AIR COOLING FOR HIGH TEMPERATURE POWER ELECTRONICS

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2014 Thermal Management Systems Symposium
September 22–24, 2014
Denver, Colorado
14TMSS-0022

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NREL/PR-5400-62920

Project Objective

- Enable air-cooling thermal management of automotive power electronics, with a focus on high-temperature devices
  - Design, optimize, build, and demonstrate an air-cooled inverter
  - Compare to conventional cooling systems: thermal resistance, coefficient-of-performance, volume, weight

Motivation

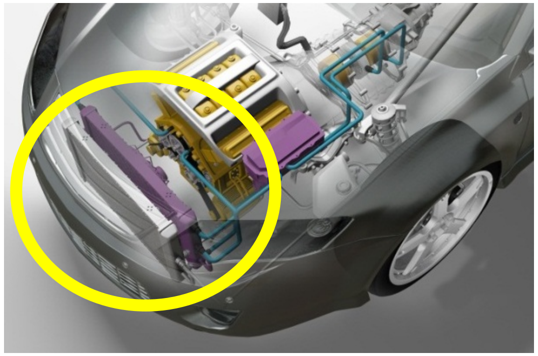
- Help industry achieve the DOE APEEM 2015 30-kW (55-kW peak) inverter targets (12 kW/L, 12 kW/kg) through improved thermal management
- Provide pathways to meeting 2020 targets (13.4 kW/L, 14.1 kW/kg)

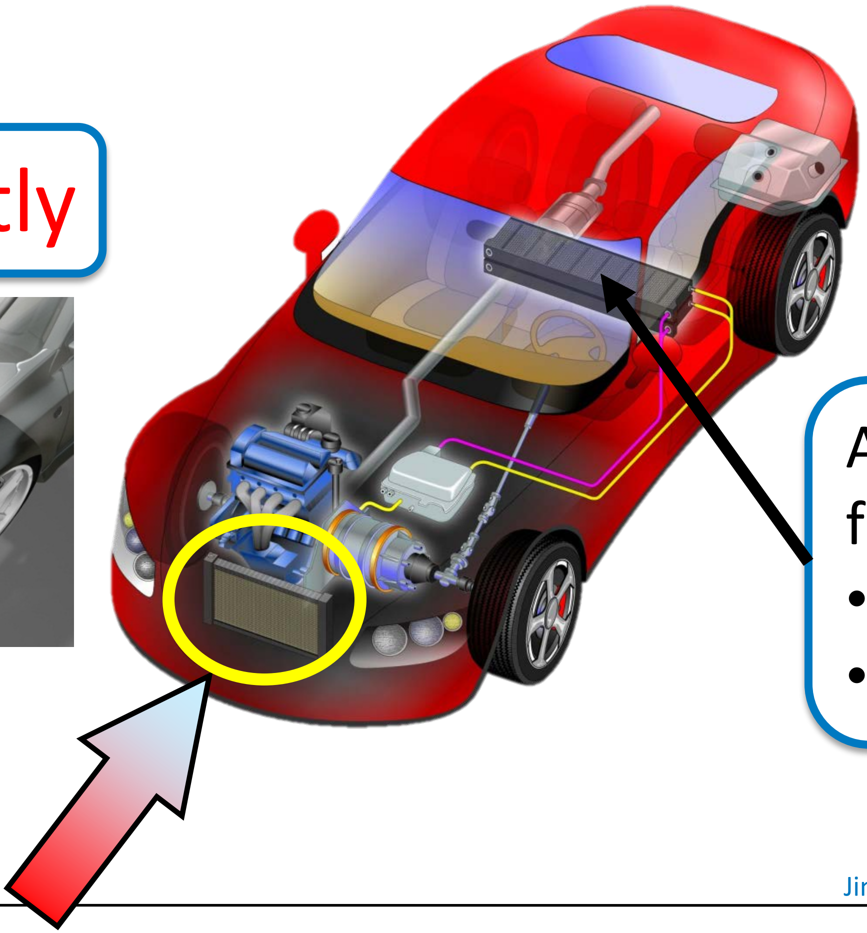
Power Density, Specific Power, Efficiency

Cost

All vehicles are air cooled

Just indirectly





Air cooling a goal for batteries:

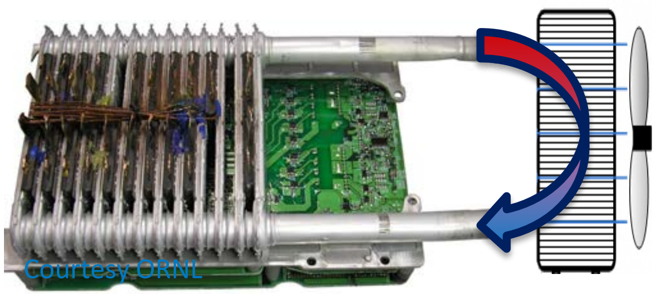
- Simple
- Direct

Jim Snyder, NREL Image Gallery 15165

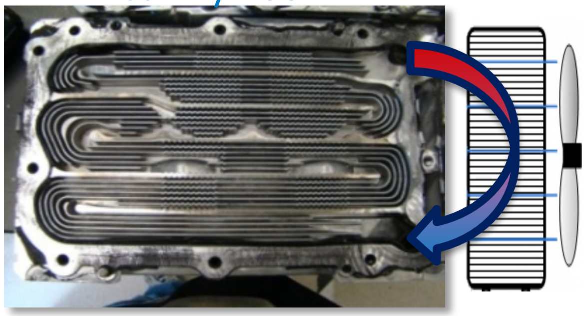
Indirect Air Cooling via Liquid Cooling

Intermediate liquid cooling loop rejects heat to air

LS 600H 2008



Camry 2007



Direct Air Cooling

Has been done before

Low Power

Honda Insight (12 kW)

Low Power Density

AC Propulsion (150 kW)

Prototype: not in vehicle

Mitsubishi SiC Inverter
(50 kVA/L, 400 V output, 156 kVA)

SiC = Silicon Carbide

Air as a Coolant

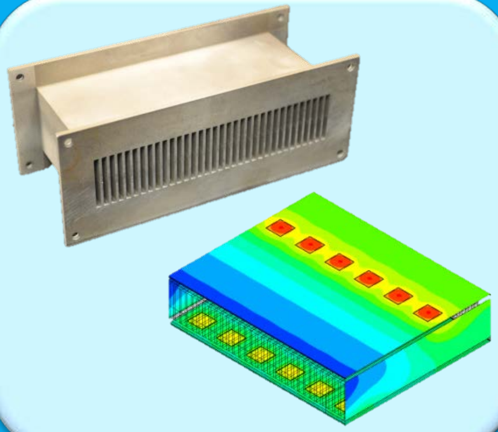
Advantages

- Rejecting heat directly to air can eliminate intermediate liquid-air loops
- Attractive for high-temperature device (wide-bandgap) applications
- Air can be used to cool other components (e.g., capacitors)
- Air is benign, is not carried, and does not need to be replaced
- Air is a dielectric and can contact the chip directly
- No global warming potential
- No liquid leaks

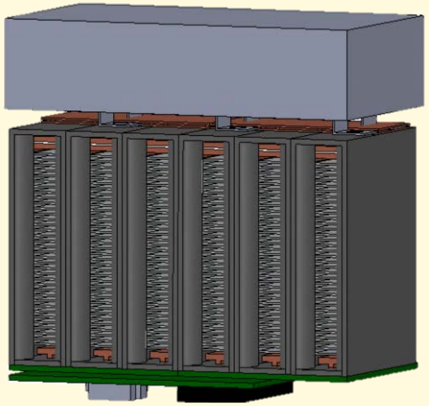
Challenges

- Air is a poor heat-transfer fluid (low specific heat, density, conductivity)
- Large volume of air is needed
- Large surface area increases heat transfer, but increases volume
- Potential parasitic power of fan
- Not yet used in production vehicles
- Filtering, fouling, fan noise

System-Level Analysis



Cooling Technology



Packaging

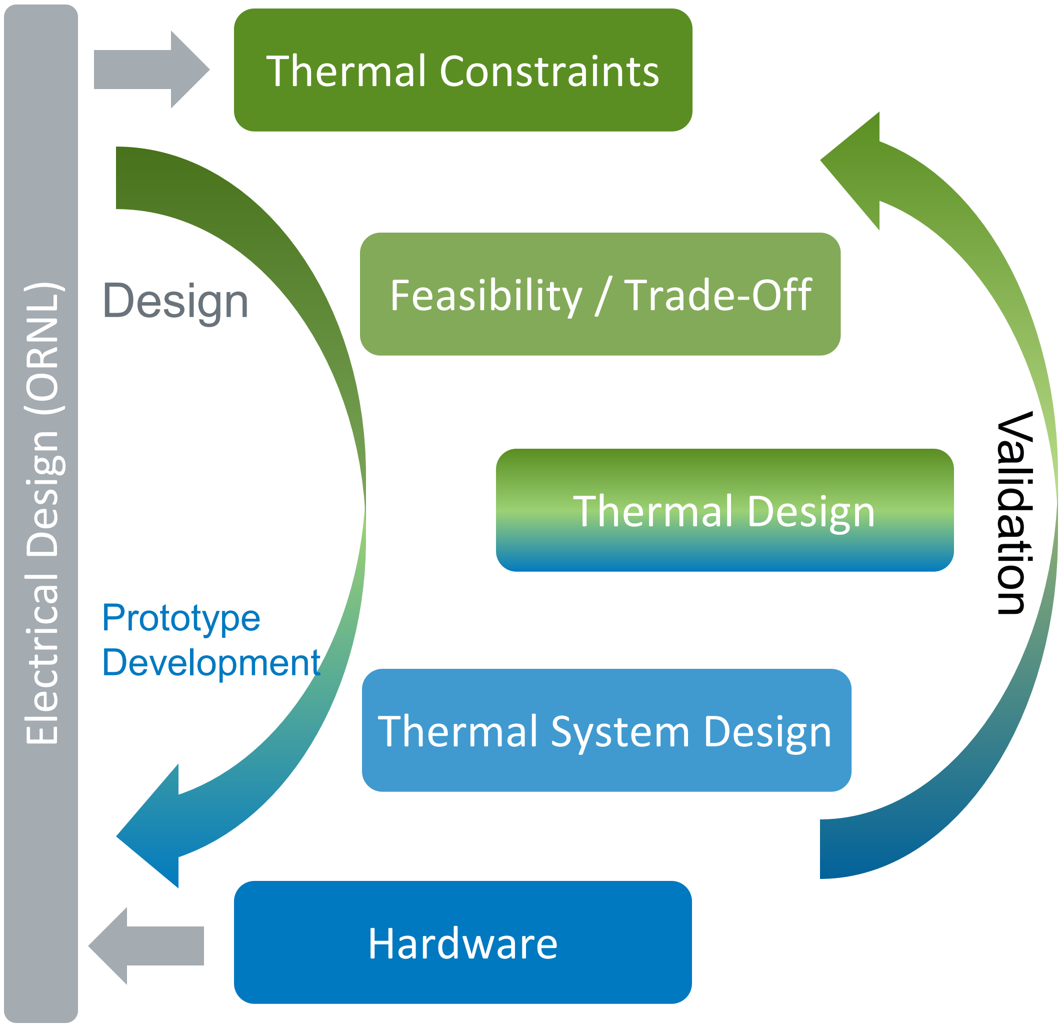
Balance of System

- Maximum Temperatures
- Device Efficiency

- Inverter Components
- Under-hood Location

- Parasitic Power (Fan)
- Air Source

High-Temperature Air-Cooled Inverter

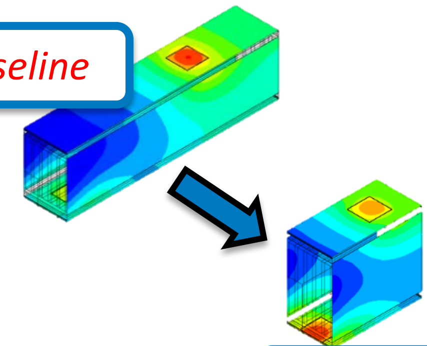


- **Electrical Design:** Device type and location; electrical duty cycles; temperature-dependent losses, efficiency
- **Thermal Constraints**: Maximum junction temperature; heat generation; coolant temperature
- **Feasibility / Trade-Off**: Modeling; extrapolate to inverter scale
- **Thermal Design:** Sub-module testing and model validation; fan/ducting testing; optimization
- **Thermal System Design**: Balance-of-system analysis; full system models
- **Hardware**: Module prototype, improve design; balance-of-system testing

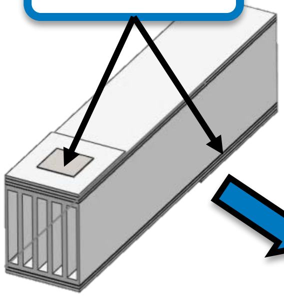
Module Optimization to Inverter Level Characterization

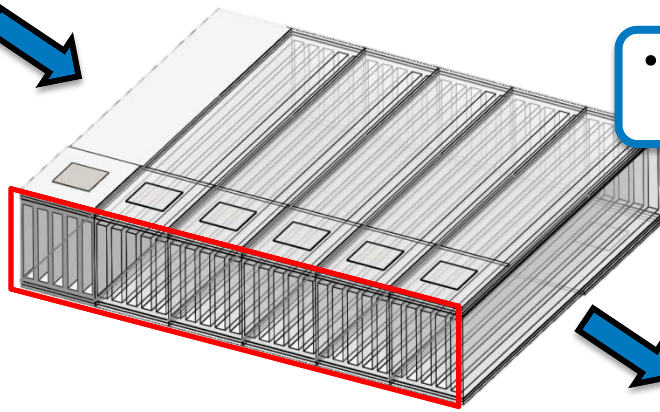
<u>Heat dissipation for 55-kW peak power</u>

From conservative analytical analysis ~ 2.7 kW heat (95% efficient)



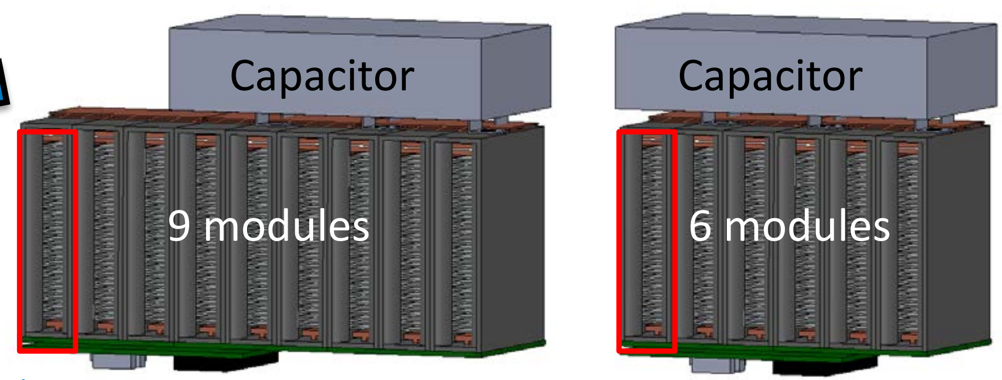
- Fixed device heat generation and temperature (175°C)
- Parametrically optimized geometry by varying air flow rate using computational fluid dynamics (CFD) – ANSYS Fluent





- Extrapolated sub-module modeling and testing results to module level

- Added in balance-of-inverter components[1]



[1]Casing volume adjusted for fin geometry

[1]Capacitor ~1.13 L[a], ~1.62 kg[a]

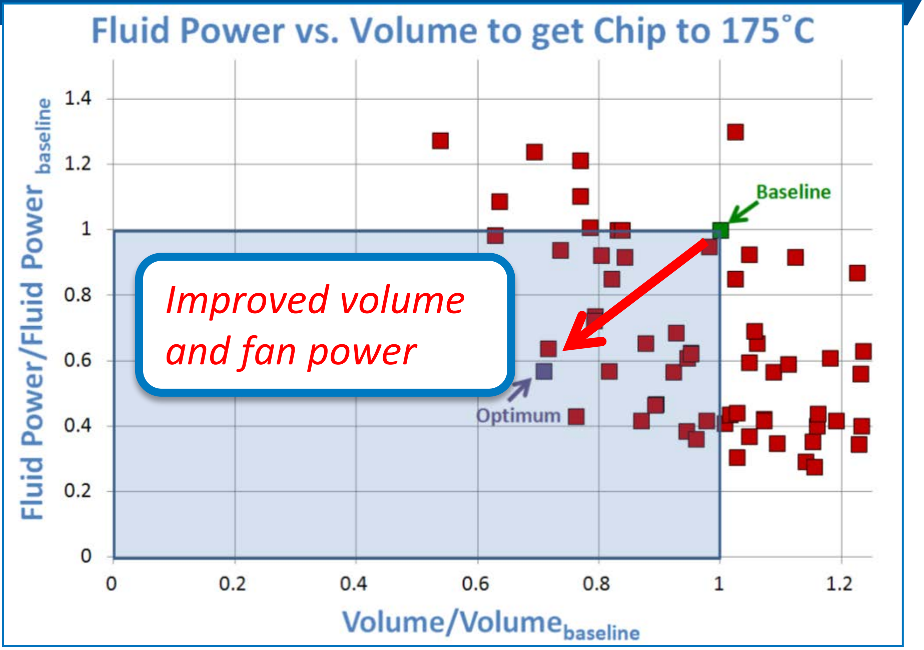
[1]Gate driver + control board ~0.88 L[a], ~0.42 kg[b]

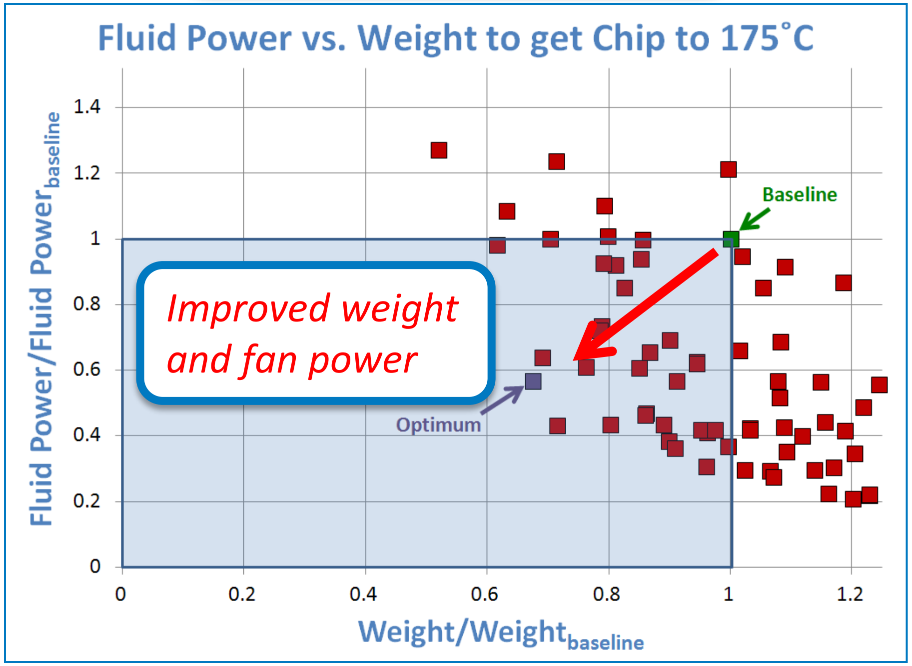
[a]Assumption provided by ORNL; [b]NREL assumption based on similar device measurement

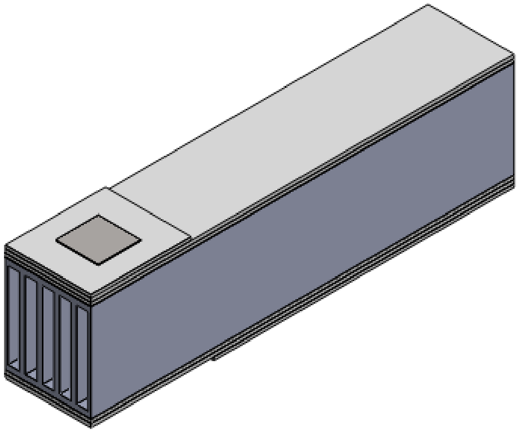
Module Design Improvement (Parametric CFD)

Parametrically Changed:

- Device Location
- Fin Height
- Fin Length
- Base Plate Thickness
- Fin Thickness
- Channel Width

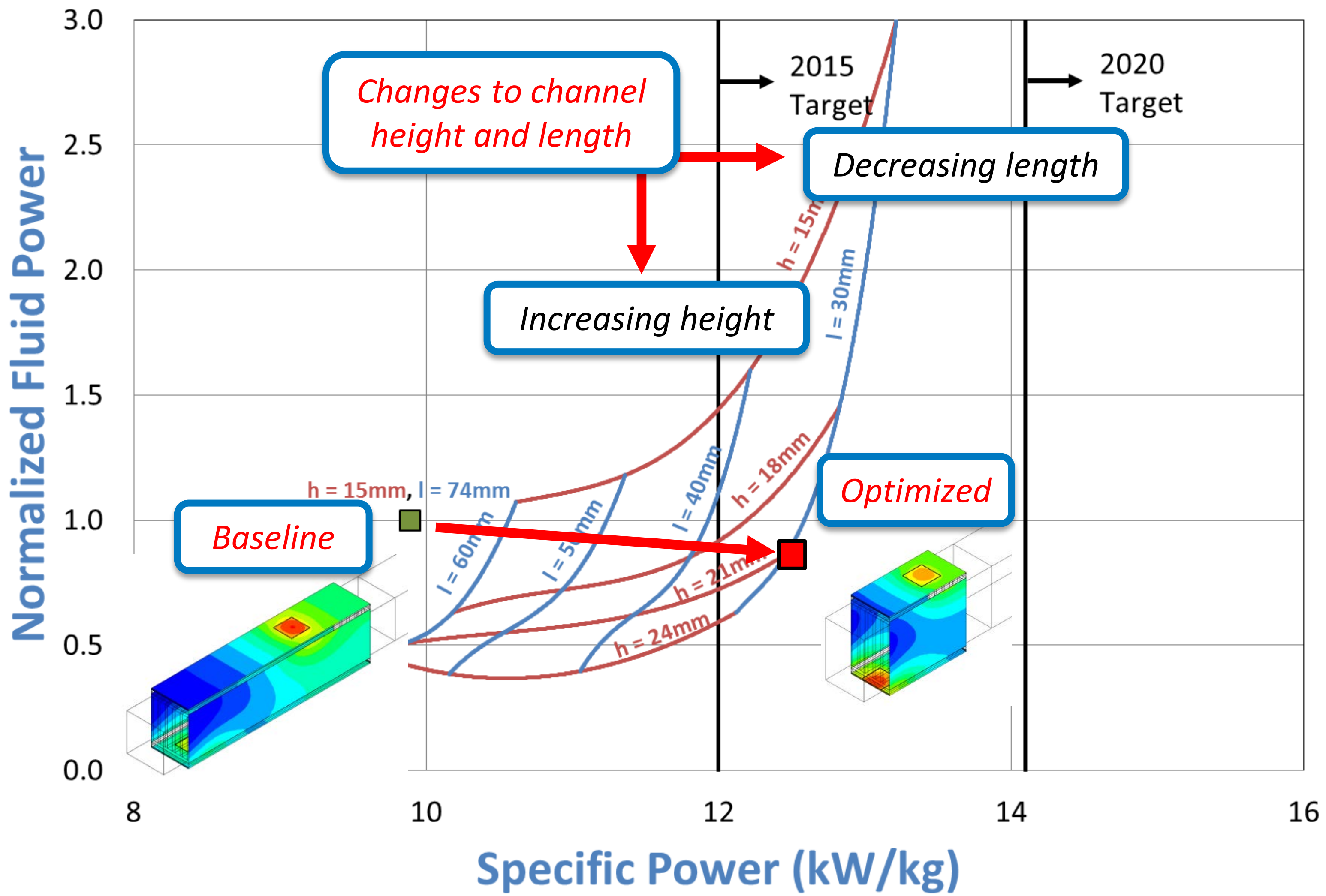






Optimized Geometries Improve Specific Power

Modeling

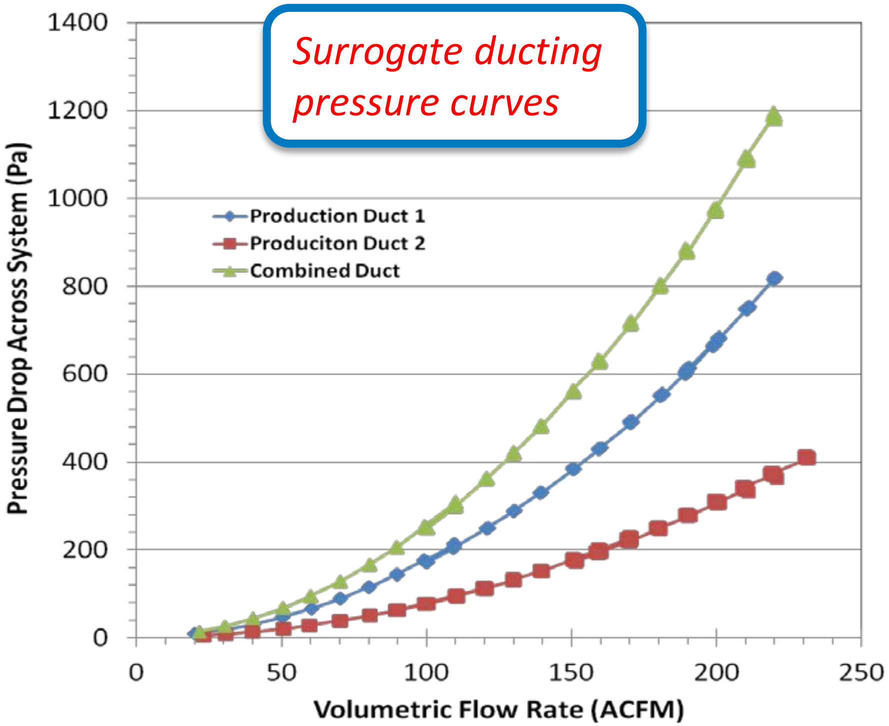


nine modules, DBC (direct-bond-copper)

Balance of System: Ducting

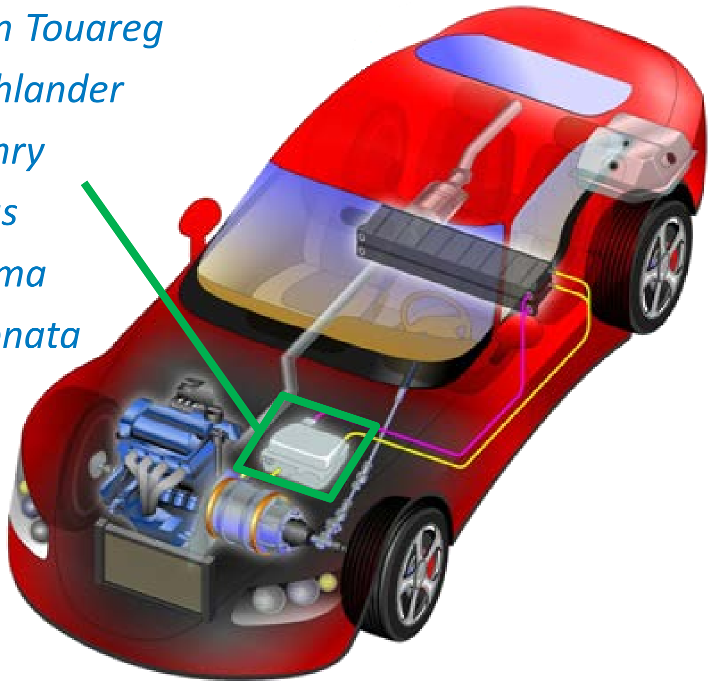
Experimental

Example Production Vehicle Air Ducts



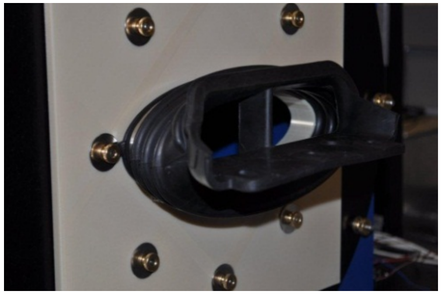
Inverter Location

Volkswagen Touareg
Toyota Highlander
Toyota Camry
Toyota Prius
Nissan Altima
Hyundai Sonata
Chevy Volt

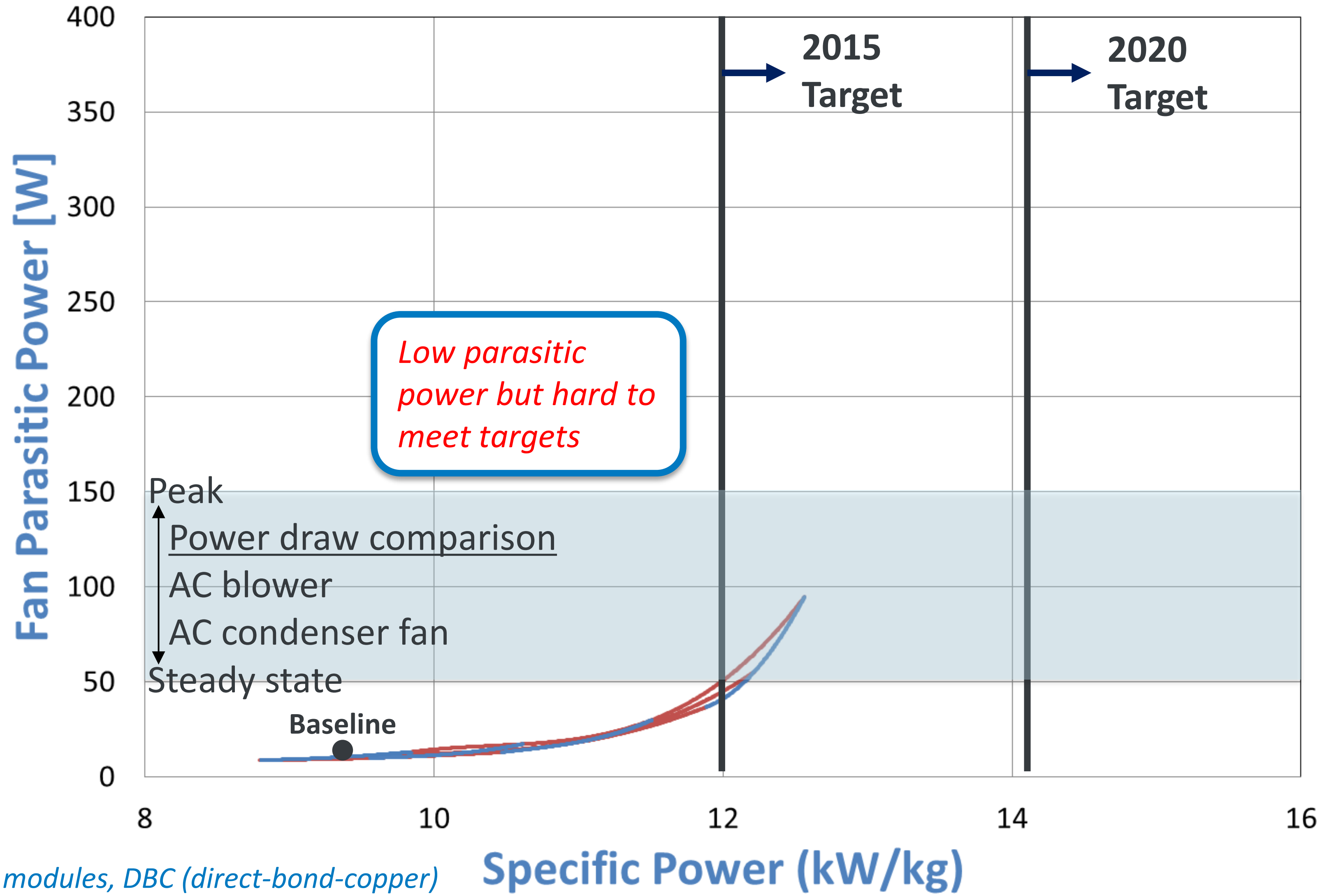


Production Duct 1

Production Duct 2

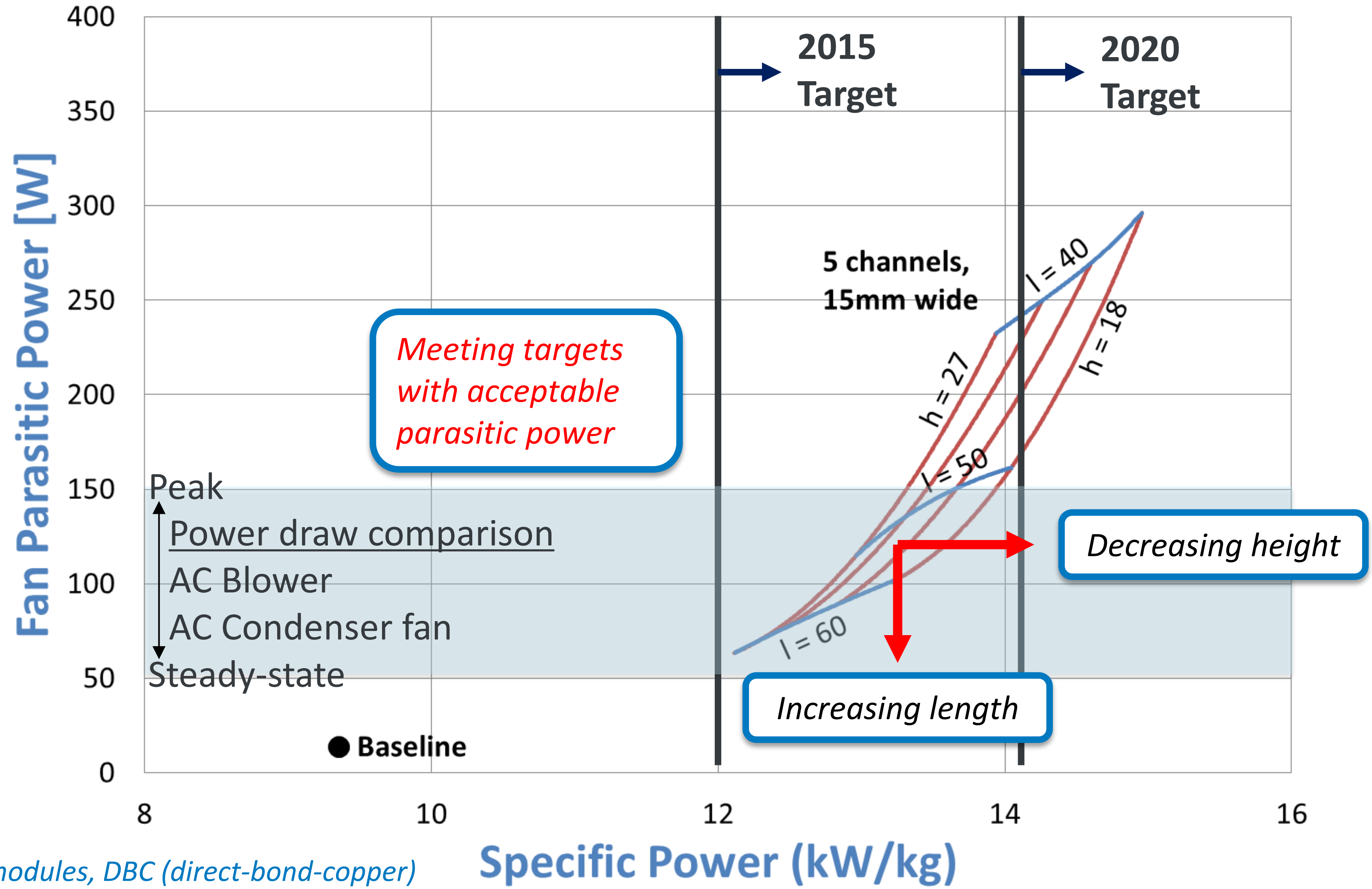


Specific Power versus Parasitic Power for Various Heat Exchanger Geometries (**Nine** Modules)



nine modules, DBC (direct-bond-copper)

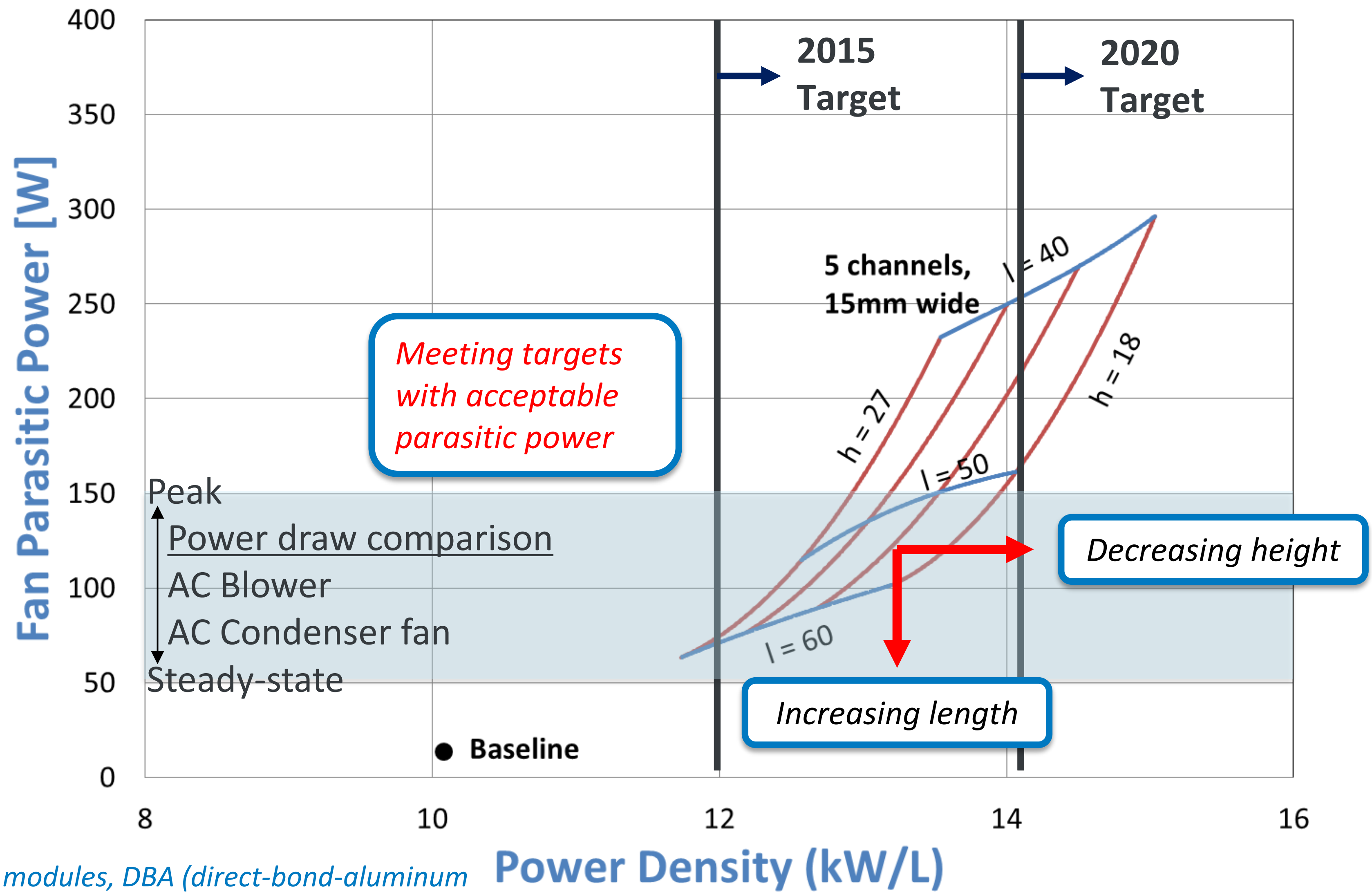
Specific Power versus Parasitic Power for Various Heat Exchanger Geometries (**Six** Modules)



six modules, DBC (direct-bond-copper)

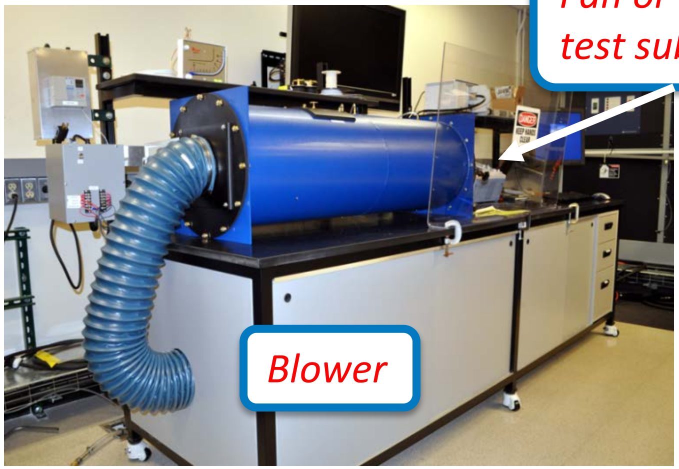
Power Density versus Parasitic Power for Various Heat Exchanger Geometries (**Six** Modules)

Modeling

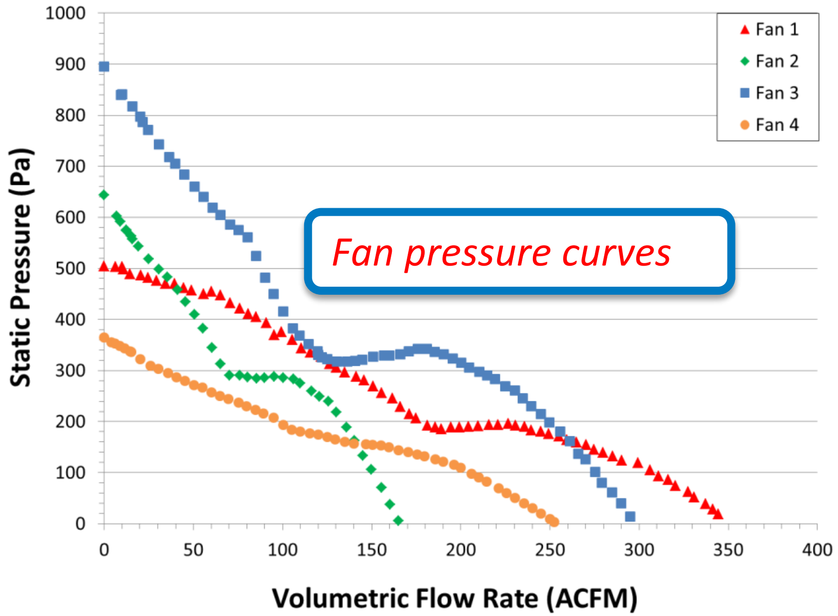


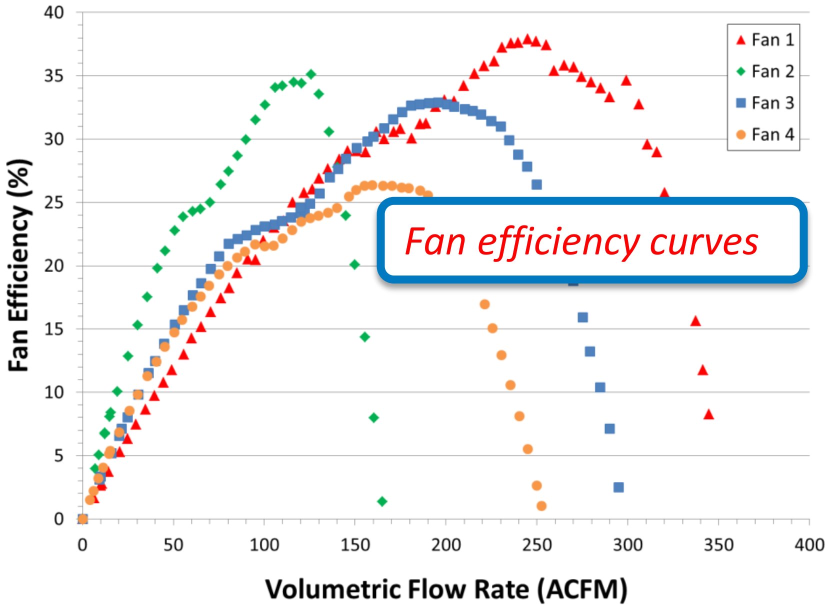
nine modules, DBA (direct-bond-aluminum

System-Level Test Bench

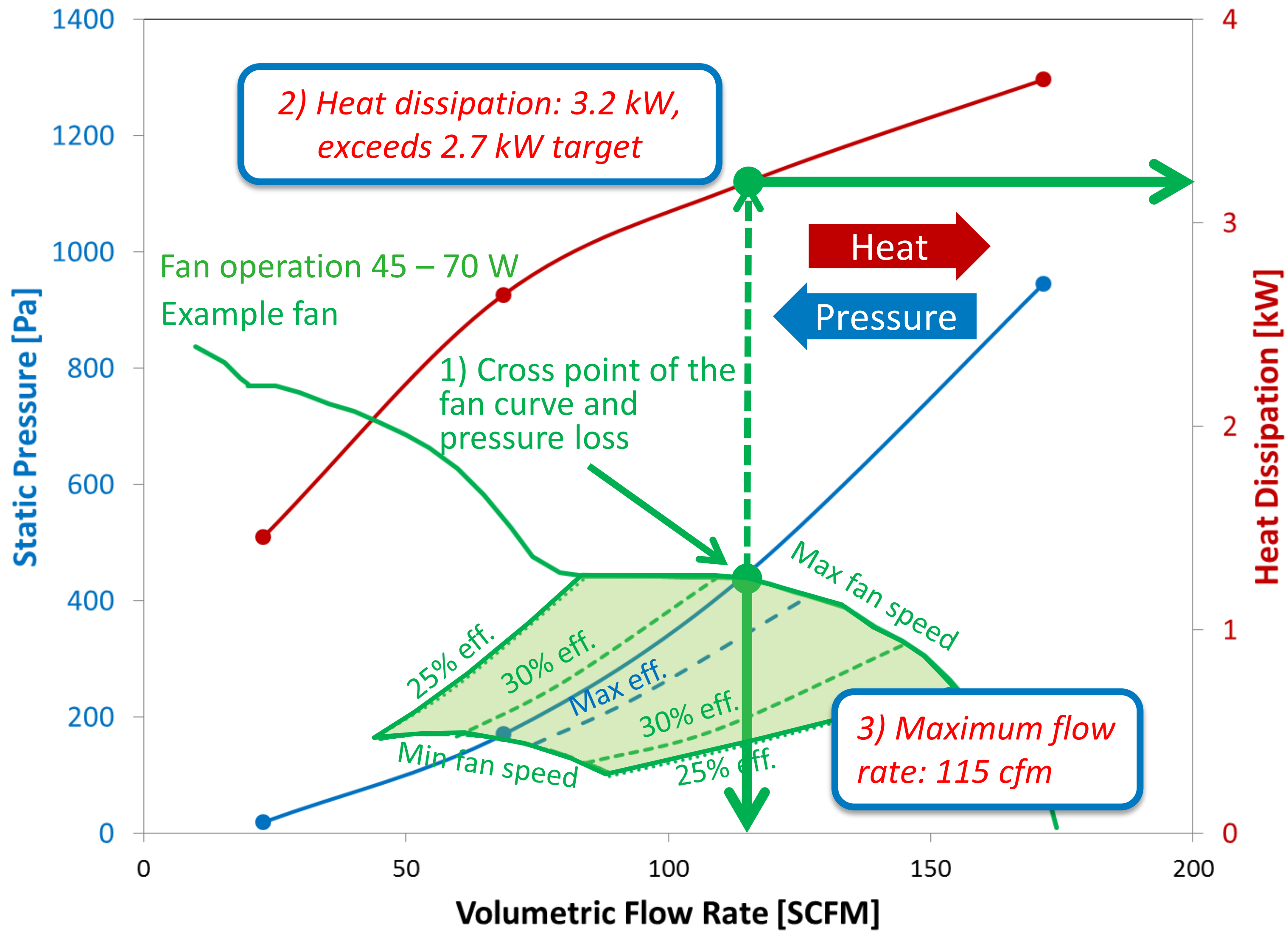


- Meets fan test standard
  - ANSI/AMCA 210-07
  - ANSI/ASHRAE 51-07
- Range: 5–500 cfm
- U_{95} Flow: ±1.5 cfm
- U_{95} Pressure: ±1.6 Pa



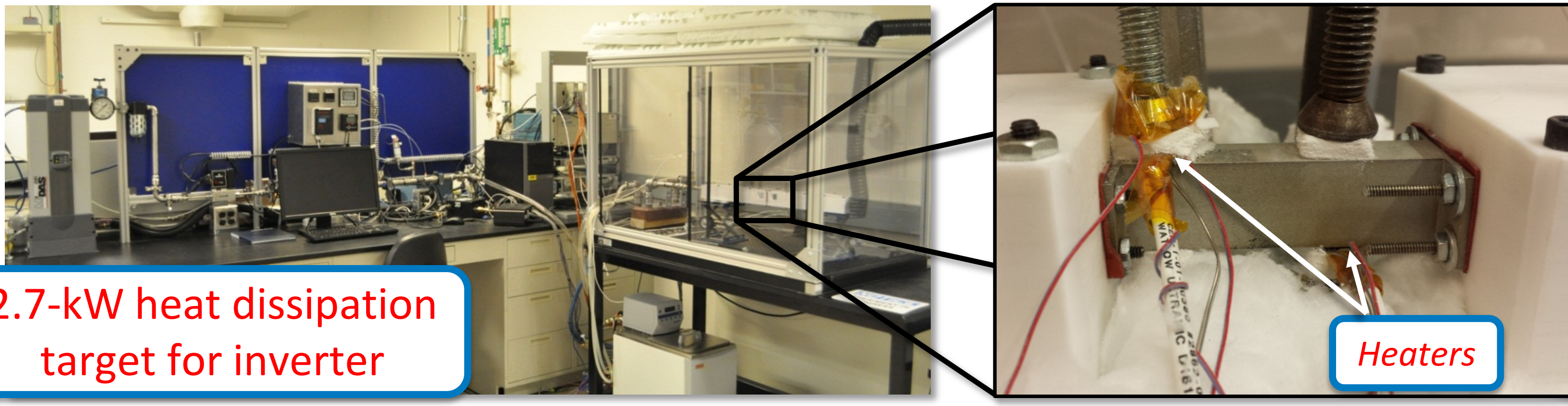


Example System Flow Study



Sub-Module Heat Exchanger Experiments

Experimental



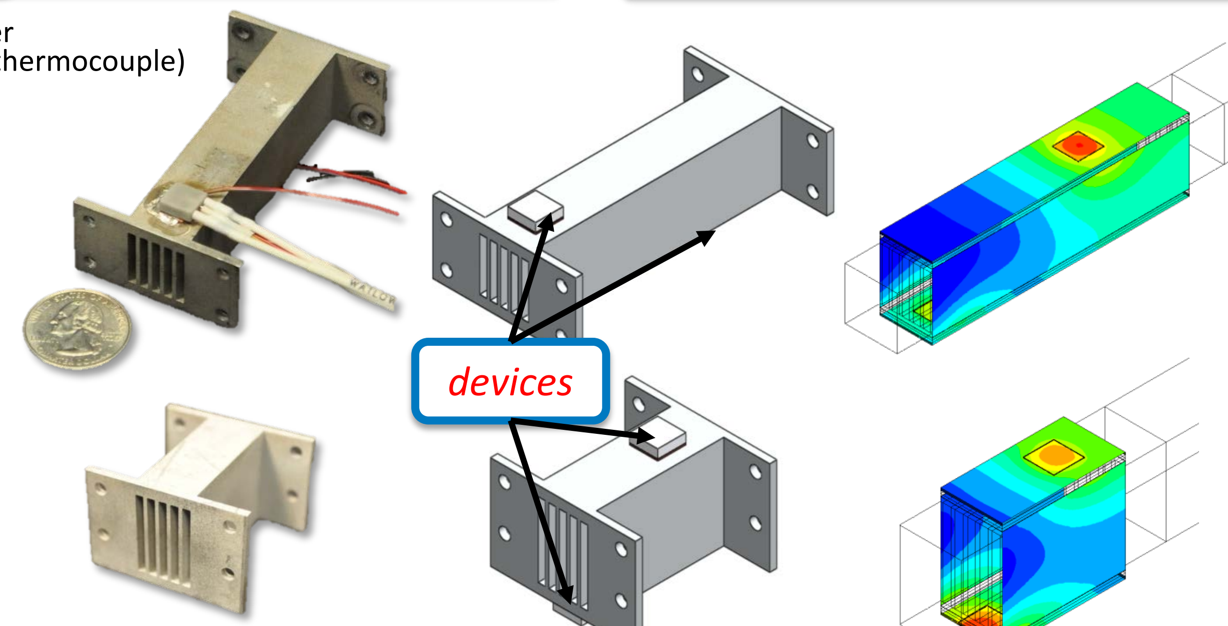
2.7-kW heat dissipation target for inverter

Baseline

Channel height – 15 mm
Channel length – 74 mm

Optimized

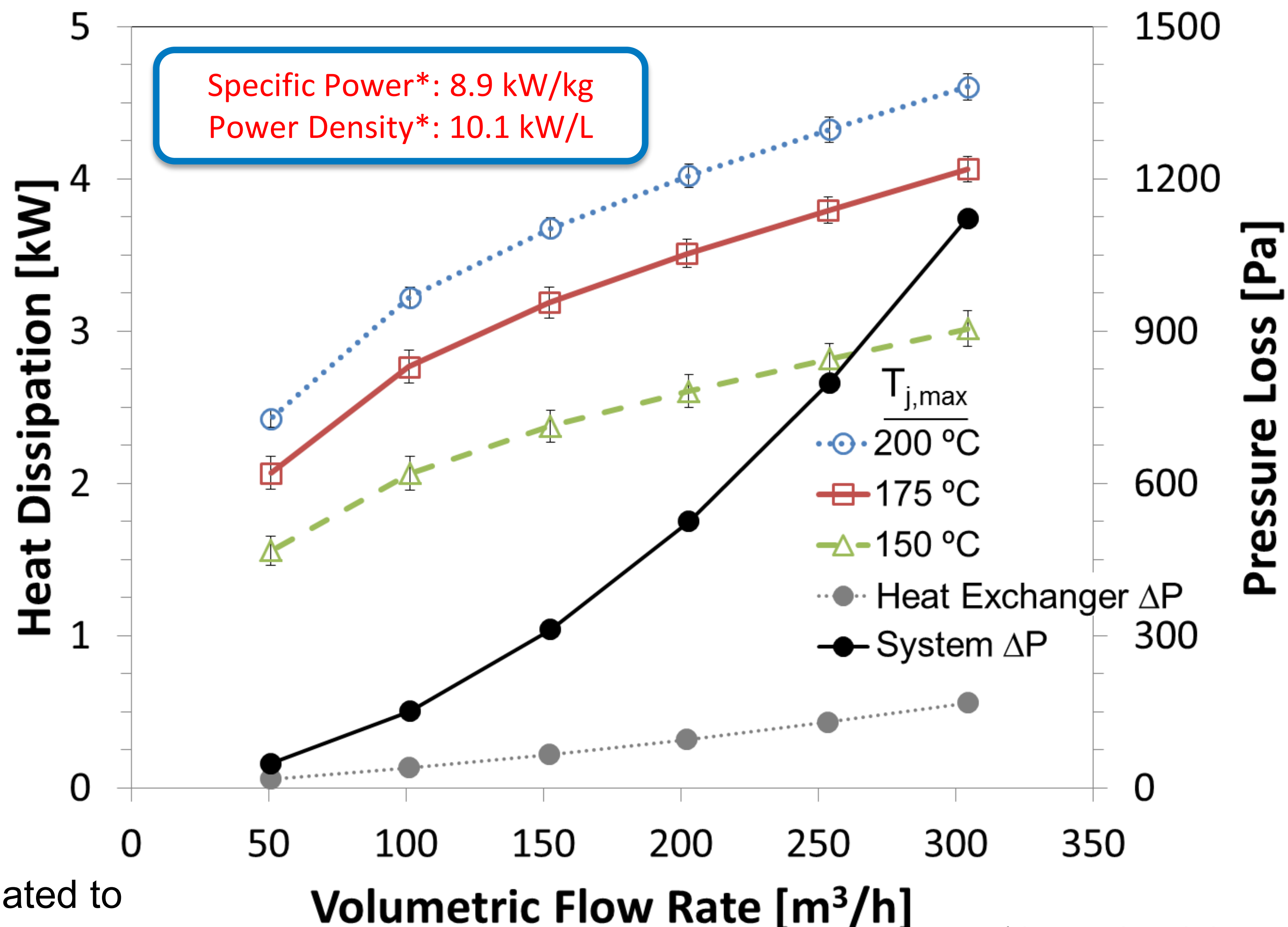
Channel height – 21 mm
Channel length – 40 mm



Prototypes provided by Sapa Extrusions USA (wire EDM)

Heat Dissipation for **Baseline** Case (Nine Modules)

Experimental

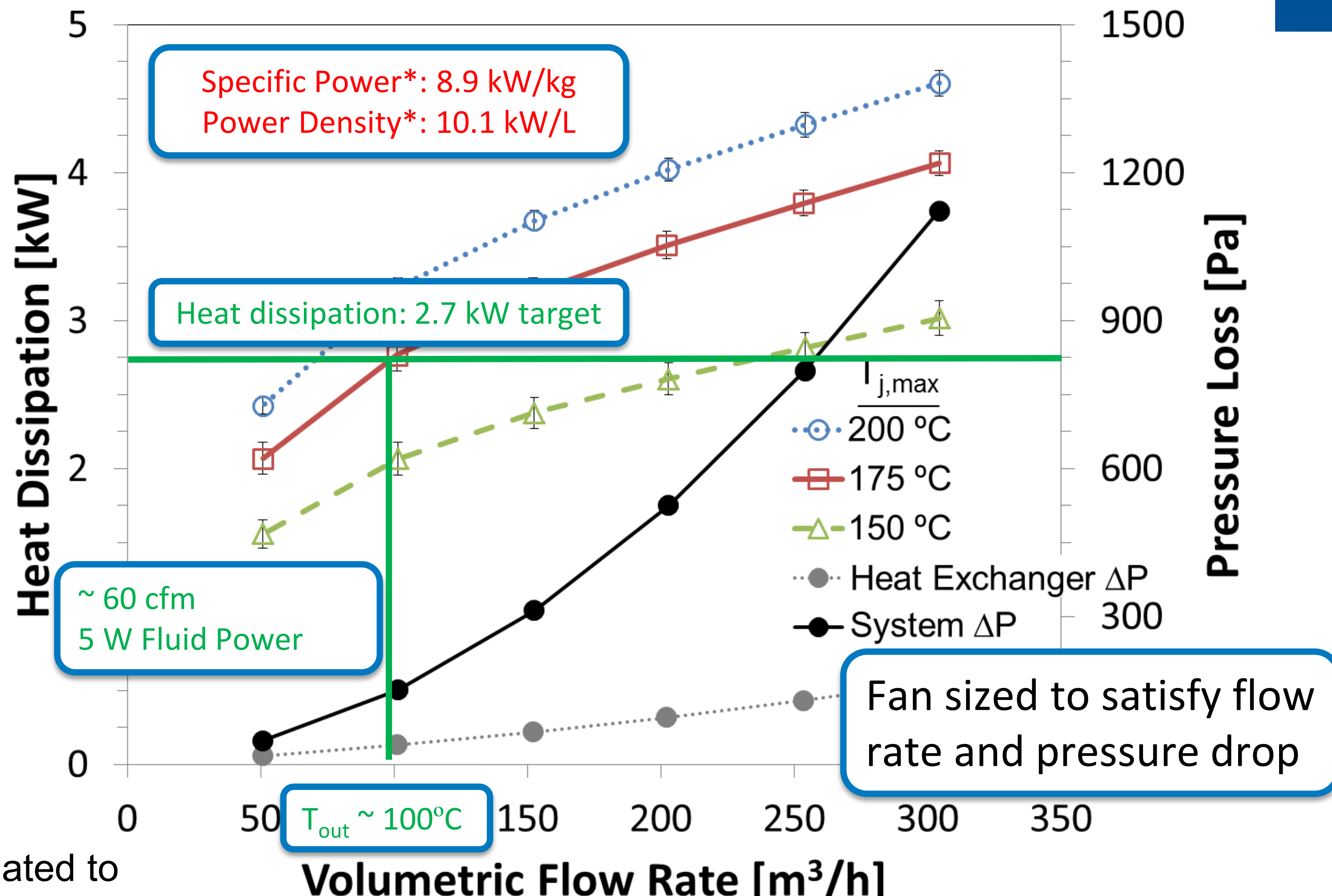


Extrapolated to inverter scale

*does not include inverter casing

Heat Dissipation for **Baseline** Case (Nine Modules)

Experimental

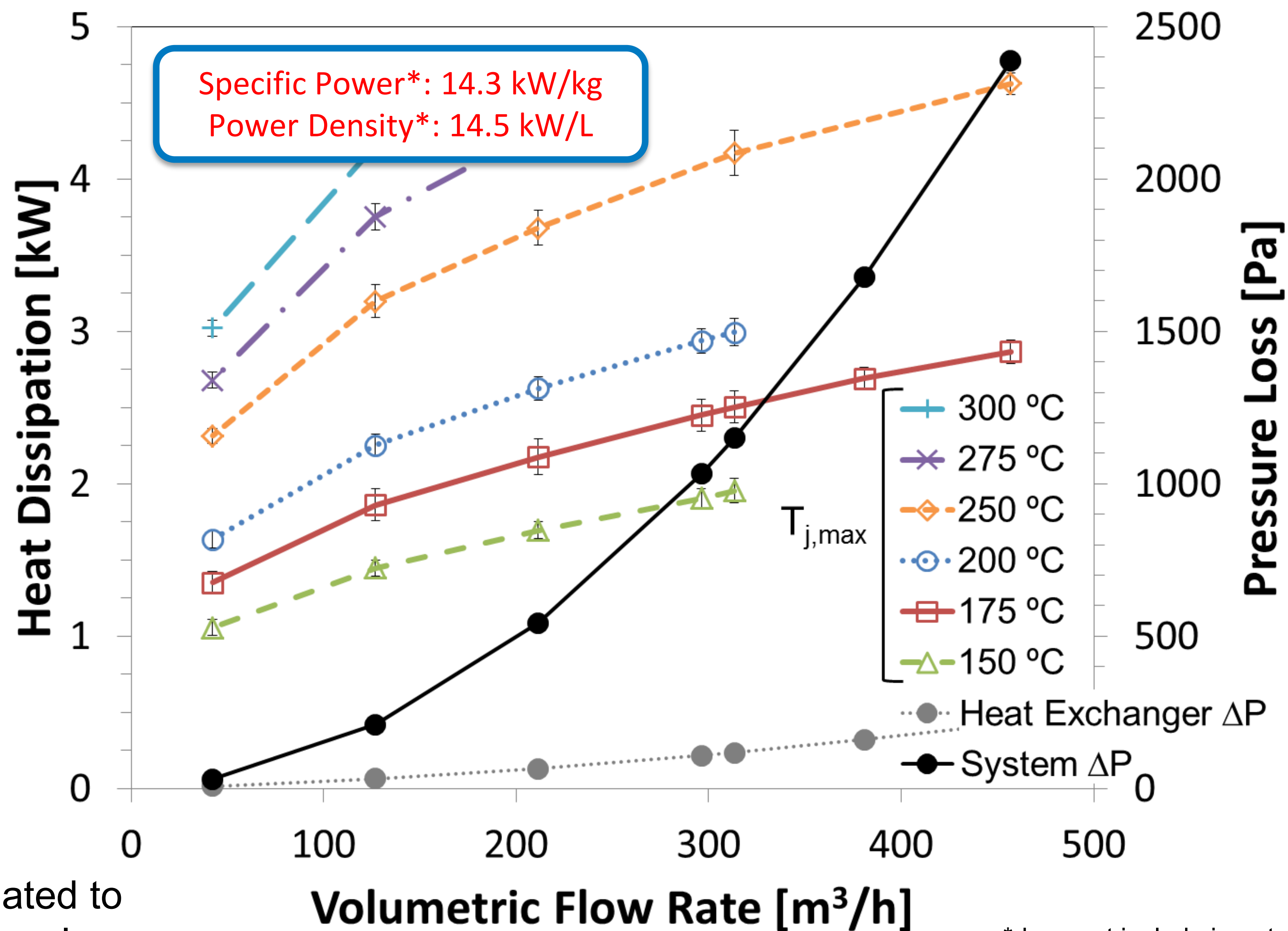


Extrapolated to inverter scale

*does not include inverter casing

Heat Dissipation for **Optimized** Case (Six Modules)

Experimental



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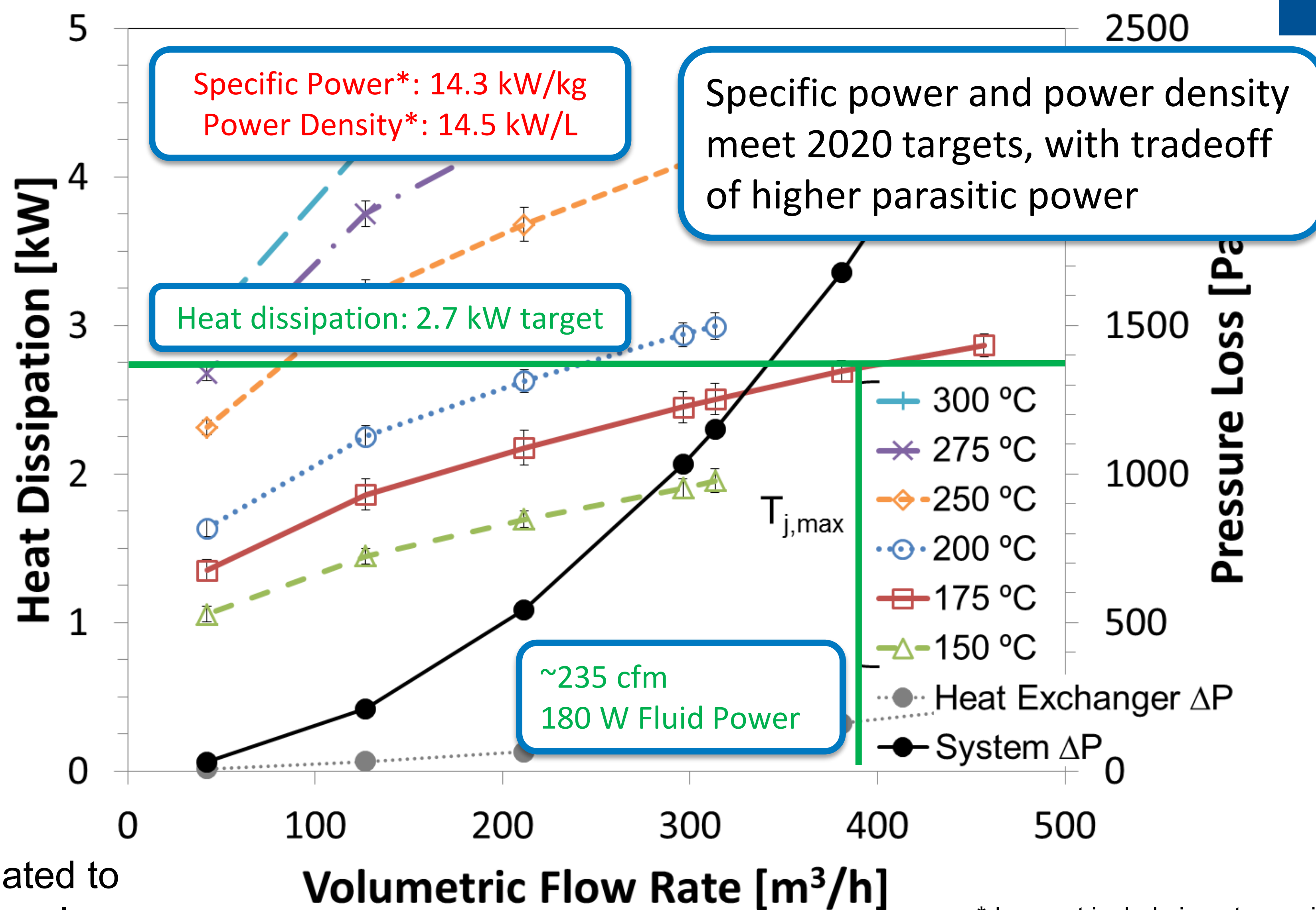
Heat Dissipation for **Optimized** Case (Six Modules)

Experimental



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Heat Dissipation for **Optimized** Case (Six Modules)

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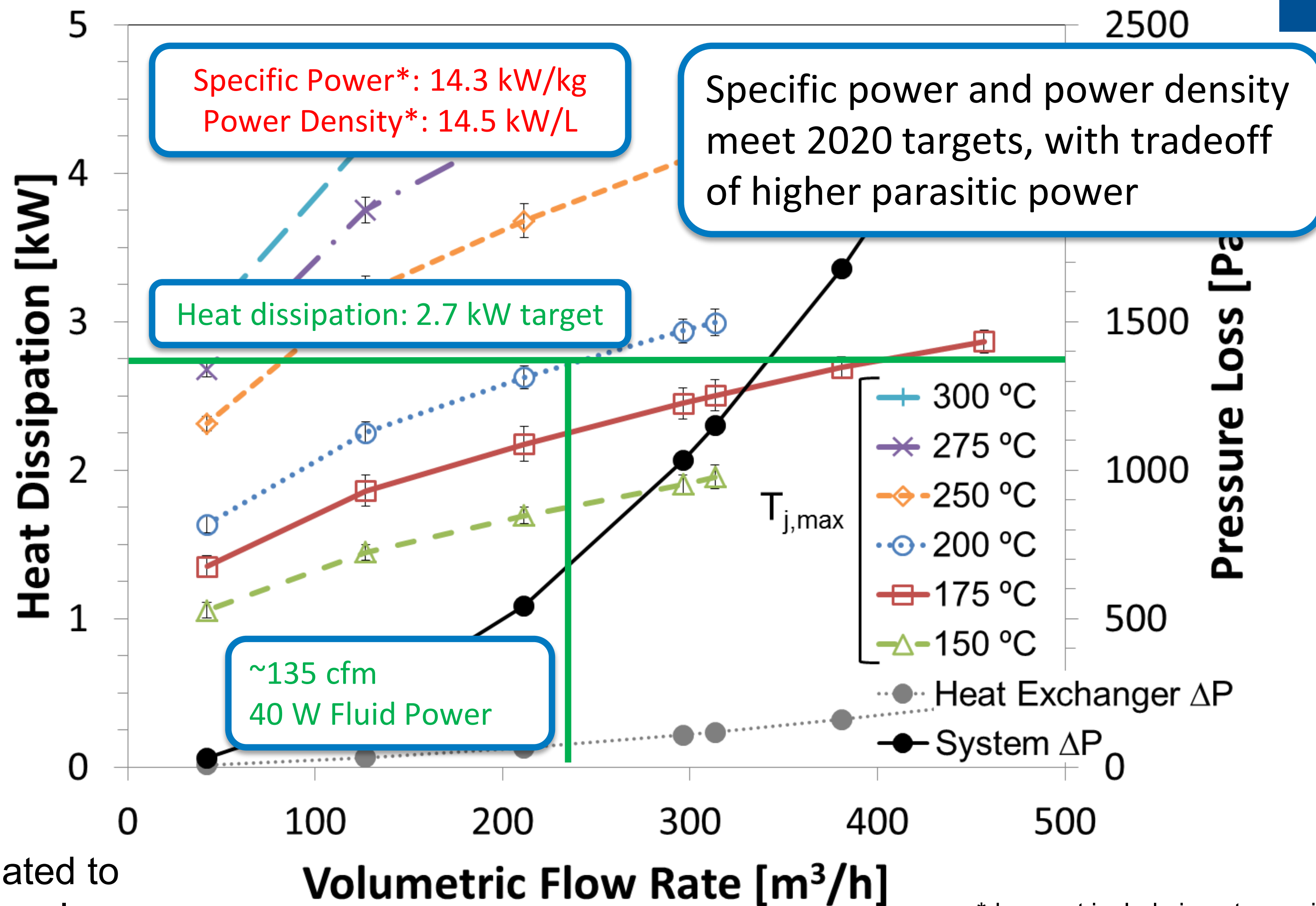

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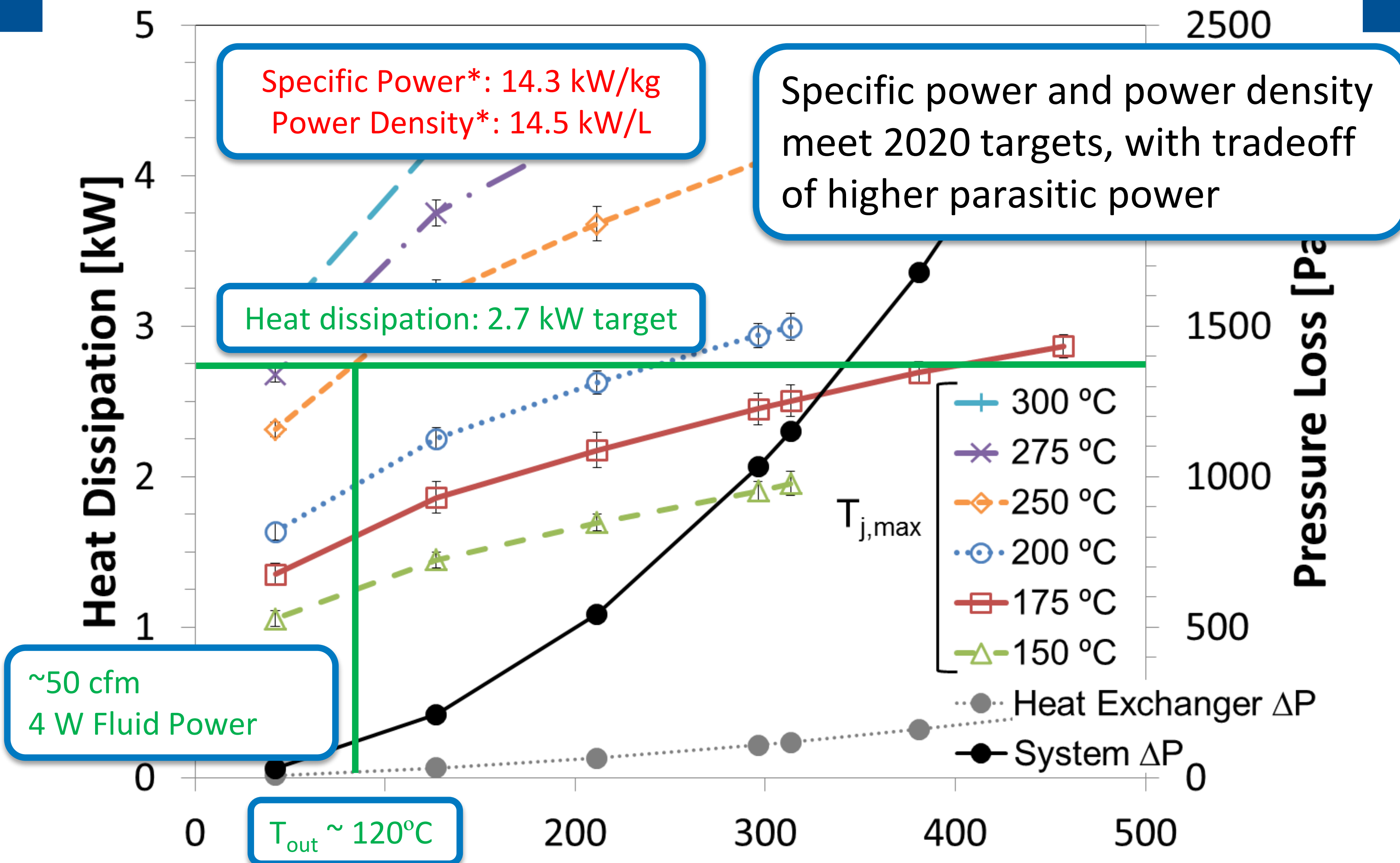
Heat Dissipation for **Optimized** Case (Six Modules)

Experimental

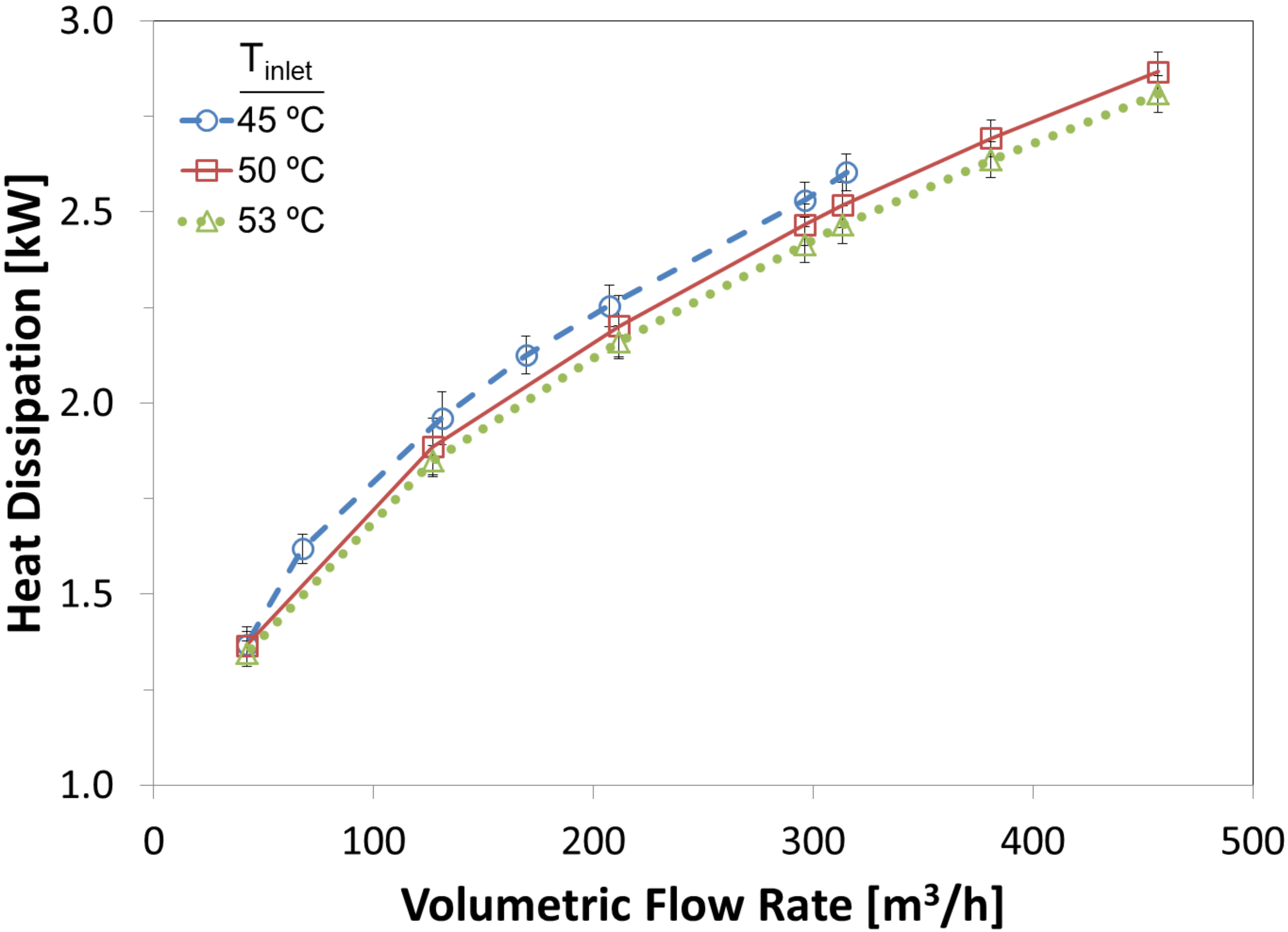


Extrapolated to inverter scale

*does not include inverter casing

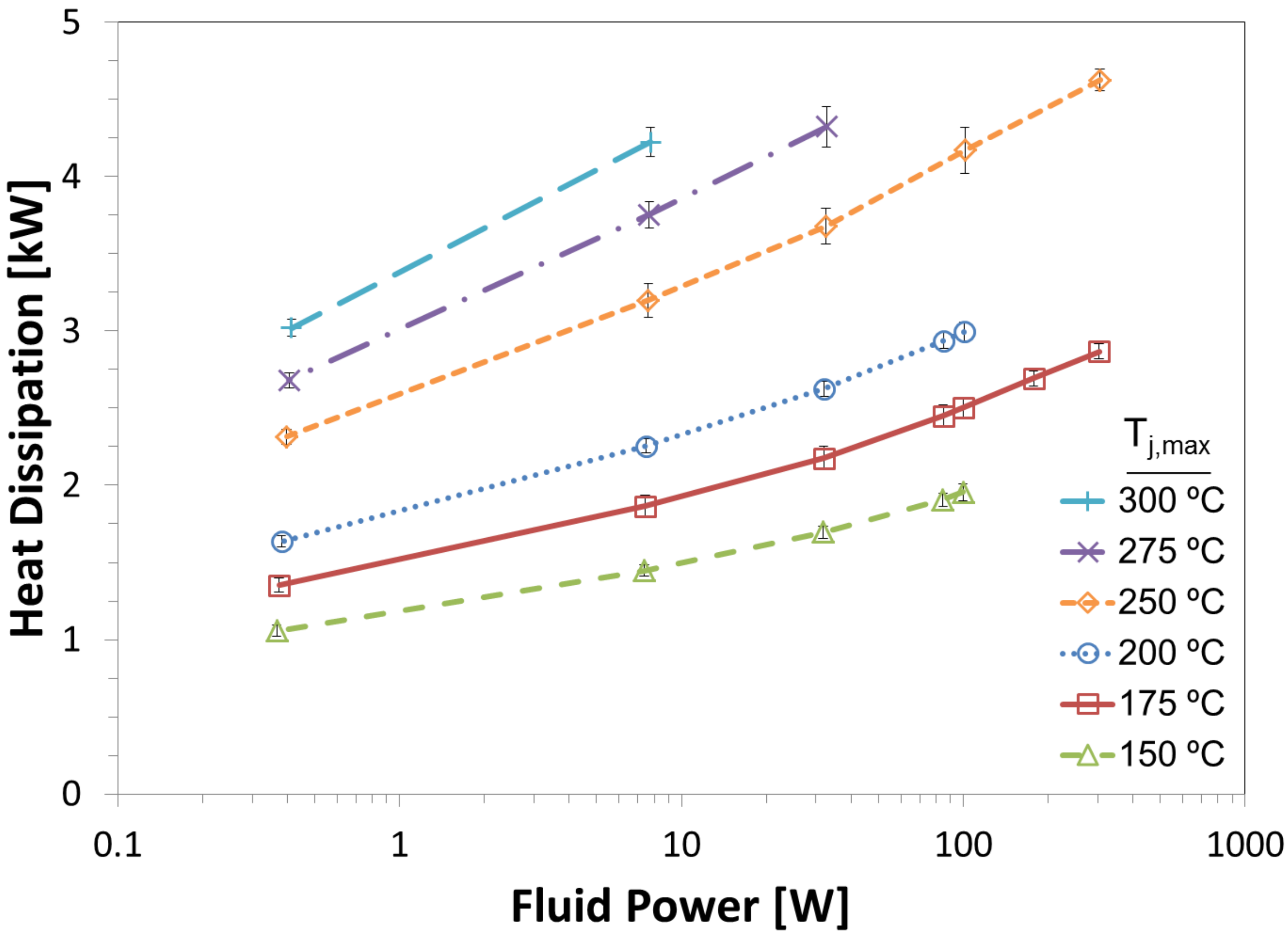
Inlet Temperature Effect (175ºC Junction Temperature)

Experimental



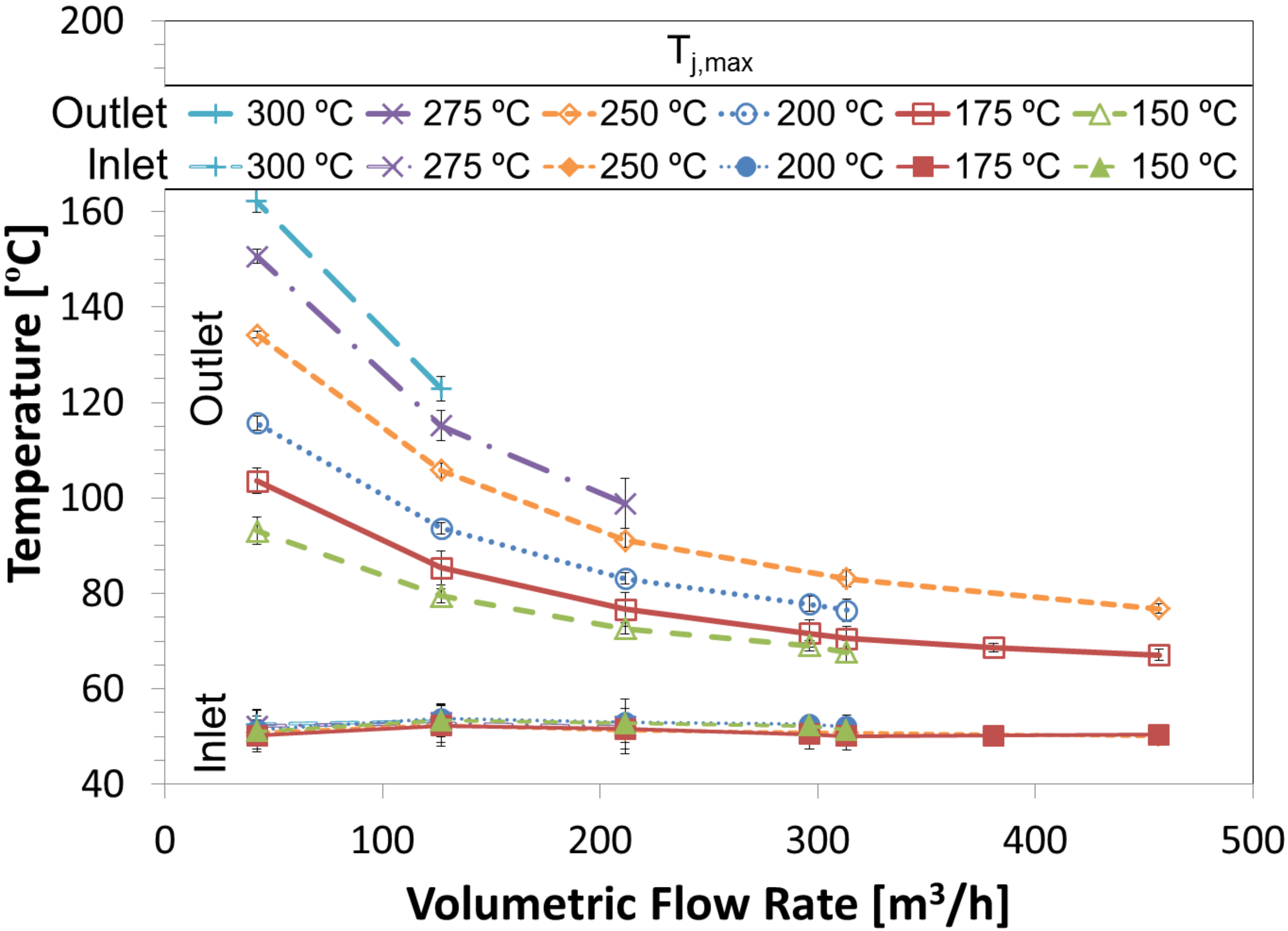
Fluid Power for Various Junction Temperatures

Experimental



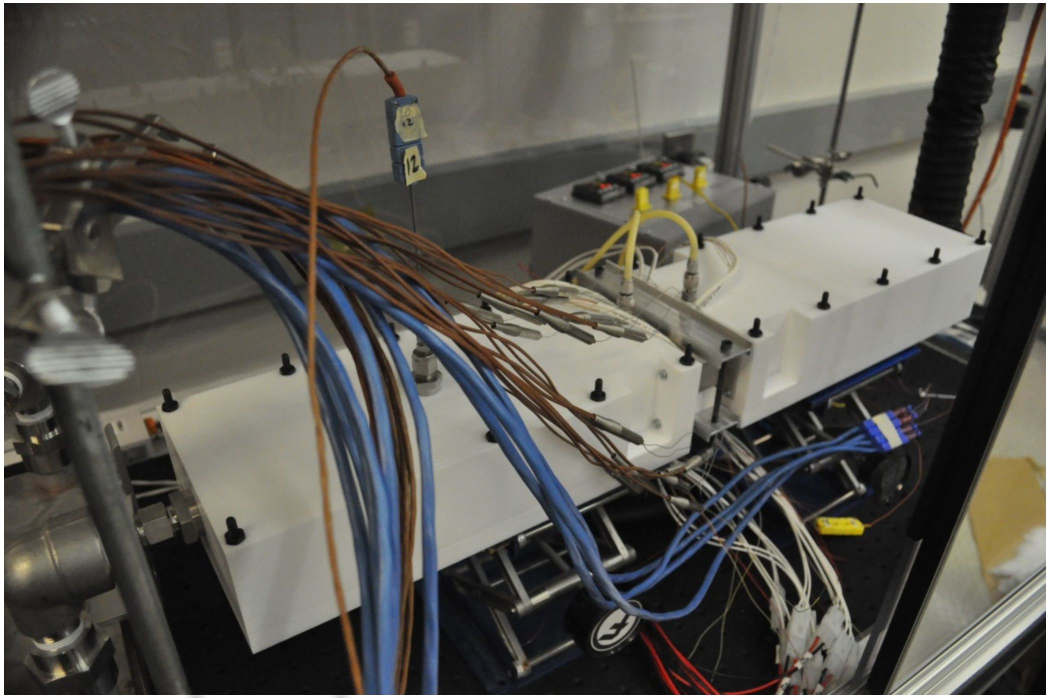
Inlet versus Outlet Temperature at Various Junction Temperatures

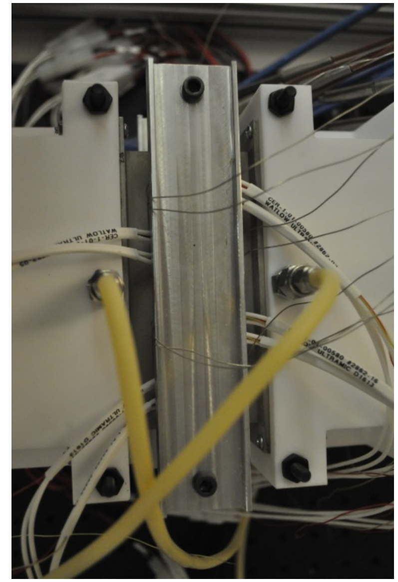
Experimental

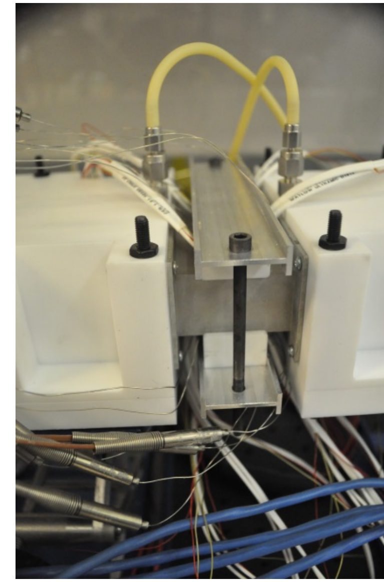


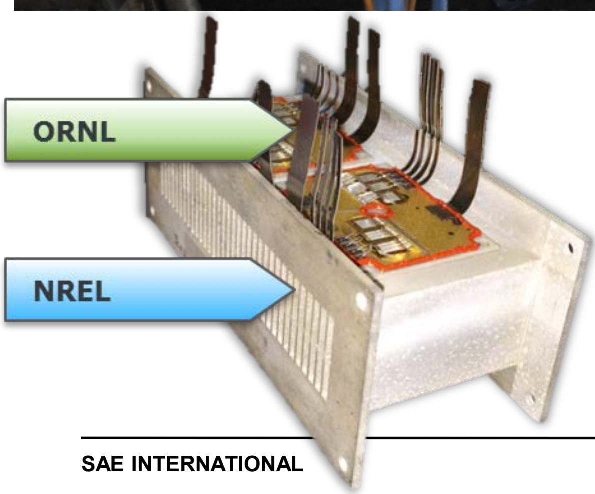
Module-Level Heat Exchanger Testing

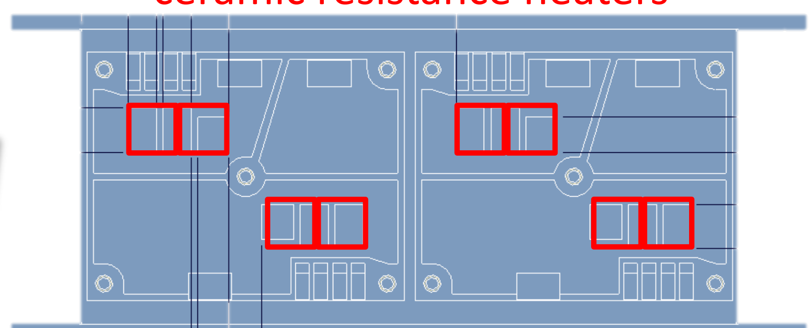
Experimental





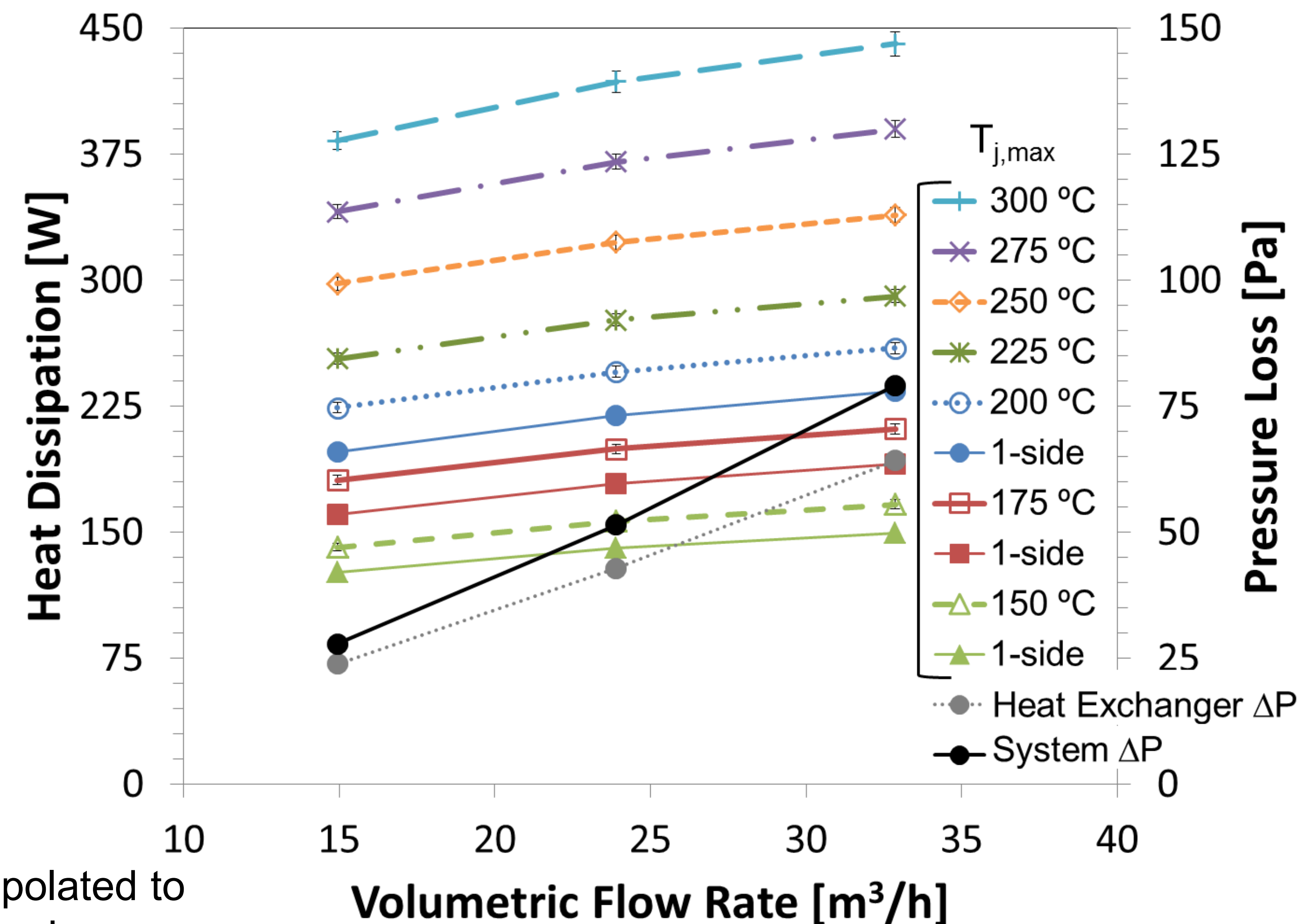






Heat Dissipation of Module-Scale Heat Exchanger

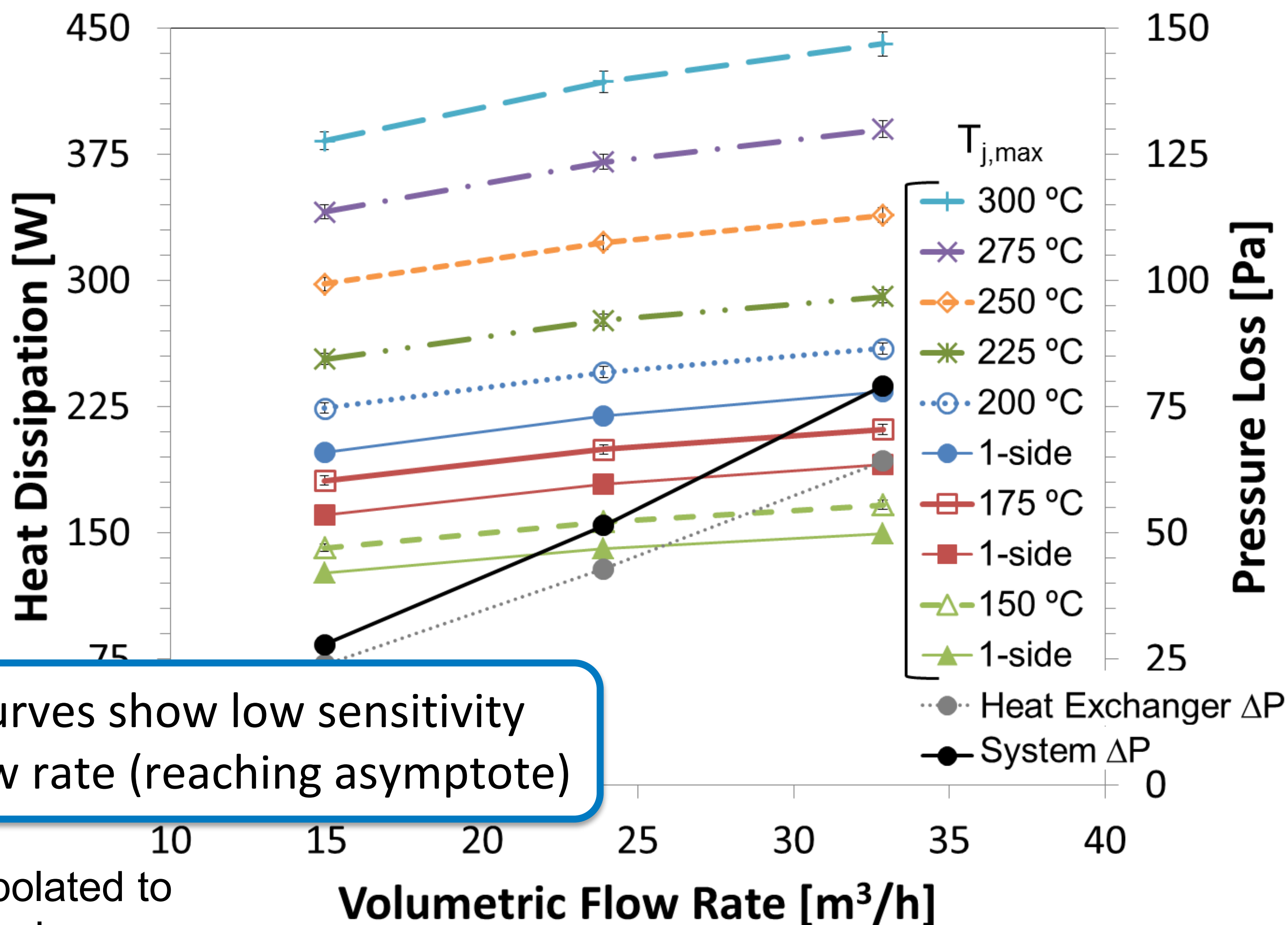
Experimental



Not extrapolated to inverter scale

Heat Dissipation of Module-Scale Heat Exchanger

Experimental

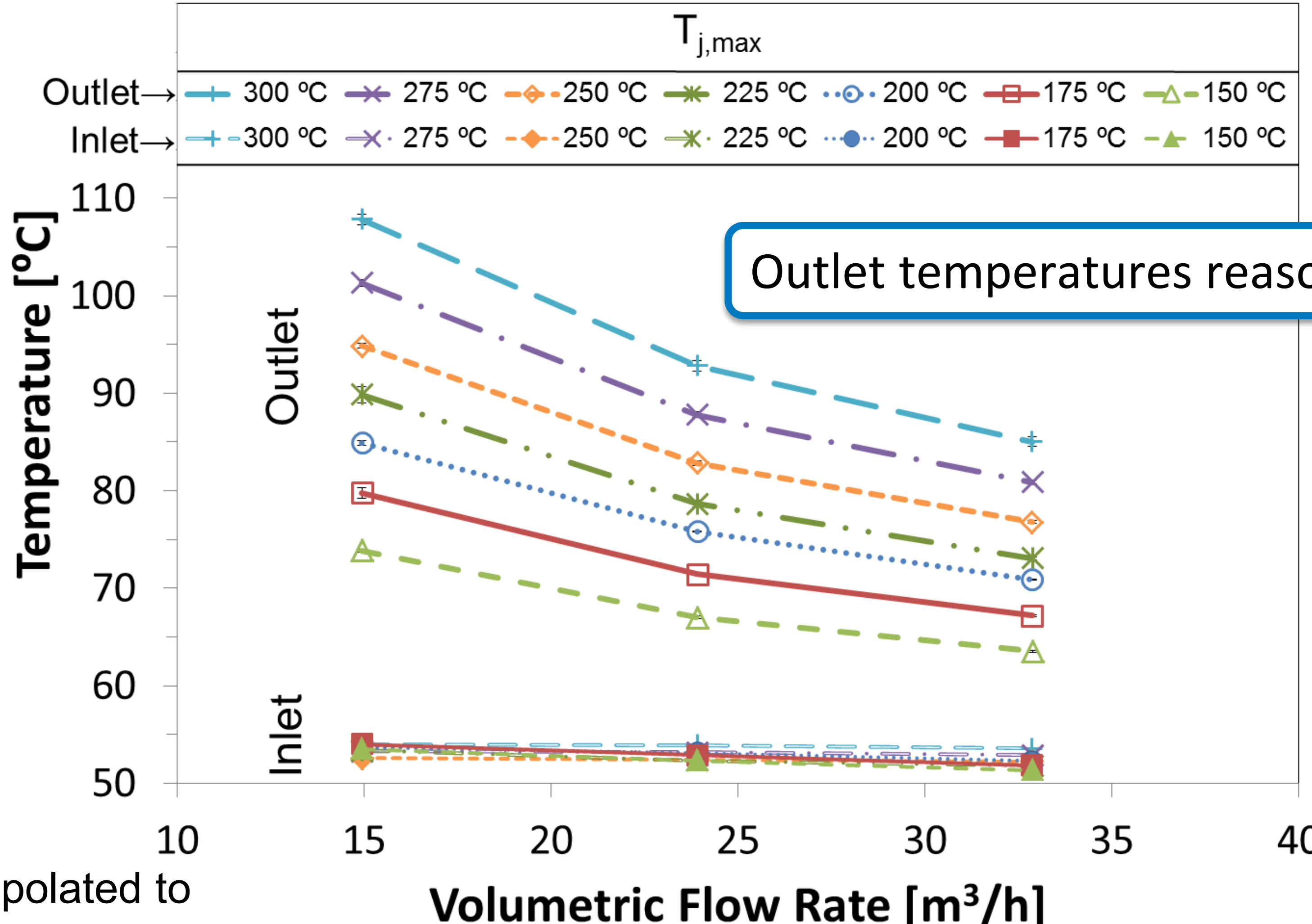


Flat curves show low sensitivity to flow rate (reaching asymptote)

Not extrapolated to inverter scale

Inlet and Outlet Temperatures of Module-Scale Heat Exchanger

Experimental



Outlet temperatures reasonable

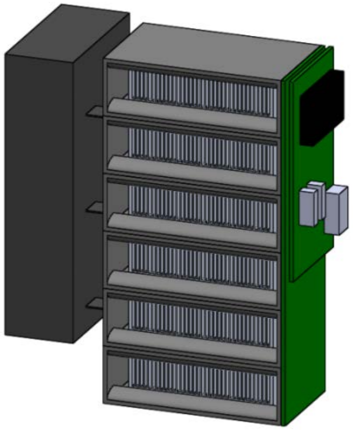
Not extrapolated to inverter scale

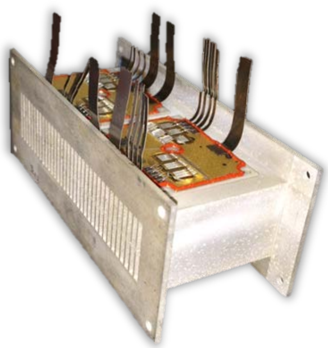
Summary

- Good potential technology for low cost, simple-to-manufacture options for high-temperature devices
- Eliminates liquid-to-air coolant loop
- Provides potential solution to cooling components with lower temperature limits (e.g., 85°C capacitor)

- Thermal performance for baseline and optimized sub-modules was characterized
- 10-kW module heat exchanger characterization and performance completed
- Parasitic power acceptable (in line with other vehicle components [e.g., A/C fan or condenser])

Conclusions





- Reducing the number of modules (with penalty of increased heat generation from increased current and increased parasitic power) is beneficial for weight and volume considerations
- Further optimization to thermal and electrical solutions would further reduce weight and volume
- Balance of inverter component design and optimization vital to meeting targets
- More advanced heat exchanger designs may improve heat transfer efficiency with tradeoffs in manufacturability and cost
- Electrical and thermal aspects need co-design to meet targets