NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Air Cooling Technology for Power Electronics Thermal Management



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“ Everything on a vehicle

is air cooled…

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is air cooled…

***ultimately* ”**

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is air cooled…

ultimately ”

Goal: Develop air-cooled thermal management system solutions that help meet DOE’s 2015 technical targets by 2014

Challenges and Barriers – Relevance

- **In current designs, heat is transferred from the source through a heat exchanger to a liquid, which is pumped to a remote location, and then the heat is rejected to air through another heat exchanger**
- **Air cooling has the potential to improve thermal management system cost, weight, volume, and reliability, helping to meet Advanced Power Electronics and Electric Motors (APEEM) technical targets**

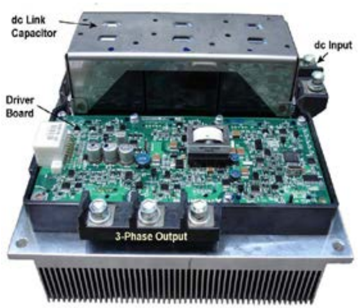
The Challenge

- **Air is a poor heat-transfer fluid**
  - low specific heat
  - low density
  - low conductivity
- **Parasitic power**
- **Perception and novelty**

Advantages

- Everything on a vehicle is ultimately air-cooled
- Rejecting heat to air can eliminate intermediate liquid loops
- Air is benign and need not be carried
- Air is a dielectric and can contact the chip directly

It Can Be Done….When?….How?



Honda Insight

Power Rating 12 to 14 kW

AC Propulsion AC-150

Power Rating 150 kW

Photograph references: Left 1st row [1], Left 2nd row [2], Right 1st row [3], Right 2nd row [4]

Overview

Timeline

Phase II start date: FY10
Project end date: FY14
Phase II complete: 50%

Budget

Total Project Funding:
DOE Share: $1,650K

Funding Received in FY11: $700K

Funding for FY12: $550 K

Barriers

- **Cost – Eliminate need for secondary liquid coolant loop and associated cost and complexity**
- **Weight – Reduce unnecessary coolant, coolant lines, pump and heat exchangers for lower system-level weight**
- **Performance – Maintain temperatures in acceptable range while reducing complexity and system-level parasitic losses**

Vehicle Technologies Program 2015 Targets

12 kW/l, 12 kW/kg, $5/kW

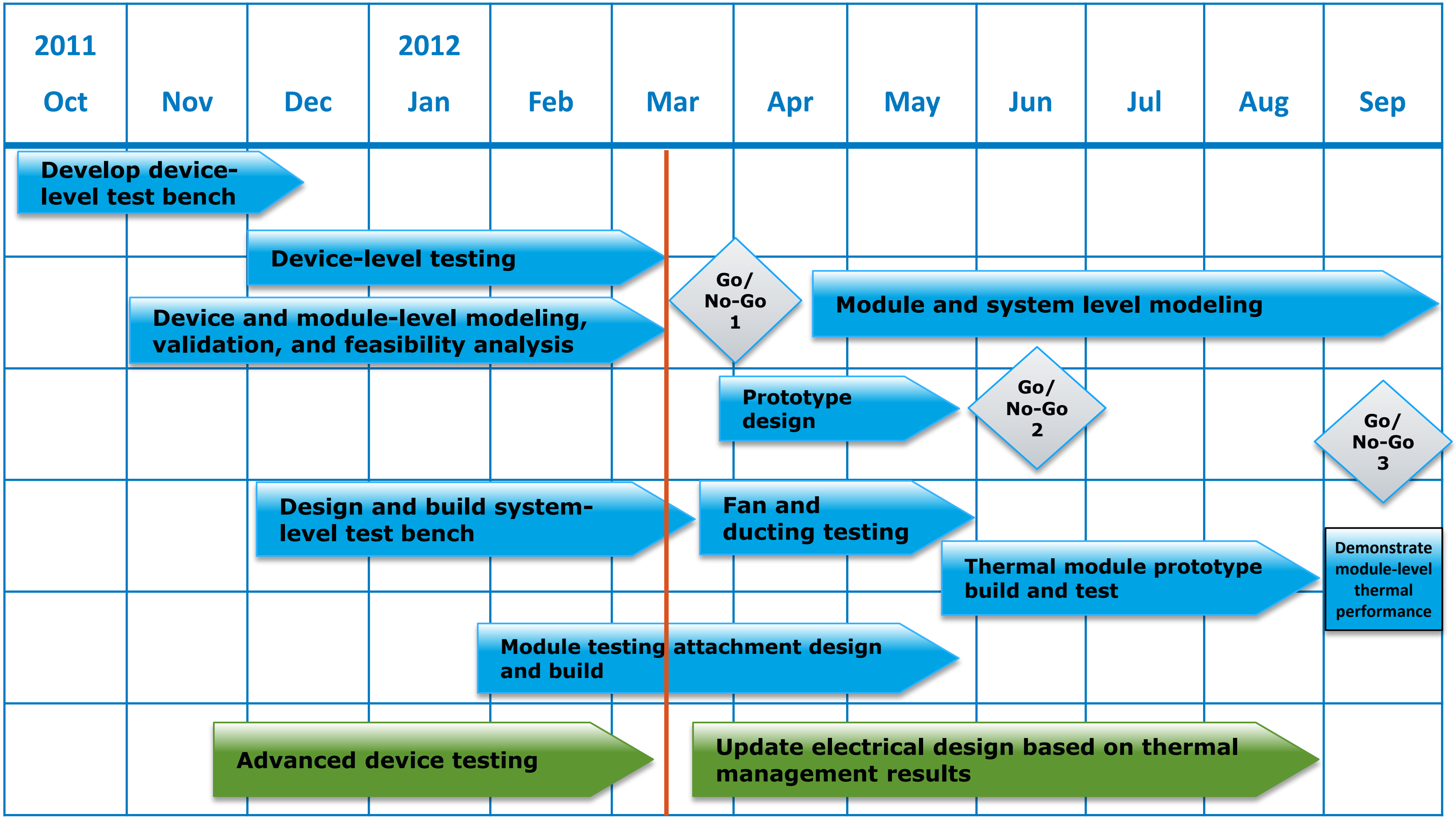
Partners

- Oak Ridge National Laboratory (ORNL)
  - Madhu Chinthavali
- GE, Momentive Performance Materials, and Sapa

FY12 Plan – Relevance

NREL Tasks

ORNL Supporting Tasks



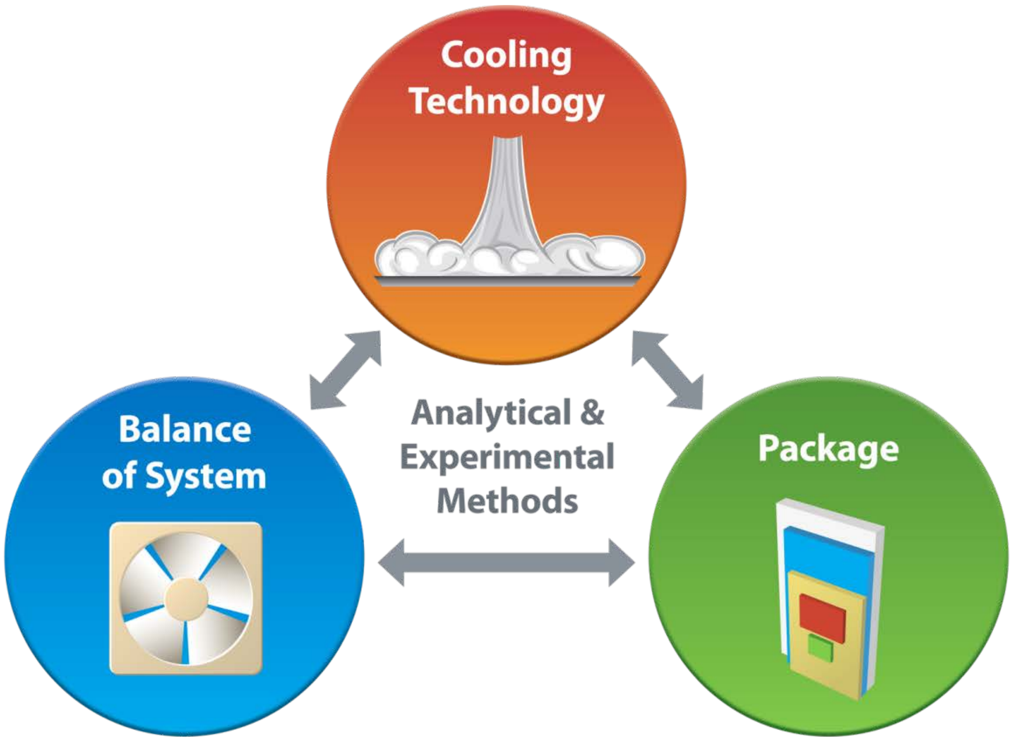
Go/ No-Go Decision Points:

1. Use modeling to determine feasibility of design, use device-level testing to validate models and use in conjunction with models to determine promising cooling approaches
2. Confirm module-level improvement over baseline and that inverter is on track to meet targets
3. Use module-level data and fan testing results to confirm adequate system performance for FY13

Milestones

Date	Milestone or Go/No-Go Decision
05/11	Go/No-Go 0: Using NREL's system-level analysis method, found that it may be possible to approach liquid-cooling power density using advanced technology for air cooling
09/11	Synthetic and steady jet study showed a 30% improvement in heat transfer with synthetic jets
12/11	Completed device-level test bench
02/12	Baseline device-level testing
02/12	Model validated
03/12	Go/ No-Go 1, Initial design feasibility: Use modeling to determine feasibility of design, validate with device-level testing
04/12	Complete system-level test bench and begin fan and ducting experiments
06/12	Go/ No-Go 2, Module prototype design review: Confirm system-level improvement over baseline and that system will meet targets
09/12	Go/No-Go 3, Module level demonstration: Use module-level data and fan testing results to confirm adequate system performance for FY13

Approach

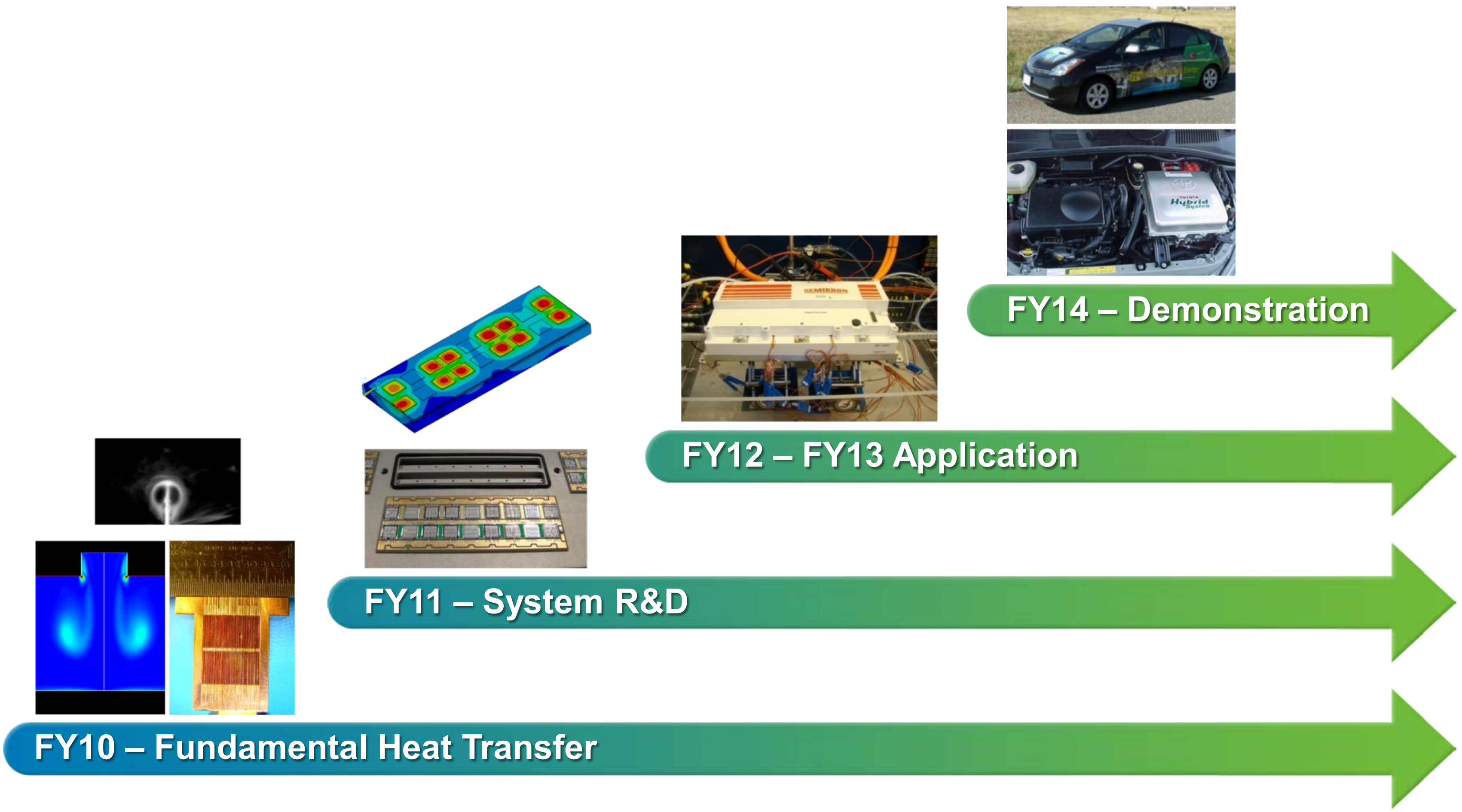


Thermal Environment
- Inverter Location
- Air Source

Device Type
- Max Temperature
- Efficiency

Vehicle Context
- Power/Duty Cycle
- Volume/Weight Limits

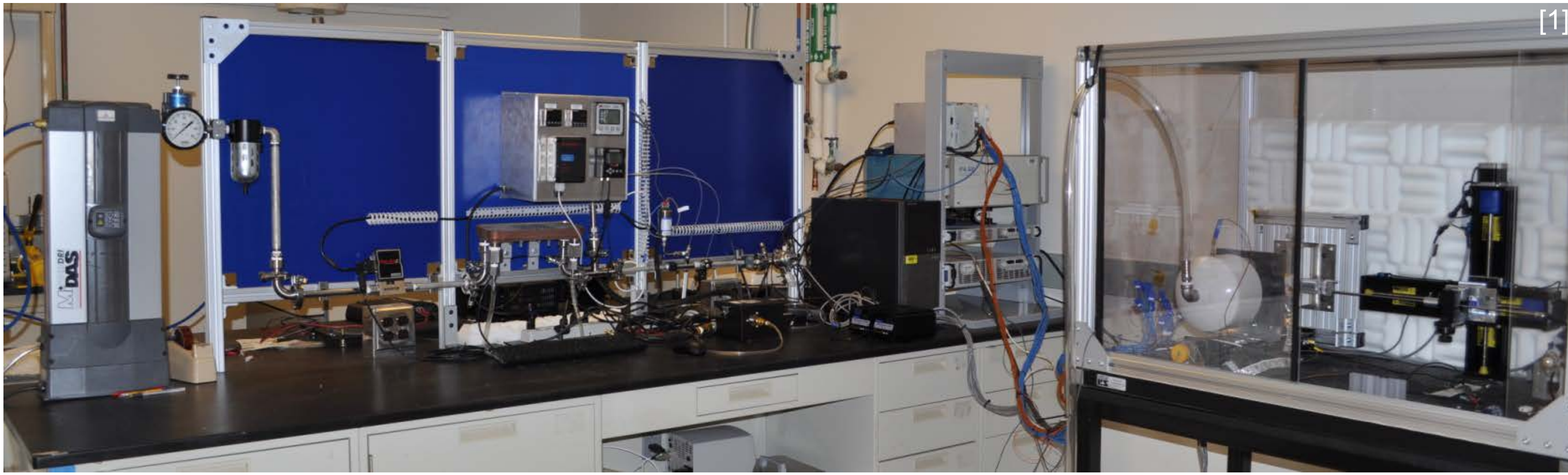
Approach



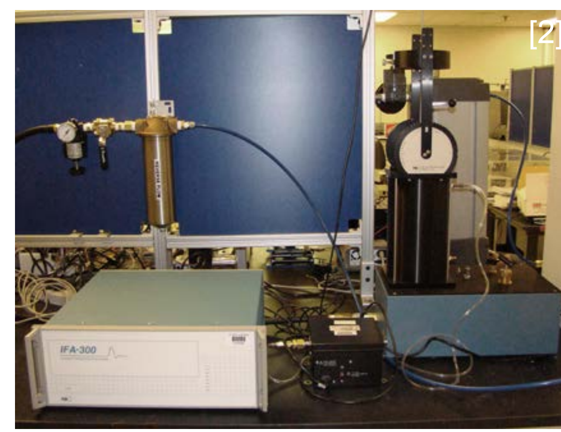
Photograph references from left to right: 1. Top [1], Right [2]; 2. Bottom [3]; 3. [4], 4. [5]

Cooling Technology

Air Cooling Technology Characterization Platform



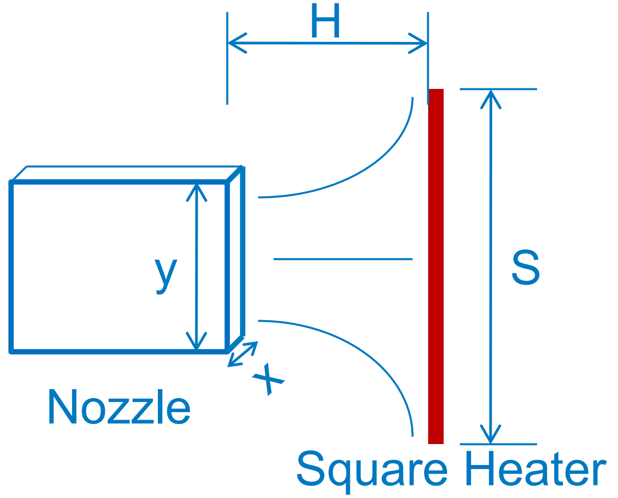
- **Air flow rate control**
- **High accuracy heat transfer measurement**
- **Velocity field characterization**
  - Hotwire anemometry
  - Particle image velocimetry
- **Computer programmable**

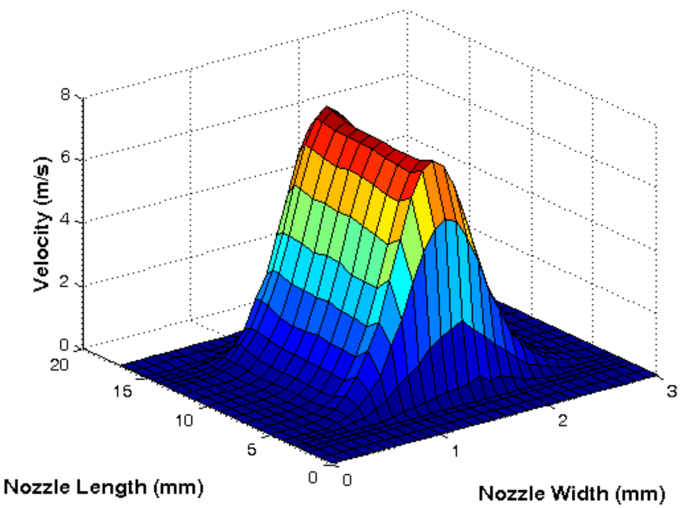


Steady and Synthetic Jet Impingement

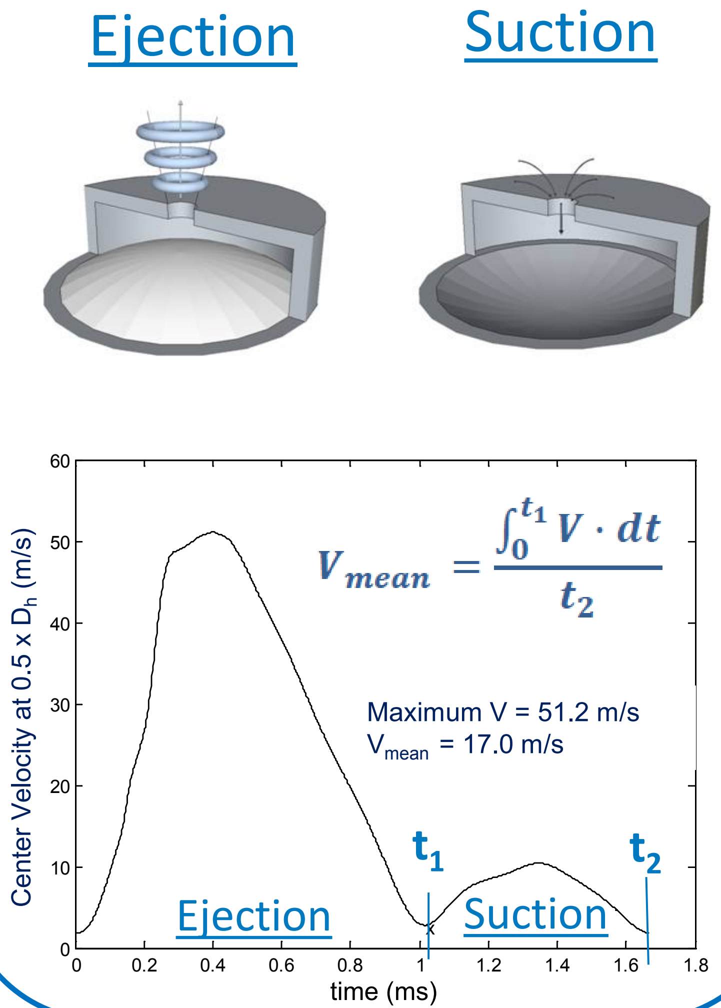
Advanced technology research

Steady Jet





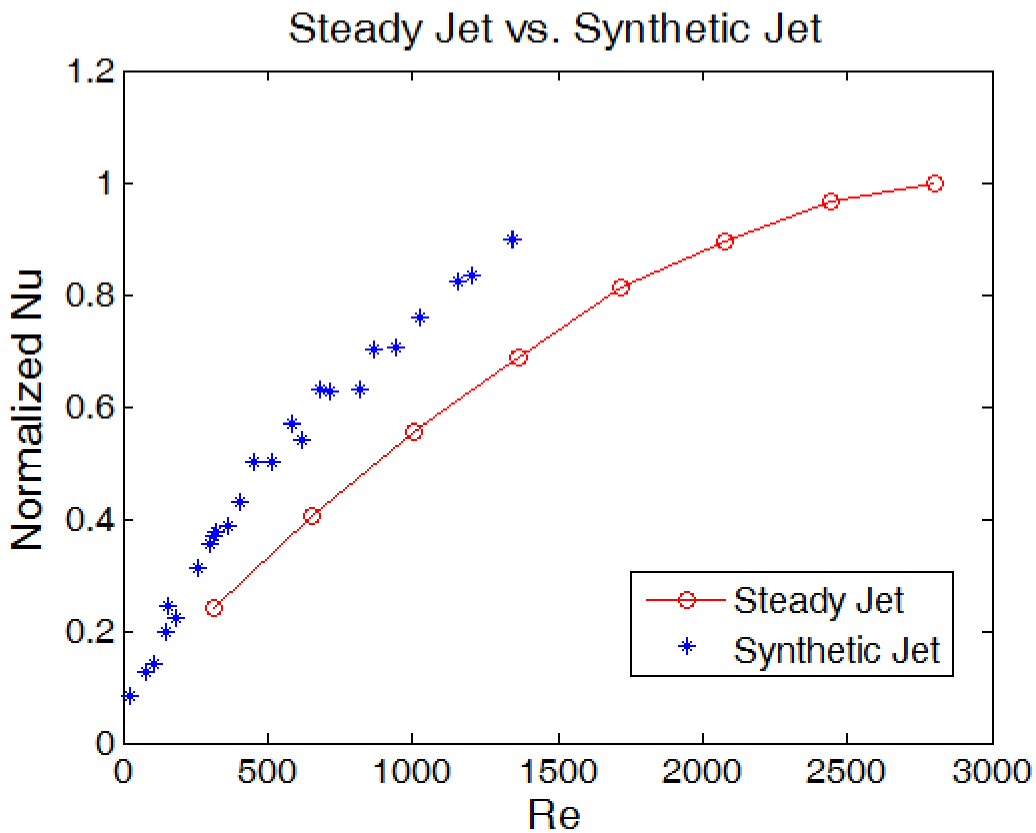
Synthetic Jet



Steady Jet vs. Synthetic Jet

Synthetic jet improved heat transfer coefficient by 30%

- **Reynolds number calculated using the center-line time-averaged mean velocity**
- **Developed steady jet heat transfer correlation**
- **Introduced dynamic Reynolds number concept to collapse steady and synthetic jet data**



* Data normalized, pending approval for publications given below

- *He, X., Lustbader, J., Arik, M., Sharma, R. "Characteristics of Low Reynolds Number Steady Jet Impingement Heat Transfer Over Vertical Flat Surfaces." ITherm 2012. San Diego, CA. May 20 – June 1, 2012. (pending publication)*
- *Arik, M., Sharma, R., Lustbader, J., He, X."Comparison of Synthetic and Steady Jets for Impingement Heat Transfer Over Vertical Surfaces." ITherm 2012. San Diego, CA. May 20 – June 1, 2012. (pending publication)*

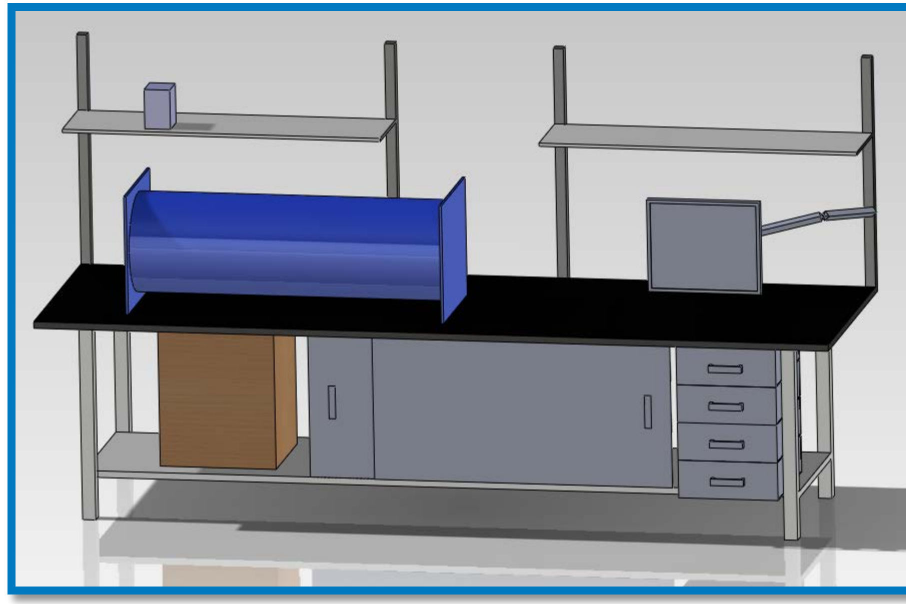
Nusselt Number: $\overline{Nu} = \frac{\bar{h} D_h}{k_f}$

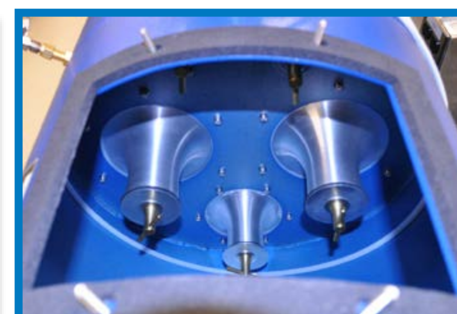
Reynolds Number: $\mathrm{Re} = \frac{V D_h}{\nu}$

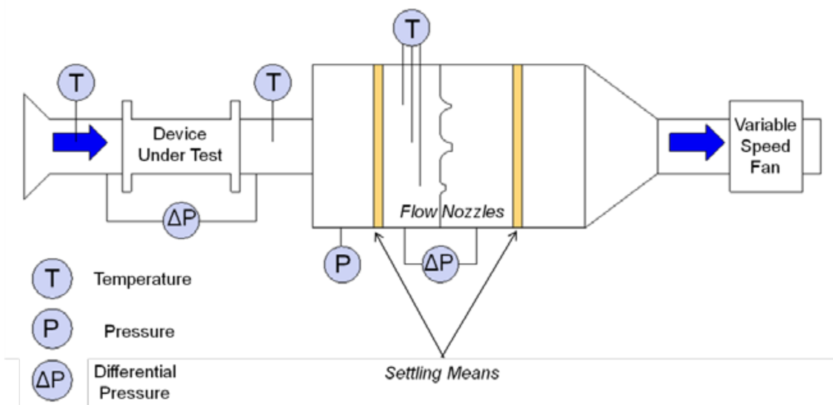
Balance-of-System

Understand parasitic loads and system coefficient of performance (COP)

- **Measure**
  - Fan performance and power
  - Ducting systems
  - Module level
  - Full System level
- **Phase I: Build complete in March**
- **Phase II, Noise Measurement: Build complete in September.**

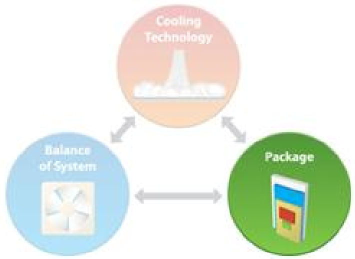


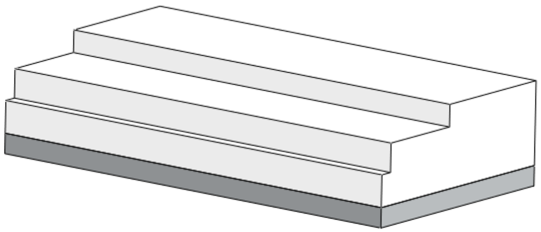


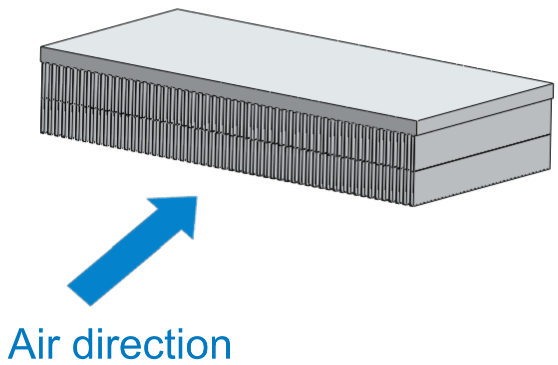


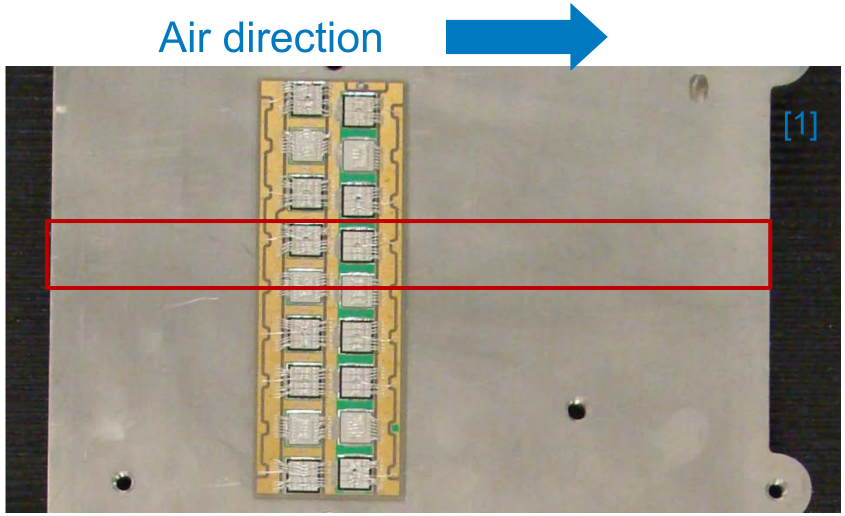
Mechanical Package

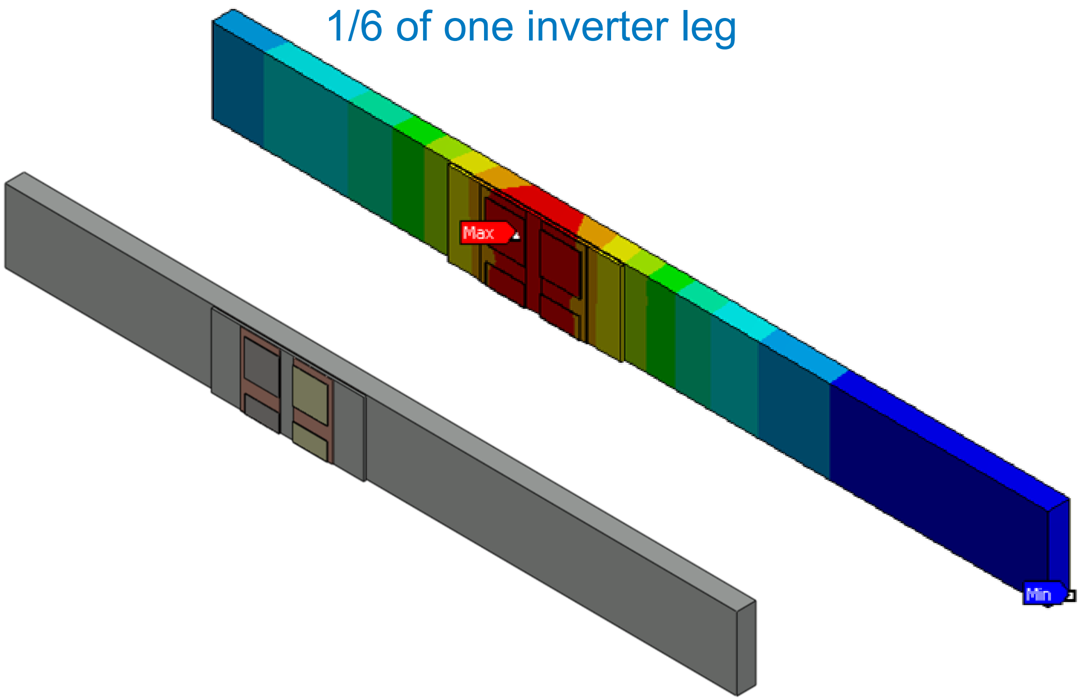
Inverter Case Study - Air Cooled

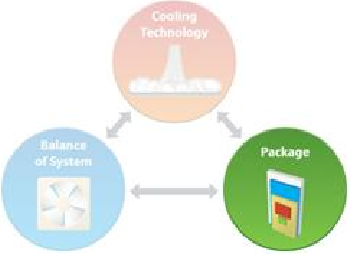






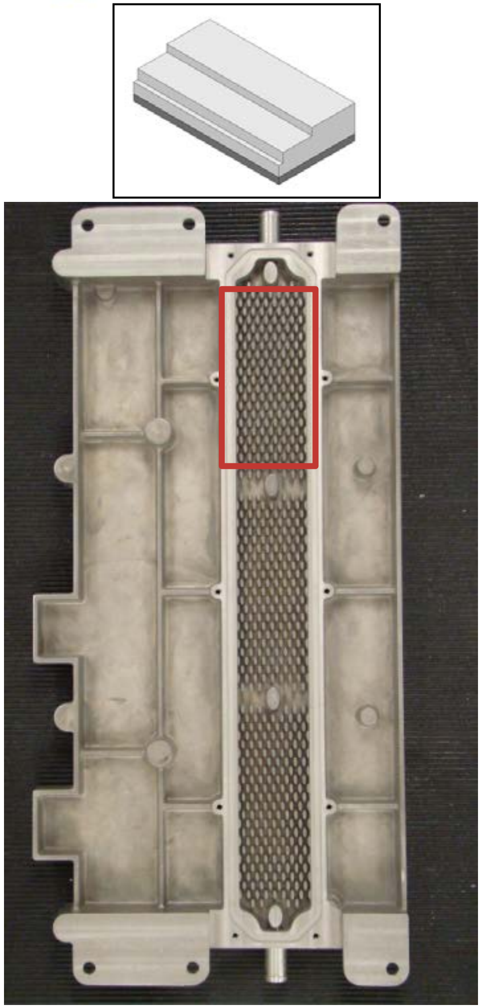






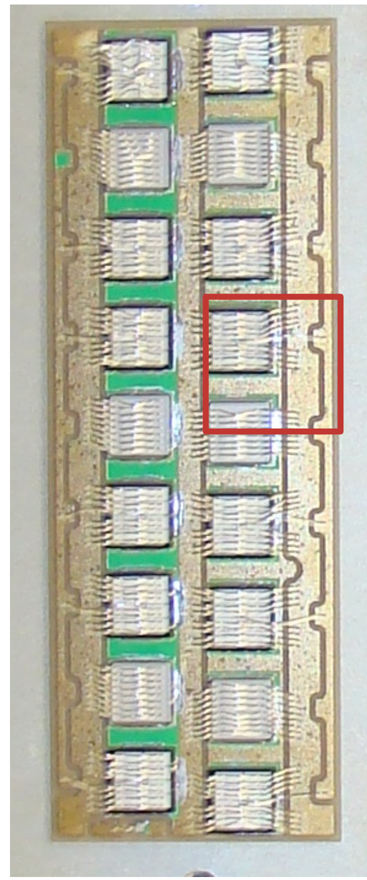
Mechanical Package

Inverter Case Study – Liquid Cooled



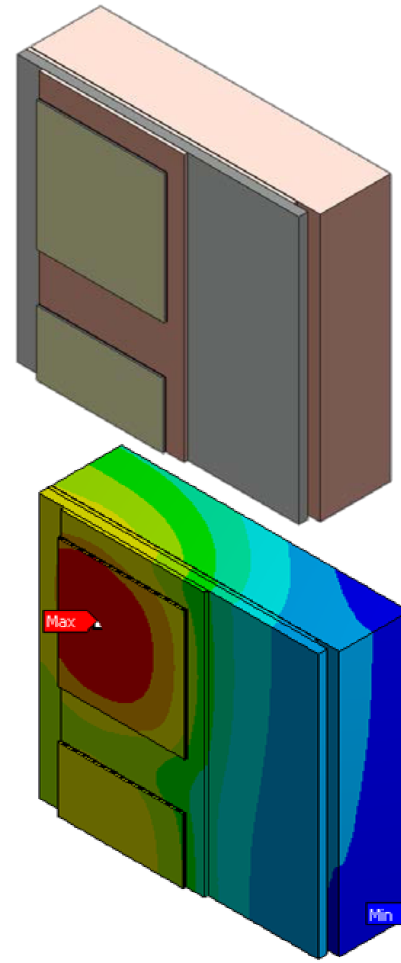
[1]

One inverter leg



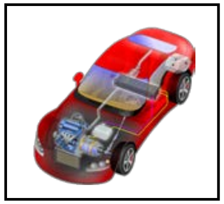
[2]

1/12 of one inverter leg



System-Level Analysis

Application Specification



Thermal Environment

Geometry Restrictions

Efficiency

Power Level

Cooling Technology Selection

Cooling Mechanism (Fin, Jet, etc…)

Area Enhancement Geometry

Interconnected Calculations

Thermal Load per Package Unit

Cooling Tech. Performance (UA)

Loss Calculation

Pressure

COP

Package FEA

Heat Exchanger Performance ($R''_{th,ha}$)

Thermal Performance

Specification Targets

Thermal Design Targets

Package Thermal Performance

Cooling Design Targets

Package Geometry

Package Materials

Package Thermal Interfaces

Package Mechanical Design

Fluid Flow Rate

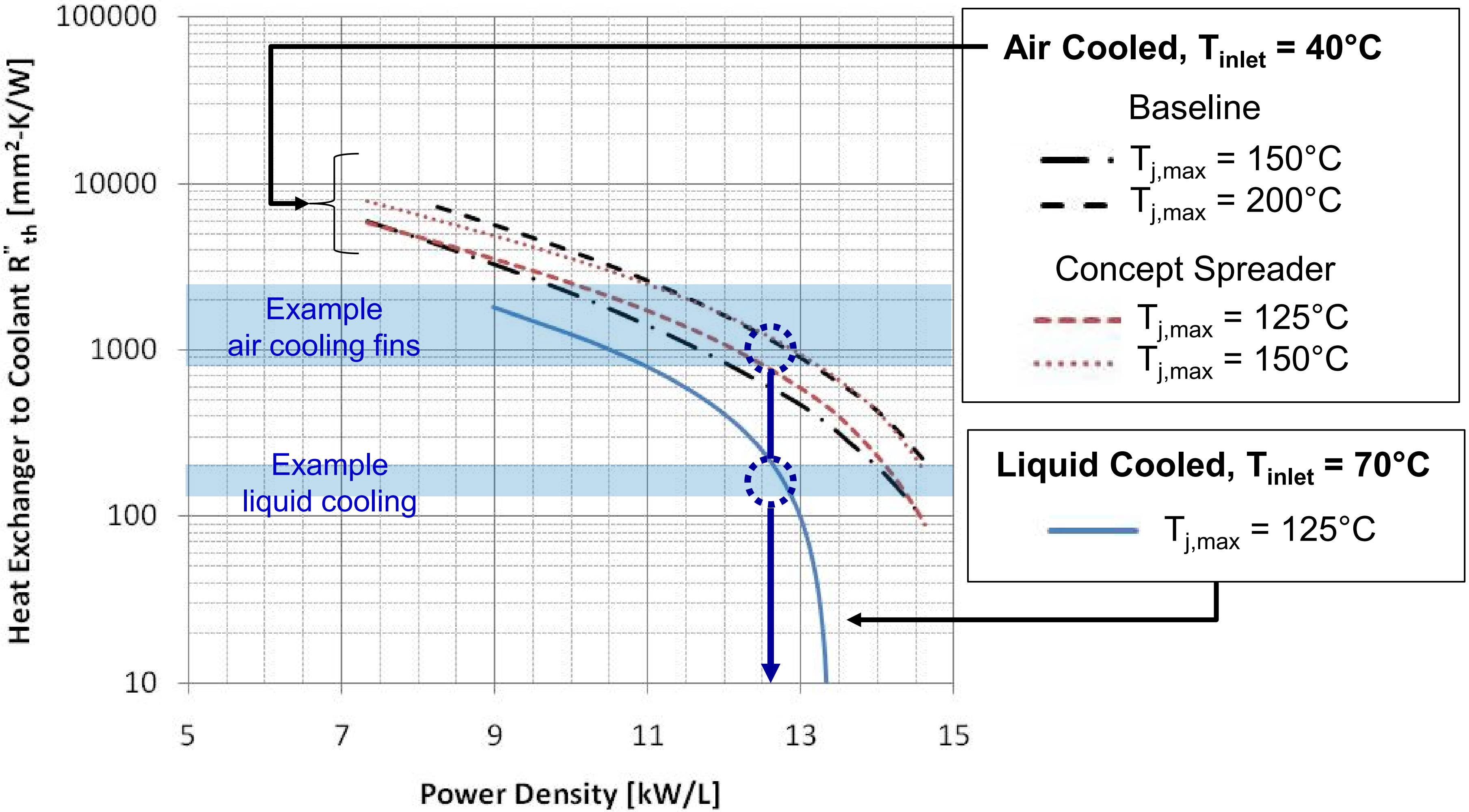
Temperature Constraints

Flow Path (Series Parallel)

Balance-of-System

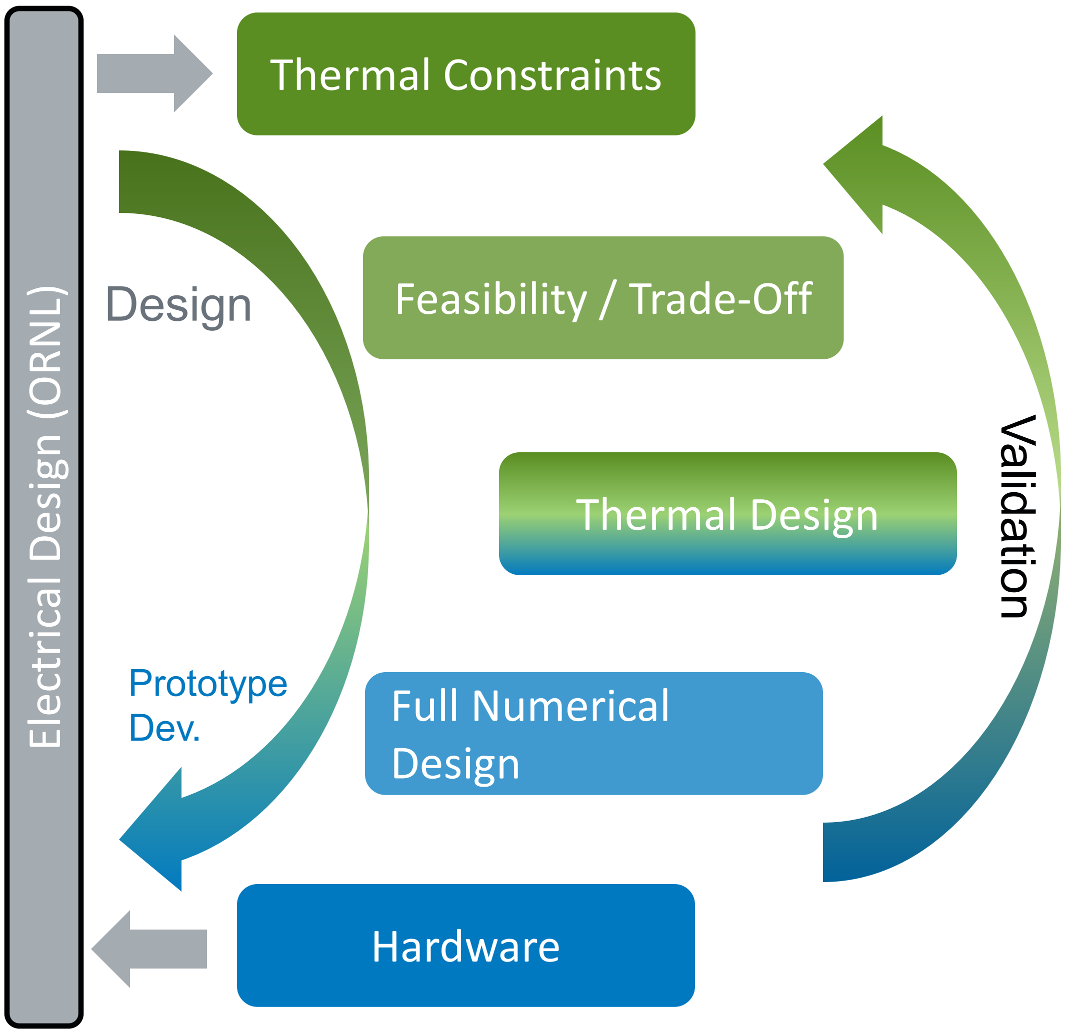
Air-Cooled System Comparison

Example design trade-offs



- *450 VDC, 400 A_{rms}, 0.5 power factor, and 125°C temperature limit*
- *Power factor adjusted to provide 3:1 heating of IGBT and diode*
- *Assumes capacitor size of 59.5 kW/L (10.53 μF/kW and 1.596e-3 L/μF)*

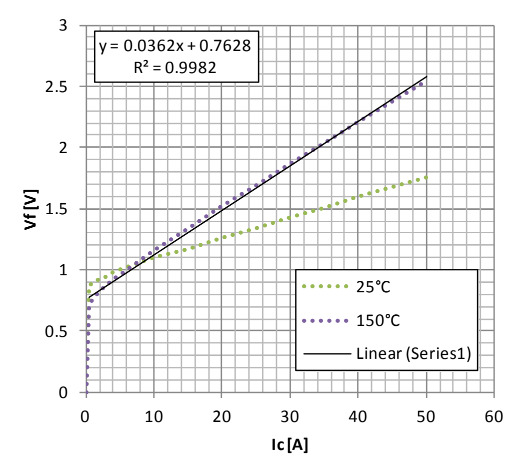
High Temperature Air-Cooled Inverter



Electrical Design

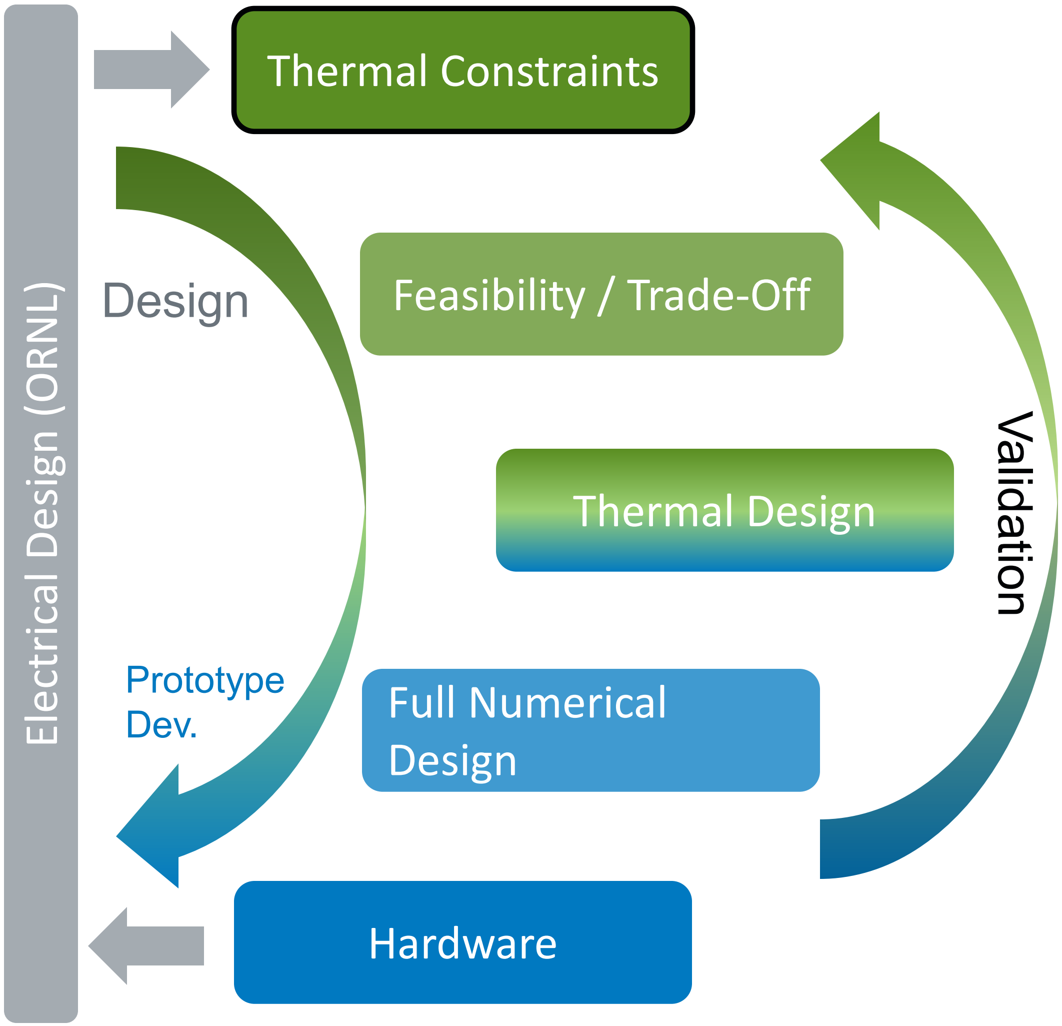
- Device type
- Device locations
- Electrical duty cycles
- Temperature-dependent loss equations
- Inverter efficiency

Diode Single Device*



**Chinthavali, M. "Wide Bandgap Materials." Section 2.1. DOE 2010 Annual Progress Report for Advanced Power Electronics and Electric Motors. Susan A. Rogers. January 2011.*

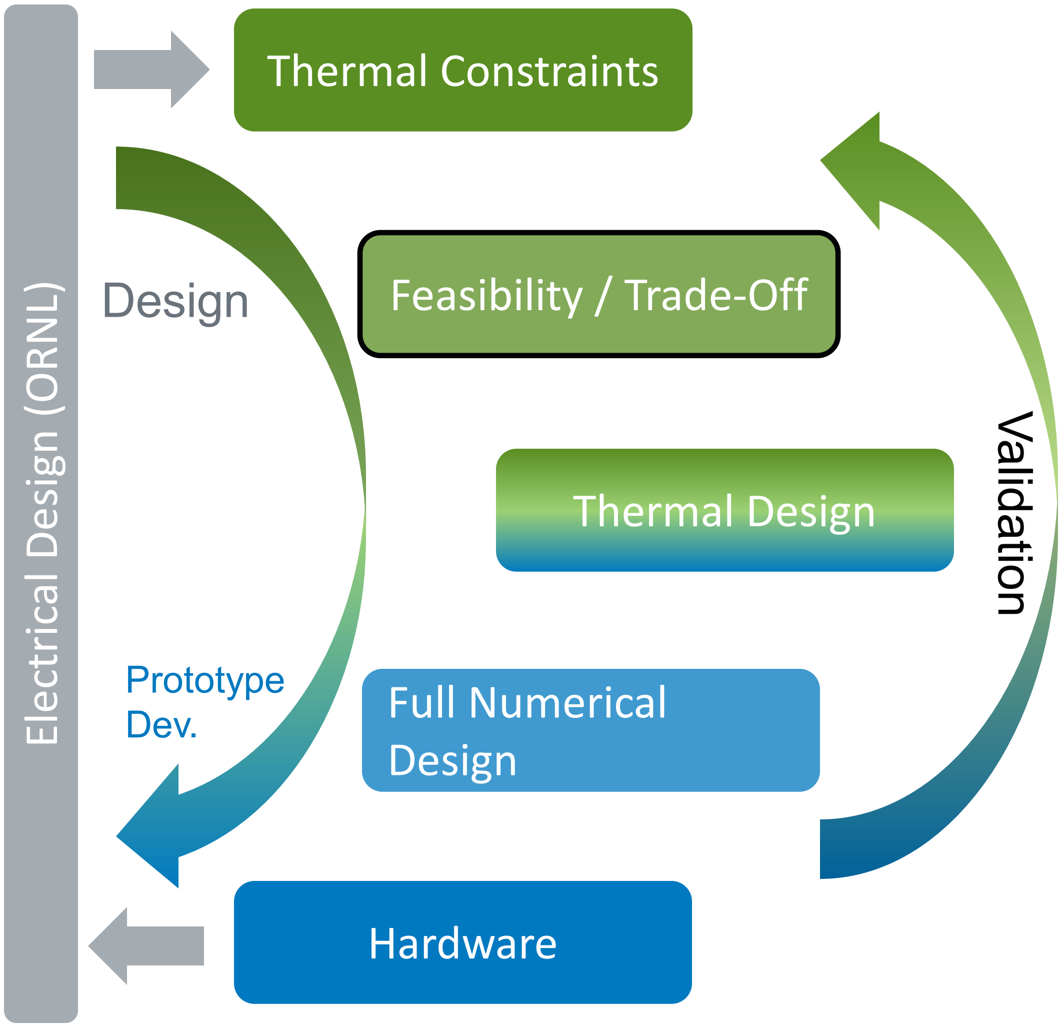
High Temperature Air-Cooled Inverter



Thermal Constraints

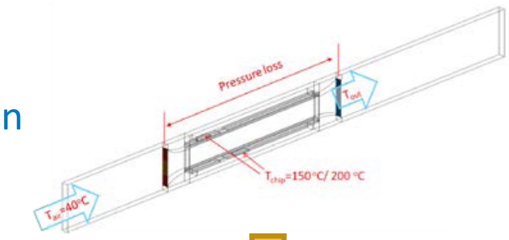
- **Maximum junction temperature**
- **Coolant temperature**
- **Heat generation**
  - Efficiency estimate
  - Analytical method
  - Switching model
- **Heat exchanger thermal requirements**

High Temperature Air-Cooled Inverter

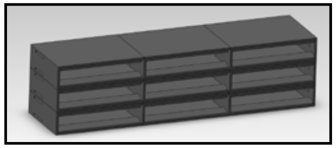


Feasibility/Trade-off

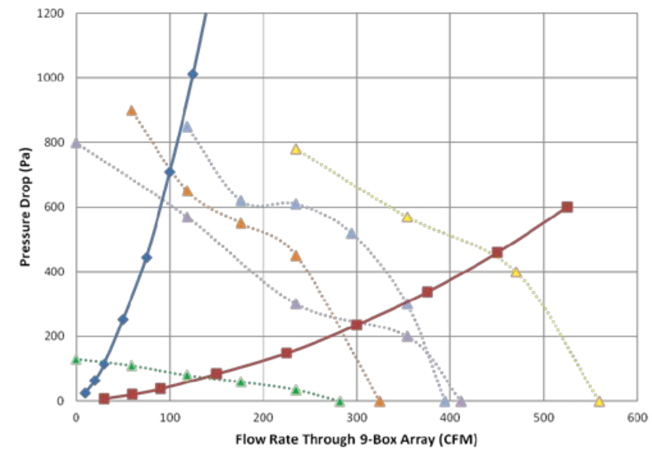
Single Fin CFD



Extrapolate system

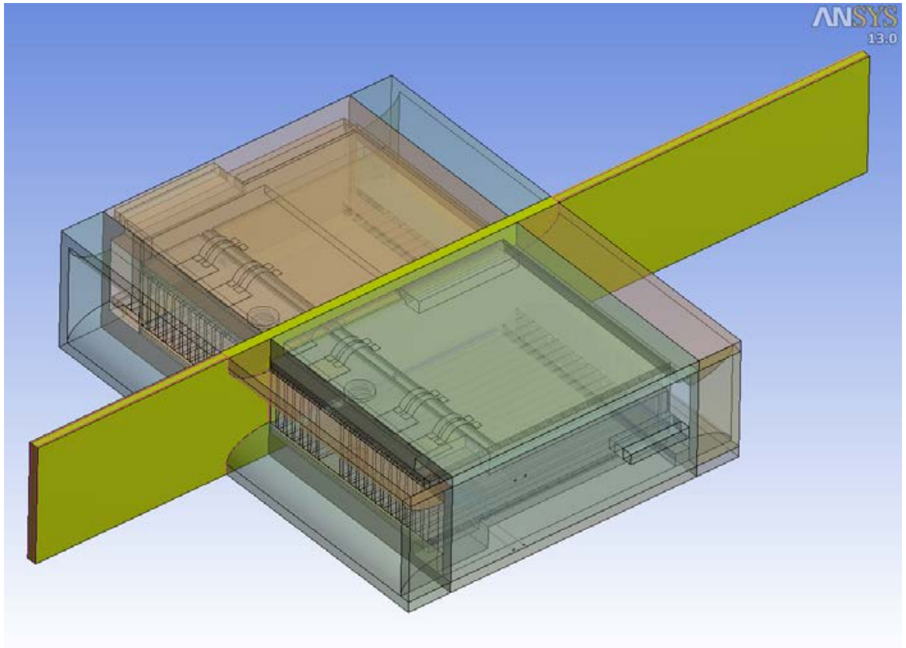


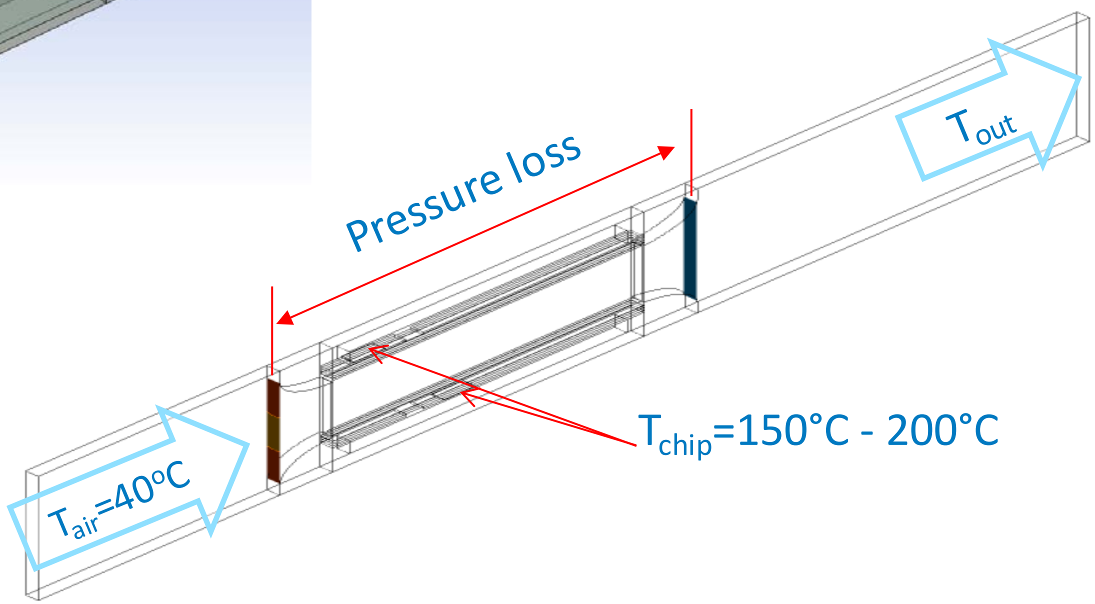
Add fan



Feasibility Study: Single-Channel Model Case

Conjugate heat transfer model for a single channel

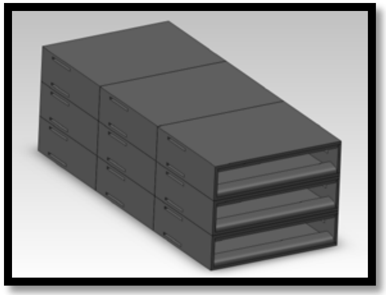


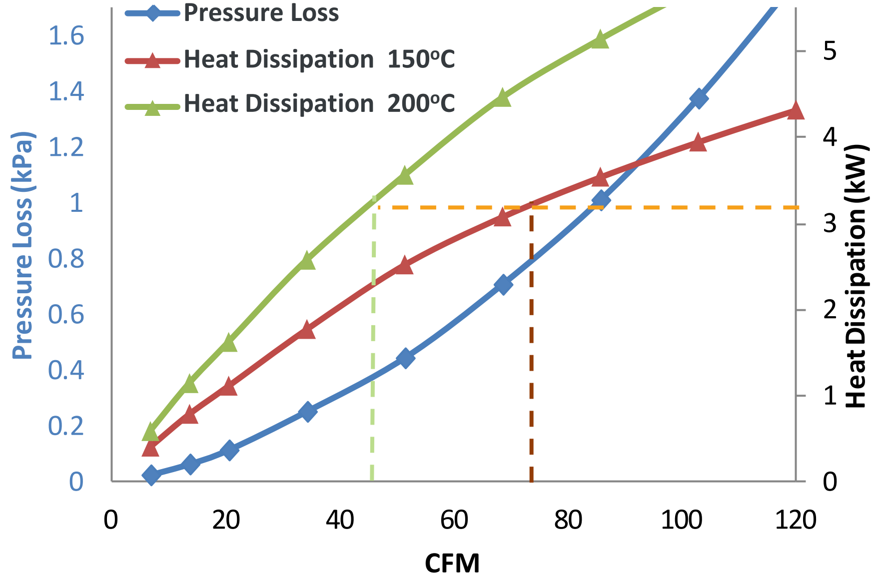


Extrapolation for Box Array

Target heat dissipation 3.2 kW

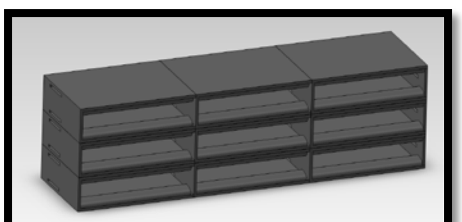
- **3 by 3 array**

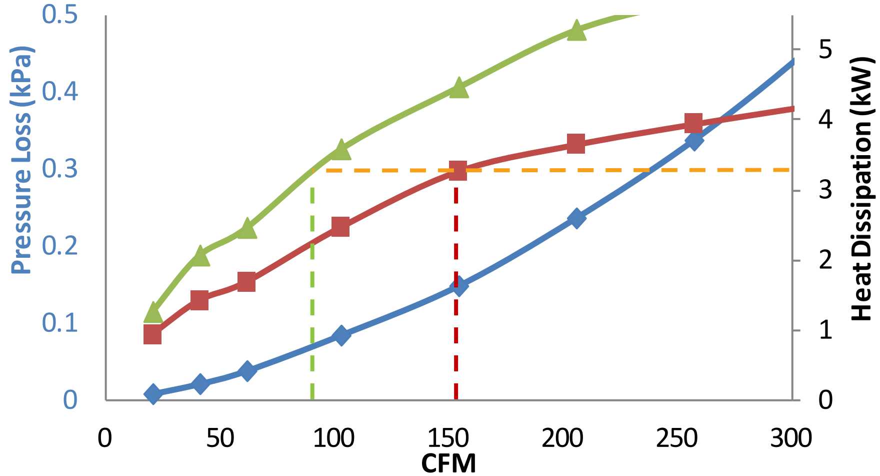




Chip Temperature [°C]	150	200
Required inlet volume flow rate [cfm]	72	45
Pressure loss [Pa]	768	374

- **9 by 1 array**

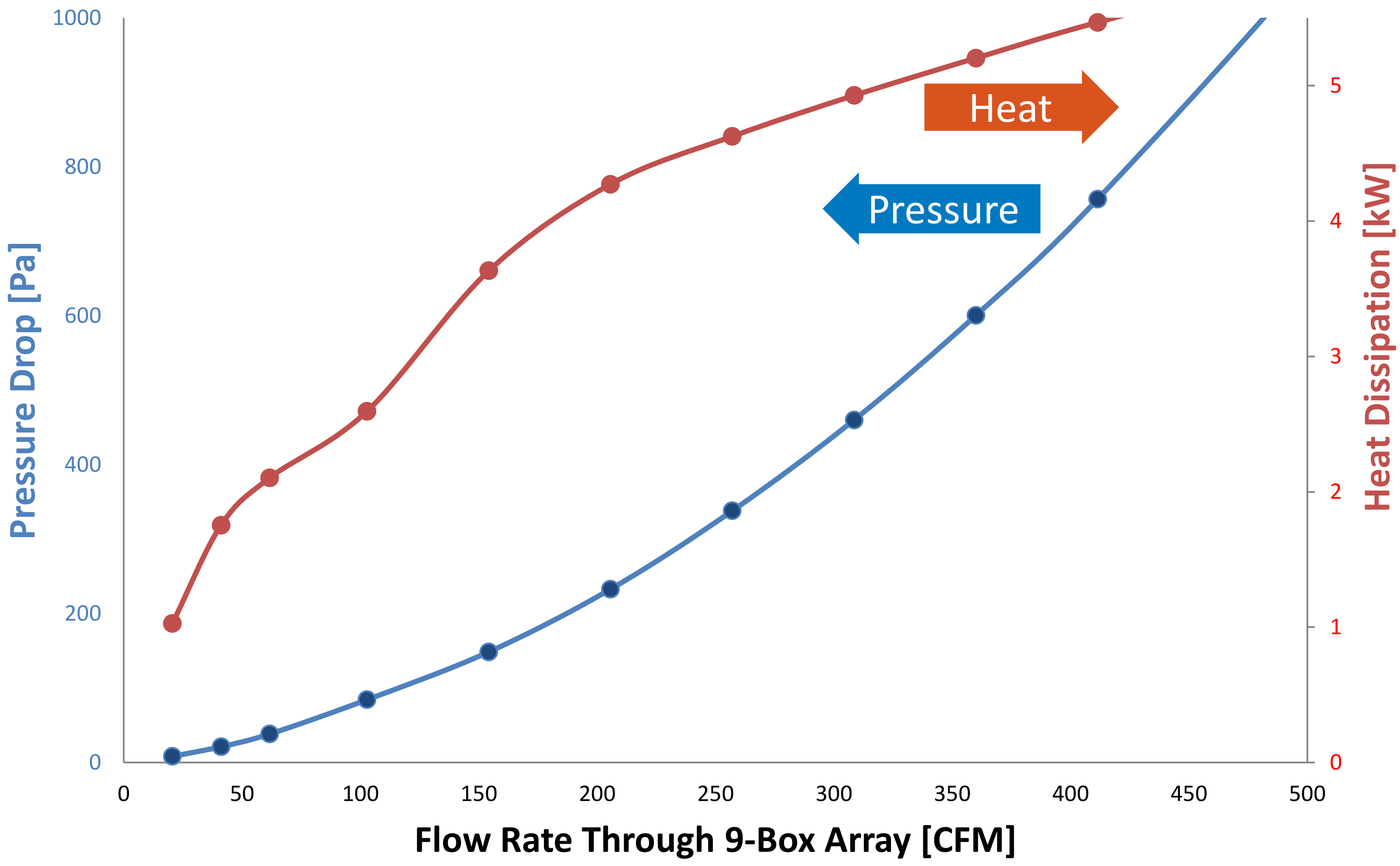




Chip Temperature [°C]	150	200
Required inlet volume flow rate [cfm]	150	102
Pressure loss [Pa]	143	84

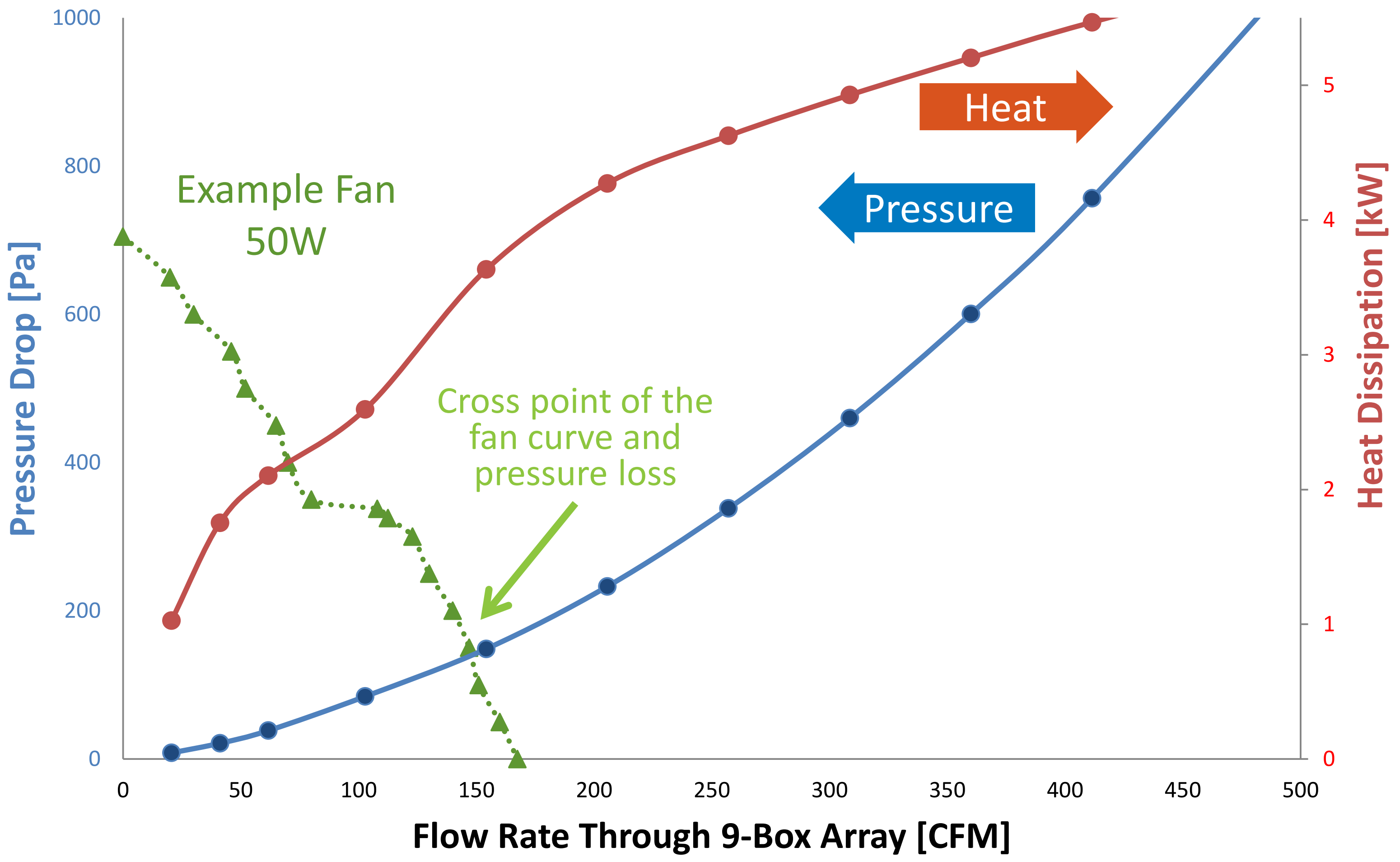
Example System Flow Study

9-by-1 array design, 175°C



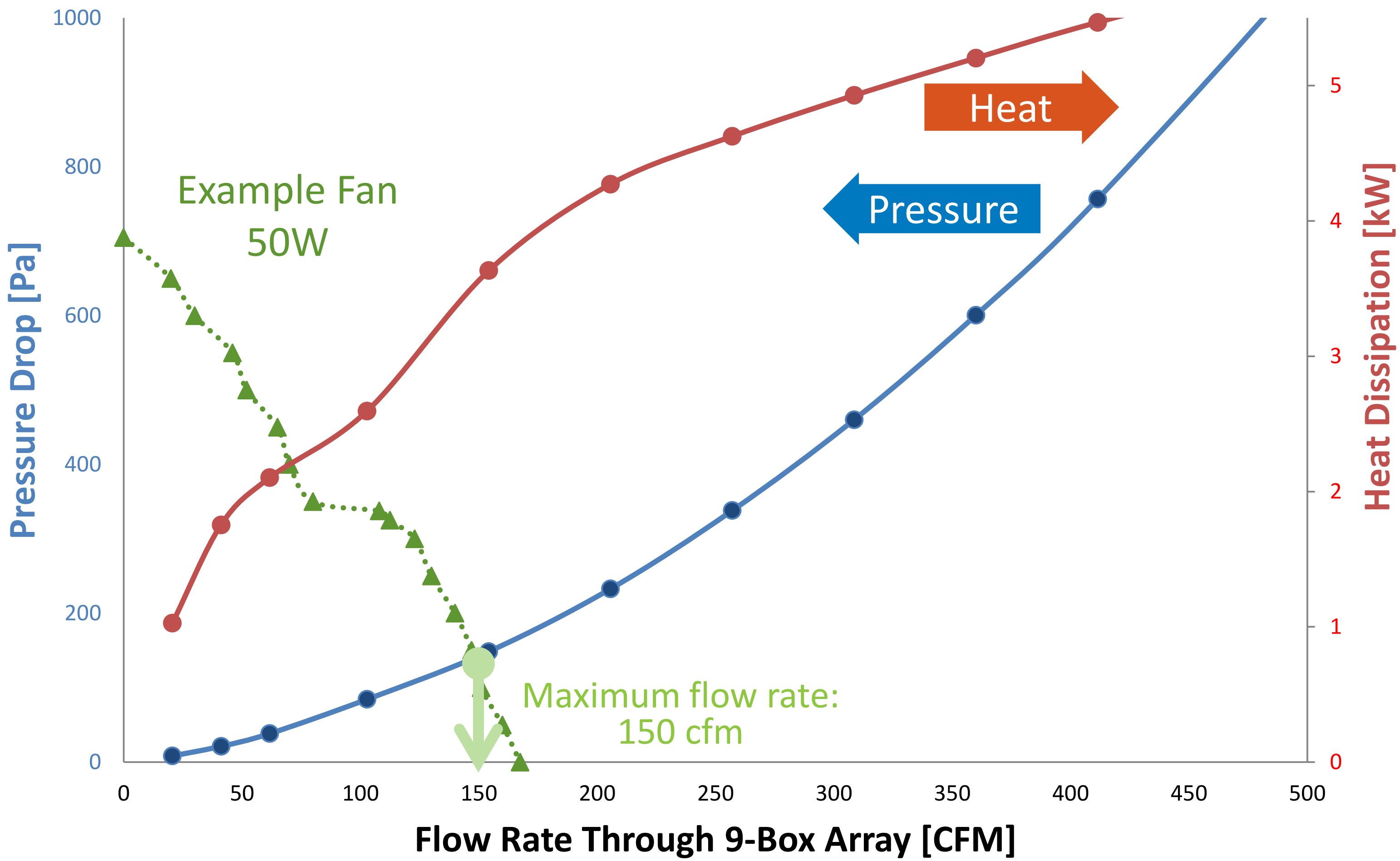
Example System Flow Study

9-by-1 array design, 175°C



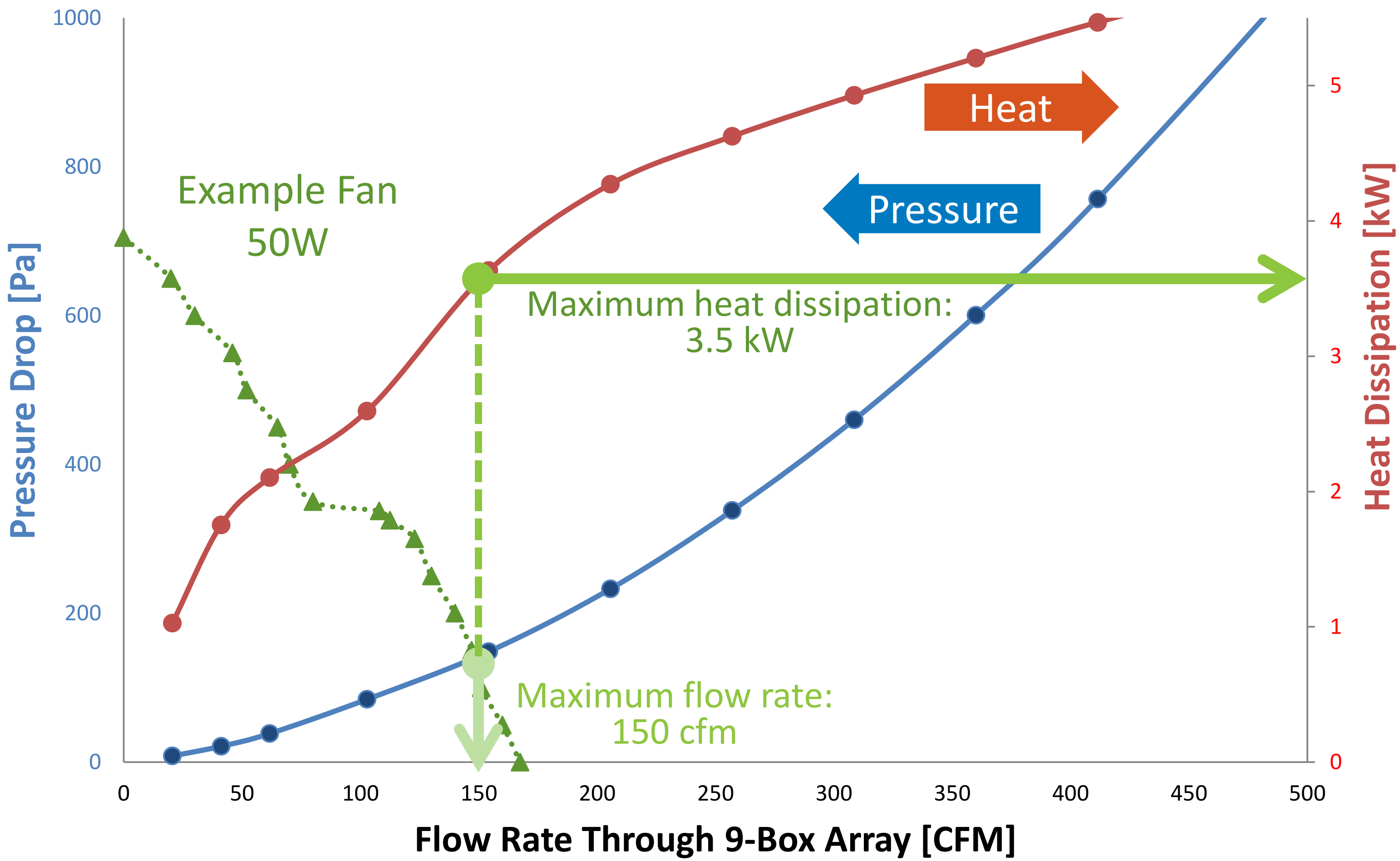
Example System Flow Study

9-by-1 array design, 175°C

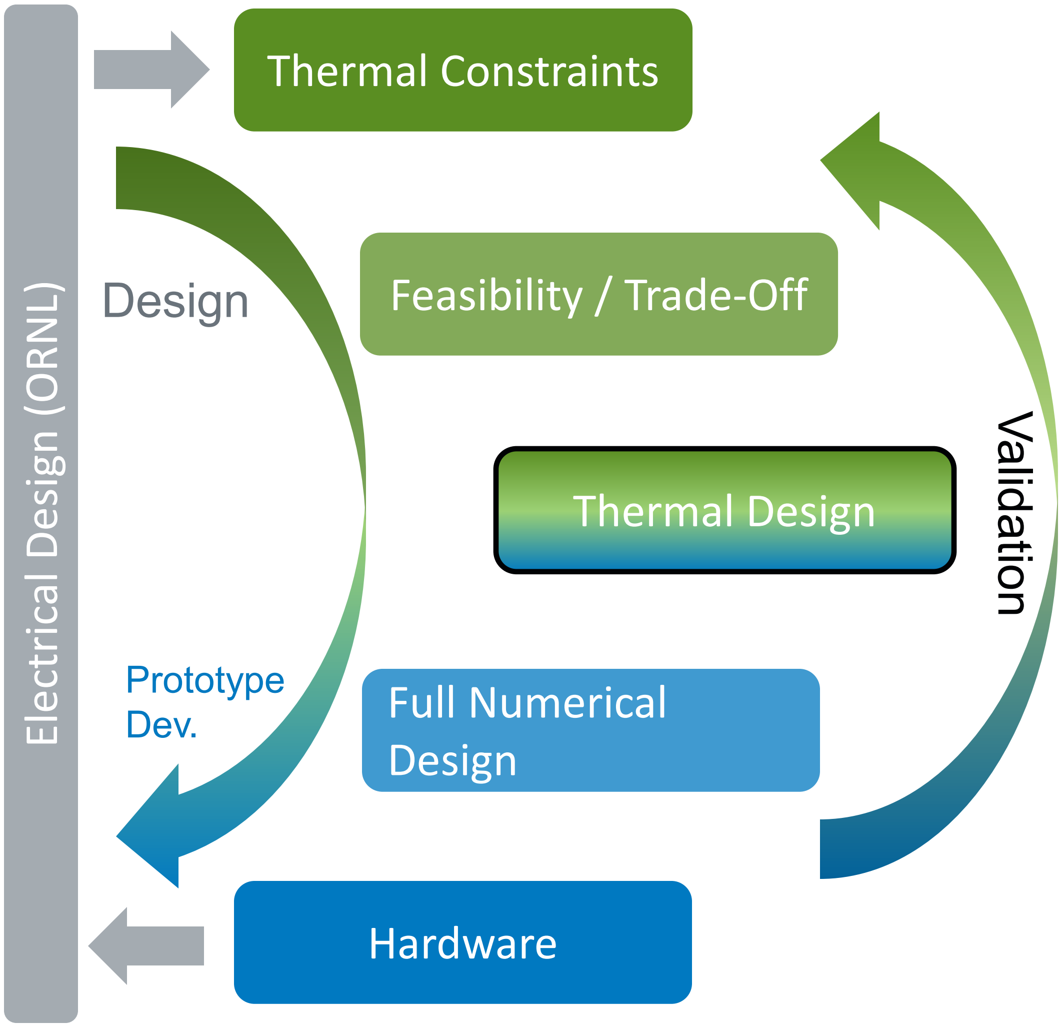


Example System Flow Study

9-by-1 array design, 175°C

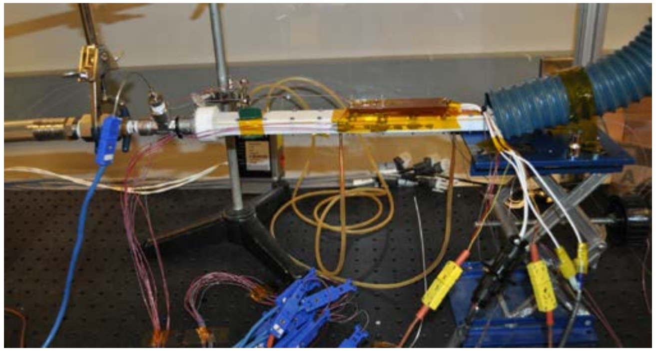


High Temperature Air-Cooled Inverter

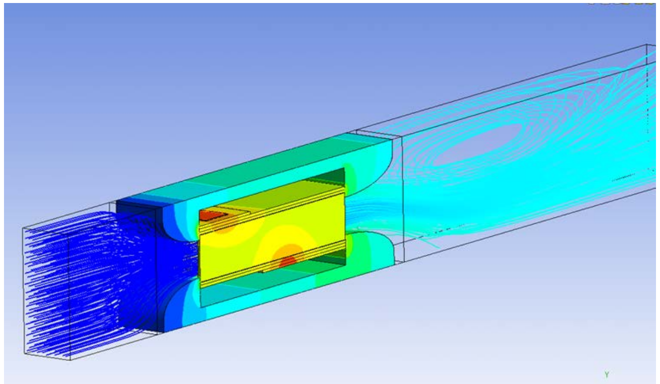


Thermal Design

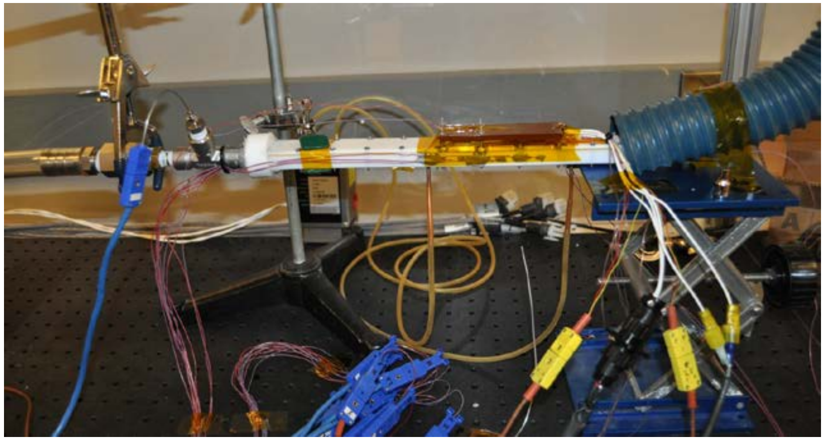
Design concept and balance-of-system testing

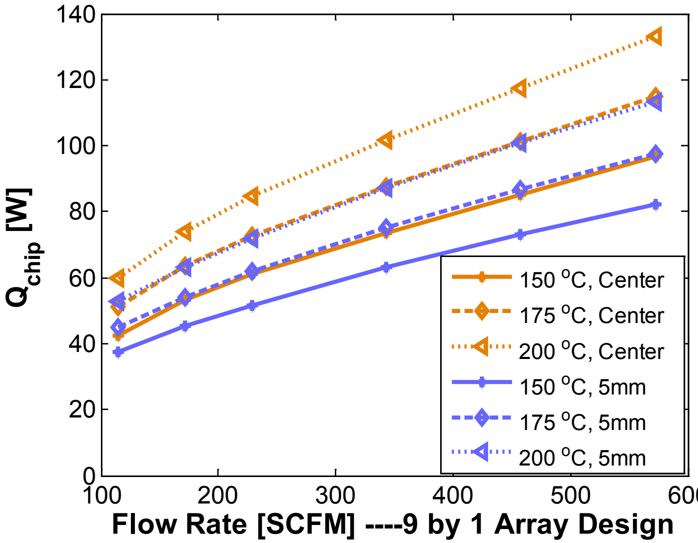


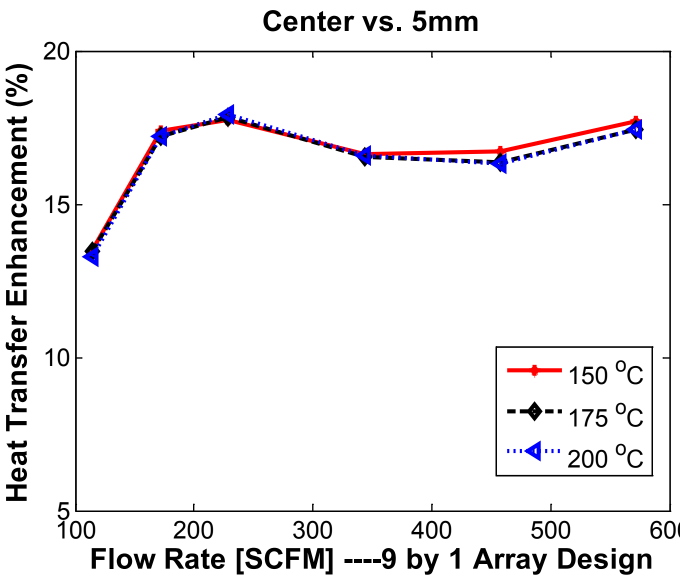
Model validation and design optimization



Device Test Results

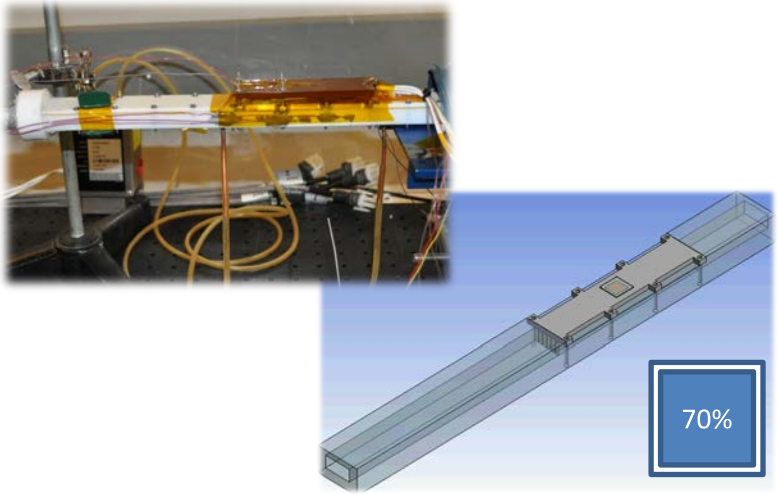


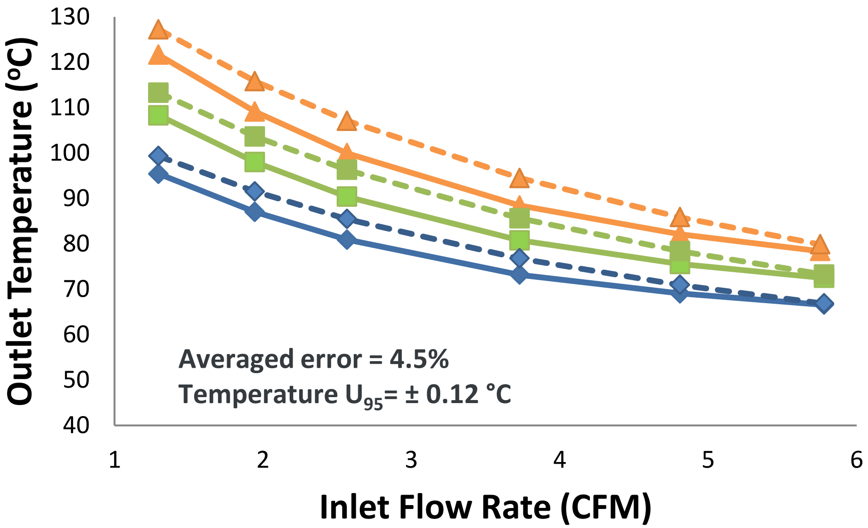




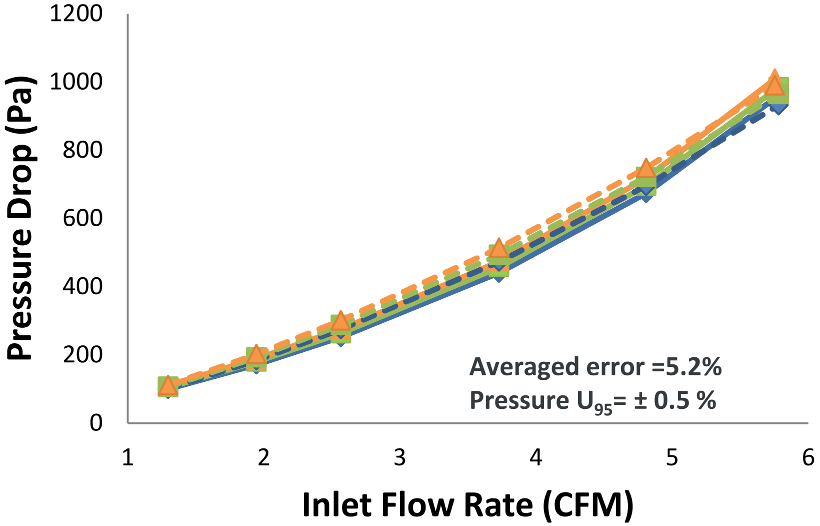
Model Validation

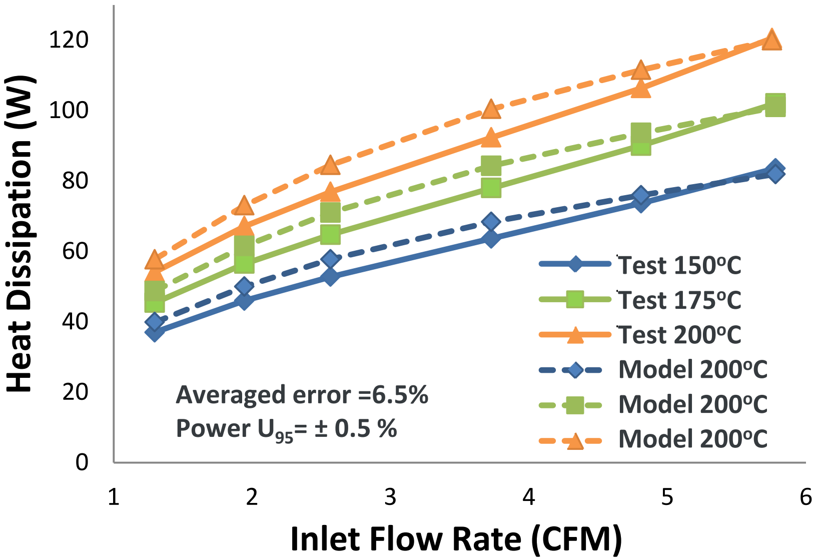
Less Than 6.5% error between model and experiment





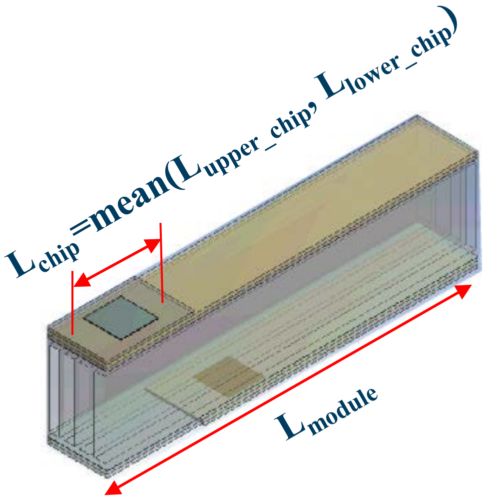
- Chip temperature: 150°C, 175°C, 200°C
- 5 W/mK heat transfer coefficient at the exterior walls
- 70% thermal contact between device and fin



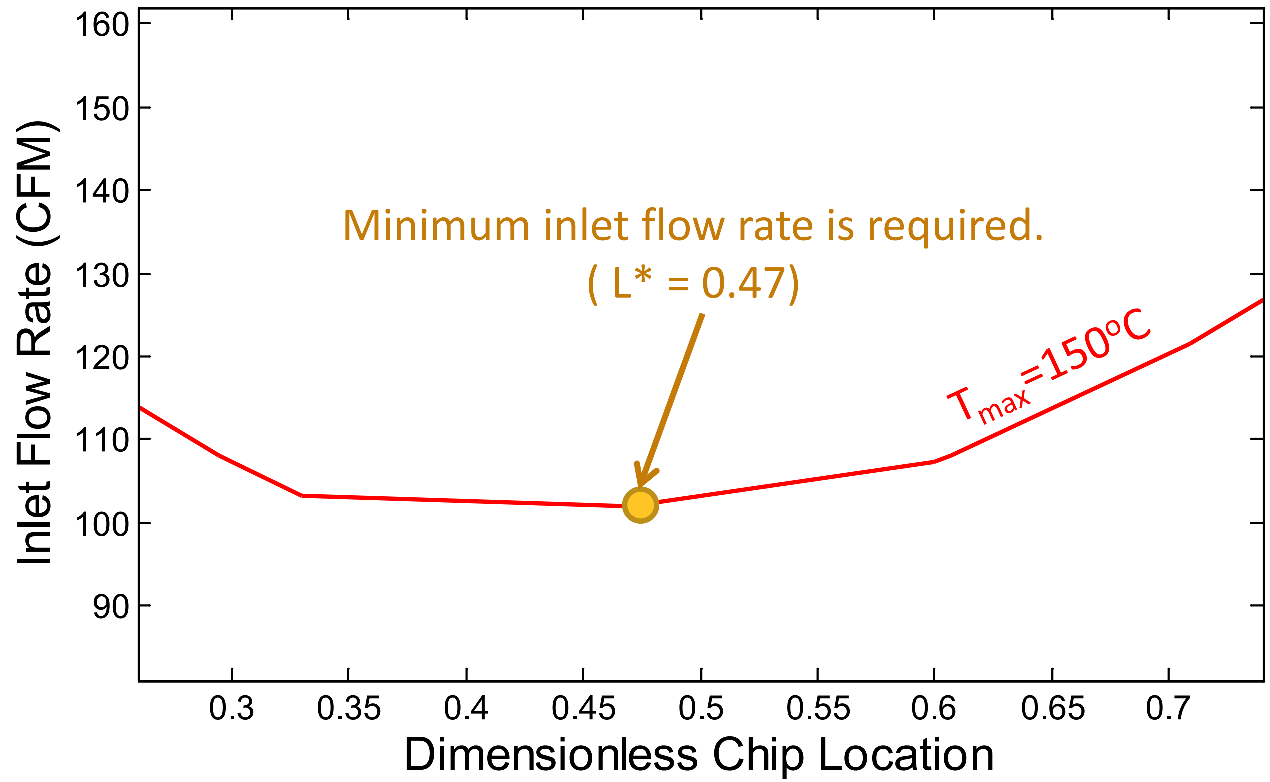


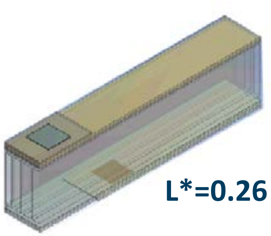
Module Design Improvement

Parametric study: Chip location

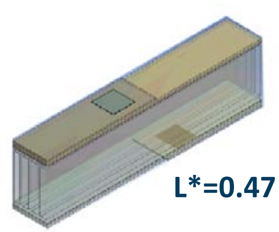


$$L^* = \frac{L_{chip}}{L_{module}}$$





L*=0.26



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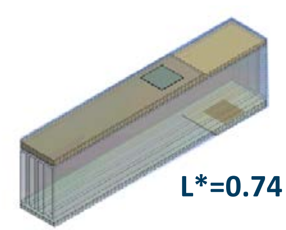
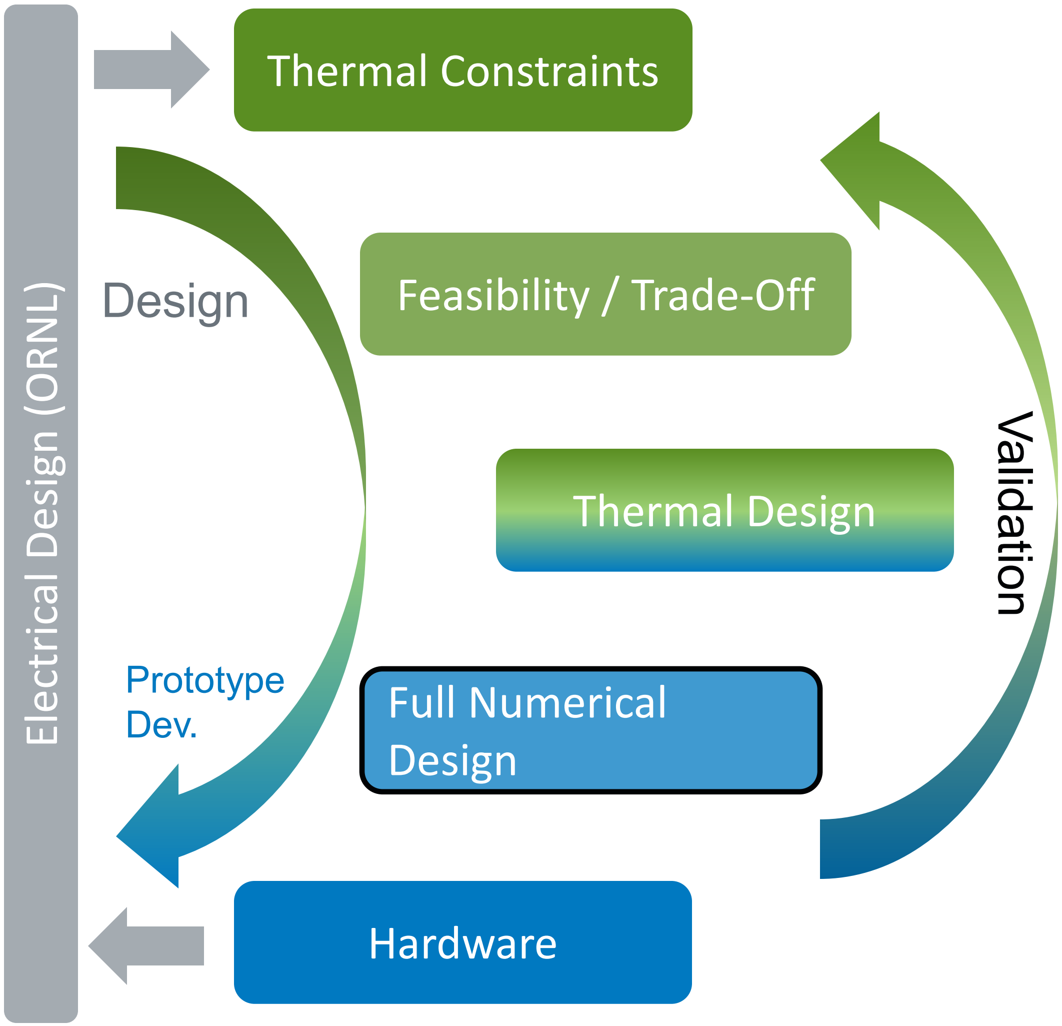


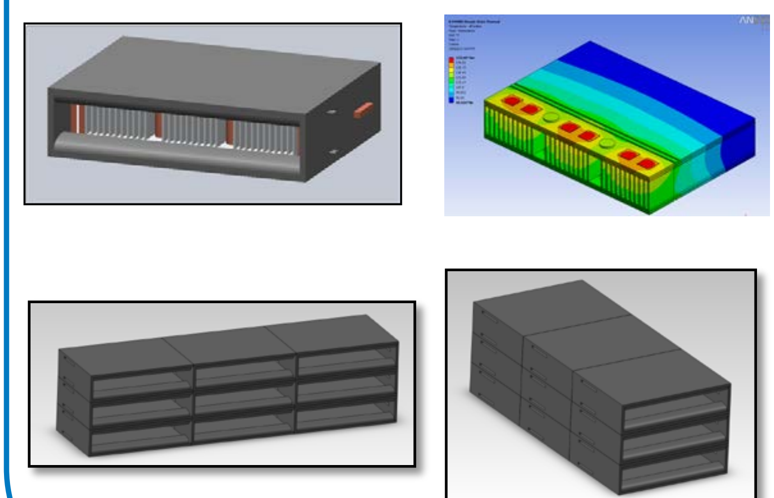
L*=0.74

High Temperature Air Cooled Inverter

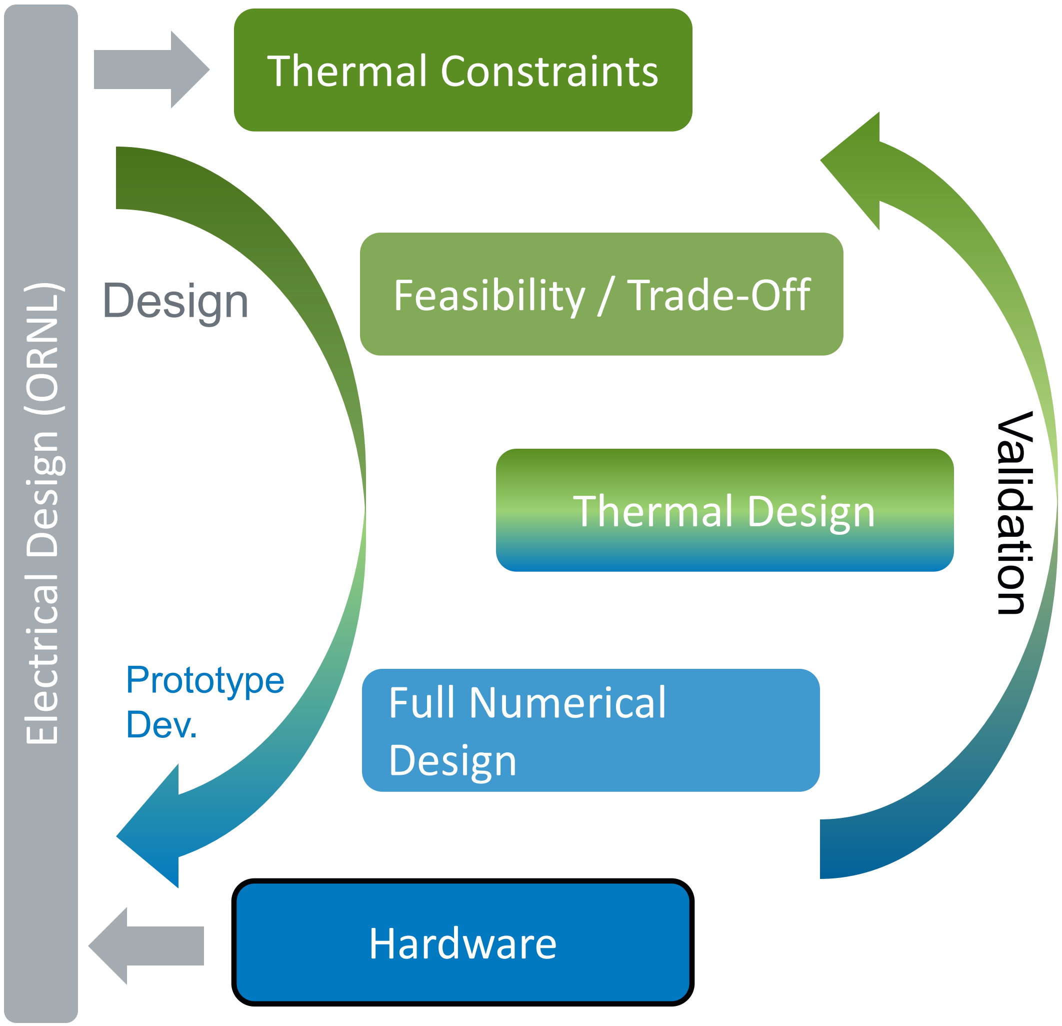


Full Thermal Design

- **Large conjugate heat transfer model to finalize prototype design**
- **Couple module model to balance-of-system test results**
- **Design drawings to build thermal management prototype**
- **System-level model**

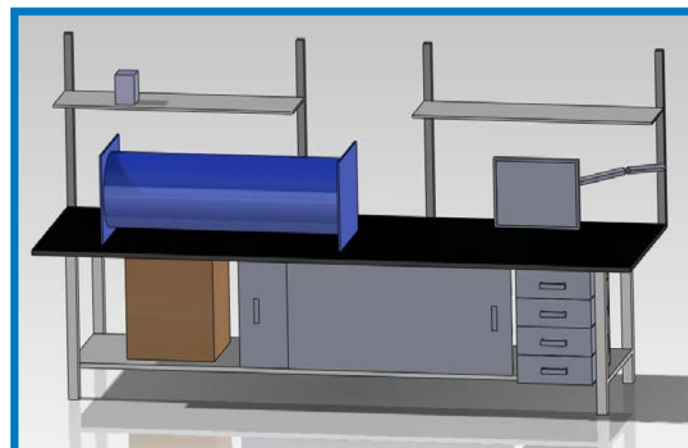


High Temperature Air Cooled Inverter



Hardware

- **Build prototype thermal management system and test on bench**
- **Use results to feedback and improve design**
- **Test 2nd generation with electrical hardware**



Proposed Future Work

- FY13
  - Build and test air-cooled module-level thermal management with electrical design from ORNL
  - Test system-level thermal management system. Demonstrate with lower power inverter from ORNL
  - Projected Go/No-Go Decision Point: If projected results meet the DOE inverter target for volume and weight, pursue full build
- FY14
  - Work with ORNL to build and test full air-cooled inverter system
  - Projected Go/No-Go Decision Point: If test results meet the DOE inverter targets for volume and weight, then vehicle-level demonstration will be pursued

Summary

DOE Mission Support

- **Overcome barriers to adoption of low-cost air-cooled heat sinks for power electronics; air remains the ultimate sink.**

Approach

- **Create system-level understanding and designs addressing advanced cooling technology, balance-of-system, and package thermal interactions; developing solutions from fundamental heat transfer, then system level design, to application – culminating in vehicle-level viability demonstration with research partners.**

Summary

Technical Accomplishments

- Showed 30% better heat transfer performance for synthetic jets than steady jets
- Using NREL's system-level analysis method, found that it may be possible to approach liquid-cooling power density using advanced technology for air-cooling
- Completed device-level test bench, tested baseline fin design, and validated CFD model
- Completed initial design feasibility study

Collaborations

- Strengthened collaboration with ORNL for collaborative high-temperature air-cooled inverter project
- Researching advanced air-cooling technology in collaboration with GE, Momentive, and Sapa
- Interacting with auto OEMs and suppliers for test data, review, and validation activities

Acknowledgments and Contact

Acknowledgments:

- Susan Rogers and Steven Boyd
  U.S. Department of Energy
- Madhu Sudhan Chinthavali
  Oak Ridge National Laboratory

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References

Slide 4

1. Honda Insight photograph: John P. Rugh, NREL
2. Honda power electronics photograph: Oak Ridge National Laboratory
3. Electric Mini Cooper photograph: DOE Advanced Vehicle Testing Activity & Idaho National Laboratory
4. AC Propulsion AC-150 photograph: Jason A. Lustbader & Dean Armstrong, NREL

Slide 9

1. Synthetic jet photograph: Gopi Krishnan and Charlie King, NREL
2. Micro-fin photograph: Charlie King, NREL
3. Inverter photograph: Mark Mihalic, NREL
4. Inverter photograph: Mark Mihalic, NREL
5. Prius photograph: NREL PIX15141

Slides 10

1. Test bench photograph: Jason A. Lustbader, NREL
2. Constant temperature anemometer, Jason A. Lustbader, NREL

Slide 13

1. Air cooling system test bench nozzle chamber: Tim Popp, NREL
2. Air cooling system test bench nozzle chamber: Tim Popp, NREL

Slide 14

1. Inverter cold plate: Kevin Bennion, NREL
2. One leg of an inverter: Kevin Bennion, NREL

Slides 27-29

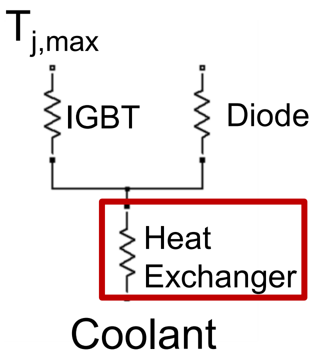
1. Device-level test bench setup: Xin He, NREL

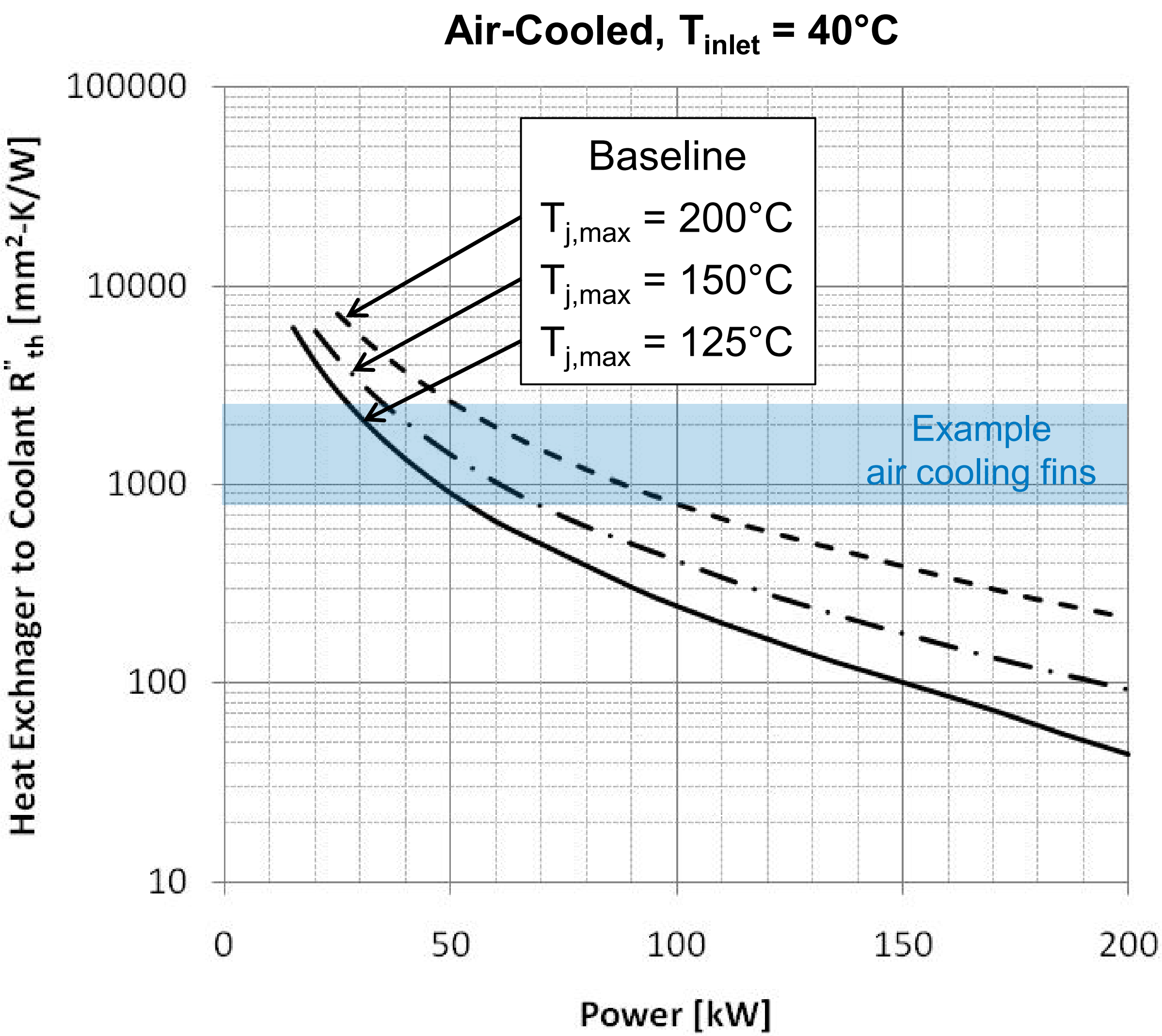
Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Air-Cooled Results

Example design trade-offs

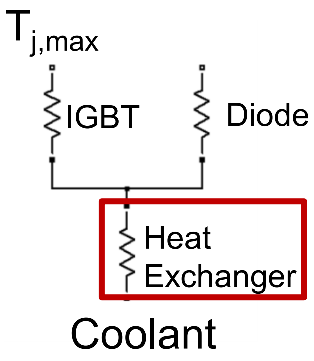


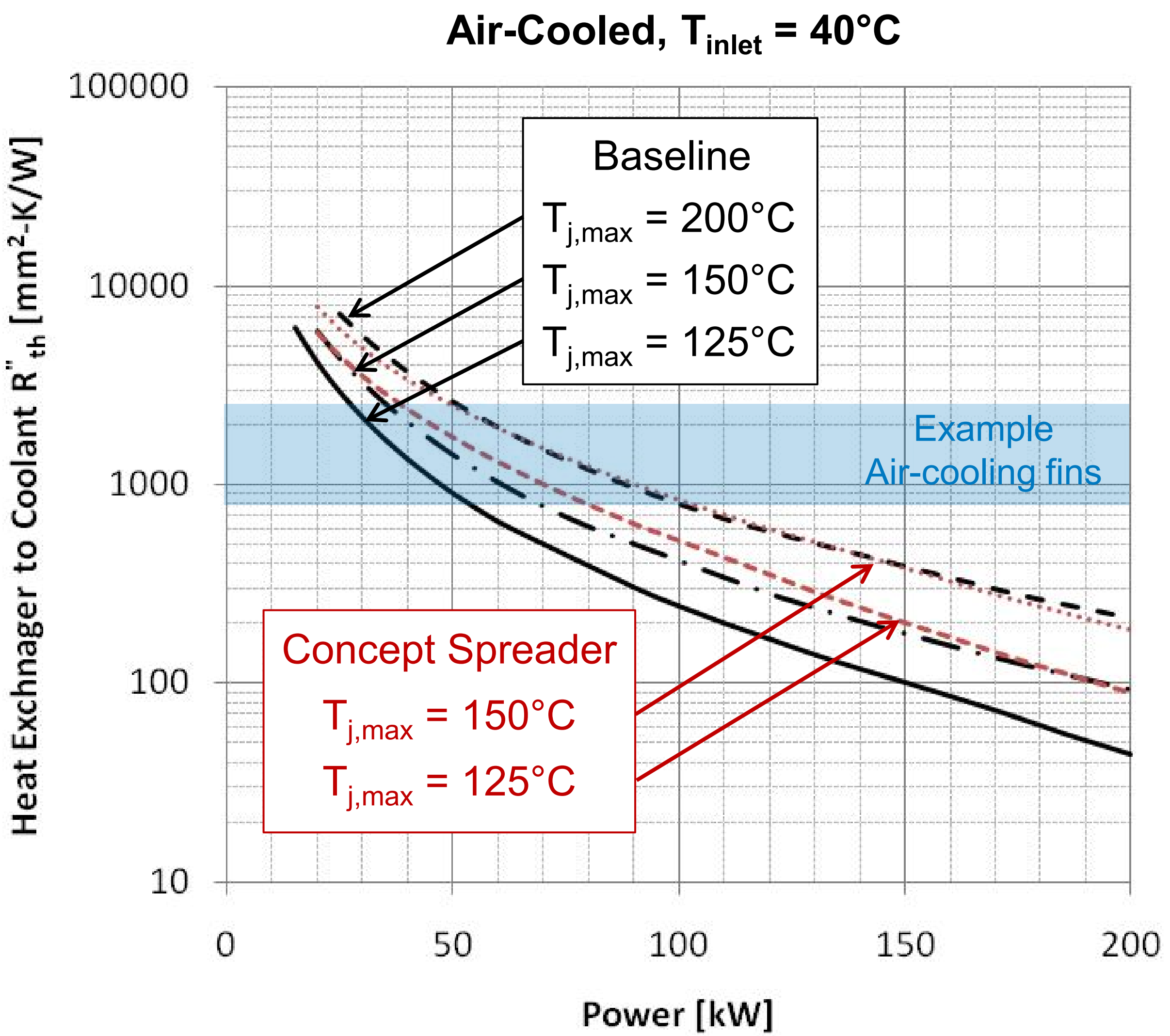


- *450 VDC, 400 A_{rms}, 0.5 power factor, and 125°C temperature limit*
- *Power factor adjusted to provide 3:1 heating of insulated gate bipolar transistor (IGBT) and diode*

Air-Cooled Results

Example design trade-offs

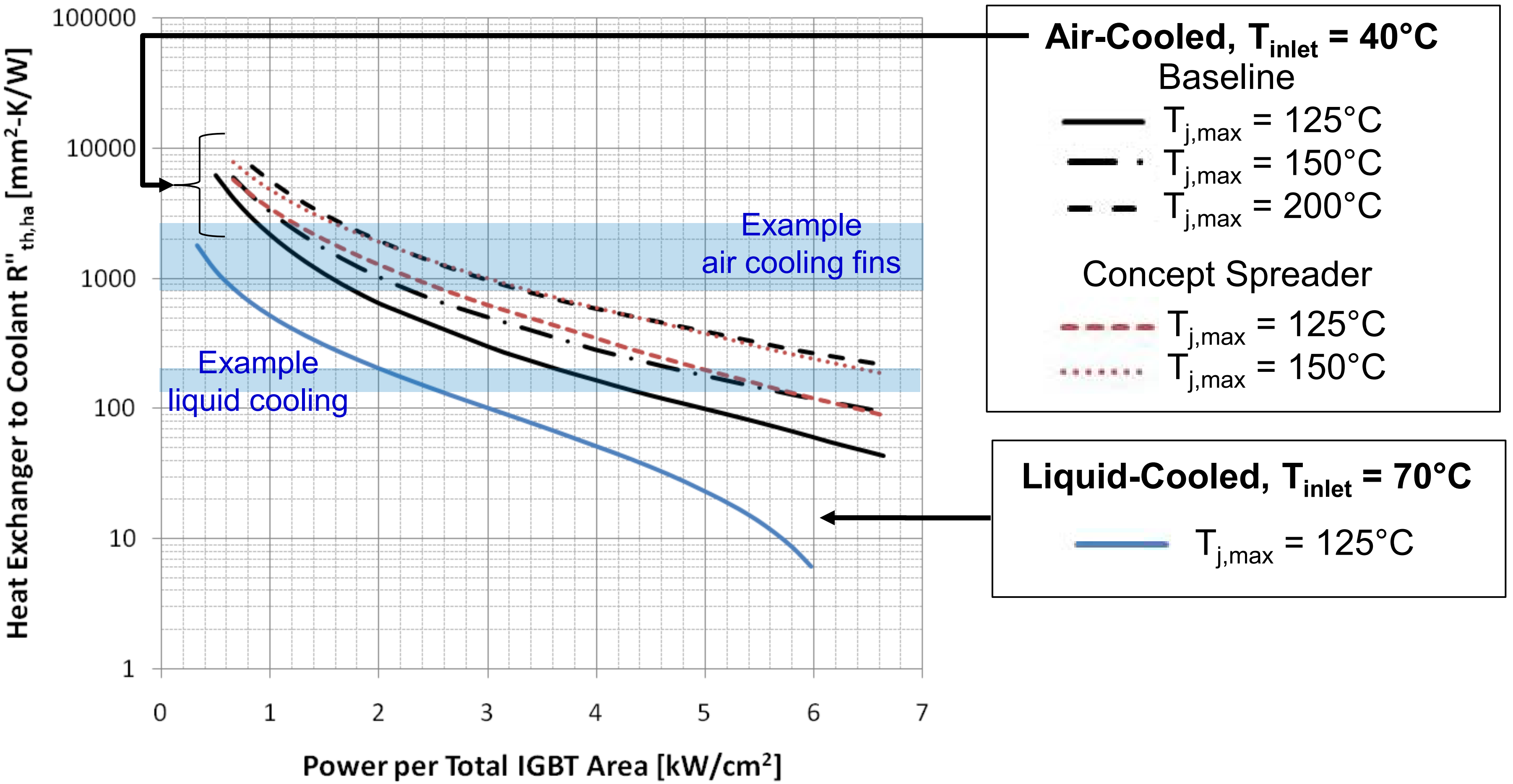




- *450 VDC, 400 A_{rms}, 0.5 power factor, and 125°C temperature limit*
- *Power factor adjusted to provide 3:1 heating of IGBT and diode*

Air-Cooled Results

Example design trade-offs



- *450 VDC, 400 A_{rms}, 0.5 power factor, and 125°C temperature limit*
- *Power factor adjusted to provide 3:1 heating of IGBT and diode*

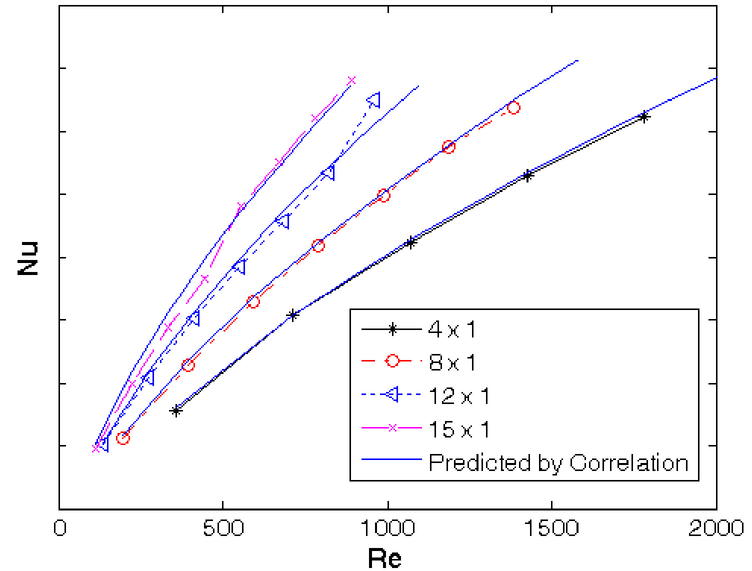
Steady Jet Nusselt Number Correlations

Correlations accurately fit experimental data

- H/D_h=5

$$Nu = 0.0784 \cdot Re^m \cdot \left(\frac{H}{D_h}\right)^{-0.15} \cdot \left(a + b \cdot \frac{y}{S} + c \cdot \left(\frac{y}{S}\right)^2\right)$$

$$m = 0.695 - \left[\left(\frac{S}{4 \cdot x}\right) + \left(\frac{H}{2 \cdot x}\right)^{1.33} + 3.06\right]^{-1}$$



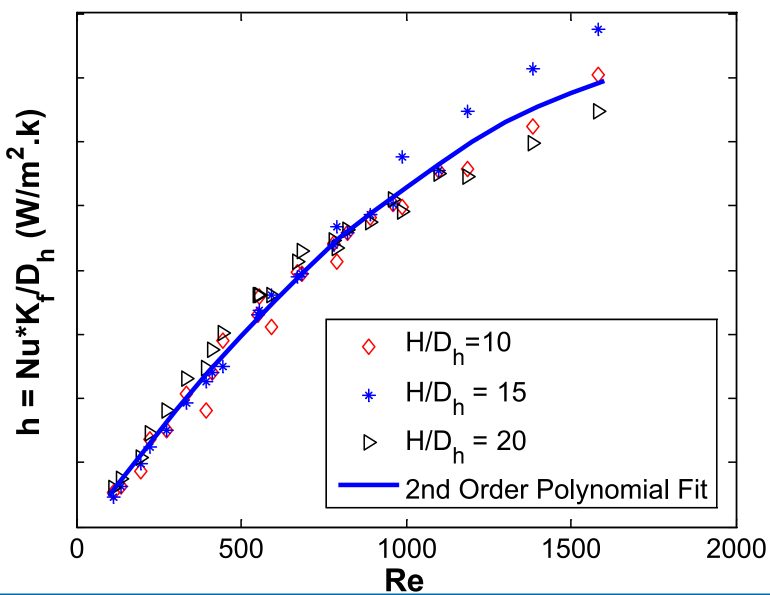
- H/D_h = 10, 15 and 20; y/x ≥ 8

$$Nu = (a * Re^2 + b * Re + c) * \frac{D_h}{K_f}$$

D_h: nozzle hydraulic diameter

a, b, c: least-squares fit based on experimental data

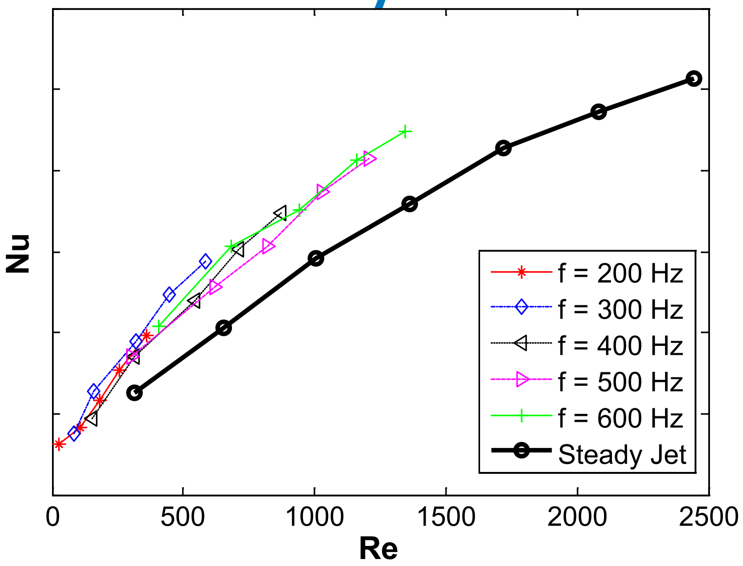
K_f: air thermal conductivity



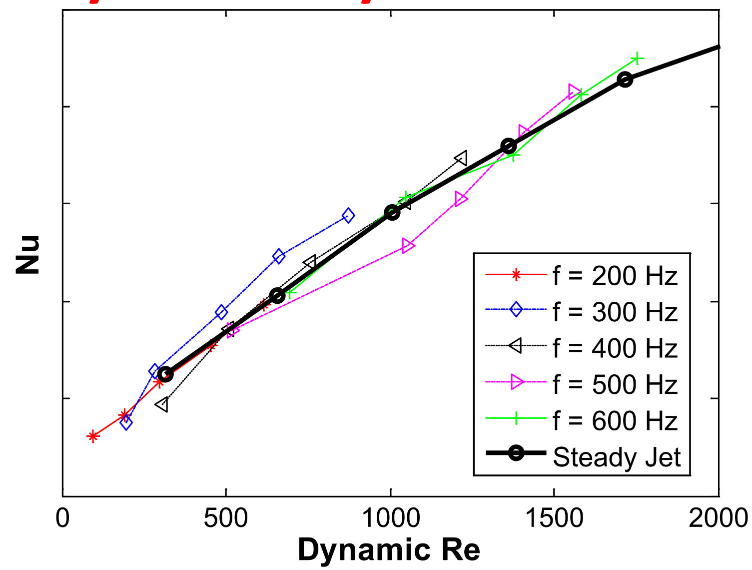
Correlating Synthetic and Steady Jet Heat Transfer

Dynamic Reynolds number collapses steady and synthetic jet Nusselt number

Conventional Reynolds Number



Dynamic Reynolds Number



- Unsteady heat transfer coefficient
  - A function of the changing rate of gas flow
  - Collapse to the steady jet heat transfer coefficient by introducing dynamic correction term in Reynolds number
- Introducing Dynamic Reynolds number for synthetic jet

$$Re_{dynamic} = Re \cdot \left(1 + C_1 \cdot \frac{D_h}{(U_{max})^2}\left(\frac{dU}{dt}\right)_{max} \cdot \left(\frac{D_h}{H}\right)\right)$$

C_1 is a calibration constant, determined based on the experimental results