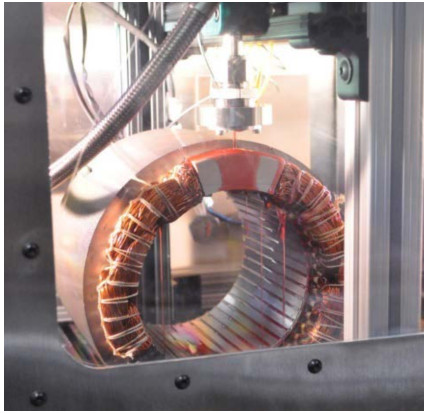
- Measuring heat transfer variation along winding.
- Quantifying impact of new or alternative cooling approaches for ATF cooling of motors.



Orifice jet center impingement



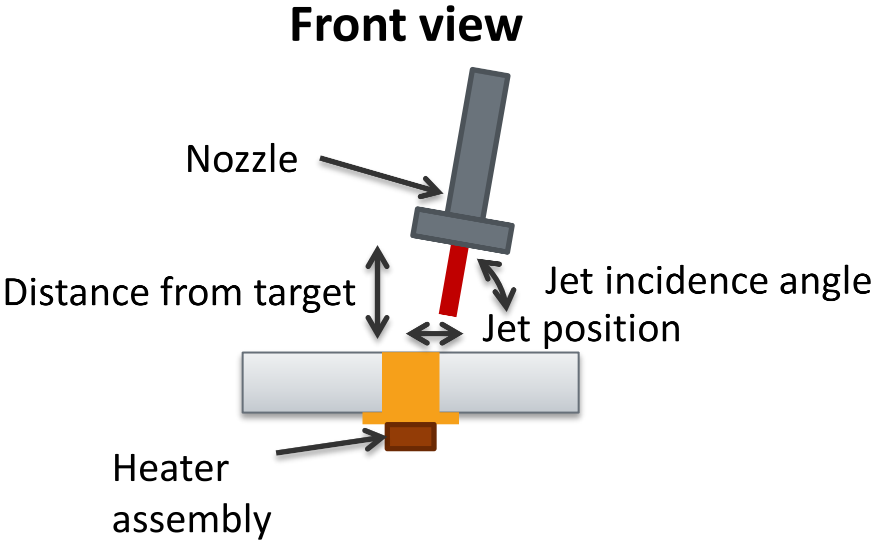
Orifice jet edge impingement



Test enclosure

Figures by Bidzina Kekelia and Kevin Bennion, NREL

Measurement Method



$$h = \frac{q_s}{A_s(T_s - T_l)}$$

$h = heat\ transfer\ coefficient$

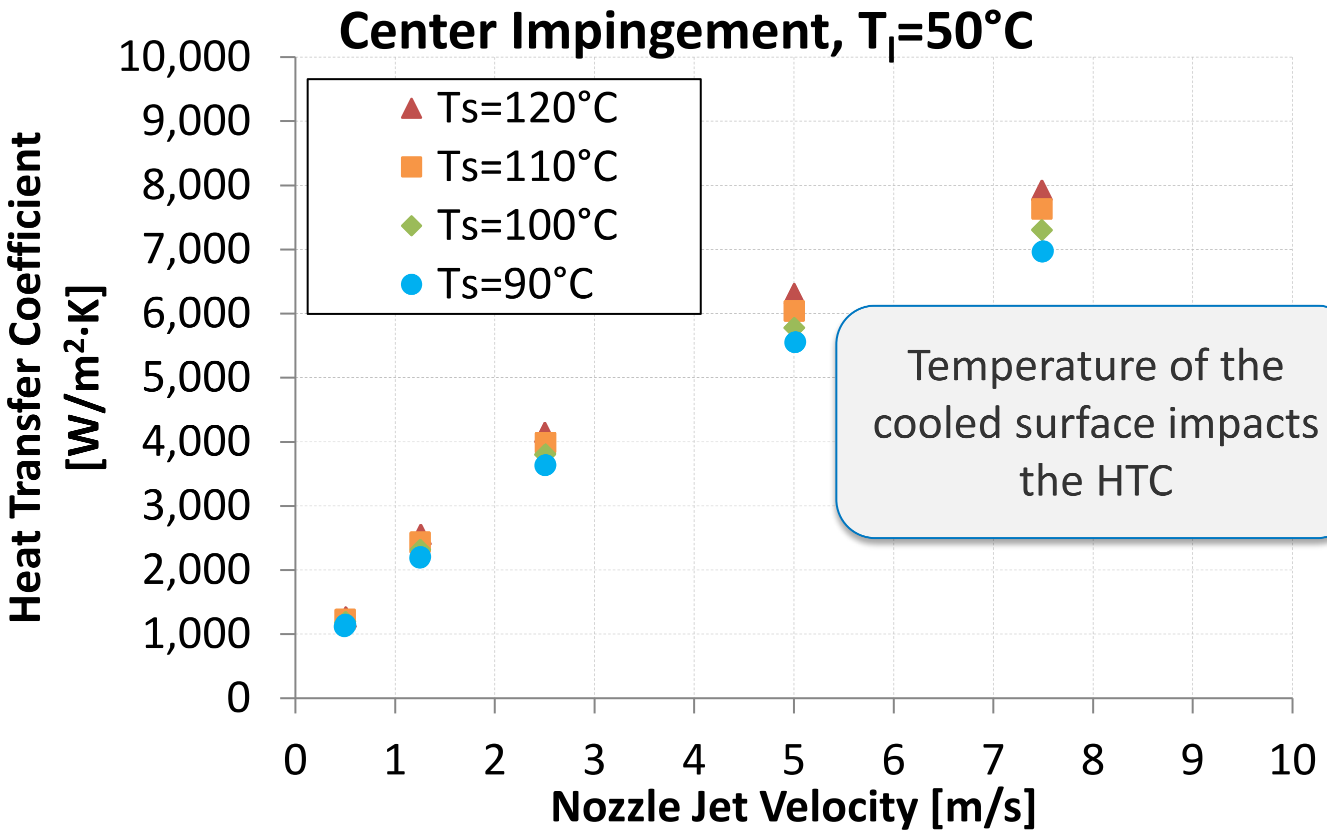
$q_s = heat\ removed\ from\ target\ surface$

$A_s = area\ of\ target\ surface$

$T_s = target\ surface\ temperature$

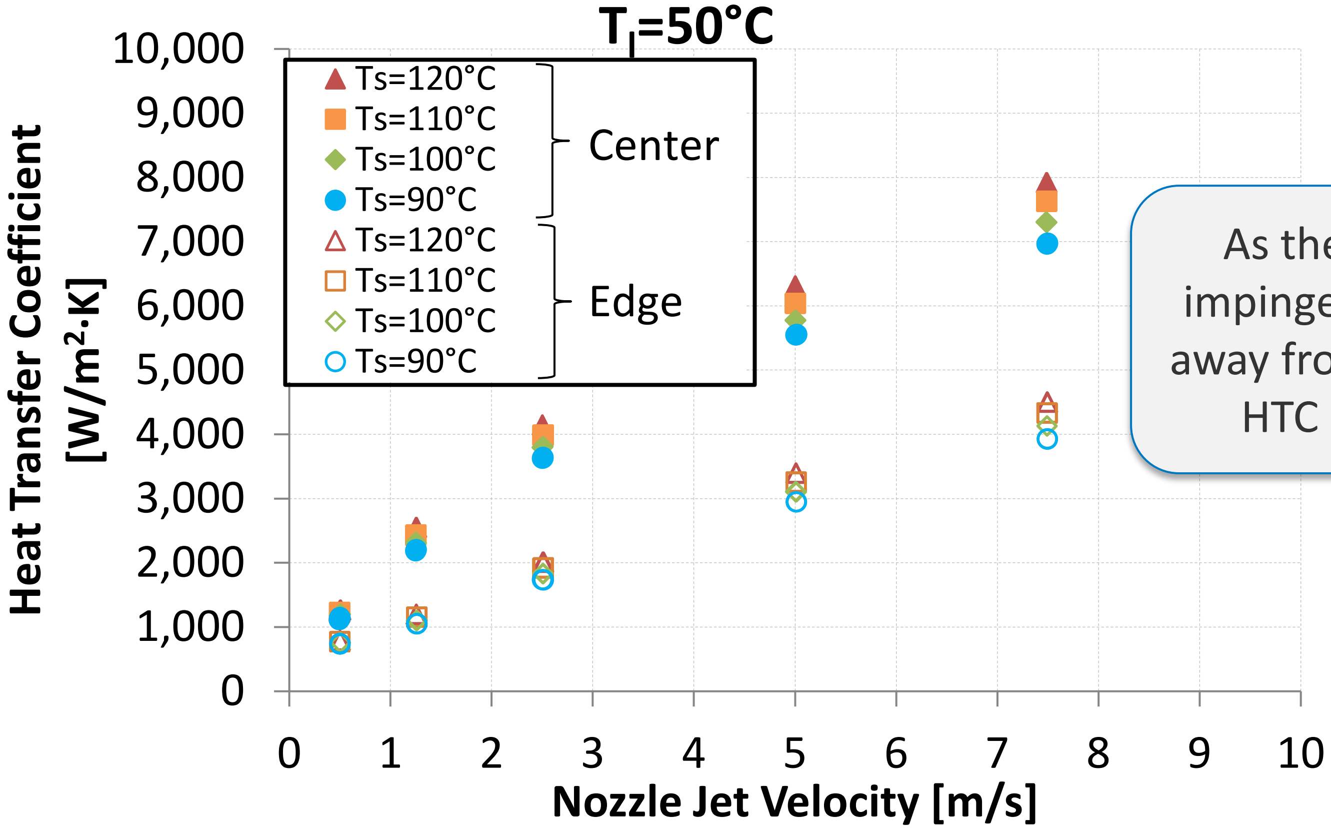
$T_l = fluid\ or\ liquid\ temperature$

Heat Transfer Comparison



Temperature of the cooled surface impacts the HTC

Heat Transfer Comparison



As the orifice jet impingement moves away from center, the HTC decreases

Summary

Tutorial Conclusions

Remaining Challenges and Barriers

- Design of a single thermal management system for power electronics and electric motor would require cooling fluids with appropriate physical, thermal, and dielectric properties.
- Material selection/compatibility of system components with coolants.
- Coefficient of thermal expansion (CTE) mismatch between components of cooling system poses a problem when thermally cycling electric-drive components.
- Leak-free sealing of cooling system components inside an integrated traction drive is challenging.

Summary

- **Active cooling is critical** for today's (and especially future) power-dense EV traction drives.
- Different manufacturers opt for different integration and consequently cooling approaches, but mostly rely on a **combination of oil and water/glycol fluids**.
- **Direct driveline fluid cooling** is potentially one of the most effective (single-phase) thermal management solutions.
- Development and wide adoption of **EV-specific dielectric fluids** is paramount for reduction of thermal management system size and achieving high system power density targets for integrated drive units.
- **Measurements of thermal path resistance and HTCs** help with design of the thermal management system.

Thank You

www.nrel.gov

NREL/PR-5400-87844

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Photo from iStock-627281636

NREL
Transforming ENERGY