NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Air Cooling Technology for Power Electronics Thermal Control

U.S. Department of Energy
Vehicle Technology Program
Annual Merit Review

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Project ID: APE019

This presentation does not contain any proprietary, confidential, or otherwise restricted information

“ Everything on a vehicle

is air cooled…

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is air cooled…

ultimately "

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 fluid 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 I start date: FY06
- Phase II start date: FY10
- Project end date: FY14
- Phase II complete: 25%

Budget

- Phase II funding
  - DOE share: $1,100K
  - Contractor share: $0.00
- FY10 Funding: $400K
- FY11 Funding: $700K

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*

Targets

- Cost, Specific Power, and Power Density

Partners (*NREL project lead*)

- Oak Ridge National Laboratory
- GE, Momentive™ Performance Materials, and Thermacore

Project Objectives – Relevance

- Develop air-cooled thermal management system solutions that help meet DOE's 2015 technical targets by 2014
- Enable heat rejection directly to ambient air, simplifying the system by eliminating liquid coolant loops, thereby improving weight, volume, cost, and reliability
- Develop and demonstrate the viability of innovative thermal management methods that maintain power electronics within acceptable temperature limits while reducing cost, weight, and volume
- FY11
  - Identify promising advanced cooling technologies, such as enhanced surfaces, synthetic jets, and advanced heat spreaders
  - Develop balance-of-system and module-level testing capability
  - Conduct system-level analysis to understand the air-cooling design space and the potential of advanced cooling technologies for thermal management improvement
  - Analyze thermal management feasibility of a high-temperature, air-cooled inverter concept (ORNL collaboration)

Project Milestones – Relevance

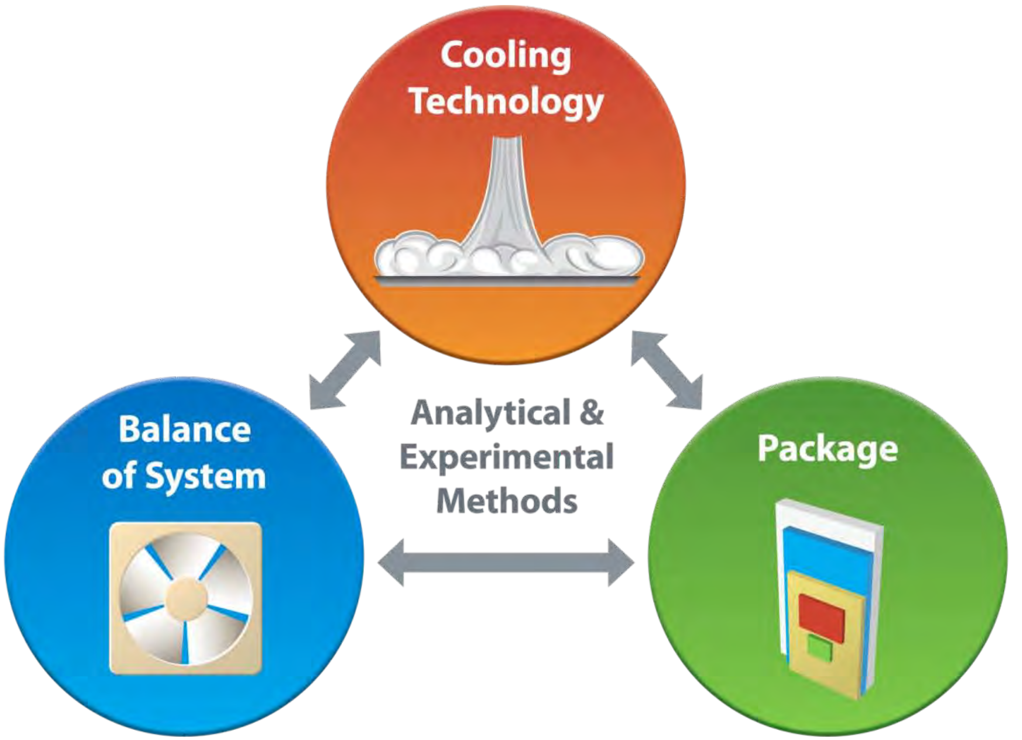
FY2010

- Completed preliminary review of synthetic jet technology (3/10)
- Created the Air Cooling Technology Characterization Platform (6/10)
- Found equivalent or better performance of synthetic jets than steady jets under tested flow regime (8/10)
- Developed system-level thermal analysis of air-cooled system (9/10)

FY2011

- Established high-temperature, air-cooled inverter work plan with ORNL (2/11)
- Applied system thermal analysis approach to full inverter and evaluated air cooling design space (4/11)
- Completed synthetic jet performance comparison to steady jets (5/11)
- Complete balance-of-system test stand (6/11)
- Finish initial surface enhancement screening (7/11)
- Complete high-temperature, air-cooled 30 kW continuous, 55 kW peak, inverter thermal management feasibility study (8/11)

Approach

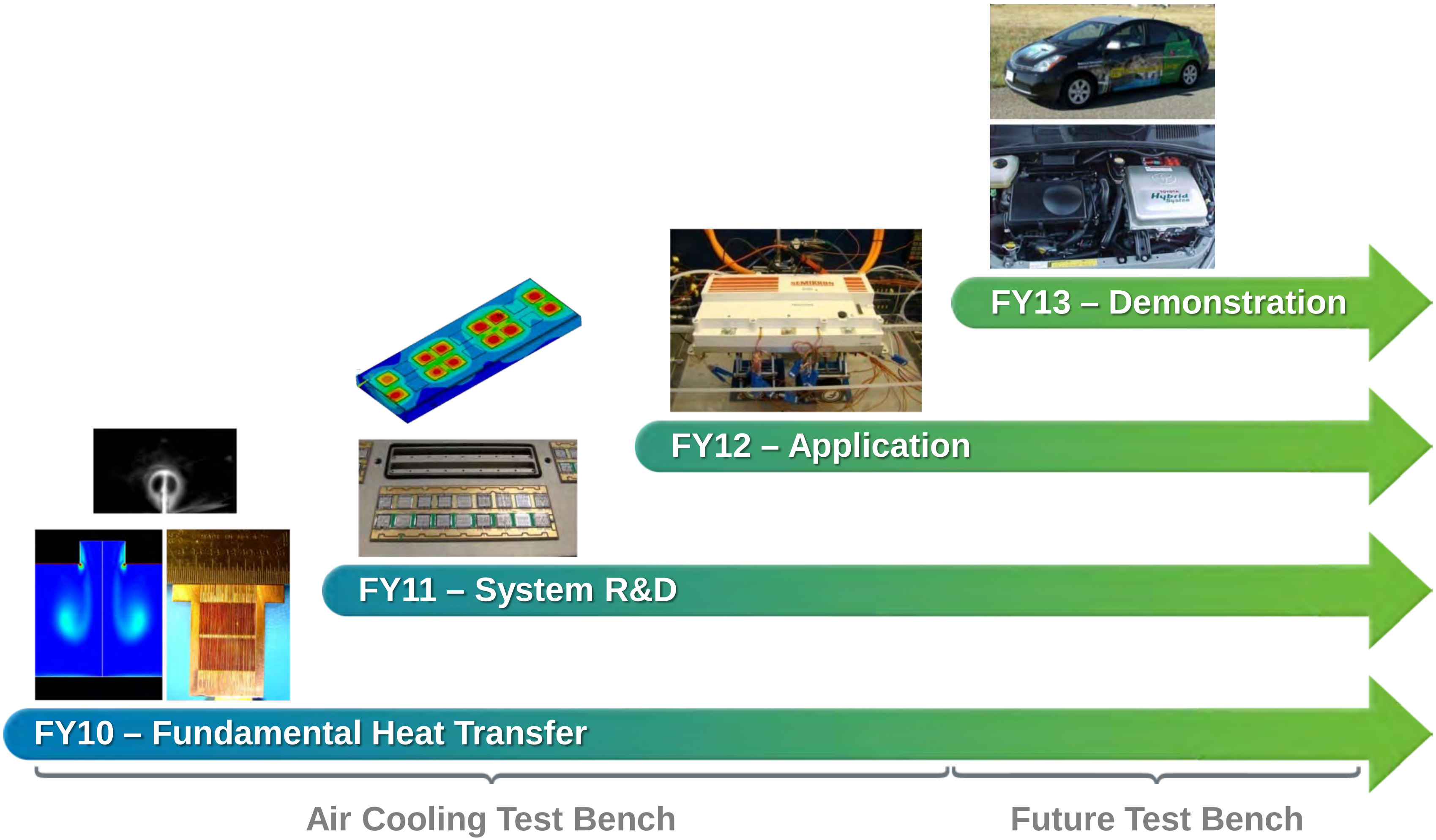


Thermal Environment
- Inverter Location
- Air Source

Device Type
- Max Temperature
- Efficiency

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

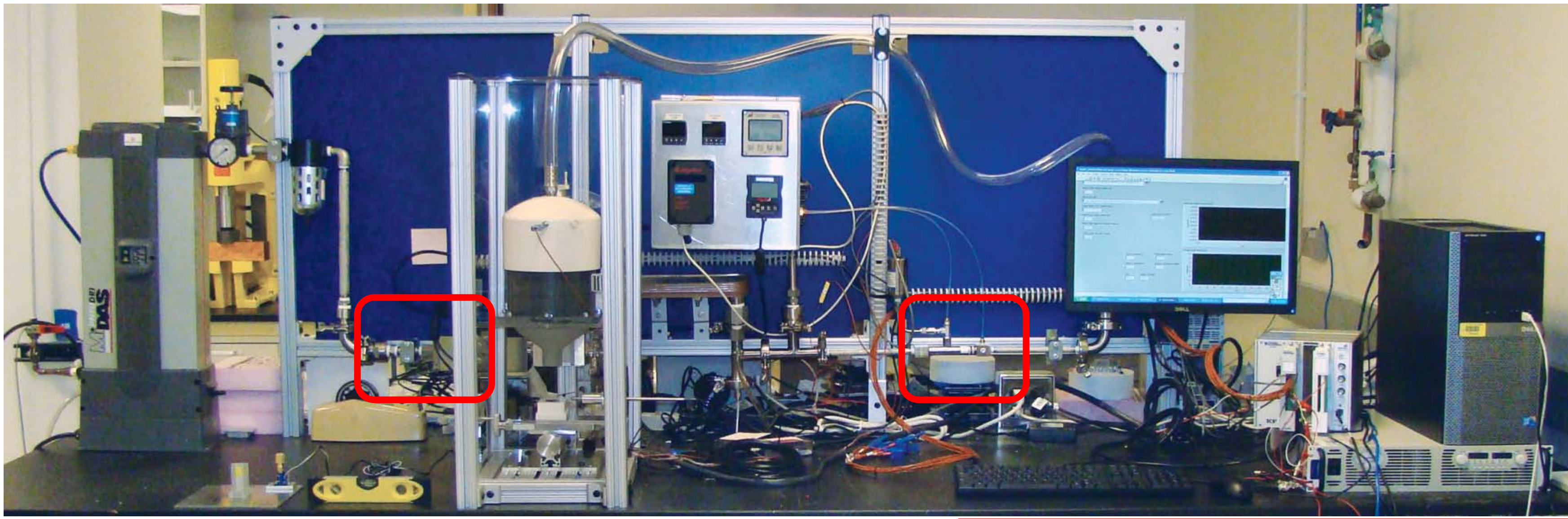
Approach



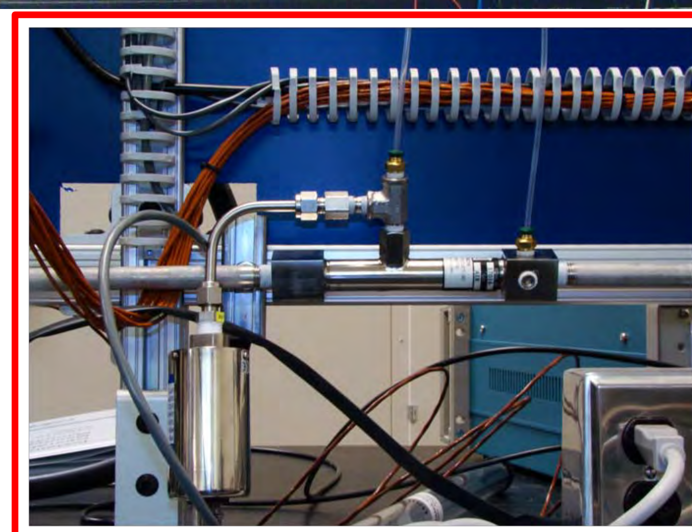
Photograph references from left to right: 1. Top [1], Right [2]; 2. Bottom [3]; 3. [4], 4. [5]

Cooling Technology – Accomplishment

Air Cooling Technology Characterization Platform



- Air flow rate control
- High accuracy heat transfer measurement
- Velocity field characterization
- Automated control and data acquisition



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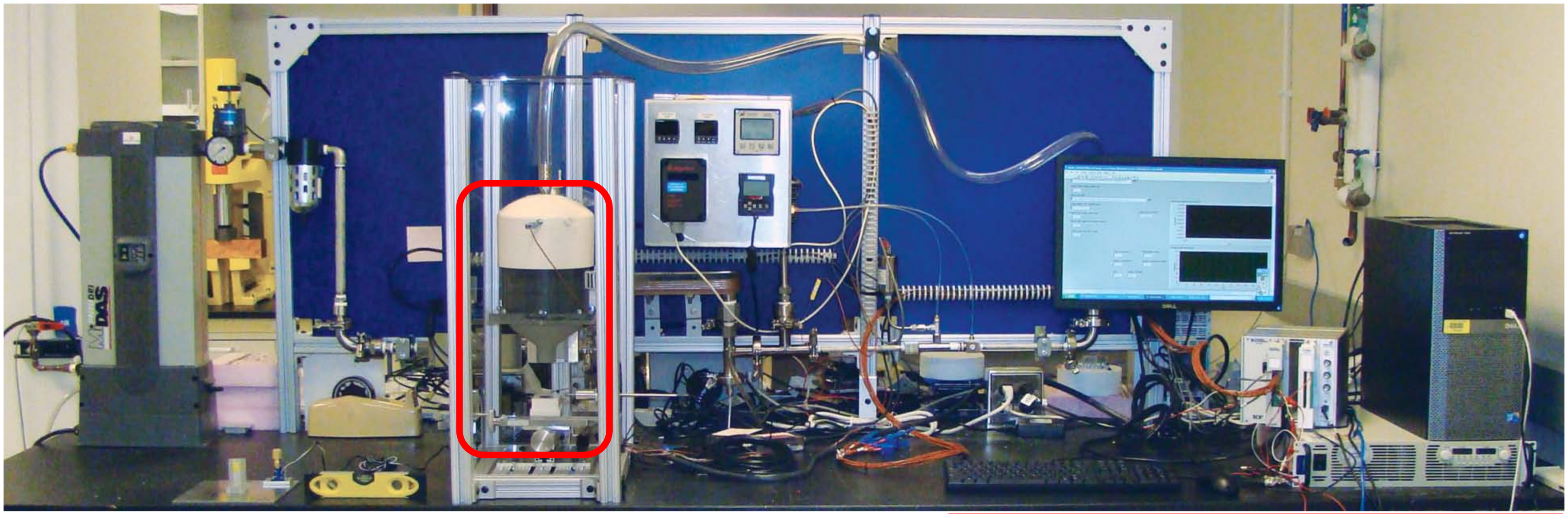
Cooling Technology – Accomplishment

Air Cooling Technology Characterization Platform



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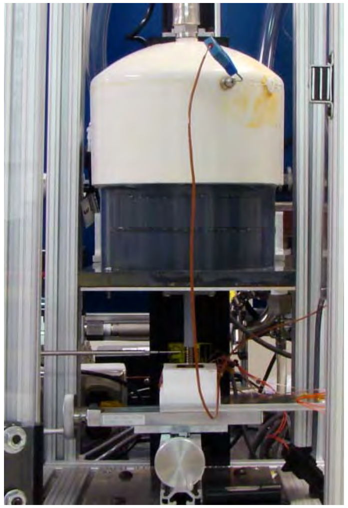

Photograph references : Top [1], Bottom [2b]

Cooling Technology – Accomplishment

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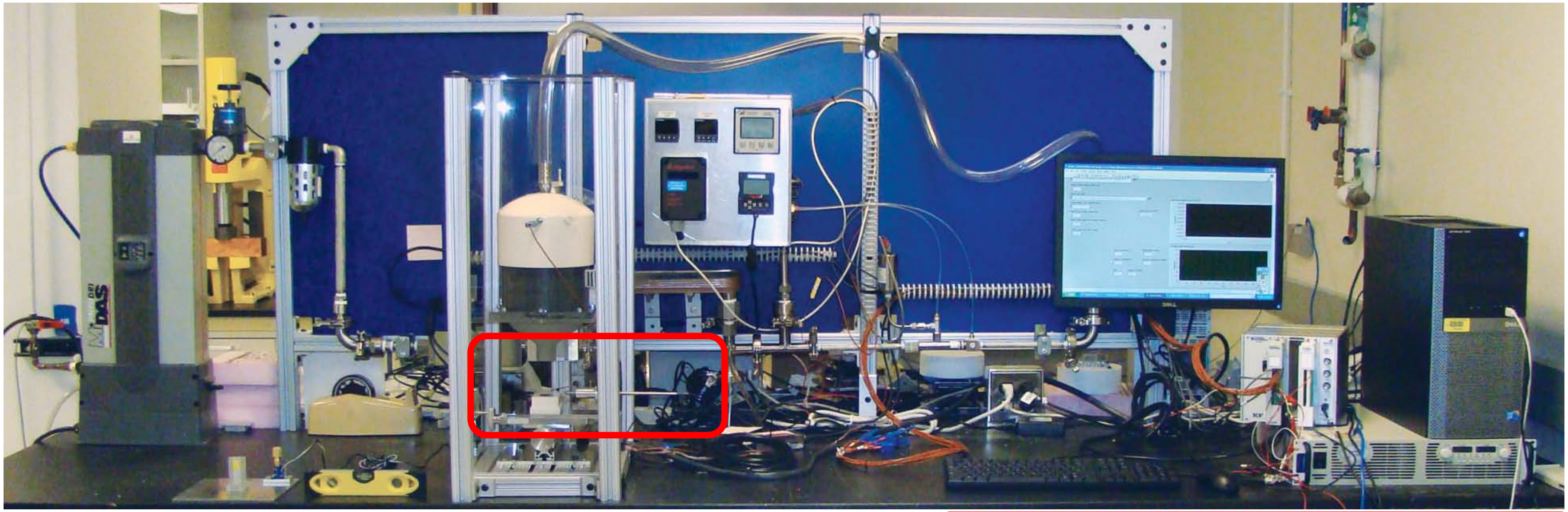

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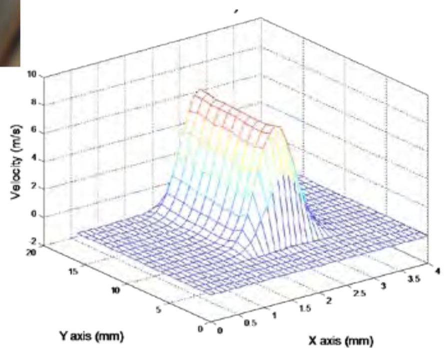

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Cooling Technology – Accomplishment

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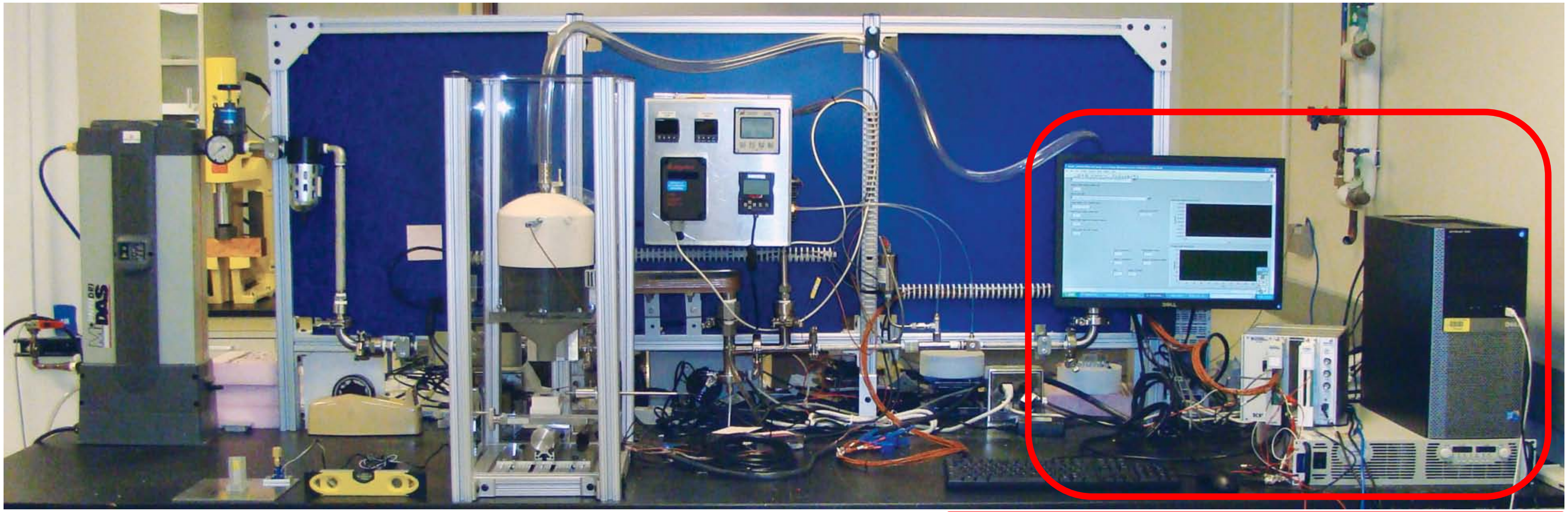

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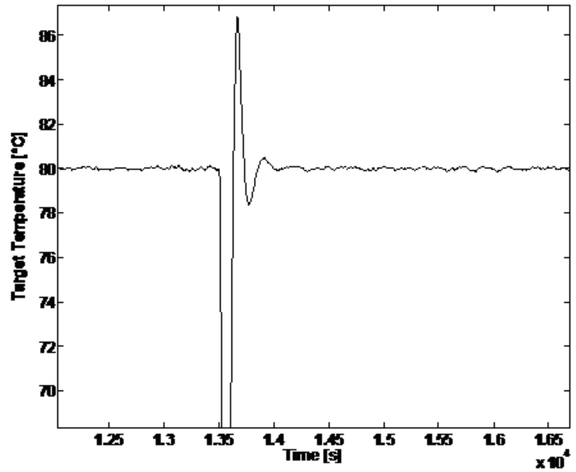
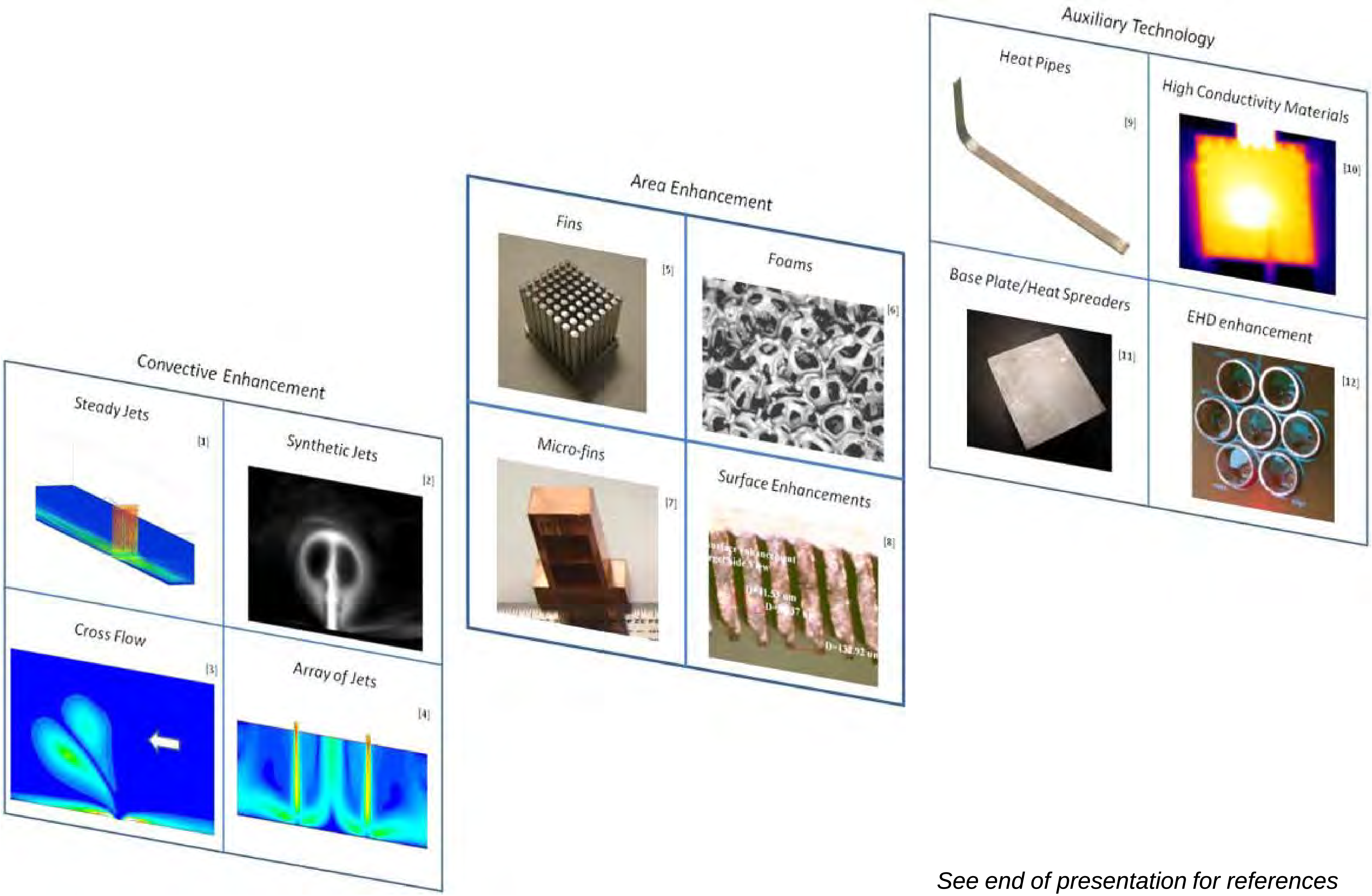


Photograph references : Top [1]

Air Cooling Technology – Accomplishment

Screening a large design space

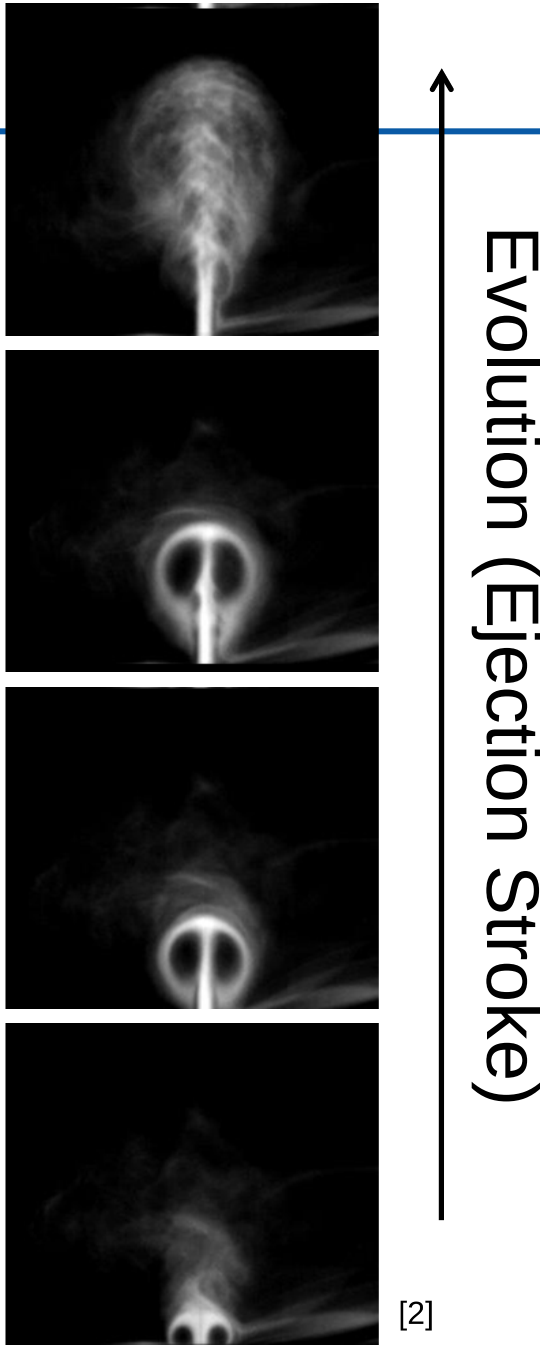


See end of presentation for references

Synthetic Jets – Accomplishment

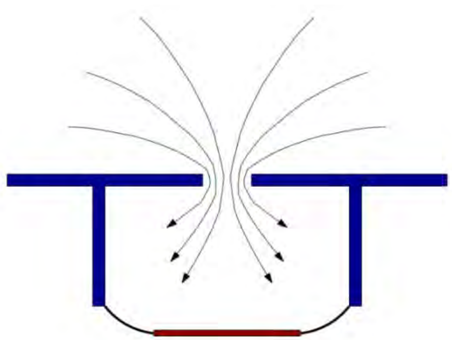
Advanced technology research

- Fully pulsatile jet
  - Near field : vortex rings/pairs
  - Far field : laminar/turbulent Jet
- Zero net mass flux
- Vorticle structures transfer momentum
- Simple fabrication

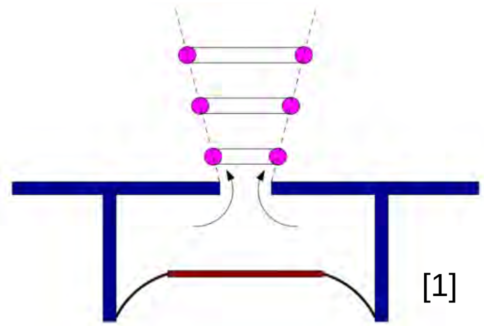


[2]

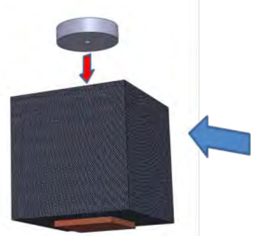
Suction



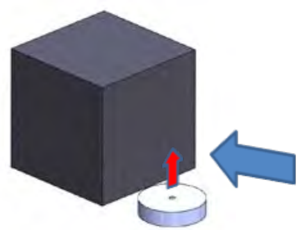
Ejection



[1]



Impinging + Cross-Flow

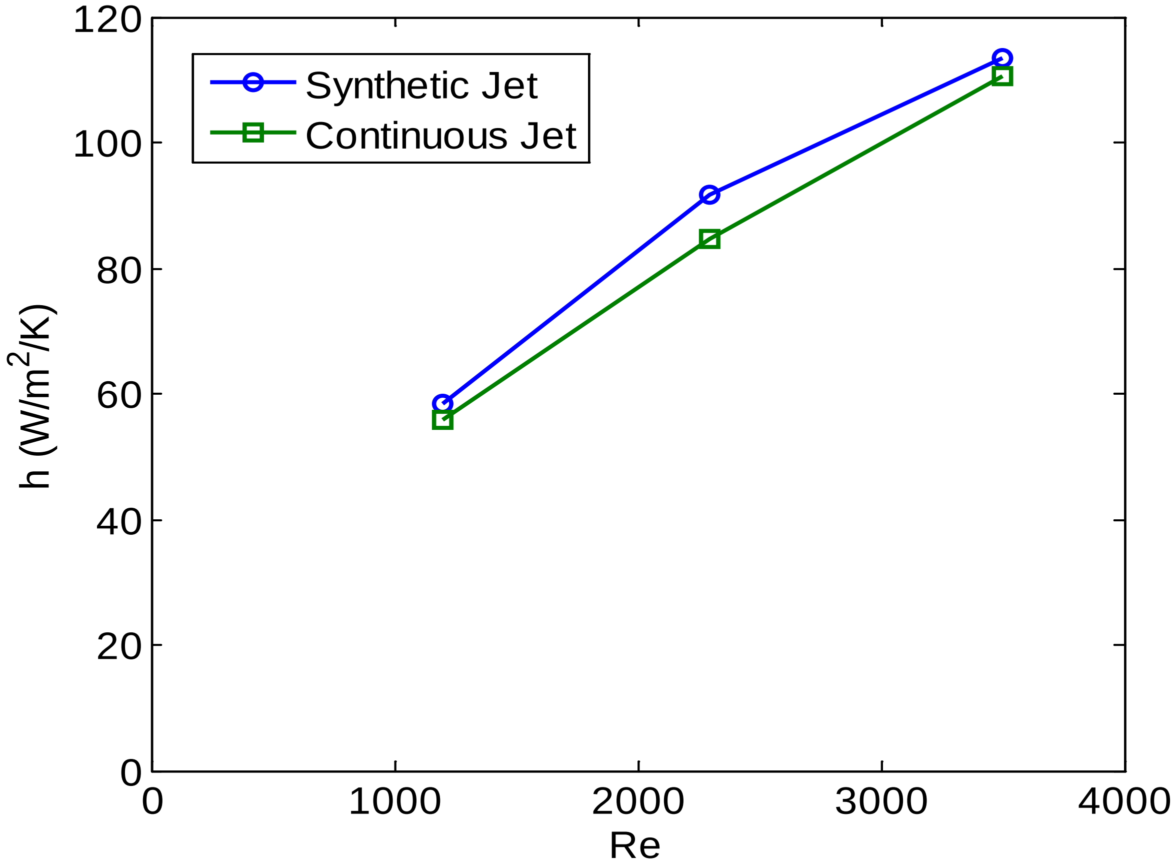


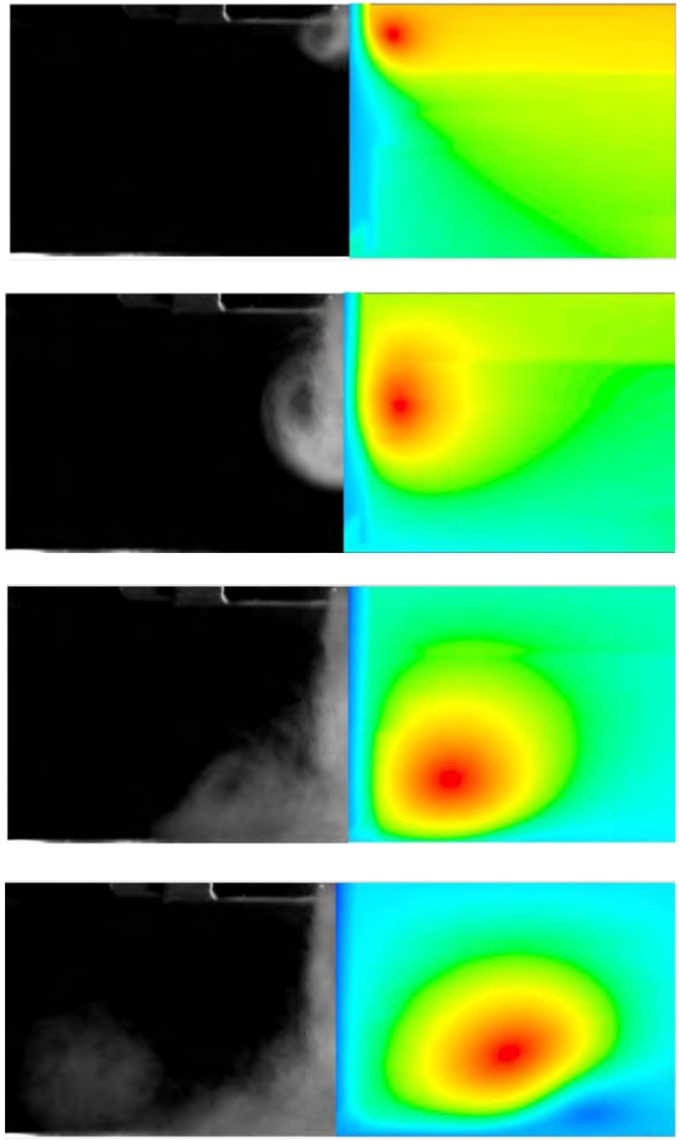
Leading Edge + Cross-Flow

Interior + Cross-Flow

Synthetic Jet Compared to Steady Jet – Accomplishment

Synthetic jets equal or better heat transfer with simpler design

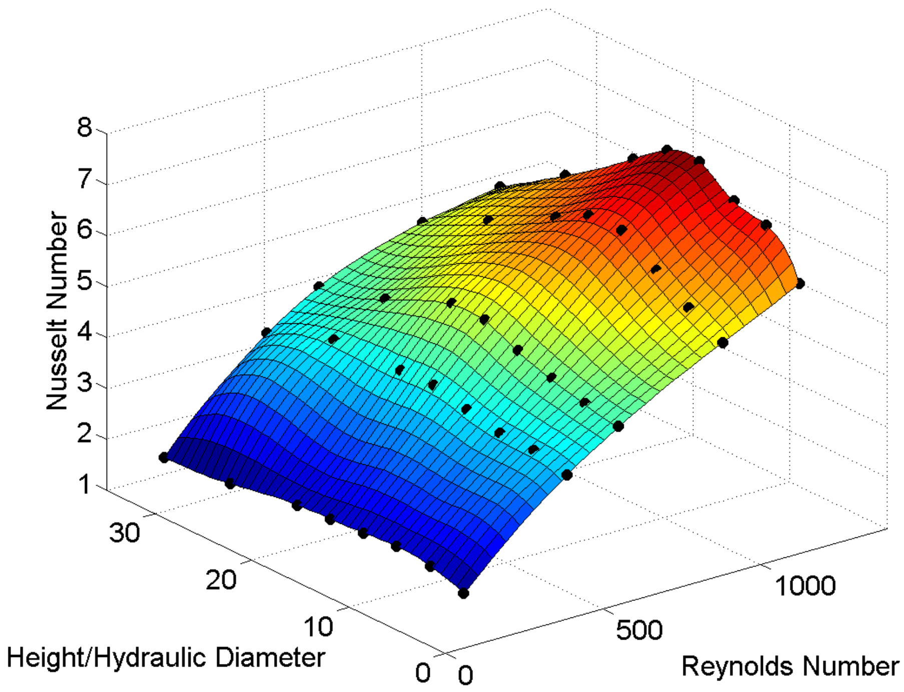


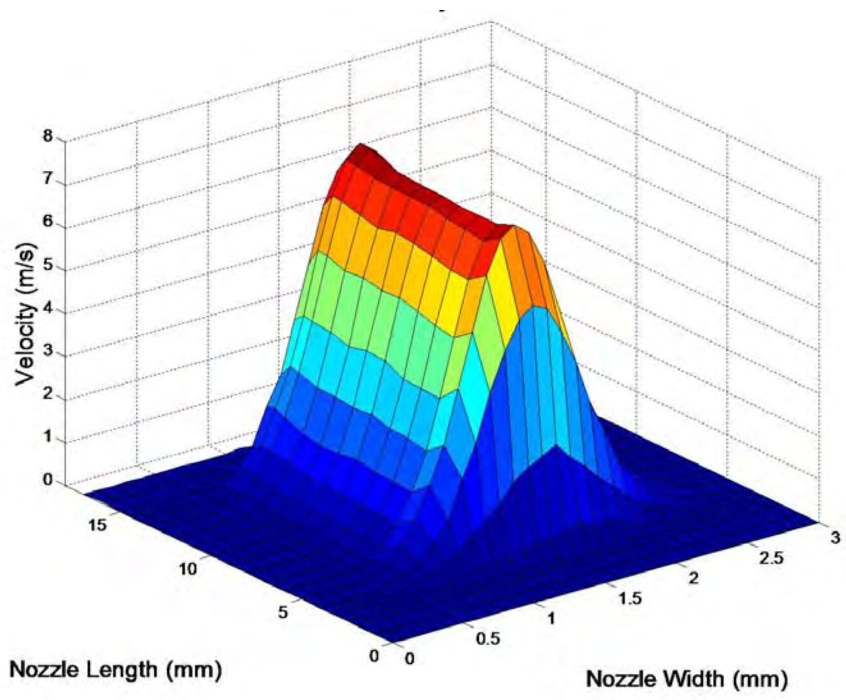


Steady Jet Characterization – Accomplishment

Fundamental heat transfer research collaboration, example results

- Characterized steady slot jets for comparison to synthetic jets
- Synthetic jet data to be provided by industry partner



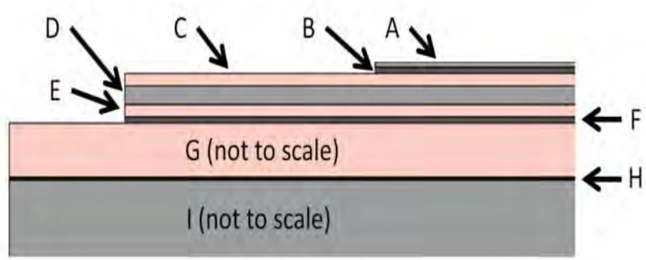


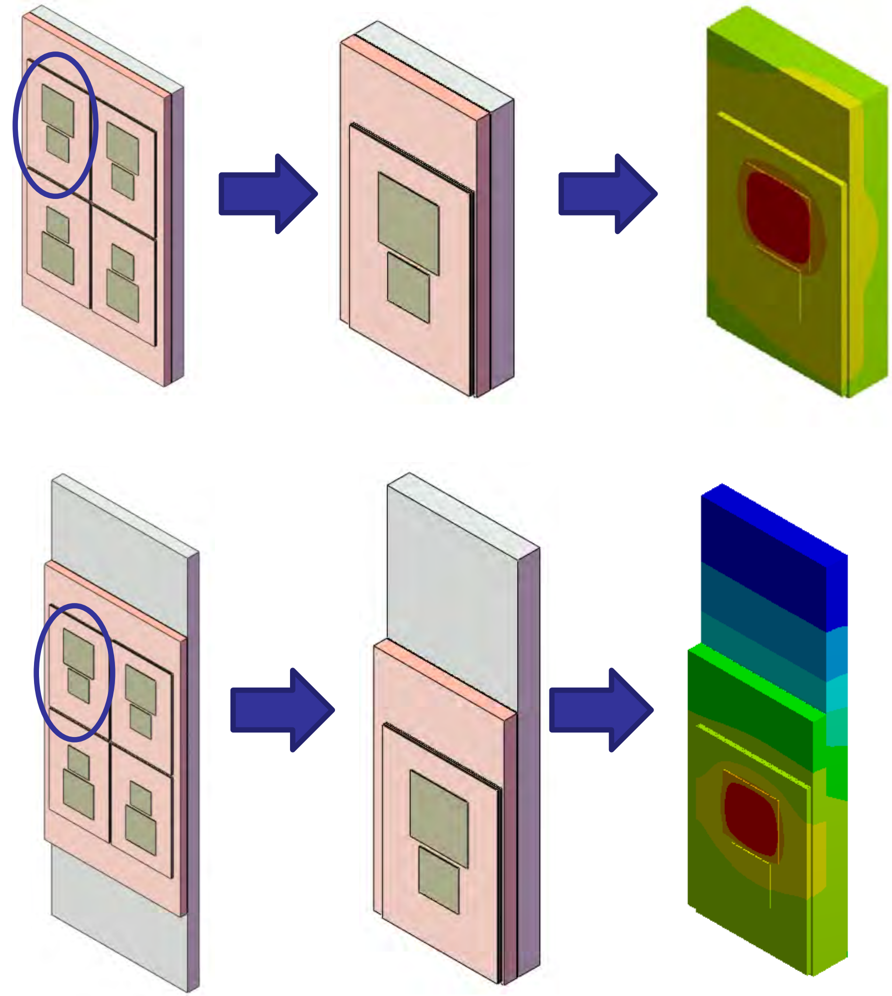
Steady jet nozzle 12X1 [mm]

Package Mechanical Design – Accomplishment

Package design thermal impacts

- Leverage work on the thermal system and performance task
- Finite element model of packages for system analysis

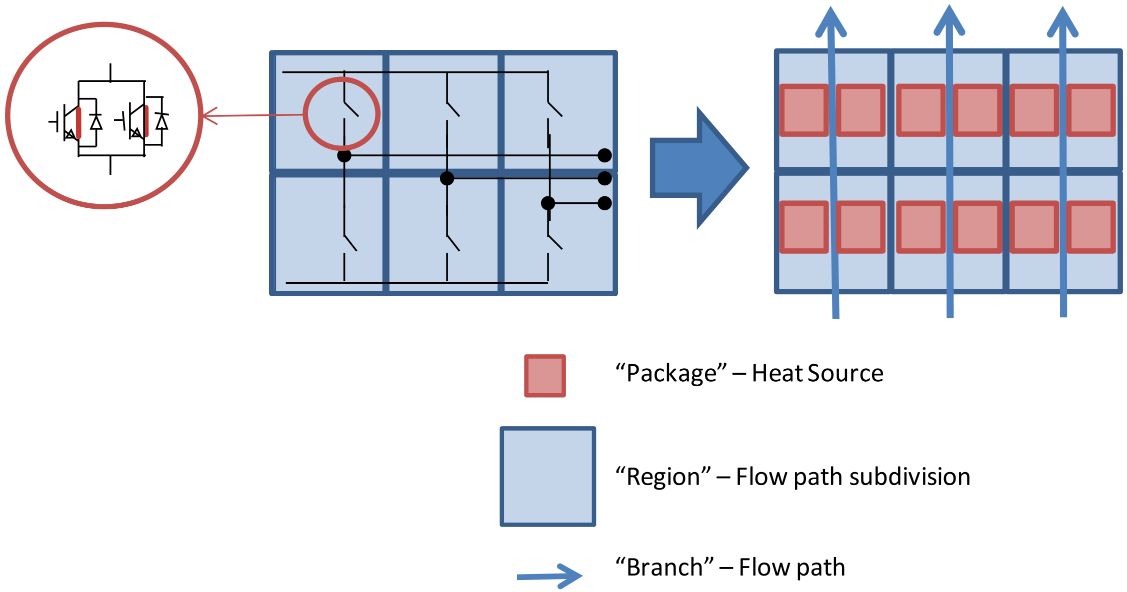




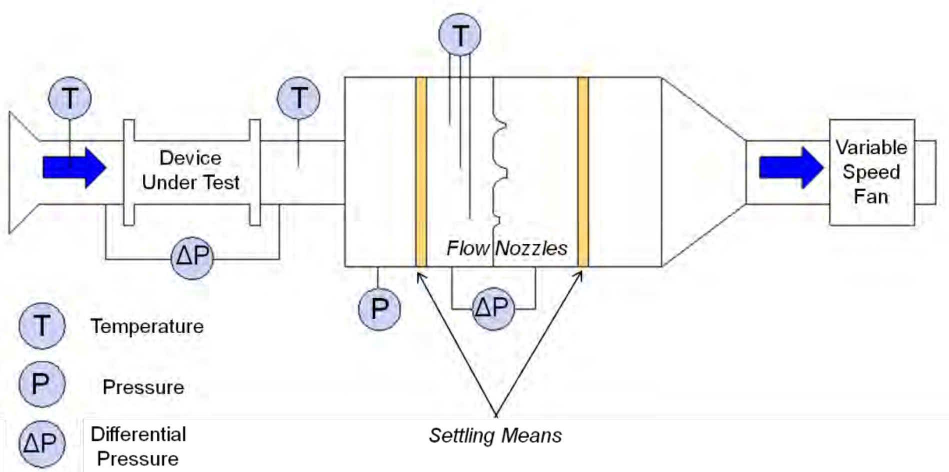
Balance-of-System – Accomplishment

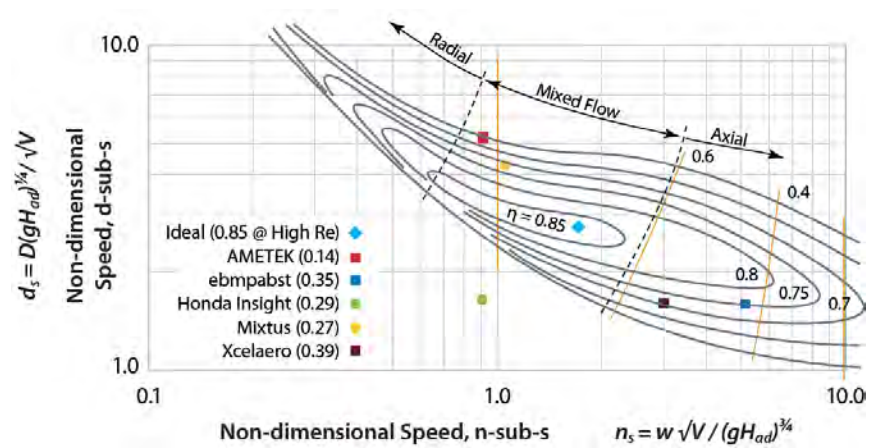
Understand parasitic loads and system COP

- General high level coolant system model
- Wide range of prime mover performance
- Expanding experimental capabilities

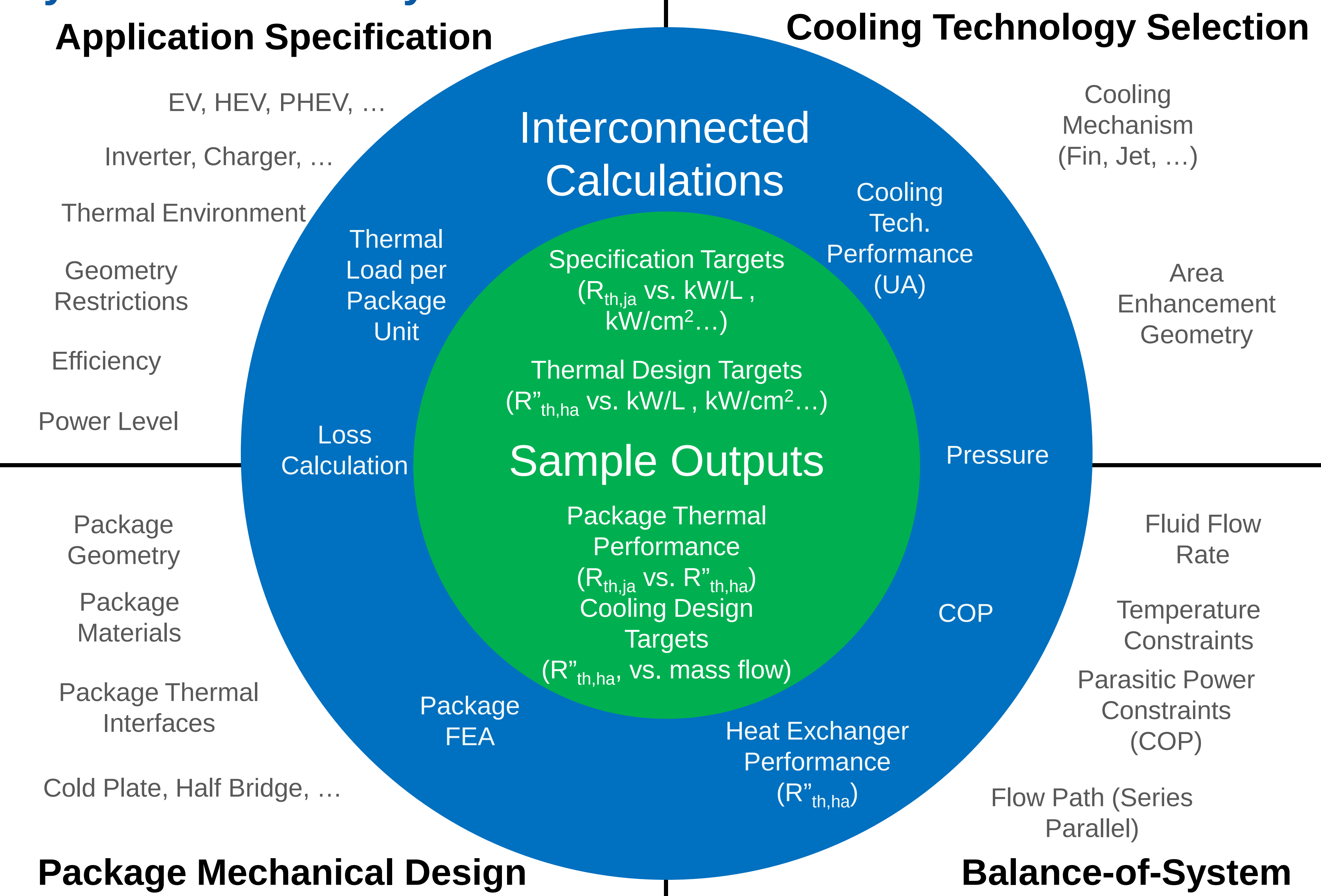


System Test Bench



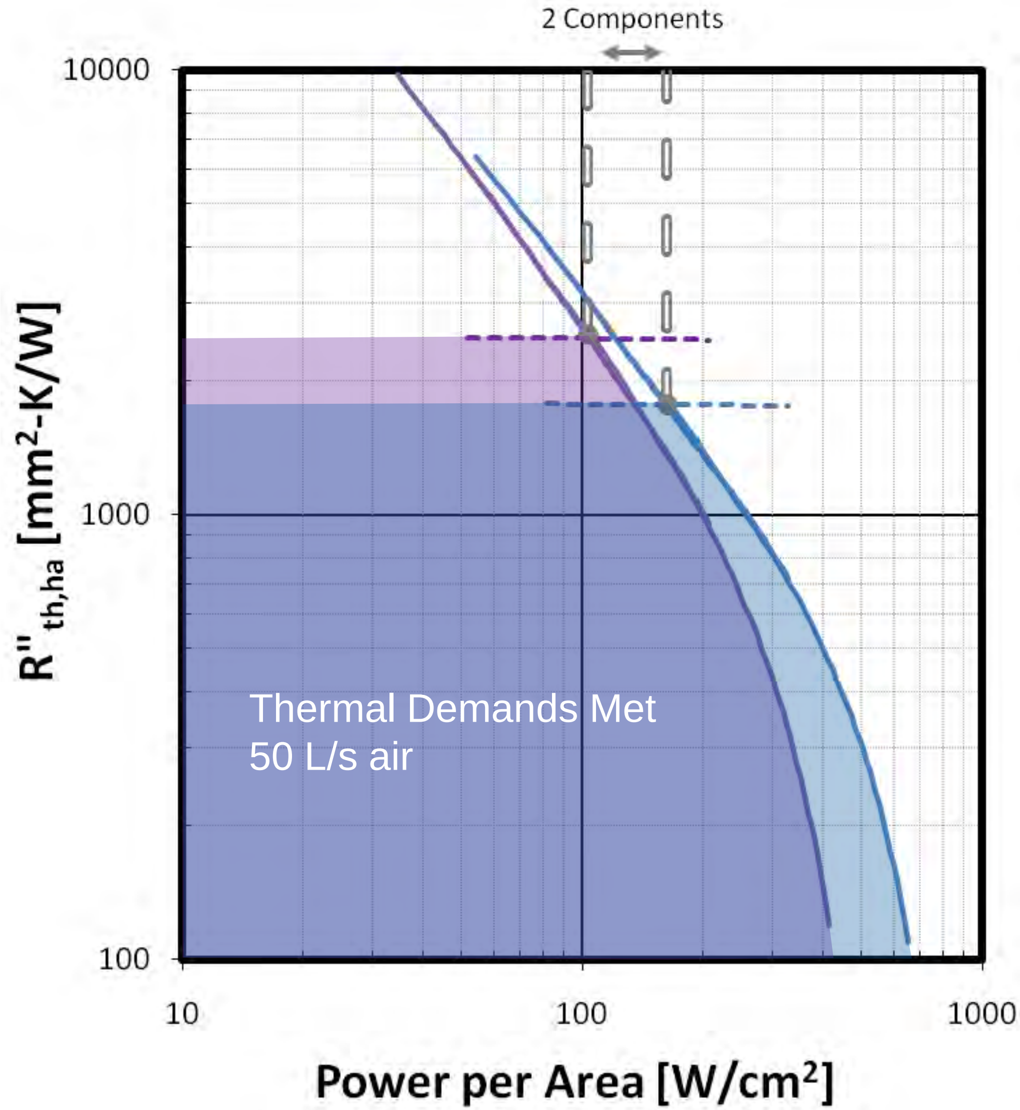


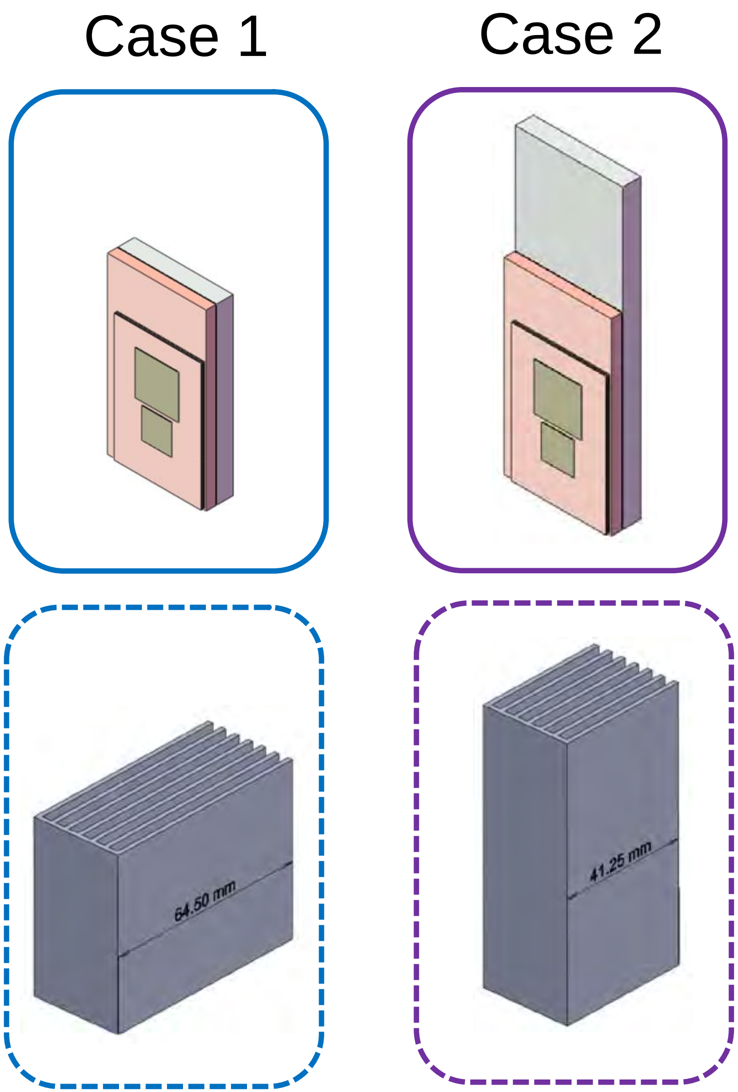
System Level Analysis



System Level Analysis – Accomplishment

20 kW DC-DC converter with air cooled fins case study



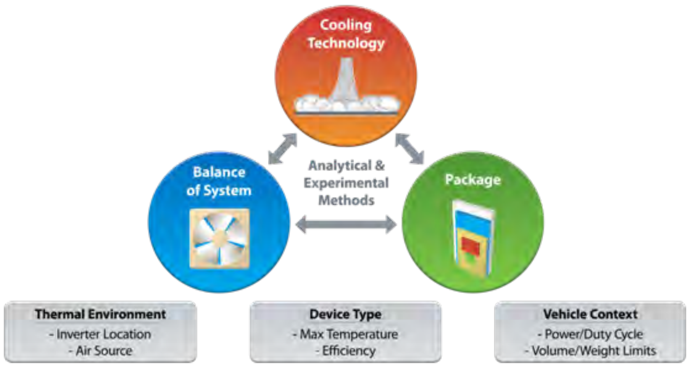


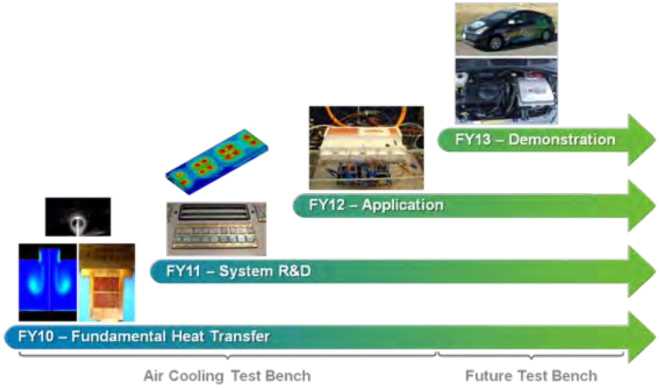
Collaborations

- ORNL (High Temperature Air Cooled Inverter)
  - **FY11: Thermal feasibility**
    - NREL will continue its system level air cooling thermal design including cooling technology, balance-of-system, and high-level package thermal analysis
    - NREL will complete high temperature air-cooled inverter thermal management and balance-of-system feasibility study
    - ORNL will focus its work on wide-band-gap materials in preparation for FY12 high-temperature air-cooled inverter design
  - **FY12: Module design phase**
    - NREL to improve heat transfer design and experimentally evaluate simulated heat load module thermal management system
    - ORNL to complete module electrical design and build initial prototype for validation
  - **FY13: System design phase**
    - ORNL to build and test low power inverter prototype
    - NREL to build and test thermal management system with low power inverter
  - **FY14: System build and demonstration**
    - NREL to build and test full system thermal management system
    - ORNL to build full inverter and test
    - High-temperature air-cooled inverter performance characterized and reported
- Other interactions
  - Electrical & Electronics Technical Team
  - GE, Momentive, and Thermacore

Future Work

- FY11
  - Design and build system-level air-cooling test bench. Use test bench to implement most promising technology on a multi-heat source array
  - Explore other novel air-cooling technologies and surface enhancements
  - Address balance-of-system questions, developing knowledge and solutions for fans, filters, and ducting
  - Complete high-temperature air-cooled inverter thermal management and balance-of-system feasibility study
- FY12
  - Thermal management design of high-temperature air-cooled inverter module (ORNL collaboration)
  - Test simulated heat module for validation of thermal management design
  - Research advanced air-cooling technologies, such as enhanced surfaces, boundary layer perturbation, synthetic jets, heat spreaders, and advanced fin design
  - Analyze system level designs and evaluate balance-of-system solutions





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

- Developed system-level analysis approach for power electronics air cooling
- Established more direct collaboration with ORNL
- Found equivalent or better performance of synthetic jets than steady jets under tested flow regime
- Developed the Air Cooling Technology Characterization Platform for advanced cooling technology research

Collaborations

- Established collaboration plan with ORNL to develop needed thermal system knowledge for FY12 high-temperature inverter project
- Researching advanced air-cooling technology in collaboration with GE, Momentive, and Thermacore
- Interacting with auto OEMs and suppliers for test data, review, and validation activities

Acknowledgements and Contact

Acknowledgements:

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Team Members:

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Kevin Bennion

Xin He

Charlie King

Gopi Krishnan

Sreekant Narumanchi

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Phone: (303)-275-3653

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 10-13

1. Test bench photograph: Gopi Krishnan and Dean Armstrong, NREL
2. a. Laminar flow element detail; b. Settling chamber and target; c. Constant Temperature Anemometer, Jason Lustbader, NREL

Slide 14

1. Stream function from a computation fluid dynamics (CFD) calculation of a steady slot jet, Gopi Krishnan, NREL
2. High speed capture of the emergence of a synthetic jet, Gopi Krishnan, NREL
3. Velocity contours from a CFD calculation of vortex ring formation in cross flow, Gopi Krishnan, NREL
4. Velocity contours from a CFD calculation of two steady jets, Gopi Krishnan, NREL
5. Pin fin heat sink from Cool Innovations, Gopi Krishnan, NREL
6. Porous carbon foam under a microscope, Mark Mihalic, NREL
7. Micro fin heat exchanger, Charlie King, NREL
8. MicroCool Surface from Wolverine, Mark Mihalic, NREL
9. A heat pipe, Jason Lustbader, NREL
10. IR image of a thermally conductive material, Charlie King, NREL
11. Aluminum heat sink/spreader, Gopi Krishnan, NREL
12. Ionic wind device, Jason Lustbader, NREL

Slide 15

1. Synthetic jet schematic: Krishnan, G., & Mohseni, K. (2009). ”Axisymmetric Synthetic Jets: An Experimental and Theoretical Examination”. AIAA Journal, 47 (10), 2273-2283.
2. Synthetic jet flow visualization photographs: Gopi Krishnan and Charlie King, NREL