**National Renewable Energy Laboratory**
*Innovation for Our Energy Future*

# Air Cooling Technology for Power Electronic Thermal Control

***U.S. Department of Energy Annual Merit Review***

**P.I. Jason Lustbader**
**National Renewable Energy Laboratory**

**Team Members:**
*Sreekant Narumanchi*
*Gopi Krishnan*
*Desikan Bharathan*
*Charlie King*

**Thursday June 10, 2010**

**Project ID: APE019**

# Overview

## Timeline

- Project start date: FY06
- Project end date: FY13
- Percent complete: 50%

## Barriers

- Air is a poor heat transfer fluid
- Air density is low – requires significant volume
- Parasitic power
- Perception and novelty

## Budget

- Total project funding
  - DOE share: $1750k
  - Contractor share: $0.00
- FY09 Funding: $350k
- FY10 Funding: $400k

## Partners

- Interactions
  - FreedomCAR Electrical & Electronics Technical Team
  - Oak Ridge National Laboratory
  - Delphi, PowerEx, Semikron, GE

- Project lead: NREL

# Project Objectives - Relevance

- Develop and apply air cooling technology to improve power electronics thermal control design and influence industry – enhancing system performance to meet FreedomCAR technical targets for weight, volume, cost, and reliability
- Enable heat rejection directly to the sink, namely, ambient air – simplifying the system by eliminating liquid coolant loops
- Develop system capable of 150-200 W/cm$^2$ while maintaining chip operating temperature below 150°C
- Create solutions that help reduce fuel use and improve sustainability
- FY10
  - Develop novel micro-fin air cooled heat sink – prototype and test
  - Research new novel cooling technologies – synthetic jets
  - Evaluate fan efficiency for input into system level analysis

# Project Milestones - Relevance

## FY2009

- Developed novel micro-fin based air cooled heat sink concept
- Created CFD model to predict performance and improve on design
- Tested commercially available fans and showed a range of performance
- Filed invention report for the novel micro-fin based heat sink design
- **DOE Milestone**: Summarized findings in DOE milestone report

## FY2010

- Completed preliminary review of synthetic jet technology, including initial flow visualization – proceed with feasibility study (3/10)
- Established more direct collaboration with ORNL (3/10)
- Complete synthetic jet feasibility study – go/no-go on application (8/10)
- Develop system level thermal analysis of air cooling system (9/10)
- **DOE Milestone**: Summarize findings for DOE milestone report (9/10)

# Challenges and Barriers - Relevance

## Advantages

Everything on a vehicle is ultimately air cooled

Rejecting heat to air can eliminate intermediate fluid loops

Air is benign and need not be carried

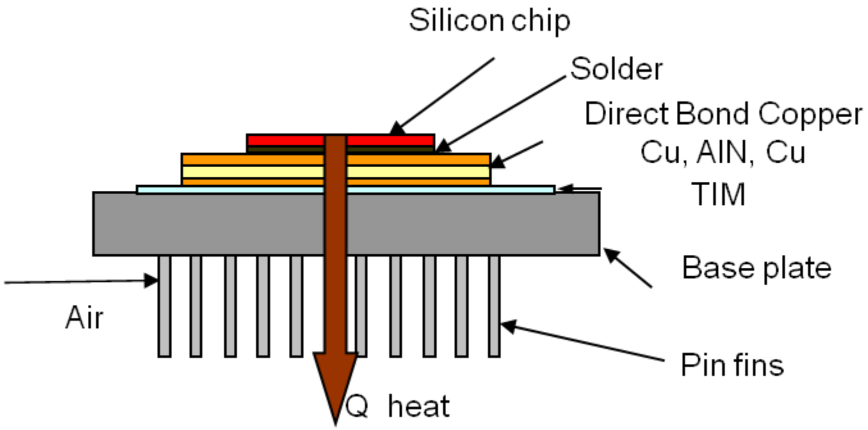
Air is a dielectric and can contact the chip directly

## Challenges

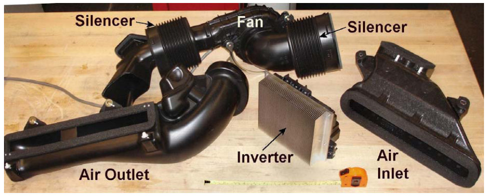
Air has a low specific heat

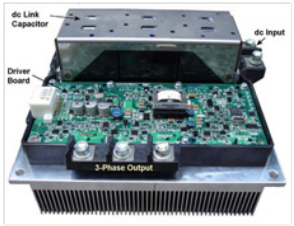
Air is a poor heat-transfer fluid

Air density is low



# Examples of Automotive Air Cooling - Relevance





## Honda Insight package

Power Rating 12 to 14 kW
Active air cooling
Electric blower ~ 120 W
Heat load ~ 700 W

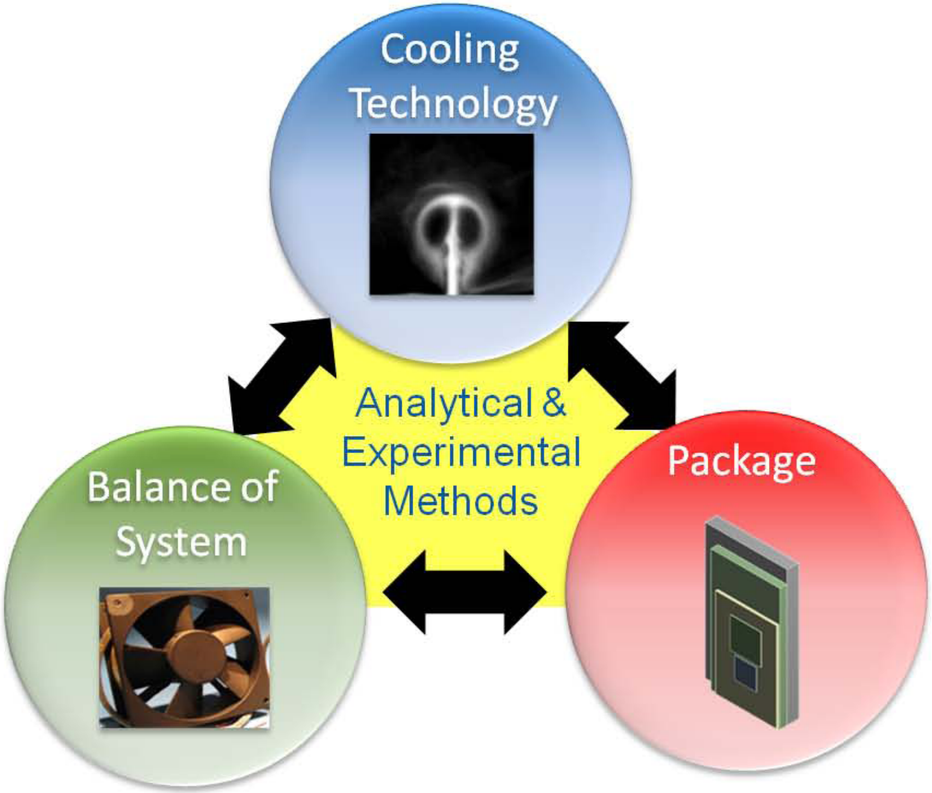
## AC Propulsion V2G model AC-150

Power Rating  150 kW
Active air cooling
Electric blower ~  ??? W
Heat load ~  2000 W

- *Electric Mini Cooper picture (right, 1st  row): DOE Advanced Vehicle Testing Activity & Idaho National Laboratory*
- *Honda power  electronics pictures (left, 2nd row): Oak Ridge National Laboratory*

# Air Cooled System Thermal Design - Approach

1. Novel micro-fin design
2. Synthetic jet investigation
3. Other novel technologies



Cooling Technology

Analytical & Experimental Methods

Balance of System

Package

1. System level analysis
2. Fan performance
3. Other (filters, ducts)

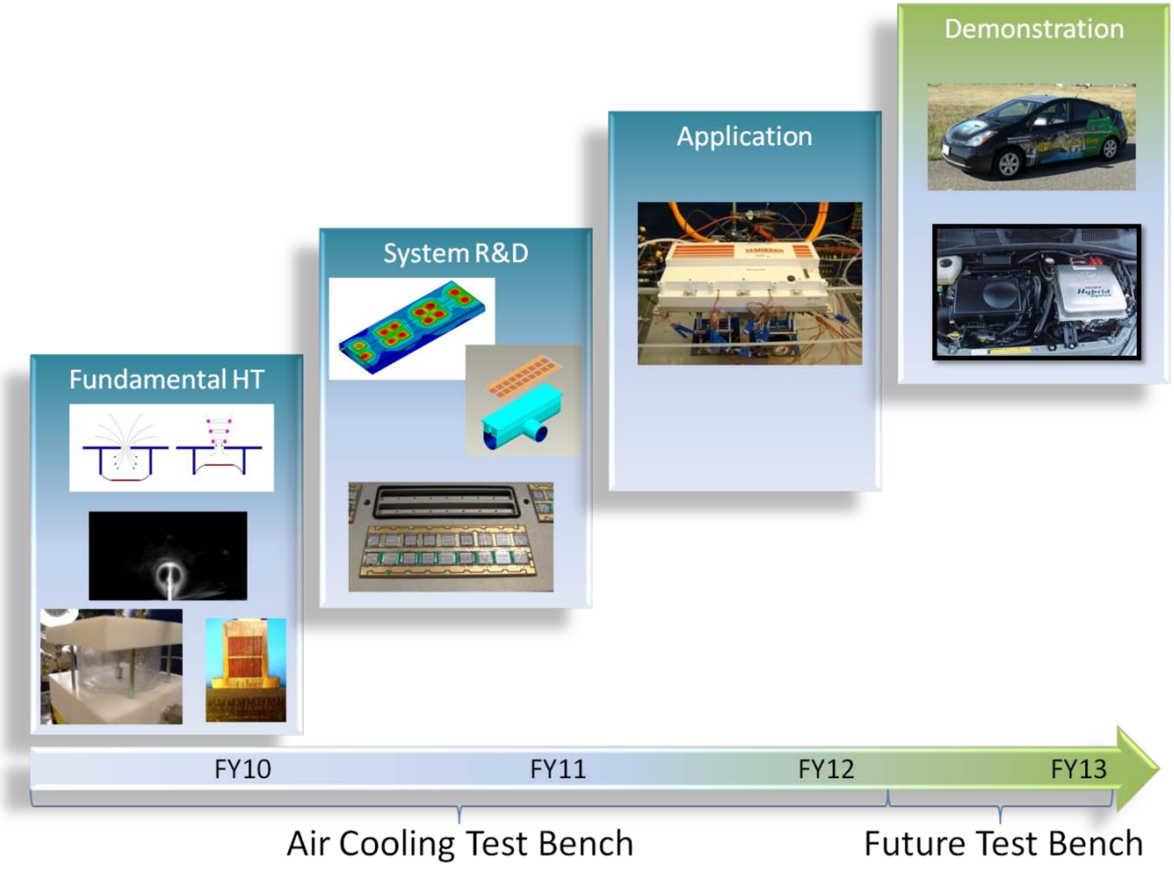
1. Thermal design trade-offs
2. Collaborate with ORNL on influence of electrical design

Thermal Environment
-Ambient
-Air Source

Device Type
-Max Temperature
- Efficiency

Vehicle Context
-Power/ Duty Cycle
-Volume/weight limits

# Research and Development - Approach



Demonstration

Application

System R&D

Fundamental HT

FY10

FY11

FY12

FY13

Air Cooling Test Bench

Future Test Bench

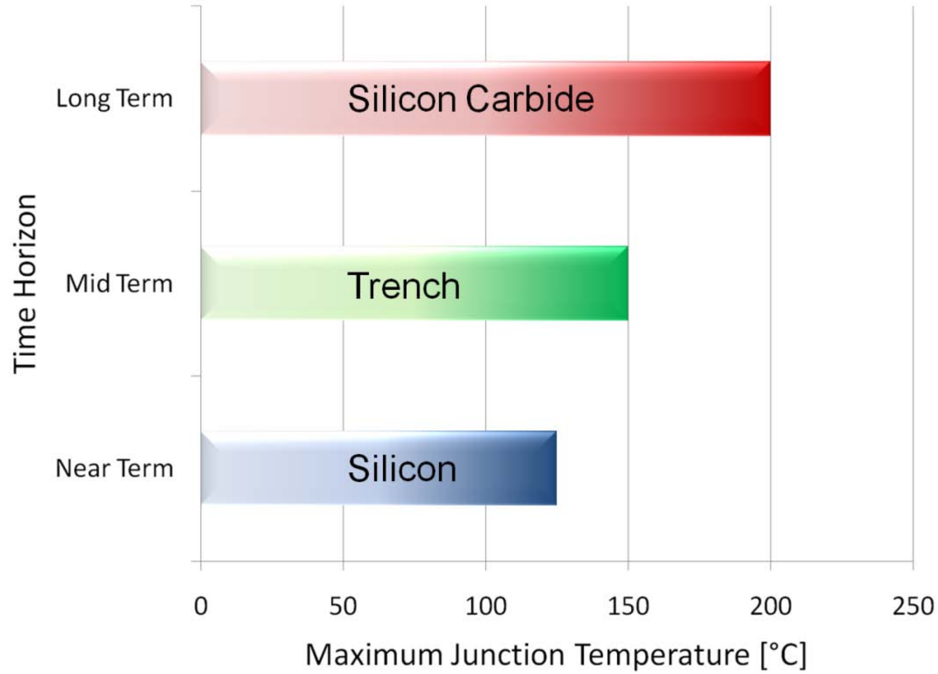
1. Research novel cooling technology fundamental heat transfer
2. Scale cooling technology to inverter scale and investigate balance of system
3. Apply system design to inverter and find opportunities for improvement
4. Demonstrate prototype at vehicle level

# Thermal Environment

| Source | Temperature Range (°C) | Challenge/Opportunity |
|---|---|---|
| Under Hood | 100 to 140 | Not suitable for cooling devices at 125°C |
| External ambient air | 30 to 45 | Highly suitable for cooling |
| Cabin air | 10 to 25 | Limited advantage over ambient air. Penalty on air conditioners |

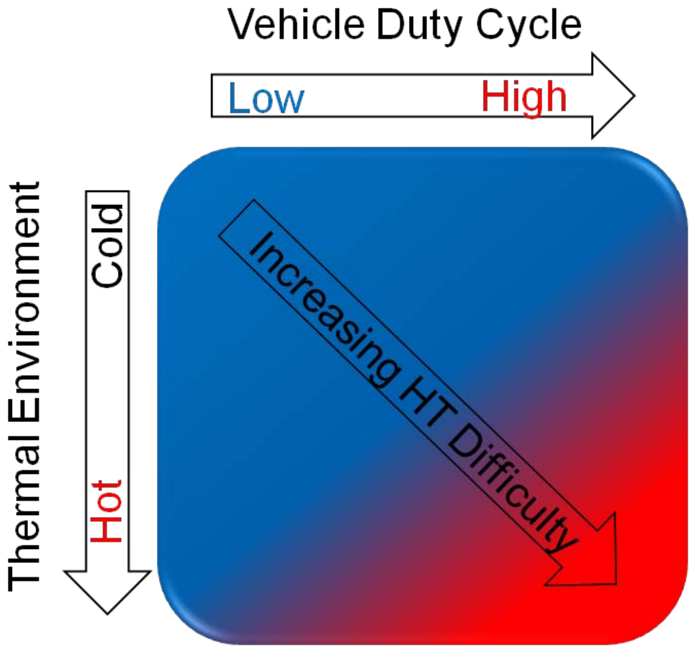
Need to understand system trade-offs driven by air source local thermal environment which are influenced by inverter location

# Device Type and Vehicle Context



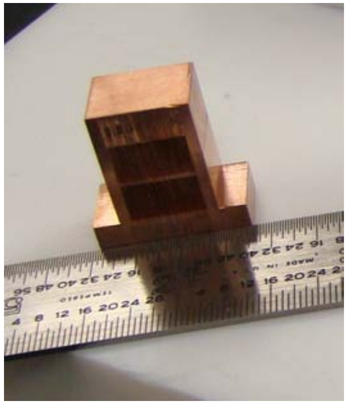
Improving device efficiency and maximum operating temperature will increase air cooling system opportunity

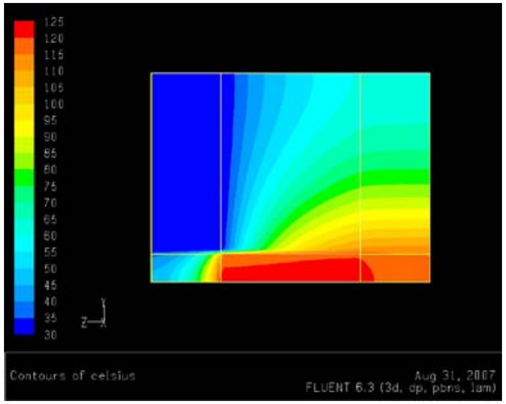
Variability of air cooling system allows for control to load conditions, maximizing “real world” system COP

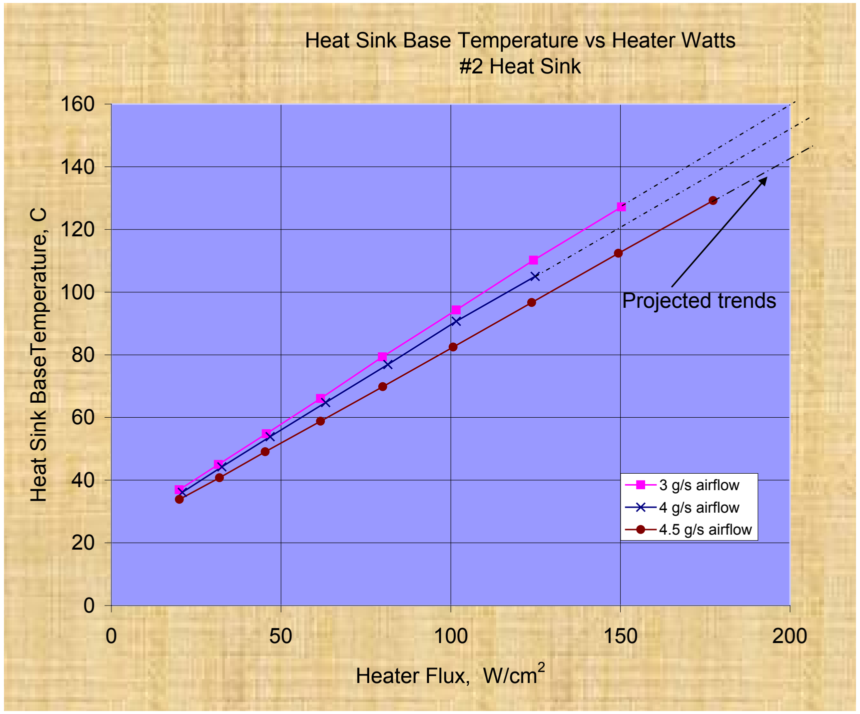


# Previous - Technical Accomplishments

- ASPEN model for system trade-offs
- Developed micro-fin design quick estimator software package
  - Showed that micro-fin air cooling can remove up to 150 W/cm$^2$
- Fabricated and tested air-cooled heat sinks, with excellent agreement in performance between model and test results
- Developed innovative air-cooled heat sink concept
  - Heat transfer area doubled
  - Pressure loss decreased by 50%
  - Colder air directed to hotter areas

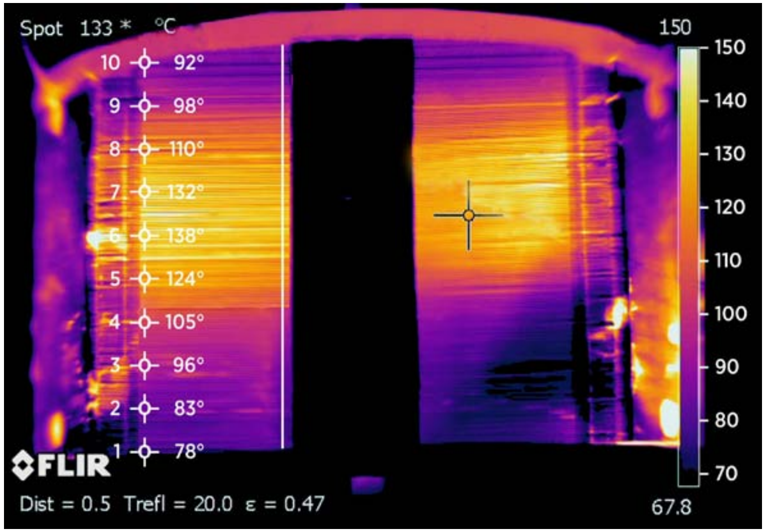


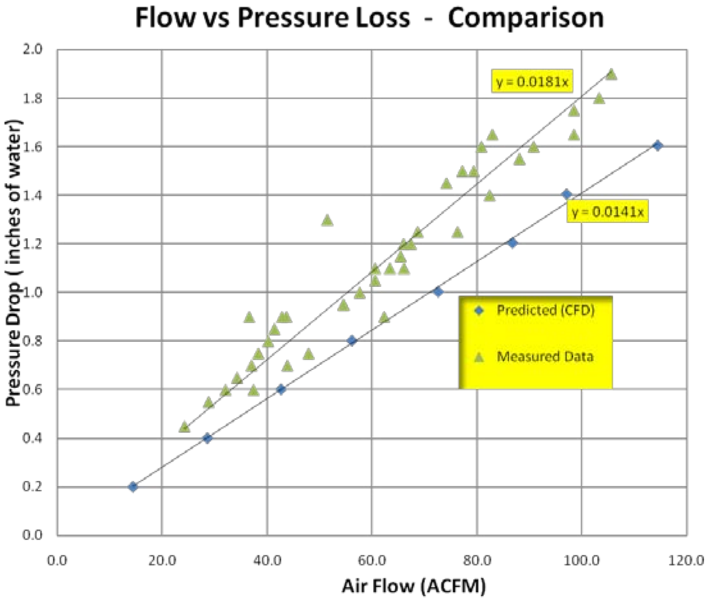




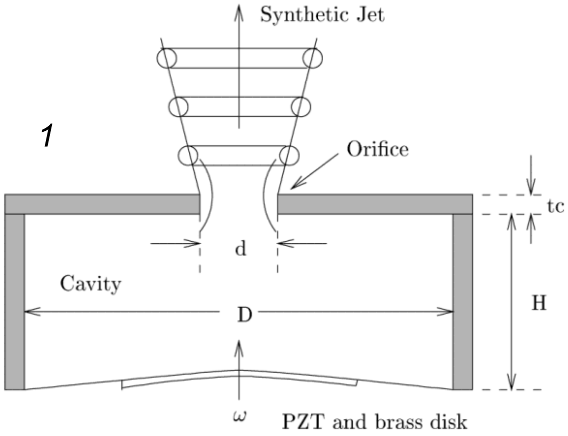
# Technical Accomplishments

- Fabricated and tested prototype micro-fin based novel air cooled heat sink
- Design and experimental results are under review by NREL patent committee
- Measured pressure loss higher than predicted, believed to be due to inconsistent fin spacing
- Validated models and demonstrated ability to reject 3000 W at 1.8 inches of water, using 21.1 W of fluid power



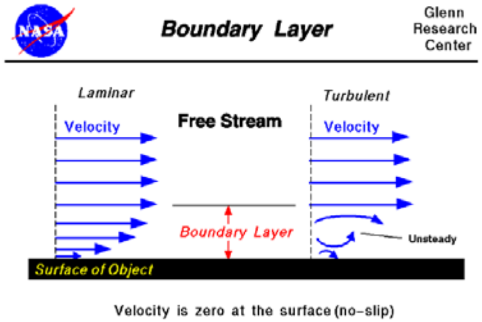


# Technical Accomplishments



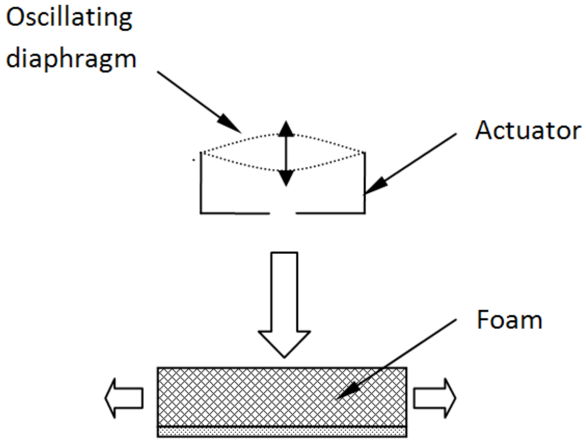
- Fully pulsatile jet
- Zero net mass flux : No external plumbing
- Imparts momentum : Influences medium
- Low electric power : Low cost
- Simple fabrication : High reliability
- Dominant vortical structures

## Heat Transfer Enhancement Strategy



Increase Momentum Transfer

Increase Surface Area



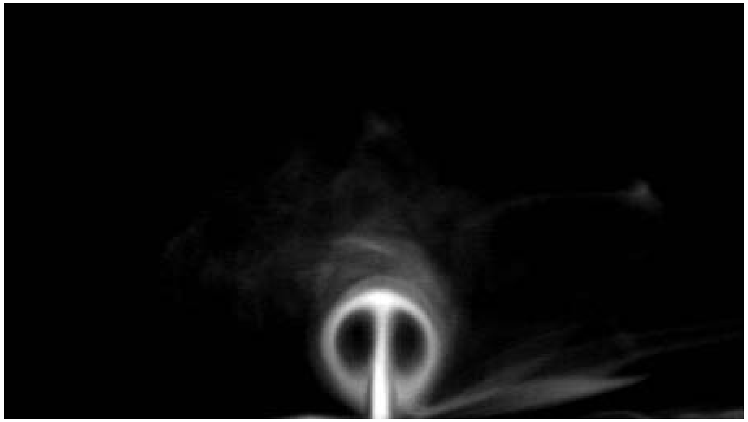
---

1. Crook, A., Crowther, W.J., Wood, N.J. ‘A parametric study of a synthetic jet in a cross flow’, 22nd International Congress of Aeronautical Sciences, Harrogate, UK, 2000

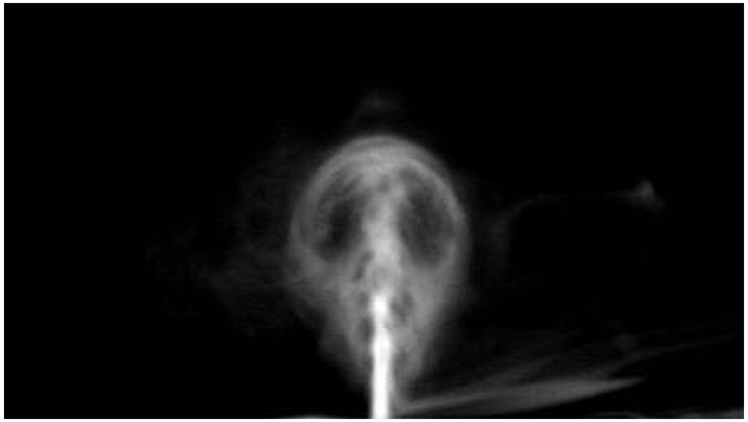
# Technical Accomplishments

## Evolution of a Free Synthetic Jet : Ejection Stroke

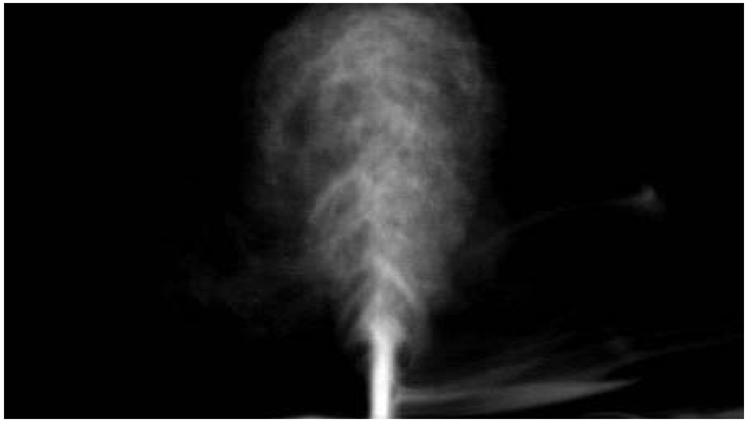
1. Roll up of shear layer



2. Vortex ring + trailing jet



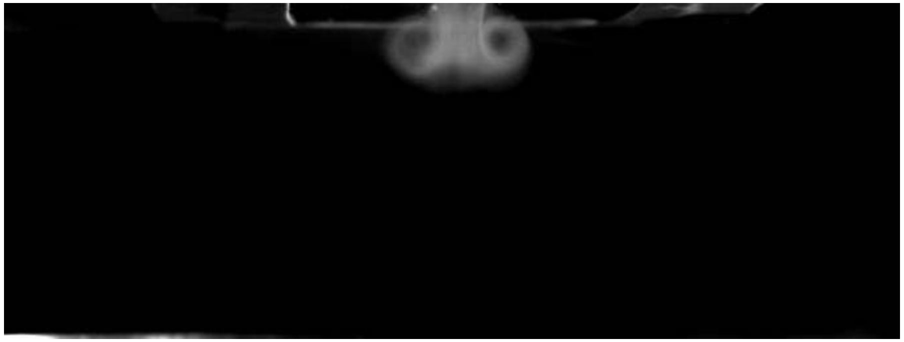
3. Break up of vortical structure



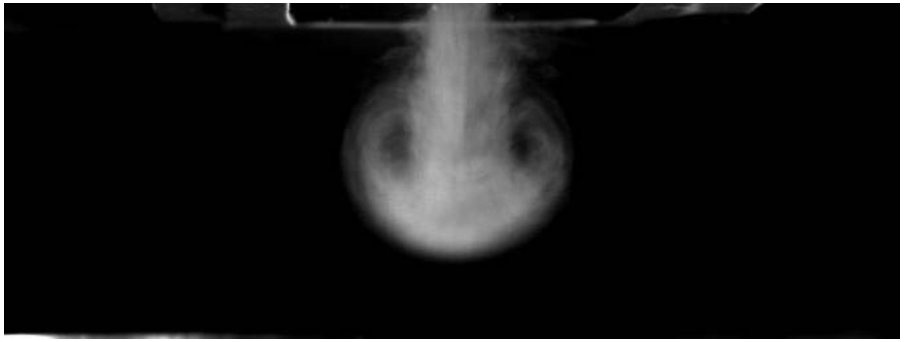
4. Transition to a turbulent jet

# Technical Accomplishments

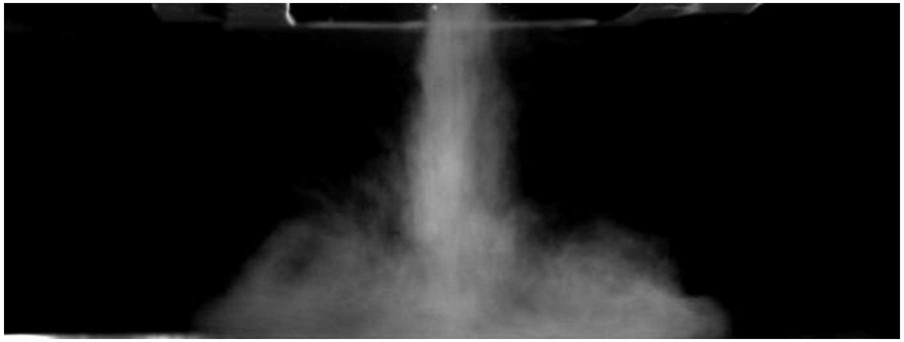
## SJ Impingement on a Flat Surface



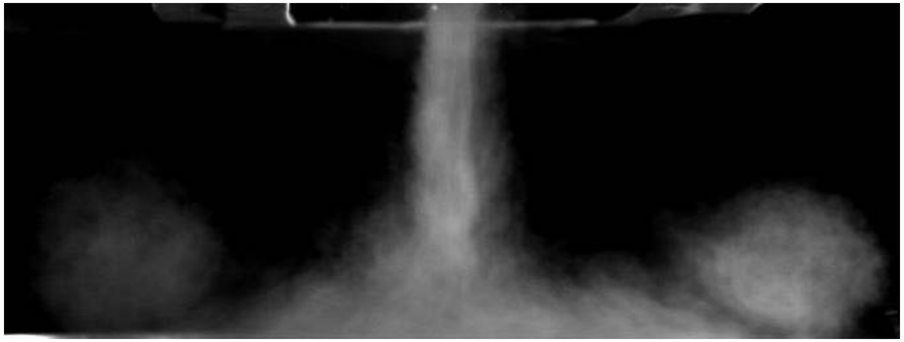
1. Roll up of shear layer



2. Evolution of free jet



3. Impingement

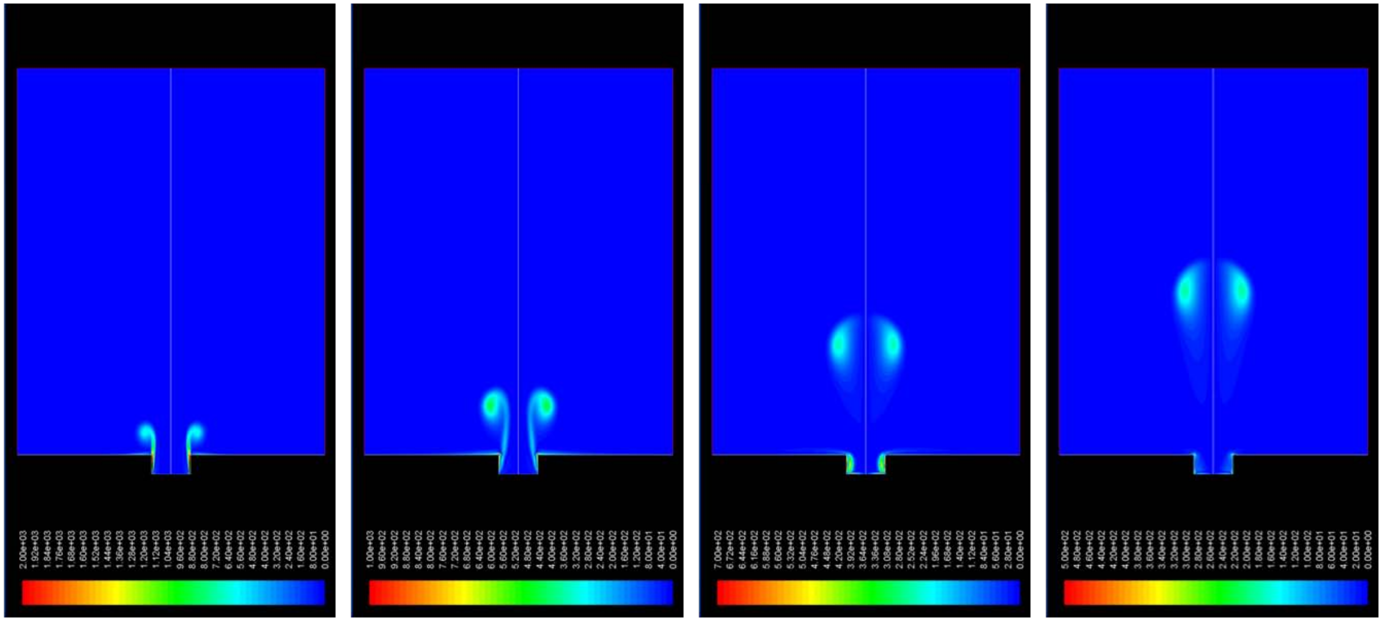


4. Secondary vortical structure

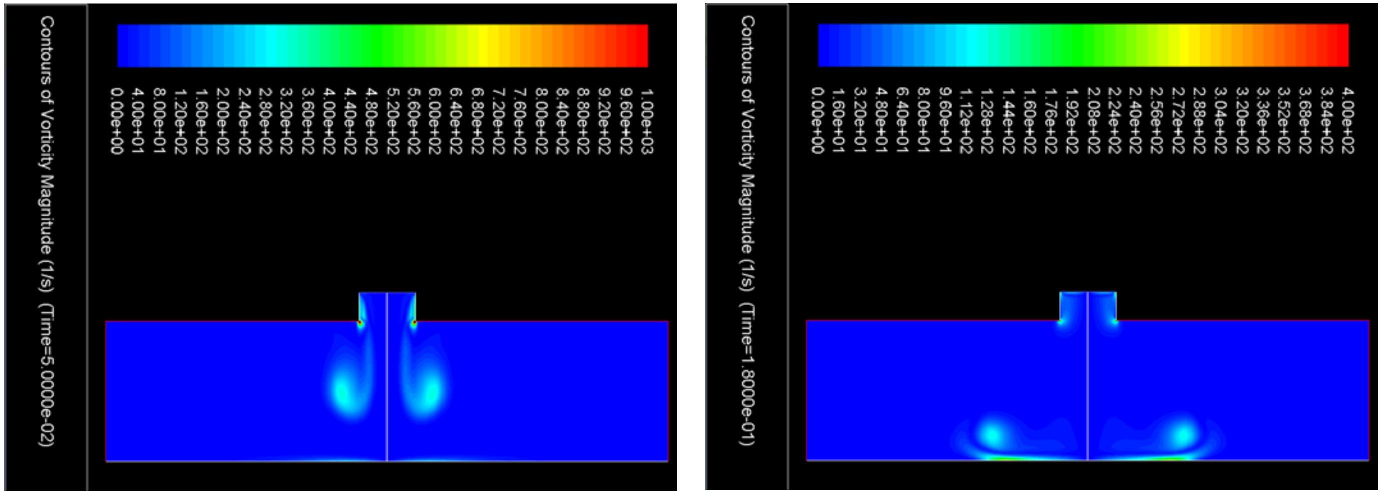
# Technical Accomplishments

Computational Fluid Dynamics Model Development

1. Laminar vortex ring formation

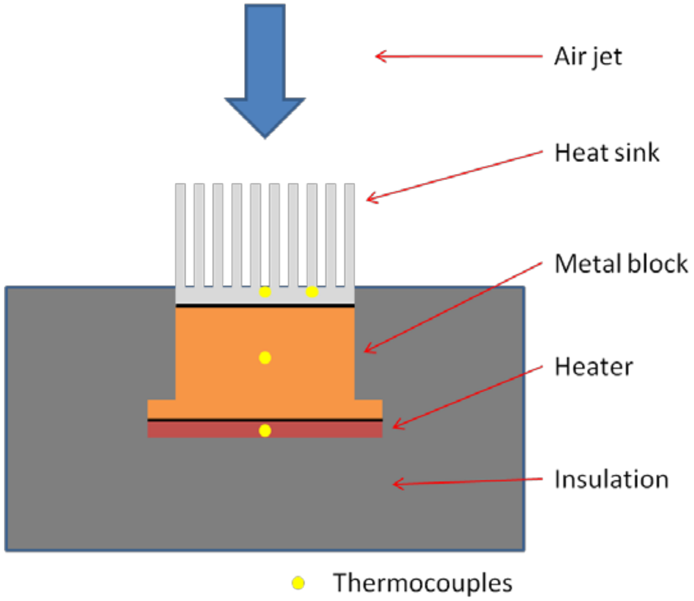


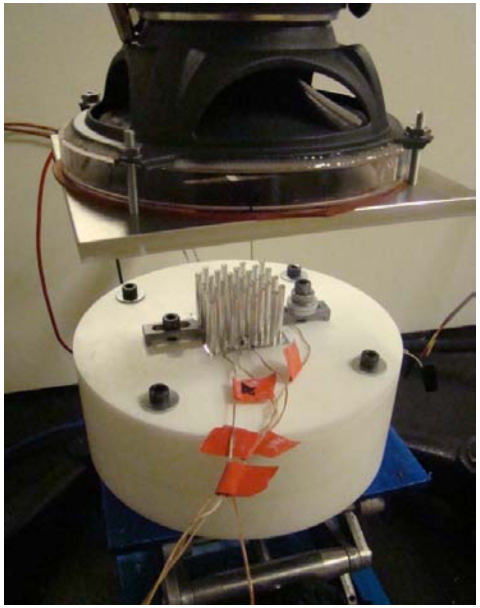
2. Laminar vortex ring impingement



# Technical Accomplishments

## Experimental Setup for Synthetic Jet Heat Transfer

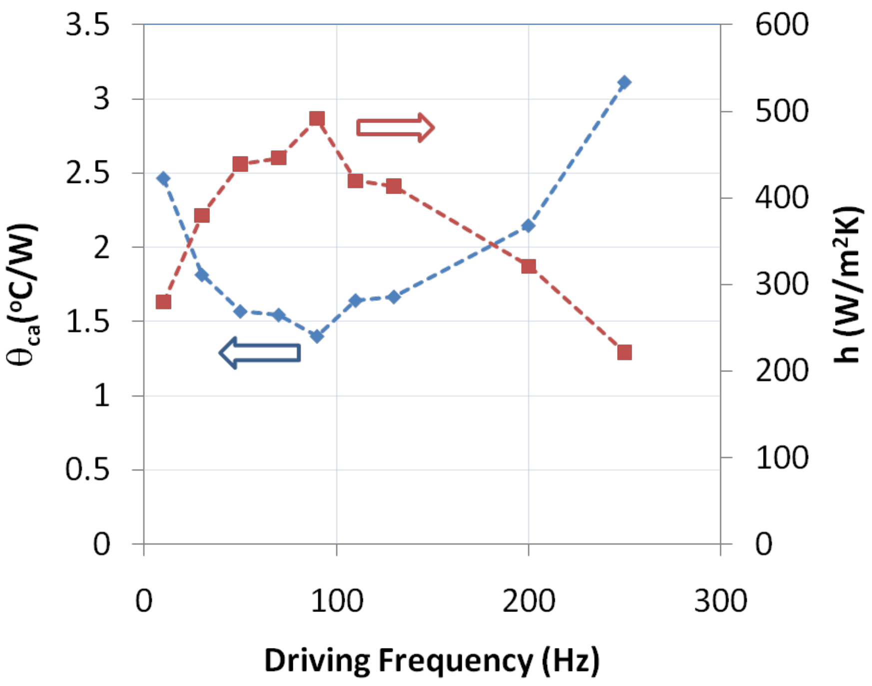


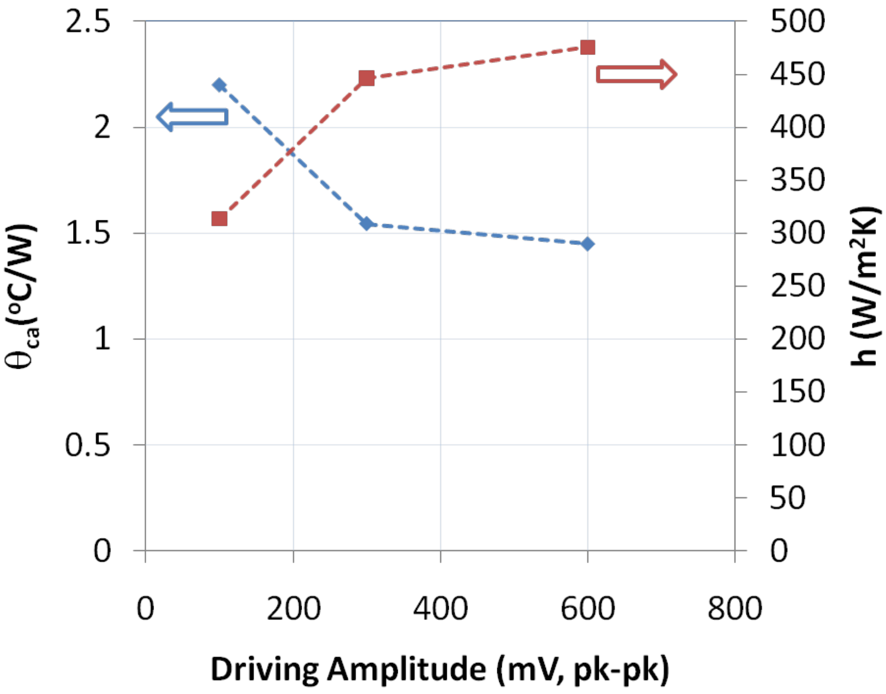


- Test apparatus to measure fundamental heat transfer performance of synthetic jets on extended surfaces
- Heat transfer performance measured as a function of:
  - Amplitude
  - Frequency

| Variable | Value | Units |
|---|---|---|
| $Q_{input}$ | 5.1 | W |
| $A_{heater}$ | 2 | $in^2$ |
| $A_{base\ plate}$ | 1.5 | $in^2$ |
| Heat sink | 32 | pin (staggered) |
| $d_{pin}$ | 1.5 | mm |
| $d_{slot}$ | 5 | mm |

# Technical Accomplishments





- Optimal driving frequency for thermal performance maximization
- Increasing driving amplitude results in increased convective heat transfer
- The combined synthetic jet-extended surface design space will be fully characterized
- Further studies will investigate the viability of synthetic jets and extended surfaces for power electronics cooling

# Technical Accomplishments

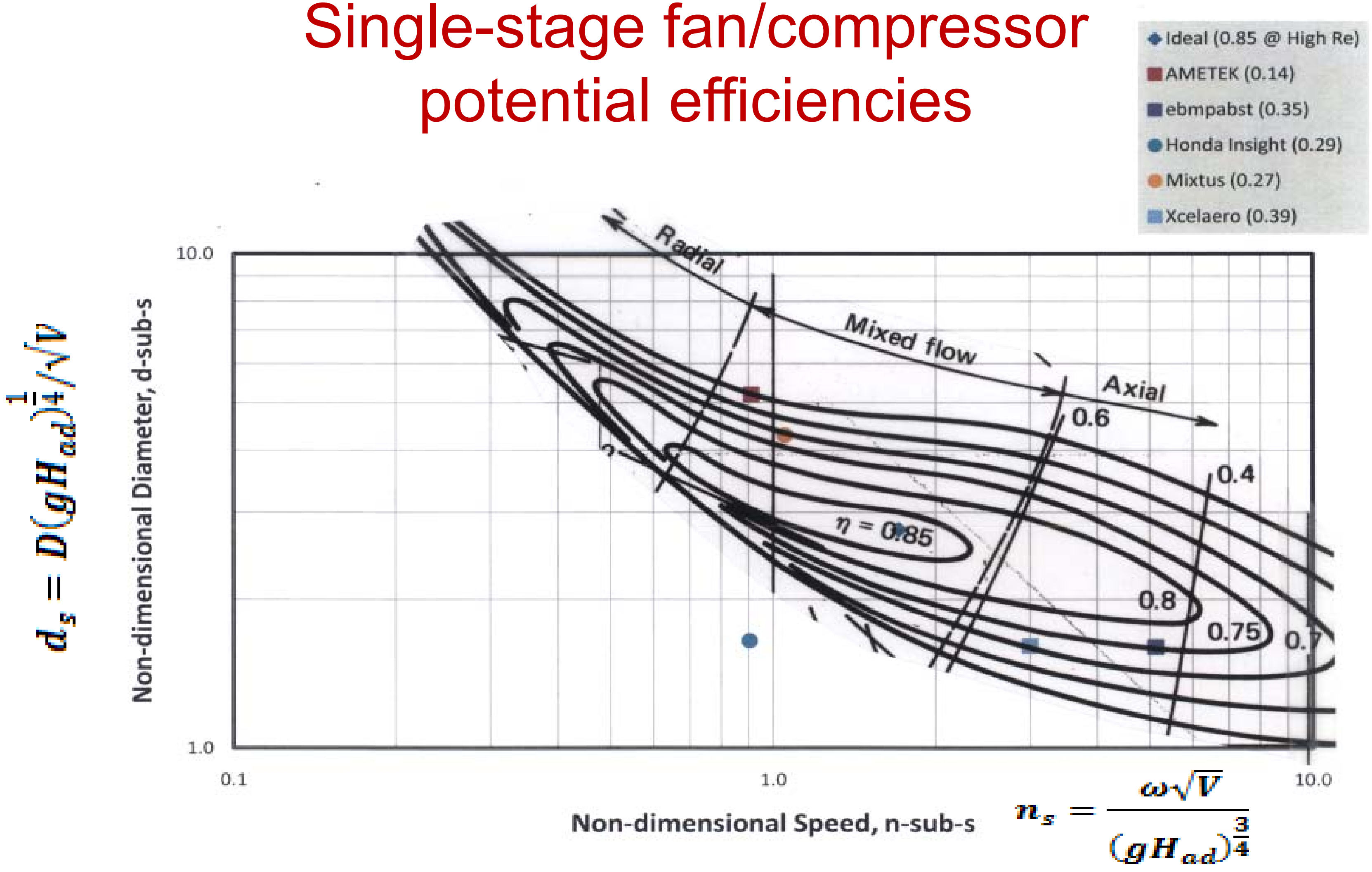
## A comparison of available fans, significant variation in performance

| **Manufacturer/Model** | | **AMETEK* Nautilair 8-inches** | **ebmpabst 8200 JH3** | **Honda* Insight Fan** | **Mixtus 7.9 E-Series** | **Xcelaero Squall 50** |
|---|---|---|---|---|---|---|
| Nominal Specification | Units | @80cfm and 3-in water | @80cfm and 3-in water | @100cfm and 1-in water | @100cfm and 2.2-in water | @100cfm and 2.2-in water |
| | | | | | | |
| Air mass flow | (g/s) | 46.28 | 43.39 | 57.85 | 57.85 | 57.85 |
| Volumetric flow | (m^3/s) | 0.0378 | 0.0354 | 0.0472 | 0.0472 | 0.0472 |
| Required pressure drop | (Pa) | 748 | 249 | 498 | 548 | 548 |
| | | | | | | |
| Mean fan diameter (d) | (m) | 0.2032 | 0.08 | 0.08 | 0.2032 | 0.0762 |
| Fan speed | (rad/s) | 576 | 1466 | 377 | 471 | 1340 |
| | | | | | | |
| | | | | | | |
| Non-dimensional speed, n-sub-s | (---) | 0.91 | 5.12 | 0.90 | 1.05 | 2.99 |
| Non-dimensional diameter, d-sub-s | (---) | 5.20 | 1.61 | 1.65 | 4.30 | 1.61 |
| | | | | | | |
| Reynolds number (ρVd/μ) | | 409162 | 161433 | 41511 | 334769 | 133907 |
| | | | | | | |
| Theoretical Fan Power | (W) | 28.24 | 8.83 | 23.54 | 25.89 | 25.89 |
| Actual Power | (W) | 200 | 25 | 80 | 96 | 66 |
| **Efficiency Overall** | **(---)** | **0.141** | **0.353** | **0.294** | **0.270** | **0.392** |

*Tested at NREL

# Technical Accomplishments

## Single-stage fan/compressor potential efficiencies



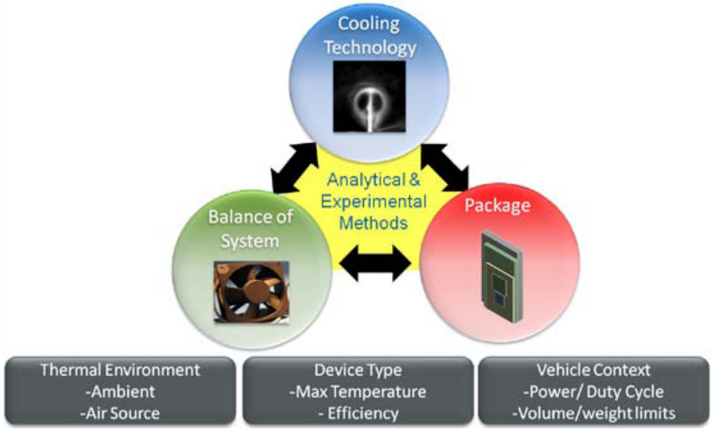
Source: Balje, *Turbomachines*, 1981

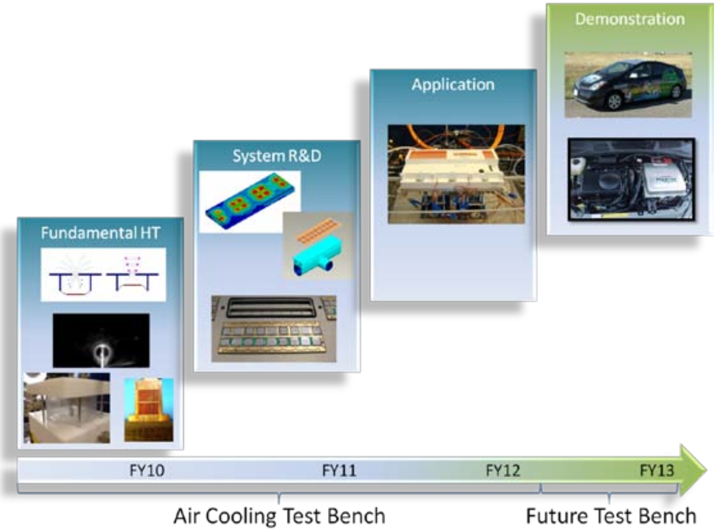
# Collaboration

- Oak Ridge National Laboratory
  - FY11:
    - NREL will continue their system level air cooling thermal design including cooling technology, balance of system, and high level package thermal analysis
    - ORNL will focus their work on wide-band gap materials in preparation for FY12 high temperature air cooled inverter design
  - FY12:
    - NREL’s air cooling thermal system research will be used to provide useful air cooling system thermal design information
    - ORNL work to define the inverter electrical design and feasibility of inverter topologies
  - FY13:
    - ORNL and NREL will collaborate to develop and demonstrate a viable high temperature air cooled inverter
- Other interactions
  - FreedomCAR Electrical & Electronics Technical Team
  - Delphi, PowerEx, Semikron, GE

# Future Work

- FY10
  - Complete synthetic jet feasibility study – go/no-go to system scale up
  - Develop system level air cooling analysis approach, looking at interaction with packaging design
  - Design and build single target air cooling test bench for fundamental heat transfer testing
  - Investigate other novel air cooling approaches
- FY11
  - Design and build system level air cooling test bench – use test bench to implement most promising technology on a multi-heat source array
  - Microchannel design has been shown to perform near program heat transfer targets – work to reduce weight, volume, size, and apply to likely system topology
  - Explore other novel air cooling technologies and surface enhancements
  - Address balance of system questions, developing knowledge and solutions for fans, filters, and ducting





# 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**

- Fabricated and tested prototype novel micro-fin heat sink design
  - Experimental validation of performance – showing 3kW heat rejection
  - Design and results under review by NREL patent committee
- Conducted initial assessment of synthetic jets
- Showed range of fan performance through testing and research

**Collaborations**

- Collaborating with industry & partners
  - Established collaboration plan with ORNL to develop needed thermal system knowledge for a FY12 high temperature inverter project
  - Interacting with Auto OEMs and suppliers for test data, review, and validation activities including: Delphi, PowerEx, and Semikron

# Contact Information

Jason A. Lustbader
Senior Engineer
National Renewable Energy Laboratory
Jason.Lustbader@nrel.gov
303-275-4443