Thermal Management for Planar Package Power Electronics

Cooperative Research and Development Final Report

CRADA Number: CRD-17-00683

NREL Technical Contact: Emily Cousineau

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-96477
September 2025

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Cooperative Research and Development Agreement Final Report

Report Date: June 24, 2025

In accordance with requirements set forth in the terms of the Cooperative Research and Development Agreement (CRADA), this document is the final CRADA report, including a list of subject inventions, to be forwarded to the U.S. Department of Energy (DOE) Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: John Deere Electronic Solutions, Inc. (JDES)

CRADA Number: CRD-17-00683

CRADA Title: Thermal Management for Planar Package Power Electronics

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Sponsoring DOE Program Office:

Office of Energy Efficiency and Renewable Energy (EERE), Vehicle Technologies Office

Joint Work Statement Funding Table Showing DOE Commitment:

Estimated Costs	NREL Shared Resources Government In-Kind
Year 1 Year 2	$125,000 $125,000
TOTALS	$250,000

Abstract of CRADA Work:

The National Renewable Energy Laboratory (NREL) and John Deere Electronic Solutions (JDES) collaborated to develop and evaluate computer models and simulations related to the thermal performance of semiconductor device packaging for an inverter of an off-road vehicle ("Semiconductor Packaging"). The objective of the research was for NREL and JDES to develop a two or three-dimensional computer-aided design model of the Semiconductor Packaging ("Computer Model") for thermal performance evaluation in a simulation. The project developed computer models of a Semiconductor Package of silicon-carbide semiconductor devices with appropriate thermal dissipation via one or more of the following thermal features: a double-sided planar cooling configuration, an air-cooled configuration, a

liquid-cooled configuration for off-road inverter applications in a relevant simulated operating environment. It is noted that surface area and prototype product embodiment consisting of air-cooled and liquid-cooled configurations may and may not be in direct contact with power semiconductor chips. The idea was to explore and develop packaging and thermal management technology for power semiconductors that was most effective in the performance yet had least burden in overall product cost for a given application.

CRADA benefit to DOE, Participant, and US Taxpayer:

NREL is a recognized leader in thermal management of power electronics for automotive electric drive applications. This project seeks to apply NREL's expertise in heat transfer to power electronics applications at John Deere. The project uses NREL's core competencies in heat transfer, and it enhances U.S. competitiveness by utilizing DOE-developed capabilities and intellectual property.

Summary of Research Results:

All tasks aligned with the CRADA were completed in collaboration between NREL and the CRADA partner. A listing of the tasks from the CRADA agreement are summarized below with descriptions of the work performed by NREL. The work is based on the patent US8541875B2 *Integrated three-dimensional module heat exchanger for power electronics cooling* invented by Kevin Bennion and Jason Lustbader.

Year 1

Task 1.1: Perform supply chain study of materials and power semiconductor devices

- JDES will perform market research into commercially available semiconductor devices with planar packaging that enables top- and bottom-side attachment.
- NREL in collaboration with JDES will research thermal interface materials (TIMs) and bonded interface materials (BIMs) to identify potential materials to support robust low-thermal-resistance interfaces for attachment of the semiconductor devices to the heat exchanger or heat sink.

NREL worked with the CRADA partner to perform a literature review related to materials, packaging, and cooling of power semiconductor devices. This included collecting and providing to the project partner relevant fluid properties for common fluids used for semiconductor package cooling as shown in Figure 1 [1-4]. In addition, NREL completed a literature review of current commercial power semiconductor packaging technologies. NREL also completed a survey of currently available commercial silicon-carbide semiconductor devices.

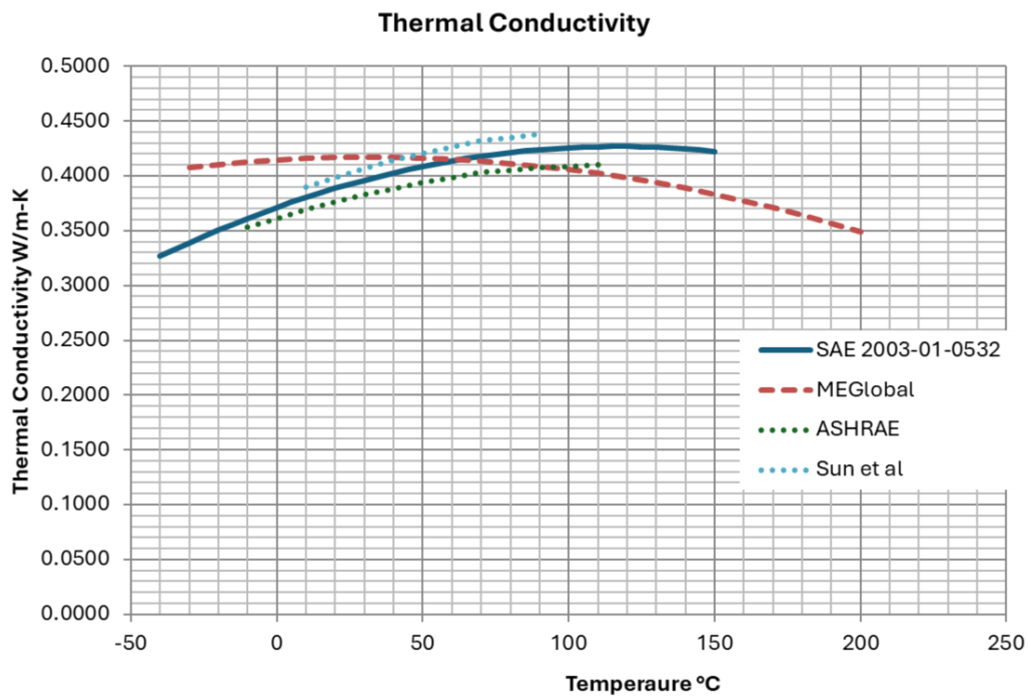

Figure 1: Comparison of several sources for thermal conductivity of 50/50 weight% water ethylene-glycol versus temperature.

Table 1: Discrete Silicon Carbide (SiC) Power metal-oxide-semiconductor field-effect transistors (MOSFETs)

Manufacturer	Number of Parts	Voltages (V)	Currents (A)	Mounting
1	24	900, 1000, 1200, 1700	4.9-90	Surface and Through Hole
2	20	650, 1200, 1700	3.7-93	Surface and Through Hole
3	7	600, 1200	15-68	Screw, Surface, Through Hole
4	5	1200, 1700	4, 6, 8, 25, 45	Surface and Through Hole
5	5	1200	12, 20, 45, 65	Through Hole
6	3	650	36.5	Through Hole
7	1	1200	25	Through Hole
8	1	700	58	Through Hole
	1	1200	32, 36	Screw
9	1	1200	20	Through Hole

Table 1 summarizes SiC Power MOSFETs available for purchase as of early 2018. The table elucidates that several manufacturers are investing in discrete SiC devices, as well as the voltages, power levels, and form factors available to help guide design and procurement decisions. The list omits devices that are "end of life" and soon to be discontinued products.

Task 1.2: Evaluate and optimize the integrated heat exchanger technology

- JDES will provide NREL with computer-aided design (CAD) files of the Computer Model for the proposed Semiconductor Packaging, where the CAD files contain technical data of JDES that: (a) was developed at private expense outside of any governmental contract or grant and (b) prior to this CRADA. NREL and JDES agree that the CAD files of the Computer Model shall not be regarded as computer software or computer programs under applicable law.
- JDES will provide thermal operating conditions, thermal specifications, and design requirements for the target Semiconductor Packaging.
- JDES will provide technical guidance to ensure design for the Semiconductor Packaging adheres to industry specifications for compliance and safety standards.
- NREL in collaboration with JDES will optimize the Semiconductor Packaging, as represented in the Computer Model, through finite element analysis (FEA) and computational fluid dynamics (CFD) modeling, such as refinement of any Computer Model for the water-ethylene glycol (WEG)-based heat exchanger. NREL will develop design approaches for both single- and double-sided cooling to meet JDES performance metrics. The analysis will investigate design alternatives with comparisons to JDES-specified baseline system.
- NREL in collaboration with JDES will evaluate the coefficient of thermal expansion (CTE) mismatch effects and thermal cycling-related degradation of thermal interfaces between the semiconductor devices and its Semiconductor Packaging, as represented in the Computer Model.

Go/No-Go: Design meets mutually acceptable performance targets based on JDES thermal specifications

- JDES and NREL will determine jointly whether the Semiconductor Packaging, as represented in the Computer Model, can meet mutually acceptable performance targets based on JDES thermal specifications and JDES specifications for target off-road heavy equipment. JDES and NREL shall determine mutually acceptable design specifications for Semiconductor Packaging, and its Computer Model, including selection of air-cooled or liquid-cooled design and associated specifications ("Selected Design').

For this task, NREL conducted finite element analysis (FEA) to model and optimize the proposed semiconductor package in collaboration with the CRADA partner. The work evaluated alternative packaging arrangements and cooling arrangements such as both single- and double-sided cooling of the selected power semiconductor package. Results from computational fluid dynamics (CFD) models were also used to predict the performance of the integrated heat exchanger technology.

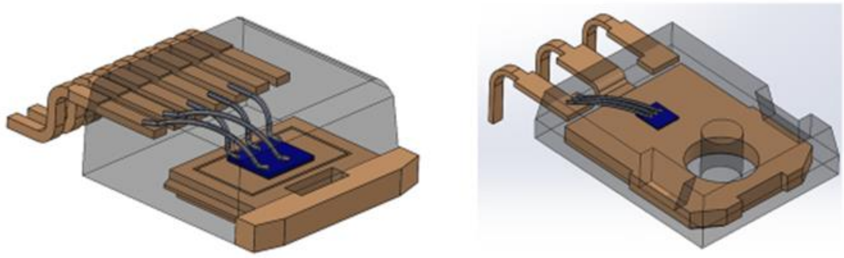

Figure 2: Left: CAD model of typical surface-mount device. Right: CAD model of typical through-hole device

Figure 2 shows high-fidelity CAD models of typical surface-mount and through-hole devices. The power die (blue) have the same dimensions in both models to highlight the relative sizes.

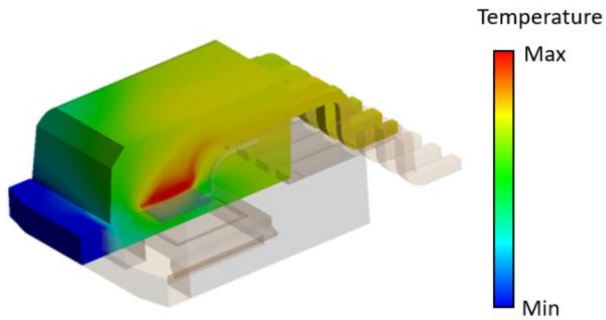

Figure 3: Plot of surface-mount device showing temperature through center

Figure 3 shows the temperature distribution through the surface-mount device. A heat load was applied to the die to represent the device losses, and a convection coefficient was applied to the bottom surface to represent a heat sink. The thermal resistance from the modeling results was validated against manufacturer datasheets.

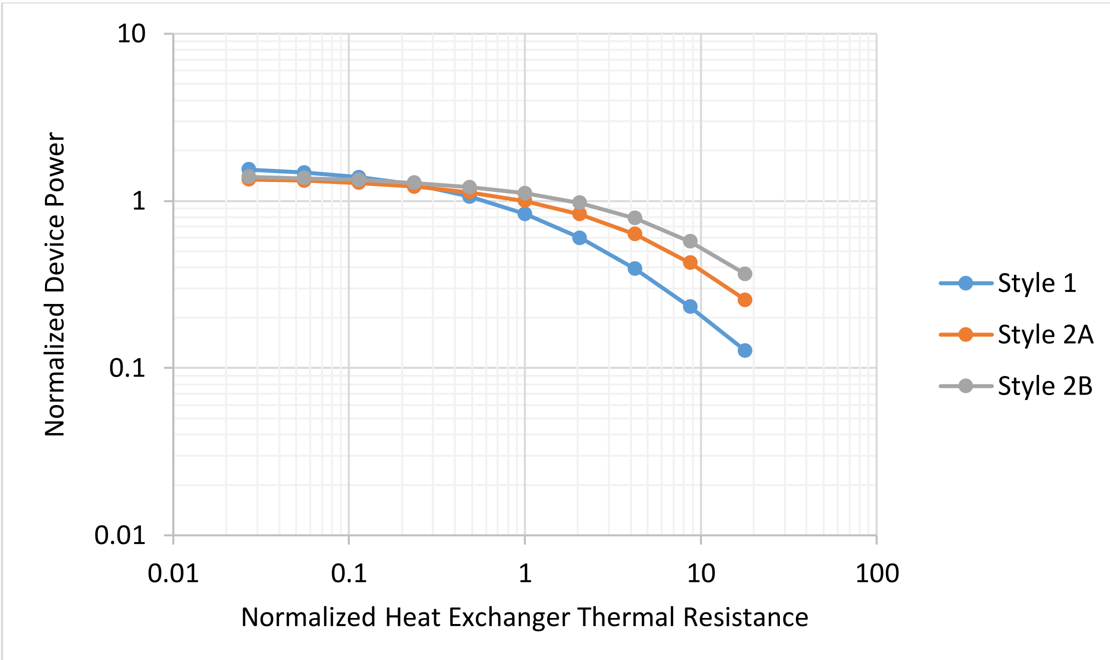

Figure 4: Comparison of three configurations (styles) of heat exchanger for surface- mount devices

Figure 4 shows a comparison of three different heat exchanger configurations for surface mount devices. The best heat exchanger for the application depends on the desired coolant flowrate, which directly impacts the heat exchanger's thermal resistance. For lower coolant flowrates style 2B is the best performer, while at high coolant flowrates style 1 is the best performer. In this application the flowrates are lower, and although style 2B performs best, style 2A provides significantly more efficient space management for multiple devices.

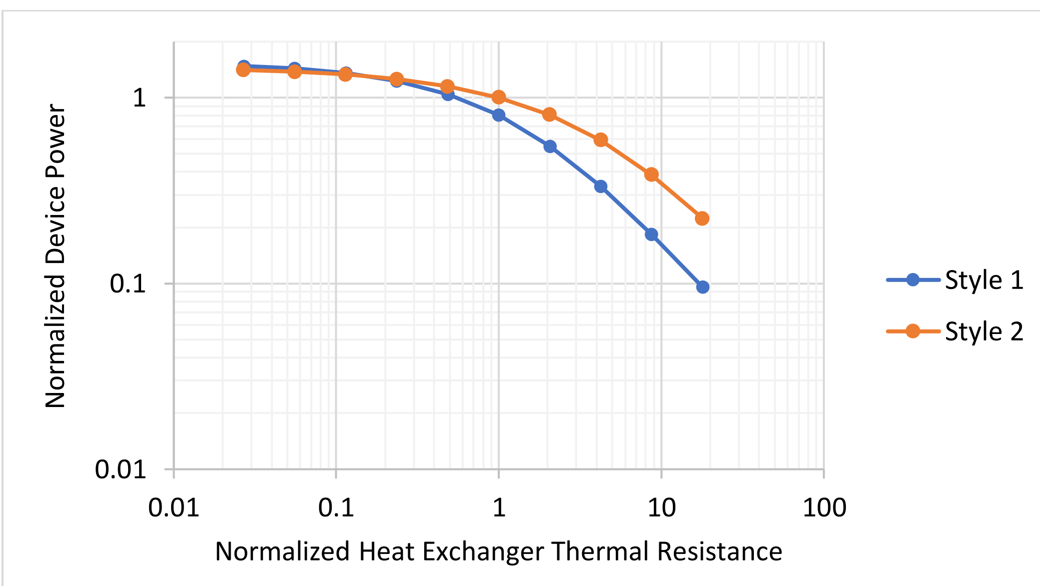

Figure 5: Comparison of two configurations (styles) of heat exchanger for through-hole-mount devices

Figure 5 shows a comparison of two different heat exchanger configurations for through-hole-mount devices. The best heat exchanger for the application depends on the desired coolant flowrate, which directly impacts the heat exchanger's thermal resistance. For lower coolant flowrates style 2 is the best performer, while at high coolant flowrates style 1 is the best performer.

The partner emphasized that surface-mount devices are more efficient for automated assembly processes. In addition, space management (minimizing overall volume) was given high priority. Given these two trade-offs, the surface-mount using heat exchanger style 2A as described earlier in this section was selected as the design.

Year 2

- Task 2.1: Experimentally test the Computer Model of the Selected Design JDES will work with NREL to ensure the Selected Design is related to typical or target inverter specifications for off-road heavy equipment.
- NREL in collaboration with JDES will refine the Selected Design based on year one results and JDES input.
- JDES evaluate the feasibility of manufacturing prototypes of the Selected Design, with its air-cooled or liquid-cooled thermal features, according to desired industry specifications and processes.
- JDES will manufacture or have manufactured couple of prototypes with thermal features in accordance with the Selected Design, where any manufacturing subcontractor shall be mutually acceptable to JDES and NREL and where the prototypes may exclude semiconductor devices that are procured separately by JDES or NREL from a semiconductor manufacturer as "commercial items." The prototype shall only include the Semiconductor Packaging to facilitate interfacing with one or more specified semiconductor devices, dies, or chipsets and shall not include any inverter prototype. However, JDES shall be responsible for testing the thermal performance of any and all prototypes with semiconductor devices that are directly bonded to air-cooled or liquid-cooled thermal features and providing a performance report to NREL. NREL, JDES or both will test the fabricated prototypes of the Selected Design with exposure to heat sources representative of power silicon-carbide semiconductor devices operating in an inverter for off-road heavy equipment to characterize thermal performance of the Selected Design.

NREL, in collaboration with the CRADA partner, built prototype components for evaluating the performance of the integrated heat exchanger technology with the semiconductor package. NREL compared the experimental data with the model-predicted performance and verified the models used for the design optimization of the semiconductor package and integrated heat exchanger.

Figure 6 shows the mechanical experimental design, including the heat exchanger with mounted device. A copper coin serves as a stand-in for the circuit board, which would include an embedded copper heat sink to conduct heat to the heat exchanger. A bearing plate presses the device into the copper coin to mimic the clamps that would be used in a production assembly. The spring-loaded screws holding the bearing plate enable precise control of the pressure.

Figure 7 shows the electrical experimental design, note that the copper heat sink doubles as an electric drain (as it would in the production assembly) and a dielectric thermally conductive pad was used (again, to mimic the production assembly) to prevent current from passing into the heat exchanger.

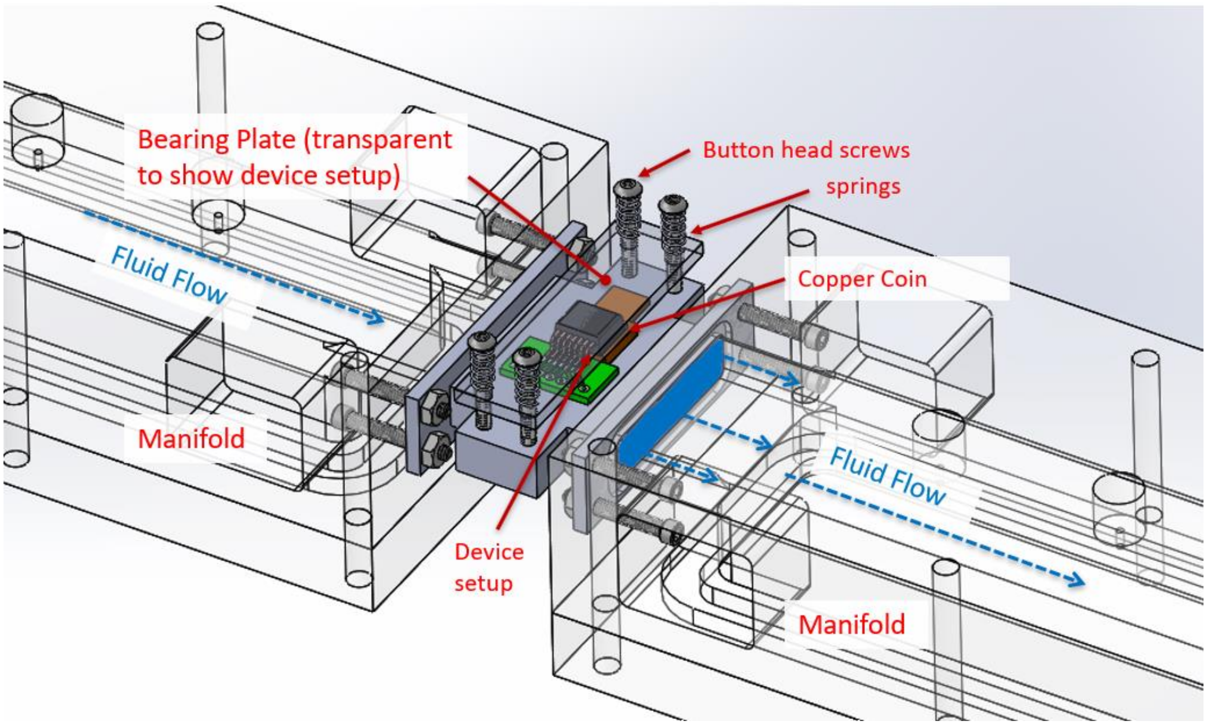

Figure 6: Mechanical experimental design

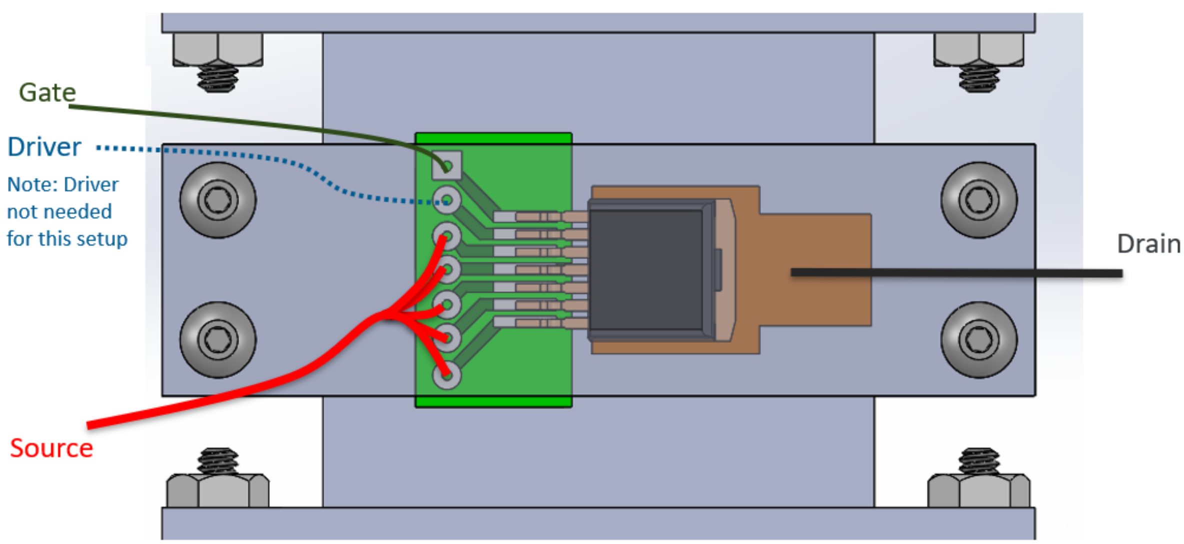

Figure 7: Electrical experimental design

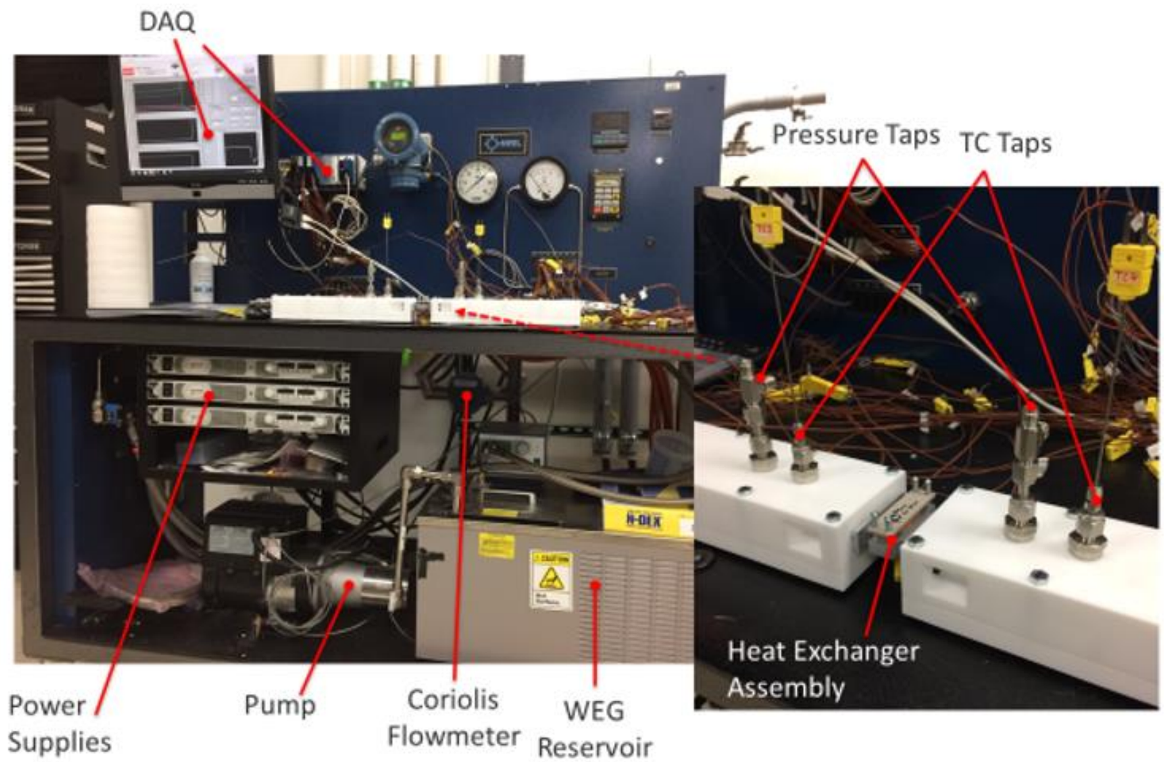

Figure 8: Experimental setup

Figure 8 shows the laboratory experimental setup of the heat exchanger including the data acquisition system (DAQ), electric power, instrumentation used to measure pressure drop, thermocouple (TC) taps to measure fluid temperature rise, and fluid storage and flow for the water ethylene-glycol (WEG).

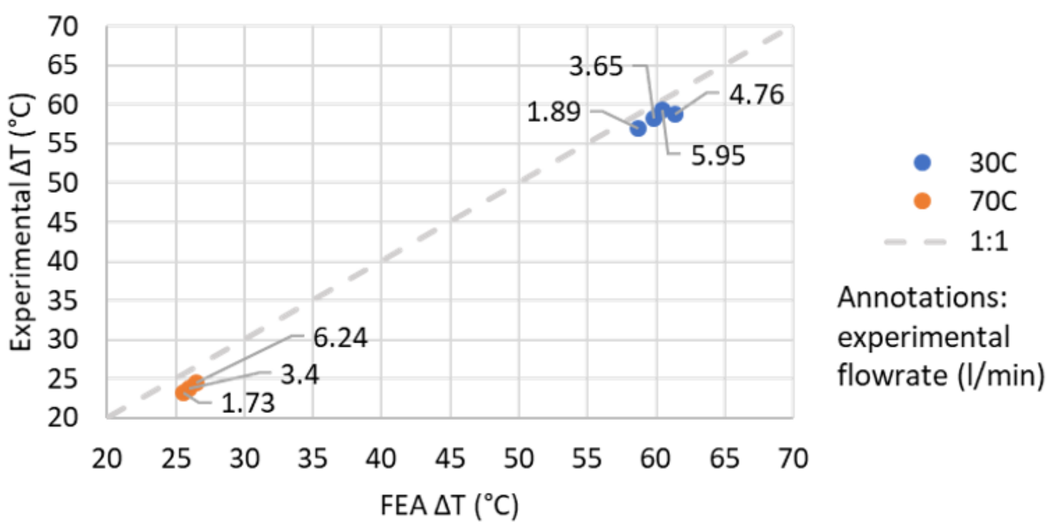

Figure 9: Correlation between model (x axis) and experiment (y axis) at multiple coolant flowrates for temperature drop from the device to the heat exchanger. ΔT refers to the temperature drop from the device case to heat exchanger.

Figure 9 shows the correlation between model and experiment for two design points representing two coolant temperatures. The correlation plots the temperature drop across the passive stack from the device to the heat exchanger. On average, the experimental results were within 6% of the FEA modeling results.

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreement's Article X.

References:

[1] 2009 ASHRAE Handbook - Fundamentals (SI Edition) Copyright (c) 2009 American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

[2] "Monoethylene Glycol (MEG) Technical Product Brochure." [Online]. Available: http://www.meglobal.biz/sites/default/files/MEGlobal_MEG_Mar2012.pdf. [Accessed: 20-Apr-2012].

[3] D. R. Cordray, L. R. Kaplan, P. M. Woyciesjes, and T. F. Kozak, "Solid - liquid phase diagram for ethylene glycol + water," *Fluid Phase Equilibria*, vol. 117, no. 1–2, pp. 146–152, Mar. 1996.

[4] T. Sun and A. S. Teja, "Density, Viscosity, and Thermal Conductivity of Aqueous Ethylene, Diethylene, and Triethylene Glycol Mixtures between 290 K and 450 K," *J. Chem. Eng. Data*, vol. 48, no. 1, pp. 198–202, Jan. 2003.

Subject Inventions Listing:

None

ROI:

None