Micro- & Nano-Technologies Enabling More Compact, Lightweight Thermoelectric Power Generation & Cooling Systems

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Terry J. Hendricks[1] , Shankar Krishnan[2]

[1]Battelle Memorial Institute
Process & Systems Engineering
Columbus, OH

[2]Pacific Northwest National Laboratory
Energy & Efficiency Division
MicroProducts Breakthrough Institute
Corvallis, OR

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Motivation - Energy & The Environment

- **Transportation Sector Energy Use**
  - **Light-Duty Passenger Vehicles + Light-Duty Vans/Trucks (SUVs)[1]**

    2002: 16.27 Quads of Fuel Usage

    2008: 16.4 Quads of Fuel Usage

    2002: ~ 5.7 quads/yr exhausted down the tail pipe

    ~ 5 quads/yr rejected in coolant system

  - **Medium & Heavy-Duty Vehicles[1]**

    2002: 5.03 Quads of Fuel Usage

    2008: 5.02 Quads of Fuel Usage

    ~1.5 quads/yr exhausted down the tail pipe
  - **7 to 8 Billion gallons of fuel /year used for Automotive A/C**
  - **Hybrid Electric Vehicles**

    Move Toward Electrification – Micro, Mild, and Full
    - Needs for On-board Power Generation
    - Needs for Electric-Driven Cooling

- **Environmental Impact**
  - **Reduce Global Warming Refrigerant Use in Automotive A/C Systems**
  - **R-134 a Leakage - Global Warming Impact - 1,300 times that of carbon dioxide**

[1] *Transportation Energy Data Book,* 2010, Edition 29, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicles Technology Program. ORNL-6985, Oak Ridge National Laboratory, Oak Ridge, Tennessee. http://cta.ornl.gov/data/index.shtml.

Motivation - Energy & The Environment

- **7 to 8 Billion gallons of fuel /year used for Automotive A/C**
  - ~6 % of Light Duty Vehicle Fuel Use; Releases approximately 62-70 Billion kg of CO_2 / year
- **Current Centralized A/C Systems Require 3.5 to 5 kW of Energy in Each Vehicle**
- **Zonal or Distributed Thermoelectric Heating, Ventilation and Air Conditioning (HVAC)**
  - Requires ~ 630 Watts Cool Driver Only and
  - ~ 2.7 kW Cool 5 Occupants
- **In Heating Mode, TE much more Efficient (COP_{heat} ~ 2.3 > 1)**
- **Current Vehicular Air Conditioner (A/C) uses Compressed R134-a Refrigerant Gas**
  - Each Vehicle Leaks ~70 g/year R134-a
  - R134-a Has 1300 times the "Greenhouse Gas Effect" as Carbon Dioxide (CO_2)
  - ~18.2 Million Metric Tons of CO_2 equivalent/year from personal vehicles in the US from operating air conditioners (does not include accident release)
  - U.S. EPA Estimtates ~58 Million Metric Tons of CO_2 equivalent/year from transportation sector (primarily R-134a) http://epa.gov/climatechange/emissions/usinventoryreport.html

Thermoelectric Systems in Automobiles

- DOE Sees a Vision and the Potential

Greenhouse Gas & Global Warming Reduction

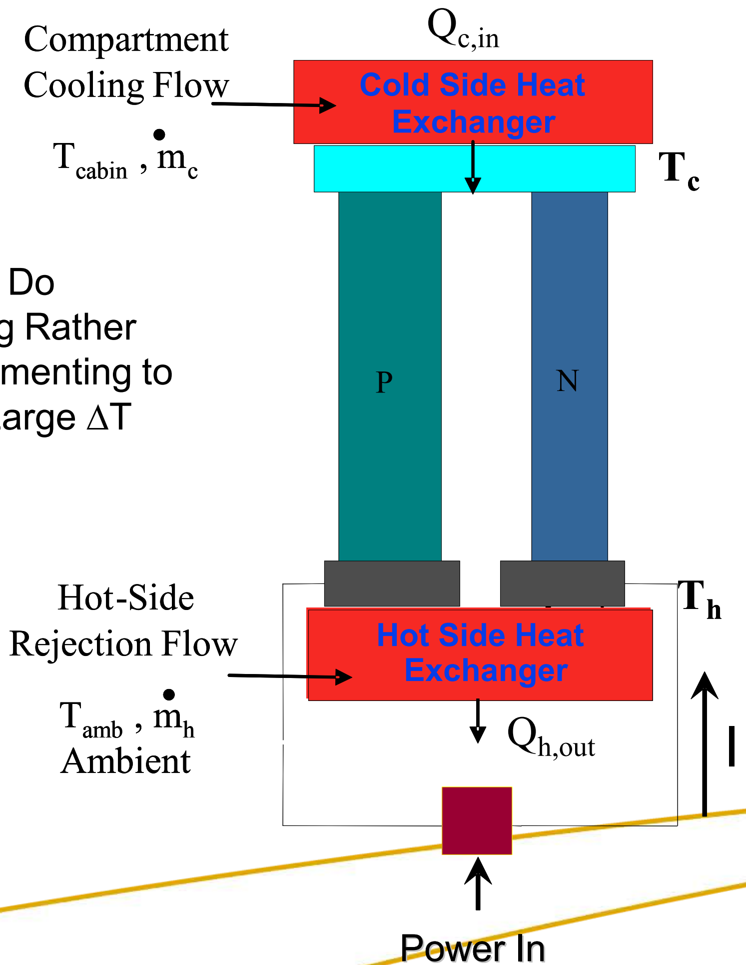
Significant Waste Heat Available in Vehicle Exhaust Streams

Need for Electrically-Driven Heating/Cooling

Advanced Thermoelectric System Design

Thermoelectric Heating/Cooling
Low-Temperature Systems

Generally Do Cascading Rather Than Segmenting to Achieve Large ΔT



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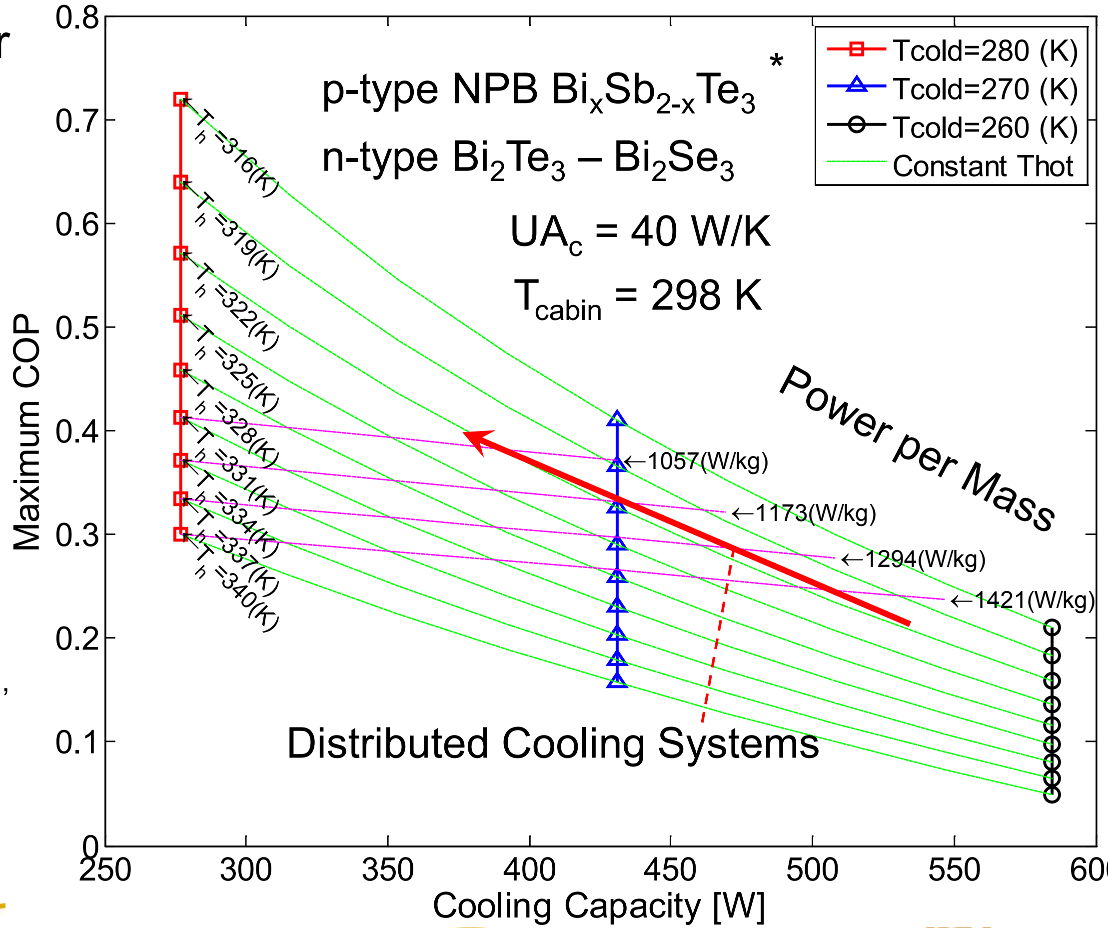
TE Cooling
Heat Exchanger / TE Device Integration Requirements

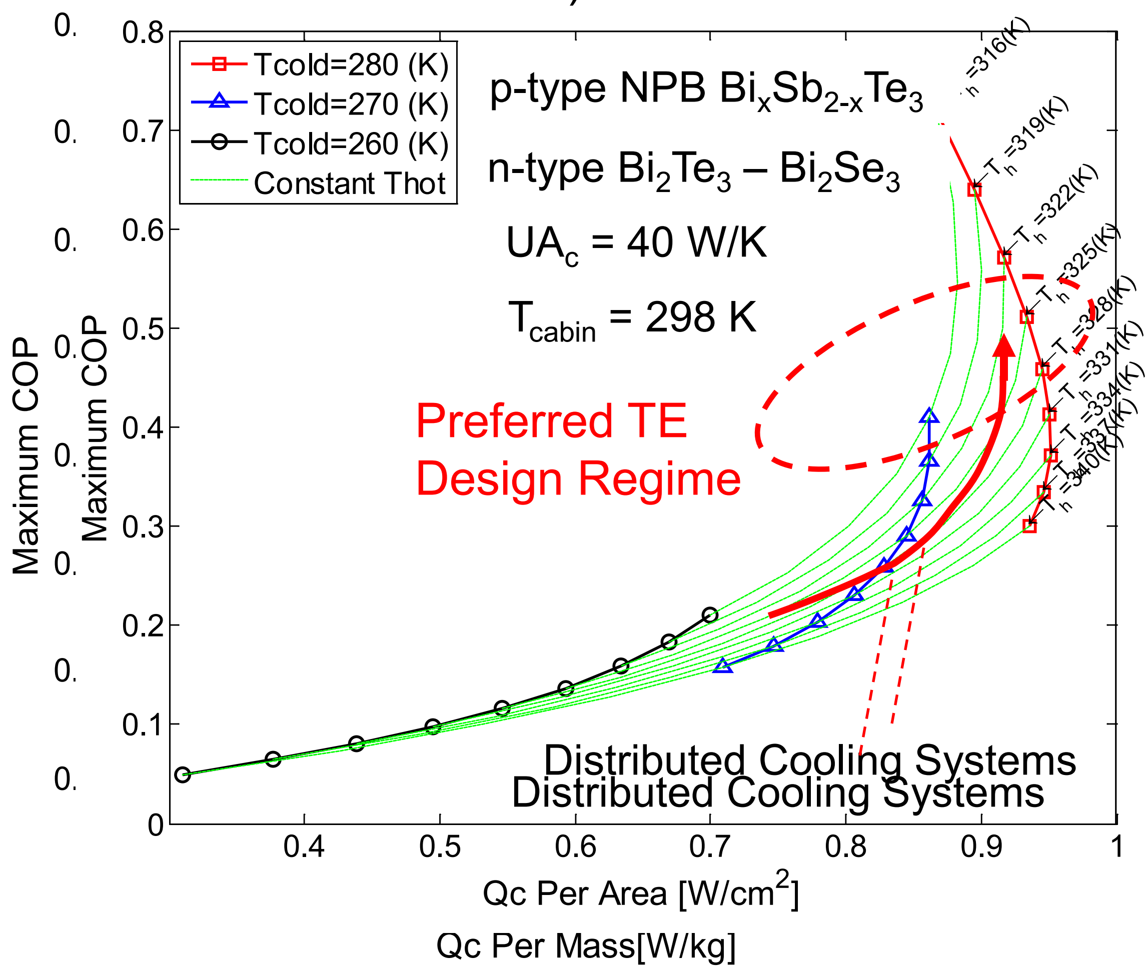
- Typical COP – Cooling Capacity – Power / Mass Relationship Shown
- Distributed TE Cooling Systems
  - Create Lower Heat Flows per Unit
  - Higher COP's
  - Lower Power / Mass
- Generally Right Directions for Automotive Distributed Cooling



* Poudel, B., Hao, Q.H., Ma, Y., Lan, Y., Minnich, A. Yu, B., Yan, X., Wang, D., Muto, A., Vashaee, D., Chen, X., Liu, J., Dresselhaus, M.S., Chen, G., Ren, Z., 2008, "High-Thermoelectric Performance of Nanostructured Bismuth Antimony Telluride Bulk Alloys," *Sciencexpress*, 10.1126, science.1156446.

TE Cooling
Heat Exchanger / TE Device Integration Requirements

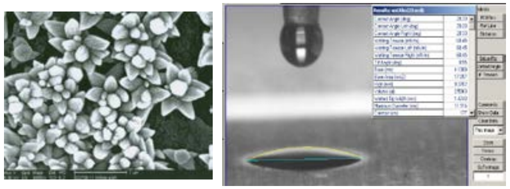
- Distributed TE Cooling Systems Generally Move Into Regions of:
  - Higher COP's
  - Higher Specific Cooling Capacity (Compact, Lightweight Systems)
  - Higher Heat Fluxes (Higher Heat Transfer Coefficients)
- Generally Higher Performance Heat Exchanger Systems Required



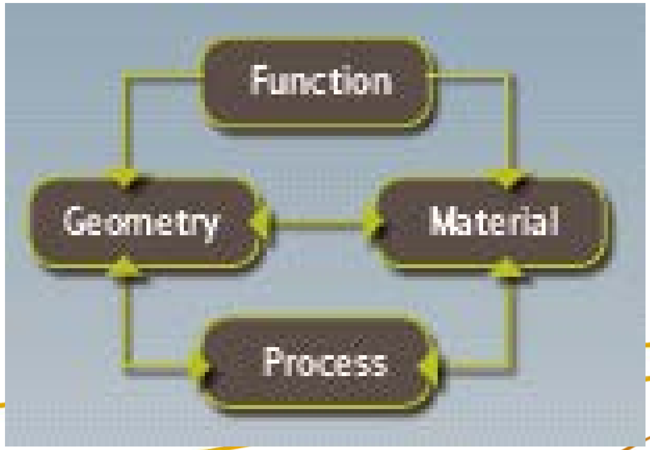
MicroTechnology in Distributed TE HVAC Systems

- DOE Project in Advanced TE HVAC Systems for Automobiles
  - Zonal Climate Control for Thermal Comfort
  - Compact Microtechnology Heat Exchangers
    - Reduce Weight & Volume
    - Low Cost Manufacturing
  - Coupled with Compact TE HVAC Systems
  - Wicking Systems for Water Management
    - Leveraging Nano-Scale Coating Technology
  - Significant Microtechnology Cost Modeling
    - Cost Sensitivities Identified
    - Low-Cost Manufacturing Avenues Being Developed
    - Sensitivities to Production Volumes
    - Material and Process Cost Drivers

Hybrid / PHEV Vehicles



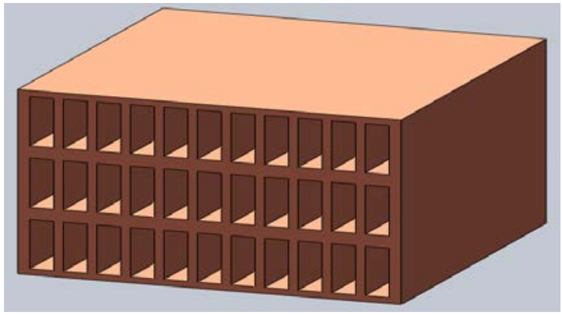
Nano-Scale Coatings

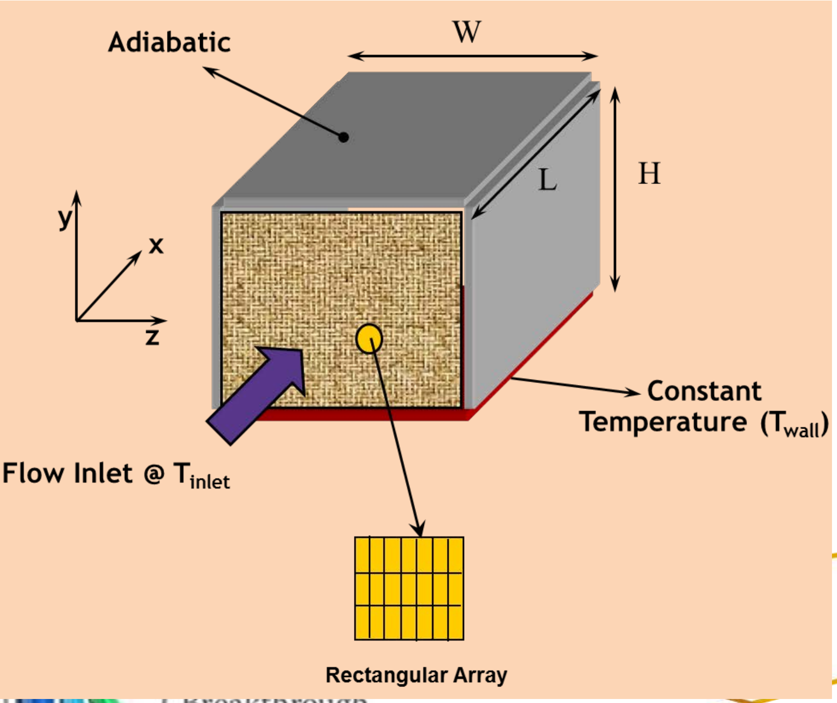


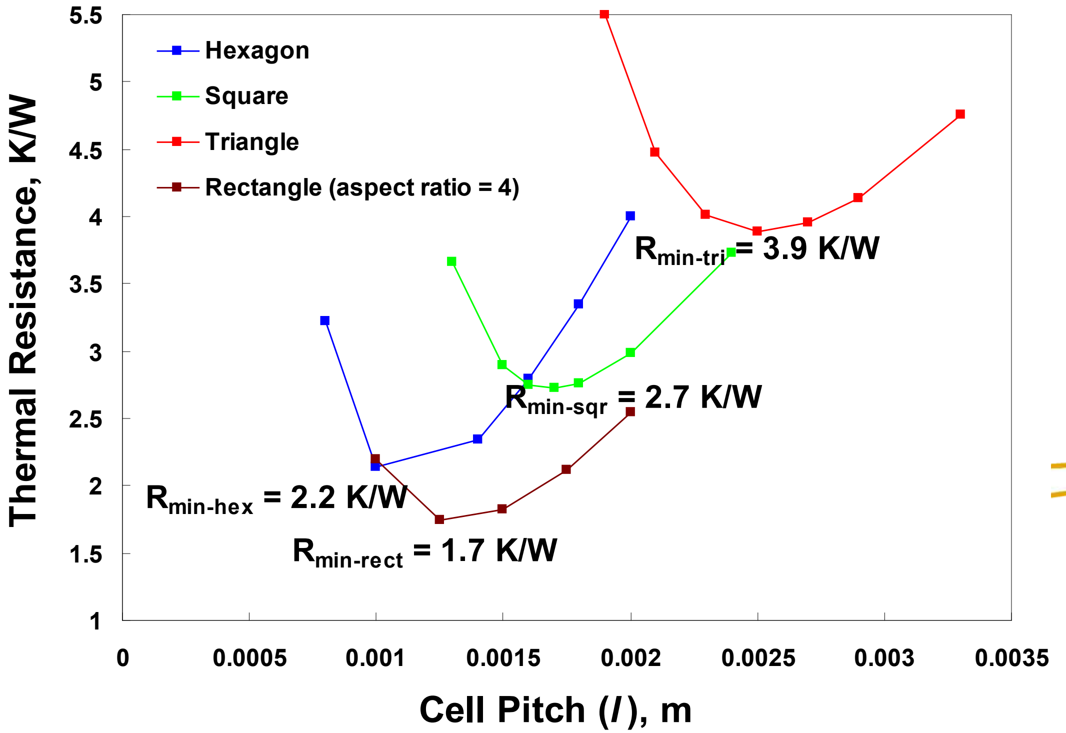
Cost Modeling Approach

PNNL Developing High-Performance Microtechnology Heat Transfer Technologies

- TE Cooling / Heating
  - Automotive Distributed HVAC Systems
  - A Number of Microtechnology Designs Are Being Investigated
  - An Example of One Such Design Is Presented Here
- Established geometry, heat transfer and pressure drop characteristics
- Semi-empirical modeling & COMSOL Modeling







Process Based Cost Modeling

Bottom-Up Approach to Estimating Cost of Goods Sold (COGS)
Based on Operation of Virtual Manufacturing Line – Breaks Down Cost by Unit Process

Model Inputs

Process Flow

Unit Process 1
Unit Process 2
Unit Process 3
Etc.

Cost Elements

Capital Equipment
Labor
Materials
Energy
Facilities
Maintenance

Process-Based Cost Model Algorithm

Not Included
Overhead & Profit
Insurance
Taxes
Inventory Management
Accounting
Marketing
Sales

Model Outputs

Cost of Goods Sold (COGS)

Fixed Costs
Capital Equipment
Maintenance
Facilities/Buildings

Variable Costs
Direct Labor
Direct Materials
Indirect Materials
Utilities

Process COGS vs. Volume and Pareto
Cost Sensitivity
ID Cost Drivers
Process to Process Comparisons
Define Fabrication Toolbox
Inform R&D Agenda

Start with Process Flow and Associated Equipment Set

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Contact: Steven.Leith@pnl.gov

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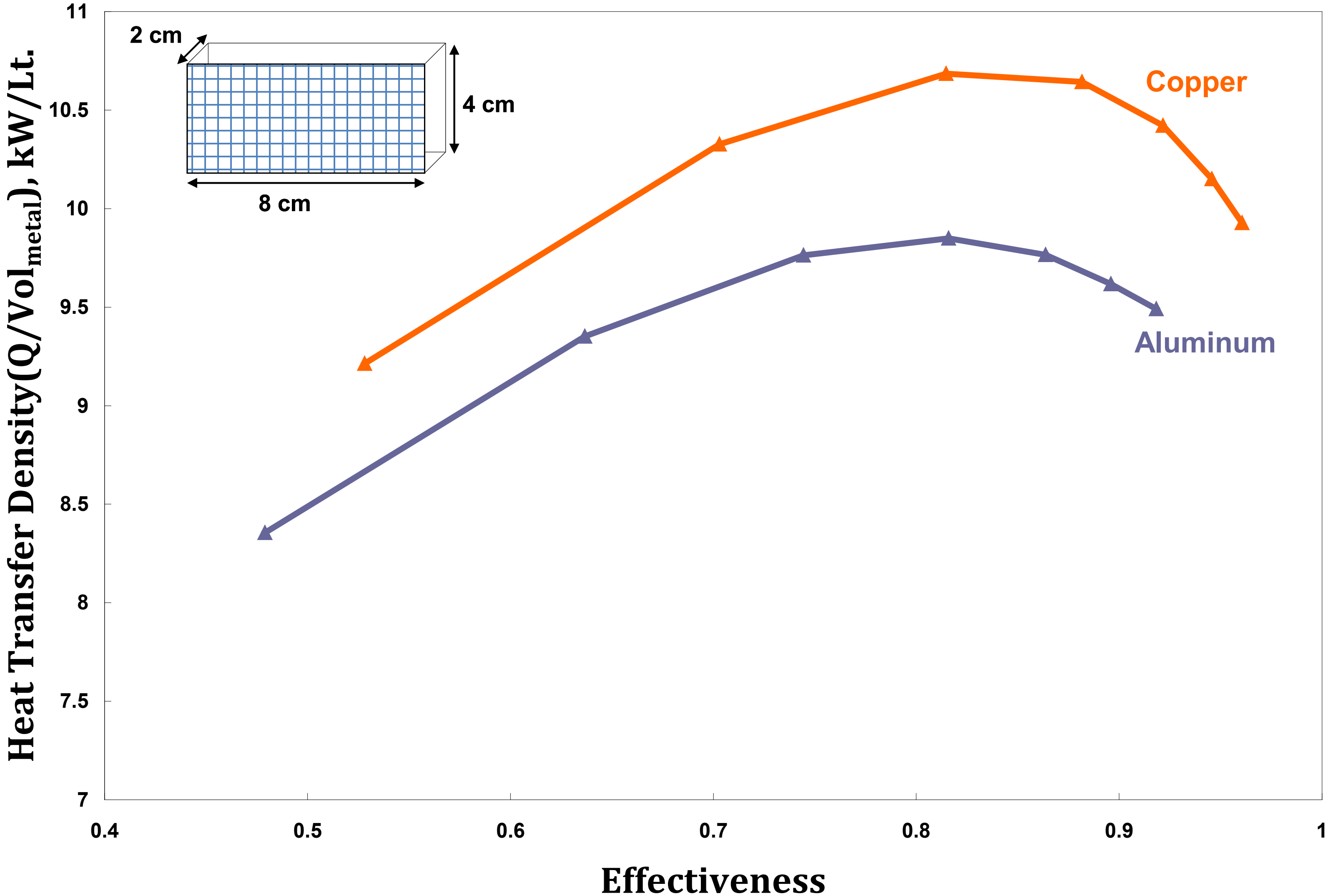
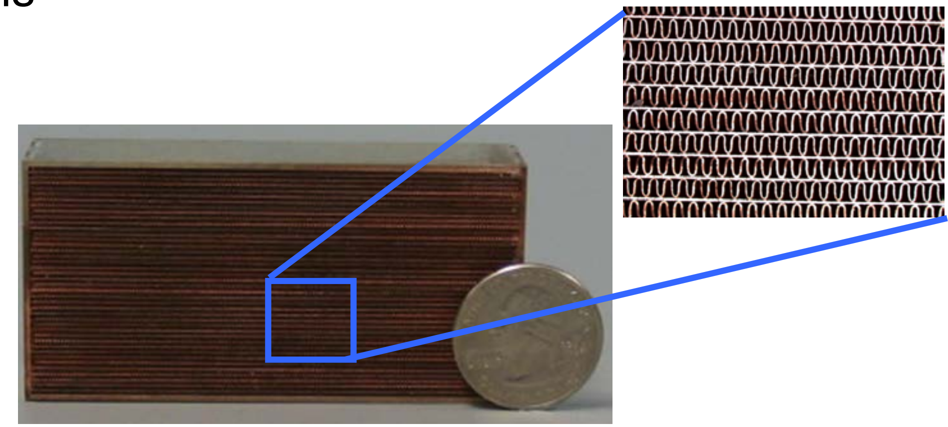
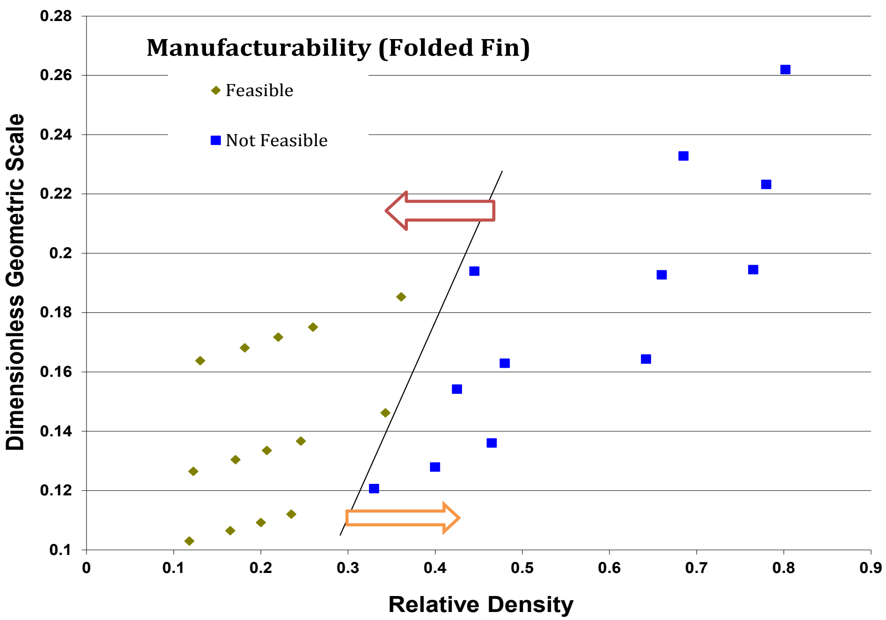
Effect of Channel Aspect Ratio on Flux Density

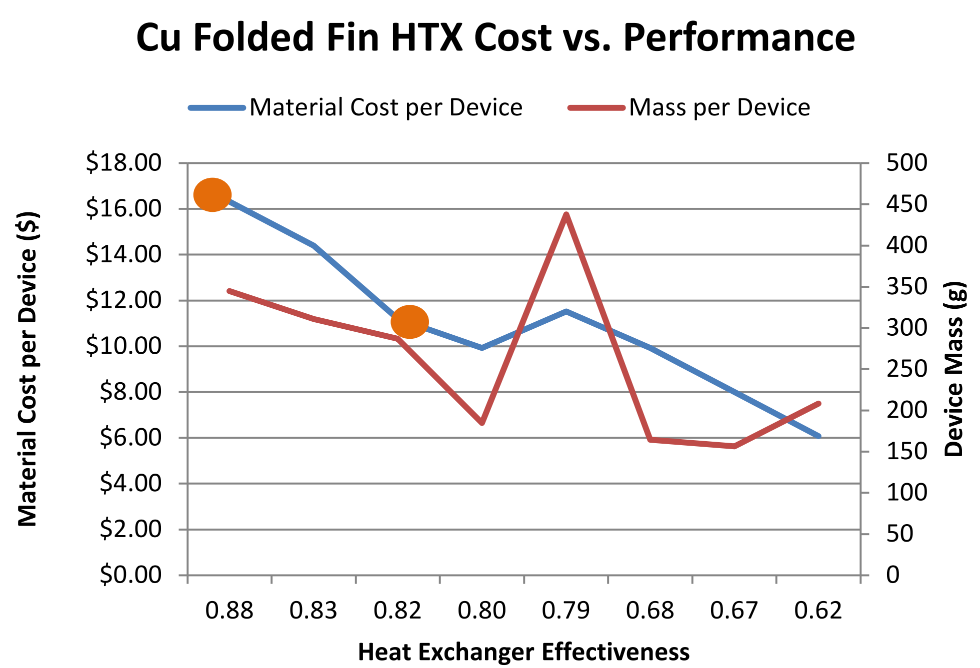


Cost Vs Performance

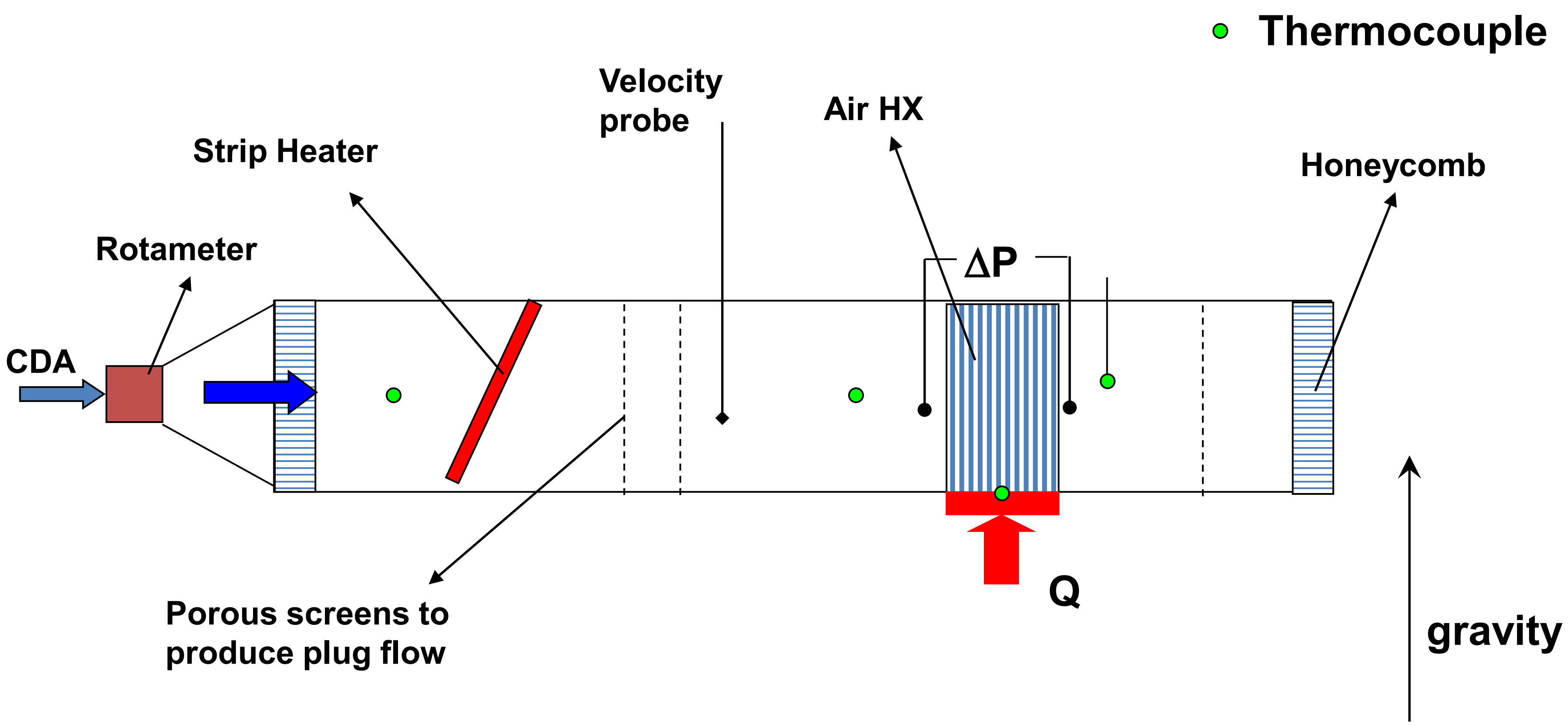
- Layered Rectangular Honeycomb Designs
- Fine Pitch Design (#1)
  - Higher Fin Density
  - Higher Performance ($\varepsilon = 0.88$)
  - Somewhat Higher Cost
- Coarse Pitch Design (#2)
  - Lower Fin Density
  - Slightly Lower Performance ($\varepsilon = 0.81$)
  - Lower Cost
- Manufacturability, Process and Cost Drivers Identified



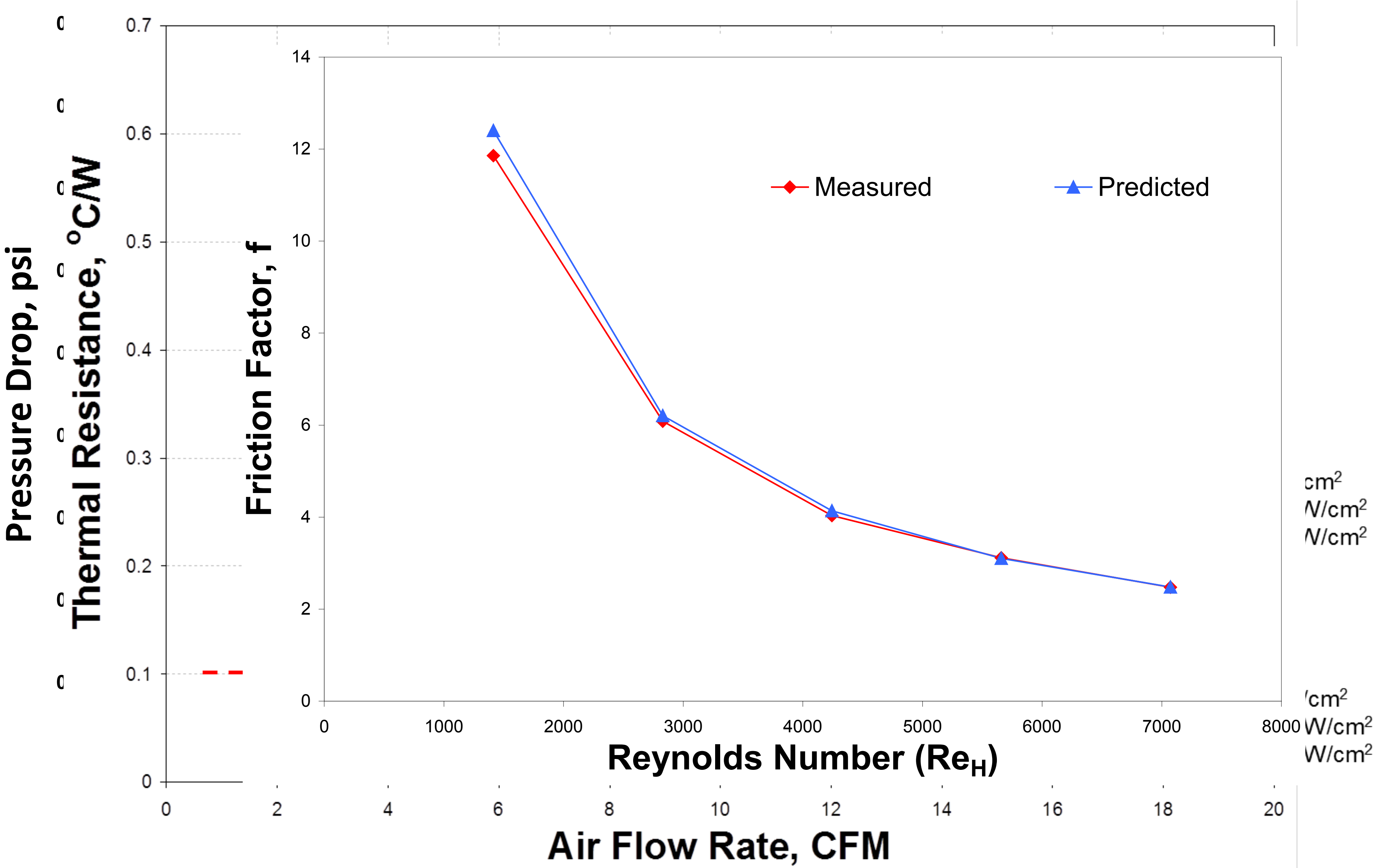




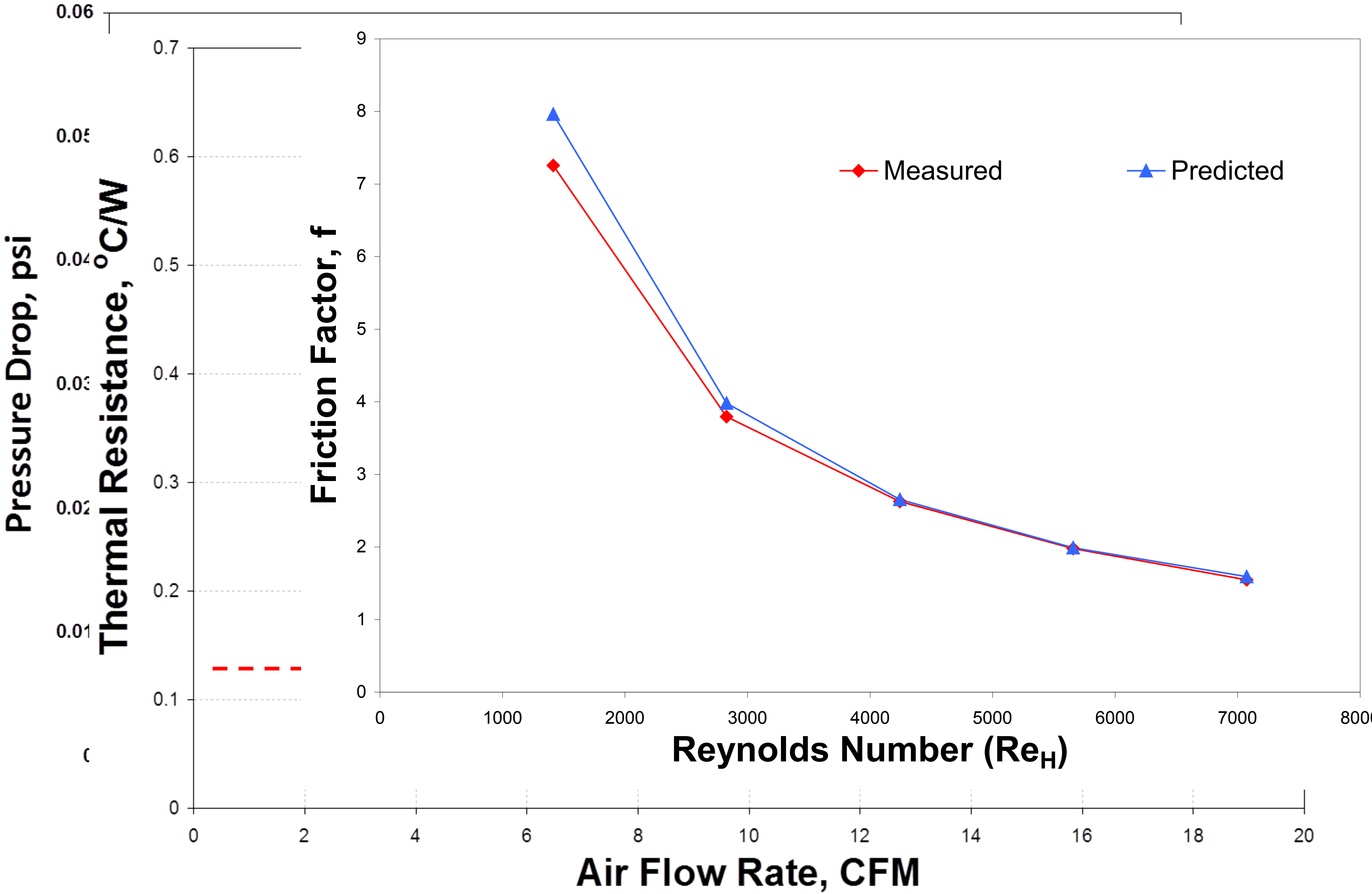
Air-Side Heat Transfer Experiments



Design #1: Fine Pitch – Tested Performance & Correlation with Models



Design #2: Coarse Pitch – Tested Performance & Correlations with Models



Cost Comparison

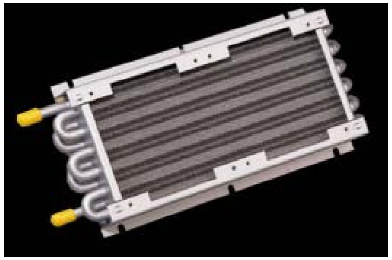
Metrics	Design #1	Design #2
$/effectiveness	$18.55	$13.66
$/W	$0.055	$0.041
$/kg	$47.32	$39.05

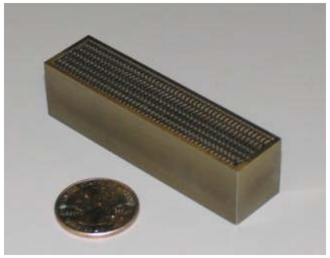
Observations & Findings

- Accounted for braze thickness and separator plate thickness based on variation in heat exchanger stack height
- Measured thermal resistance came out to be higher than predicted thermal resistance
- Friction factor & pressure drop correlated well with fluid dynamic models
- Model thermal predictions may be conservative (lower performance bound). Higher performance bound will be ~ 3% lower than the predicted thermal resistance
- Discrepancy between thermal model and measurements could be due to
  - Geometric variation in the built device
  - Delaminated layers in heat exchangers
  - Measurement errors
  - Modeling assumptions compared to actual fabricated devices

Summary

- Microtechnology Thermal Systems Required to Enable Compact, Light-weight TE Systems
  - TE Power Generation – Energy Recovery and Portable Power Applications
  - TE Cooling / Heating – Distributed Automotive Applications
- Microtechnology Thermal Systems Successfully Integrating into TE Systems





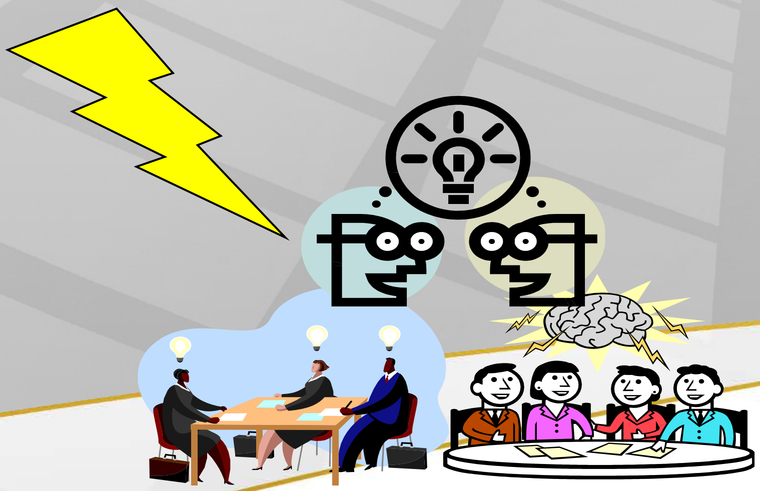
- Process-Based Cost Modeling Has Identified High- and Low-Cost Manufacturing Pathways, Processes, and Materials
  - High-Cost Designs Differentiated from Low-Cost Designs
  - Performance vs. Cost Clearly Delineated
- System Performance Modeling Integrated with Process-Based Cost Modeling
  - Powerful Combination Identifies Low-Cost, Manufacturable Microtechnology Designs
- Prioritizes R&D Investment Plans & Enables Business Decisions

Thank you for your time and interest

We are What We Repeatedly do. Excellence, Then, is not an Act, But a Habit.

Aristotle

Questions & Discussion



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ADDITIONAL BACKUP TOPICS

System Analysis Capabilities & Characteristics

- System-Level Couples Design Analysis of:
  - Hot Side Heat Exchanger Performance
  - TE Device Performance
  - Cold Side Heat Exchanger Performance
- Single or Segmented TE Material Legs
- Accounts for Hot/Cold Thermal Resistances
- Accounts for Electrical Contact Resistances
- Optimum Heat Exchanger / TE Design Parameters Determined Simultaneously
- Maximum Efficiency or COP & Maximum Power or Cooling Capacity Designs Are Possible
- Off-Nominal & Variable Condition Performance Analysis