Jet Impingement Cooling of Electric Machines with Driveline Fluids

Bidzina Kekelia, Ph.D., Senior Research Engineer
Advanced Power Electronics and Electric Machines Group, Center for Integrated Mobility Sciences
LES4ECE 2021 Virtual Conference
June 16, 2021
Leading clean energy innovation for 43 years
2,400+ employees with world-class facilities
Campus is a living model of sustainable energy
Owned by the U.S. Department of Energy (DOE)
Operated by the Alliance for Sustainable Energy

https://www.allianceforsustainableenergy.org/about.html
Scope of NREL Mission

- **Sustainable Transportation**
  - Vehicle Technologies
  - Hydrogen
  - Biofuels

- **Energy Productivity**
  - Residential Buildings
  - Commercial Buildings
  - Manufacturing

- **Renewable Electricity**
  - Solar
  - Wind
  - Water: Marine Hydrokinetics
  - Geothermal

- **Systems Integration**
  - Grid Integration of Clean Energy
  - Distributed Energy Systems
  - Batteries and Thermal Storage
  - Energy Analysis

- **Partnerships**
  - Private Industry
  - Federal Agencies
  - State/Local Government
  - International
APEEM Group: Eleven (11) staff members involved in thermal, electrothermal, thermomechanical, and reliability research activities.
DOE Electric Drive Technologies (EDT) Program

U.S. DRIVE Partners:
- US Automotive Industry (FCA, Ford, GM, OEMs)
- Electric Utility Industry
- Fuels Industry (BP, Chevron, Phillips 66, ExxonMobil, Shell)

Research Laboratories
- Oak Ridge National Laboratory
  Lead: Power Electronics and Electric Motors
- NREL
  Lead: APEEM Thermal Management/Reliability
- Others: Sandia National Labs, Ames Laboratory

Industry, Automotive Suppliers, and University Interactions

1 https://www.energy.gov/eere/vehicles/us-drive
Research Pathway for Electric-Drive Vehicle Electrification

U.S. DRIVE Electrical and Electronics Technical Team (EETT) Roadmap defines the pathway to 2025 targets

Current EV Platform
(GM’s 2017 Chevrolet Bolt BEV Chassis with Electric Powertrain)

Future Skateboard Platform Design Concept
(GM’s Flat Skateboard Chassis Containing Electric Powertrain)

<table>
<thead>
<tr>
<th>2025 Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
</tr>
<tr>
<td>$6/kW (50% reduction)</td>
</tr>
<tr>
<td>Power Density</td>
</tr>
<tr>
<td>33 kW/L (850% increase)</td>
</tr>
<tr>
<td>Power Level</td>
</tr>
<tr>
<td>100 kW</td>
</tr>
<tr>
<td>Reliability/Lifetime</td>
</tr>
<tr>
<td>300,000 miles (100% increase)</td>
</tr>
</tbody>
</table>

(ARPA-E) Aviation Electric Drive Efforts

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

Mass-based power density!

- Marathon motor: 0.2 kW/kg, η = 85%
- Remy motor: 2 kW/kg, η = 92%
- Siemens motor: 5 kW/kg, η = 95%
- ARPA-E motor (includes TMS): TBD kW/kg, η = TBD%

Source: Based on overview presentation by Dr. Michael Ohadi at the ARPA-E Workshop on Electrified Aviation, August 2019, Arlington, VA.
NREL APEEM Group Research Focus Areas

- **Power Electronics**
  - Thermal and Electrothermal

- **Advanced Packaging**
  - Designs and Reliability

- **Electric Motor**
  - Thermal Management
Power Electronics Thermal and Electrothermal Research

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

Advanced cooling
Component- and system-level heat transfer
Power Electronics: Semiconductor Device and Package Research

- Semiconductor modeling research for WBG and ultrawide-bandgap (UWBG) devices
- Electrical and electromagnetic design for power electronics packages

Multi-chip power module

Equivalent circuit of extracted package

Micro- to nanoscale device modeling
Advanced Power Electronics Packaging Performance and Reliability

- Improve reliability of new (high-temperature/WBG) technologies
- Develop predictive and remaining lifetime models
- Package parametric modeling
Thermal and Electrothermal Capabilities

Modeling Capabilities

FEA: Finite element analysis
CFD: Computational fluid dynamics
Electric Motor Thermal Management

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

Photo credit: Kevin Bennion, NREL

Figure credit: Emily Cousineau, NREL
Integrated Traction Drive System

- Current industry trend: highly integrated, compact, single unit traction drive design
- Different motor integration techniques of power electronics
- Various cooling strategies for most efficient heat removal from integrated traction drive components
  - Preferably a single fluid loop approach for integrated cooling system for motor + inverter cooling

Figure credits: Bidzina Kekelia, NREL
Active Cooling with Driveline Fluids

- Direct cooling with driveline fluids
  - Develop experimental methods to measure heat transfer
  - Quantify impact of new or alternative cooling approaches for automatic transmission fluid (ATF) cooling of electric machines
  - Measure convective heat transfer coefficients for ATF and other driveline fluid jet impingement cooling of end windings

Figure credits: Emily Cousineau, NREL

Photo credit: Bidzina Kekelia, NREL
Experimental Heat Transfer Coefficient Measurements

\[ h = \frac{Q_s}{A_s(T_s - T_f)} \]

- \( h \) = average heat transfer coefficient
- \( Q_s \) = heat removed from target surface
- \( A_s \) = area of target surface
- \( T_s \) = target surface temperature
- \( T_f \) = fluid or liquid temperature

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid temperature ( (T_f) )</td>
<td>50°C, 70°C, 90°C</td>
</tr>
<tr>
<td>Surface temperature ( (T_s) )</td>
<td>90°C, 100°C, 110°C, 120°C</td>
</tr>
<tr>
<td>Jet incidence location</td>
<td>center, edge</td>
</tr>
<tr>
<td>Jet incidence angle</td>
<td>90°, (planned: 60°, 45°)</td>
</tr>
<tr>
<td>Nozzle distance from target</td>
<td>10 mm, (planned: 5 mm, 15 mm)</td>
</tr>
</tbody>
</table>

Figure credit: Kevin Bennion, NREL
Orifice Jet Impingement Positions

Center

- a) Impinging at 90° on target center
- d) Impinging at 45° on target center

Edge

- b) Impinging at 90° on target edge
- e) Impinging at 45° on target edge

Away from edge

- c) Impinging at 90° off target edge
- f) Impinging at 45° off target edge

Figure and photo credits: Bidzina Kekelia, NREL
Orifice Jet Impingement Cooling with ATF

- Experimental measurements with Ford MERCON® LV ATF
- Target surface **topography enhancement** impact on heat transfer [1]
- Target surface **temperature** impact on heat transfer [2]:
  - Increasing target surface temperature increases heat transfer coefficient (HTC): $T_s \uparrow \Rightarrow h \uparrow$
  - Increasing surface temperature from 90°C to 120°C enhanced HTC values by **15%**
  - Likely due to increased fluid film temperature near heated surface
    - Reduced viscosity (strongly temperature-dependent for ATF)
    - Thinner viscous boundary layer (increased fluid flow above target surface)
    - Thinner thermal boundary layer with higher temperature gradients $\left(\frac{\partial T}{\partial y}\right)$ enhancing heat transfer (higher HTC)

Heat Transfer Coefficients for ATF at $T_f = 50^\circ$C

• Temperature (T) of the cooled surface affects HTC values: $T_S \uparrow \Rightarrow h \uparrow$

• Target surface temperature increase from 90°C to 120°C yielded 13%–15% increase in HTC values
Heat Transfer Coefficients for ATF at $T_f = 70^\circ$C

- Temperature ($T$) of the cooled surface affects HTC values:
  \[ T_s \uparrow \Rightarrow h \uparrow \]

- Target surface temperature increase from 90°C to 120°C yielded 14%–15% increase in HTC values
Summary

- Active cooling is critical for today’s (and especially future) power-dense electric vehicle traction drives
- Direct driveline fluid jet impingement cooling is one of the most effective (single fluid) thermal management solutions
- Experimental HTC measurements – data useful for design and modeling of electric machines for electric traction drive vehicles
  - Target surface **topography enhancement** impact on heat transfer
  - Target surface **temperature** impact on heat transfer (ATF)

\[ T_s \uparrow \rightarrow h \uparrow \]

- Current experimental measurements with Ford MERCON® LV ATF, but characterization of other driveline fluids is planned.
Thank You

Acknowledgments

Susan Rogers, U.S. Department of Energy

NREL EDT Task Leader

Sreekant Narumanchi
Sreekant.Narumanchi@nrel.gov
Phone: 303-275-4062

NREL Team Members Contributing to ATF Jet Impingement Experiments

Kevin Bennion
Emily Cousineau
Xuhui Feng
Gilbert Moreno

For more information, contact:

Bidzina Kekelia
Bidzina.Kekelia@nrel.gov
Phone: 303-275-4452

www.nrel.gov

NREL/PR-5400-80261
Additional Slides

More Information
How To Work with NREL

Visit: https://www.nrel.gov/workingwithus/technology-partnership-agreements.html

• Shared Resources Collaboration (DOE EDT Projects)

• Cooperative Research and Development Agreements (CRADAs)
  o Shared Resources
  o Funds-In

• Strategic Partnership Projects
  o Interagency Agreement
  o Funds-In Agreement
  o Technical Services Agreement

• Teaming on Proposals in Response to Solicitations
Experimental Heat Transfer Coefficient Measurements - Equations

\[ \bar{h} = \frac{Q_{surf}}{A_{surf}(T_{surf} - T_{fluid})} \]

\( \bar{h} \) = average heat transfer coefficient

\( Q_{surf} \) = heat removed from target surface

\( A_{surf} \) = area of target surface

\( T_{surf} \) = target surface temperature

\( T_{fluid} \) = fluid or liquid temperature

\( k \) = thermal conductivity

- Sides of the target are insulated and negligible losses to the sides (but not to the bottom) are assumed
- Heat flow \( Q \) in x-direction (from bottom to top), neglecting heat losses to the sides:

\[ -kA_{surf} \frac{T_{up} - T_{down}}{D_{x1}} = -kA_{surf} \frac{T_{surf} - T_{up}}{D_{x2}} = \bar{h}A_{surf}(T_{surf} - T_{fluid}) \]

- Expressing \( \bar{h} \) from above equations:

\[ \bar{h} = k \frac{T_{down} - T_{up}}{D_{x1}(T_{surf} - T_{fluid})} \]

- Expressing \( T_{surf} \) from above equations:

\[ T_{surf} = T_{up} + \frac{D_{x2}(T_{up} - T_{down})}{D_{x1}} \]

- Final equation for heat transfer coefficient calculation (after substituting \( T_{surf} \)):

\[ \bar{h} = k \frac{T_{down} - T_{up}}{D_{x1}(T_{up} - T_{fluid}) - D_{x2}(T_{down} - T_{up})} \]

Figure credits: Emily Cousineau, Bidzina Kekelia, NREL