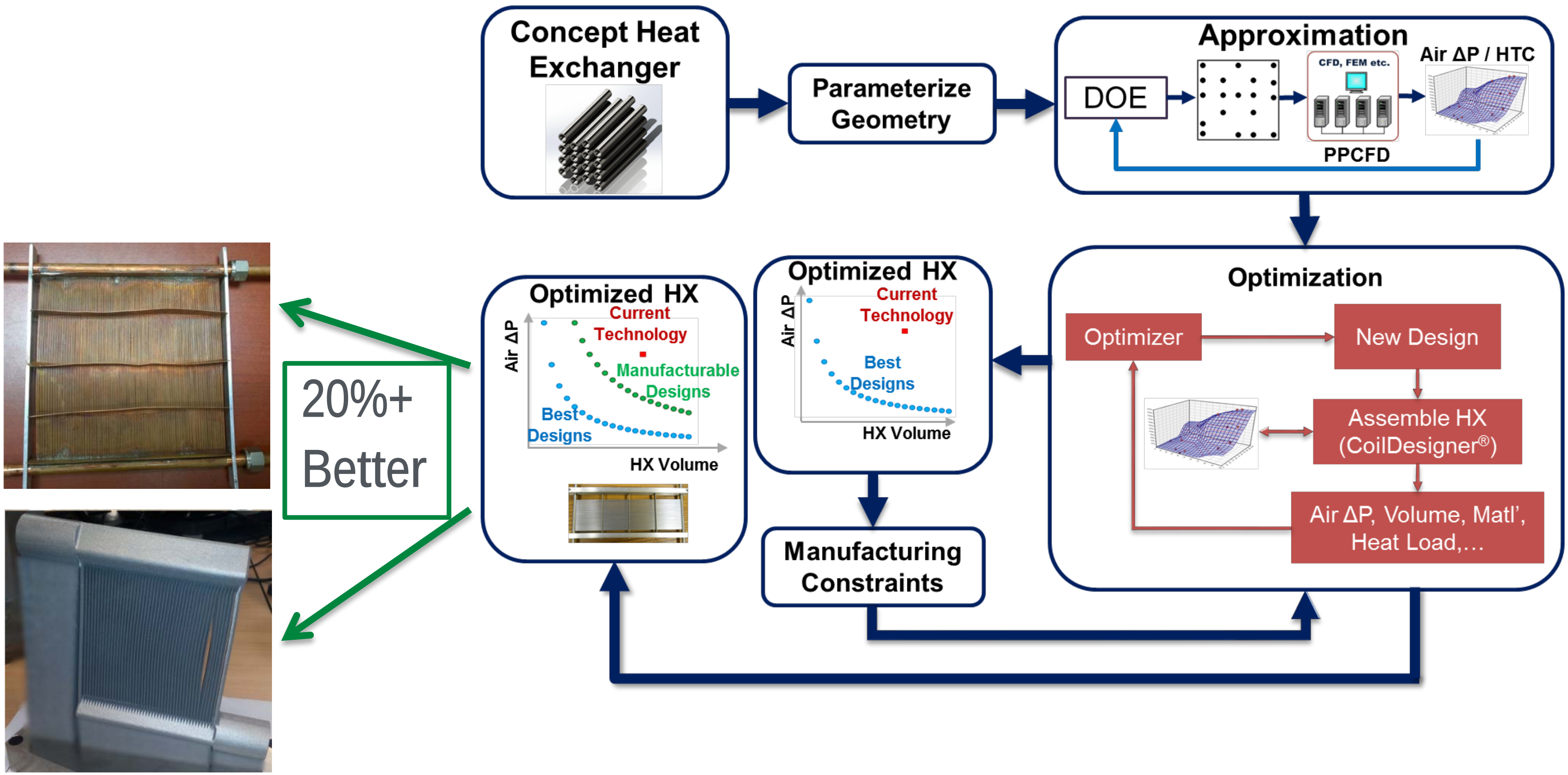
Miniaturized Air-to-Refrigerant Heat Exchangers

2016 Building Technologies Office Peer Review



U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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University of Maryland College Park

Project Summary

Timeline:

Start date: 3/1/2013

Original end date: 2/29/2016

Revised end date: 10/30/2016

Key Milestones

1. Design optimization, 3/30/14
2. Fabrication/testing, 1kW prototype, 6/30/2015
3. Fabrication/testing, 10kW prototype, 1/30/2016

Budget:

Total Budget: $1500K

Total UMD: $1050K

Total DOE $ to date for UMD: $1050K

Target Market/Audience:

Residential and commercial heat pump systems with various capacity scales.

Condenser as first choice of application

Key Partners:

Oak Ridge National Laboratory

Burr Oak Tool

Heat Transfer Technologies

International Copper Association

Luvata

Wieland

Project Goal:

Purpose: Develop next generation heat exchangers for heat pumps and air-conditioners

Target Performance: Miniaturized air-to-refrigerant heat exchangers with at least

- 20% lower volume
- 20% less material
- 20% higher performance

Target Market: To be in production within five years

Purpose and Objectives

Problem Statement: Develop miniaturized air-to-refrigerant heat exchangers that are 20% better, in size, weight and performance, than current designs **AND**
In production within 5 Years

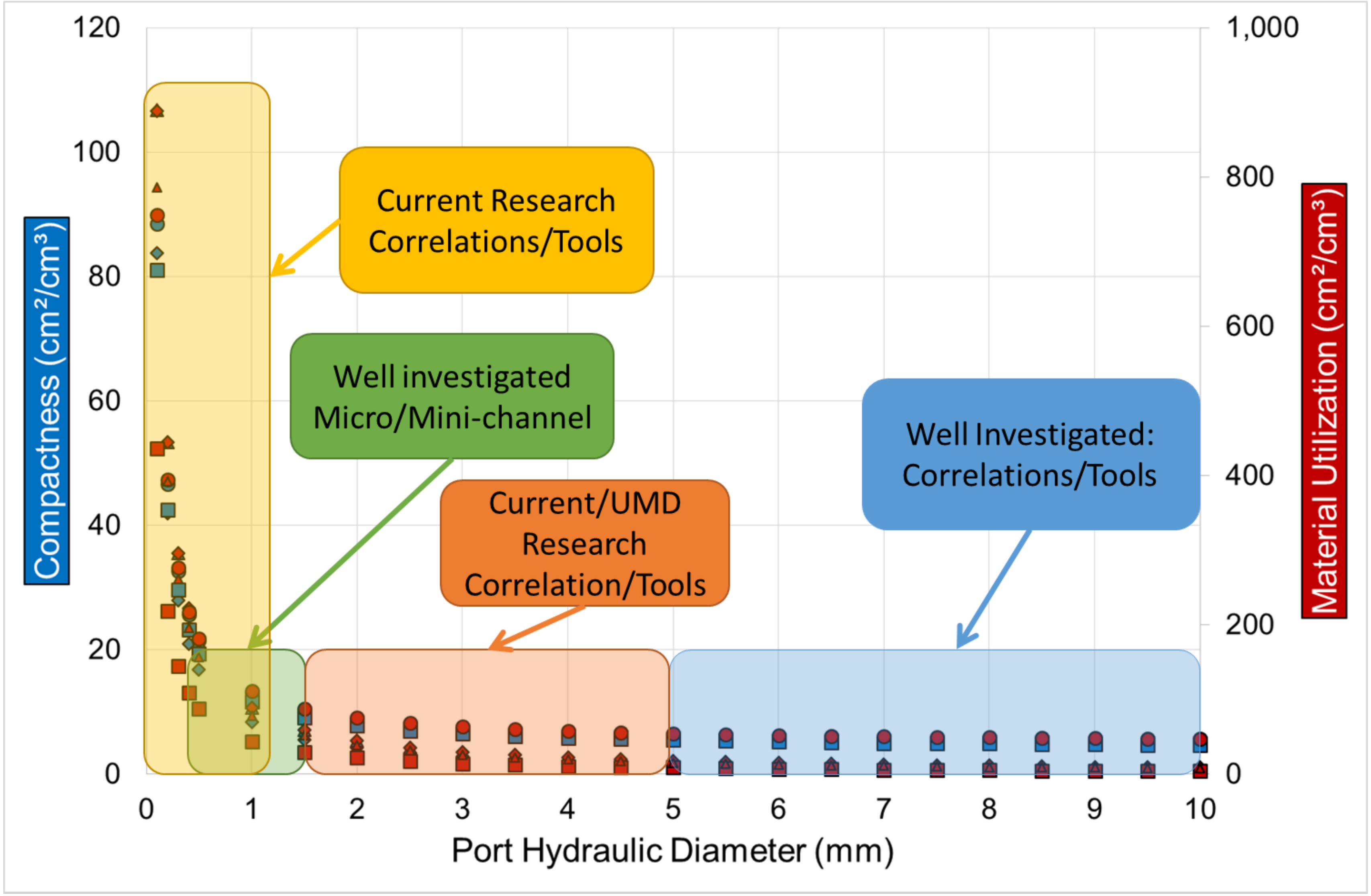
Target Market and Audience:

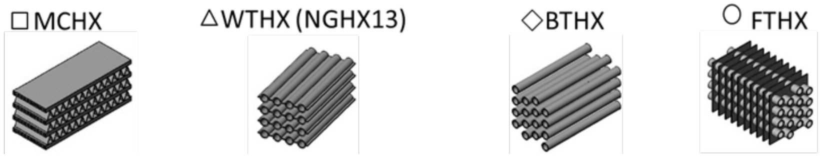
- Residential and commercial heat pumps and air-conditioners
- US Shipment of residential air-source equipment in 2011: 5.5 Million units
- US EIA 2009 Energy Consumption: 41.5% for space heating, 6.2% for AC
- Proposed heat exchanger technology will readily compete with current condenser designs for AC systems (3.7 M).

Impact of Project:

- Project deliverables include analyses tools and heat transfer correlations
- Heat exchangers (1 kW and 10 kW) that are at-least 20% better (size, weight and performance) than current designs, based on measured performance; a minimum of 3 prototypes to be fabricated and tested
- Manufacturing guidelines to facilitate production within 5 years

Future of Heat Exchangers





Approach

- Developed a comprehensive multi-scale modeling and optimization approach for design optimization of novel heat exchangers
  - Parallel Parameterized CFD
  - Approximation Assisted Optimization
- Build a test facility for air side performance measurement of heat exchangers
- Design, optimize and test 1 kW and 10 kW air-to-water and air-to-refrigerant heat exchangers
- Investigate conventional and additive manufacturing techniques
- Analyze and test system level performance of novel heat exchangers
  - Evaporator and condenser of a system based on same design

Approach : Key Issues

- Lack of basic heat transfer and fluid flow data for design and analyses of air-to-refrigerant heat exchangers with small flow channels
- Availability for small diameter tubes and manufacturing quality control
- Joining/manufacturing challenges
- Face area constraints
- Fouling and flow mal-distribution
- Wetting
- Noise and vibrations

Approach: Distinctive Characteristics

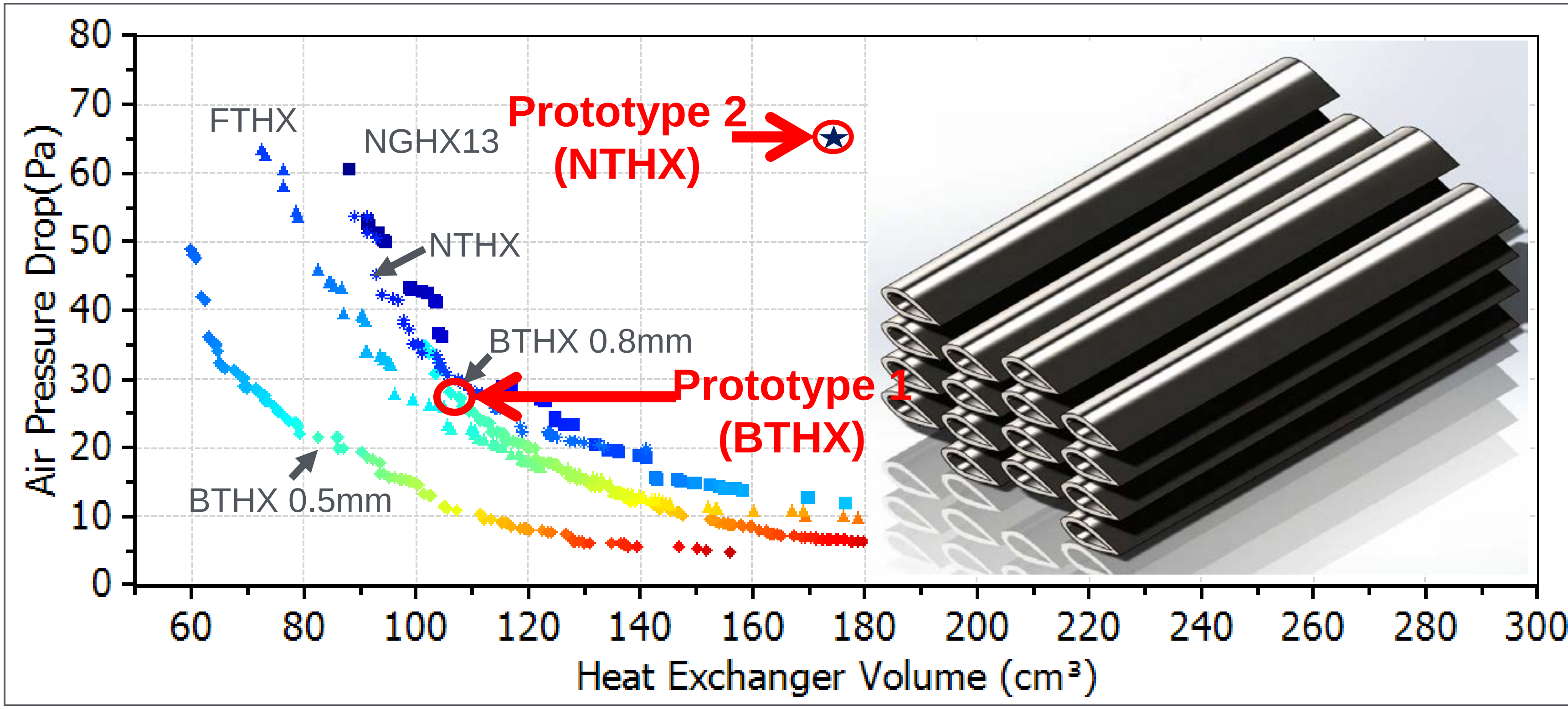
- Developed a comprehensive multi-scale modeling and optimization approach for design optimization of novel heat exchangers
  - Allows for rapid and automated CFD evaluation of geometries with shape and topology change
  - More than 90% reduction in engineering and computation time
- Focus on small hydraulic diameter flow channels
  - Bridging the research gaps
  - Heat transfer, pressure drop correlations and design tools
- Prototype fabrication and testing is in progress, with target production within 5 years
  - Initial tests show, <10% deviation compared to predicted values
- 20% size and weight reduction
  - Retrofit applications, limited load carrying capacity of roofs
  - Potential savings in logistics costs

Progress and Accomplishments

- Analyzed 15+ heat exchanger geometries
- Developed a new methodology for optimizing tube shapes – no longer constrained by circular/rectangular tubes
- Fabricated and tested three 1kW prototypes
  - Measured data for dry tests agree within 10% of predicted performance for heat transfer and 20% for pressure drop
  - Wet tests show significant pressure drop penalty
- Fabricated and tested one 10kW radiator
  - Challenges with tube blockage
- Work in progress
  - Fabrication of 3TR evaporator and condenser
  - System-test facility is developed, equipment donated by sponsors of UMD-CEEE Consortium

Accomplishments

Fixed flow rates; ΔT=50K(MCHX / NGHX13); ΔT=42K (BTHX / FTHX); ΔT=40K (NTHX)



Finned Microchannel (MCHX)

Web-Tube (NGHX13)

Round Bare Tubes (BTHX)

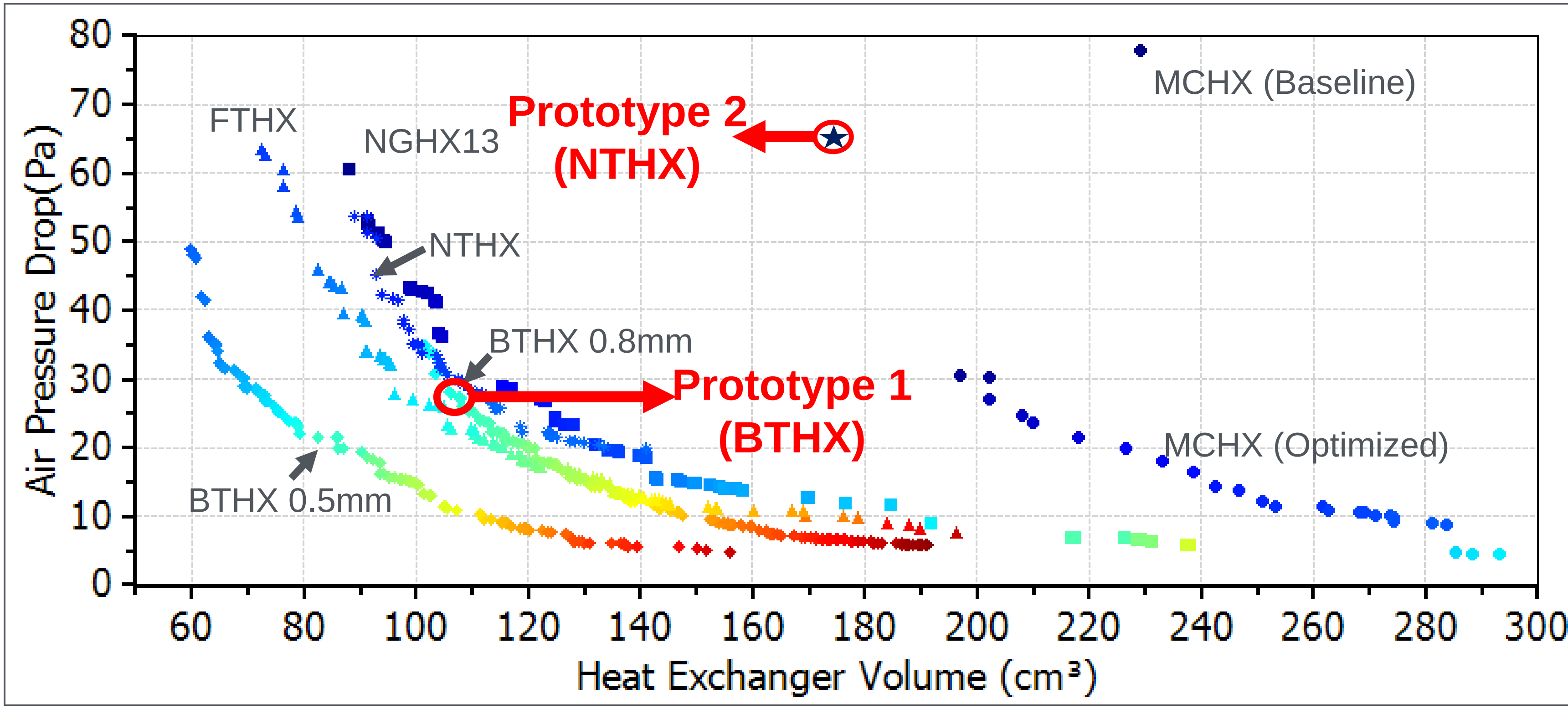
Plain Fin-Tube (FTHX)

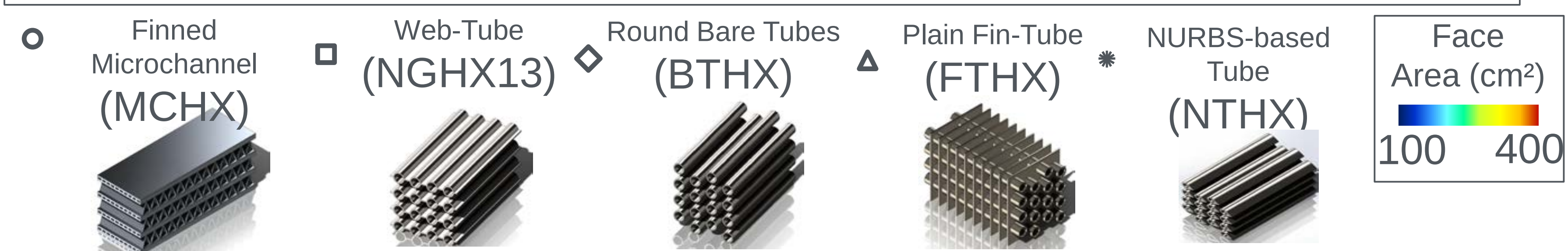
NURBS-based Tube (NTHX)

Face Area (cm²)
100 400

Accomplishments (non-Animated)

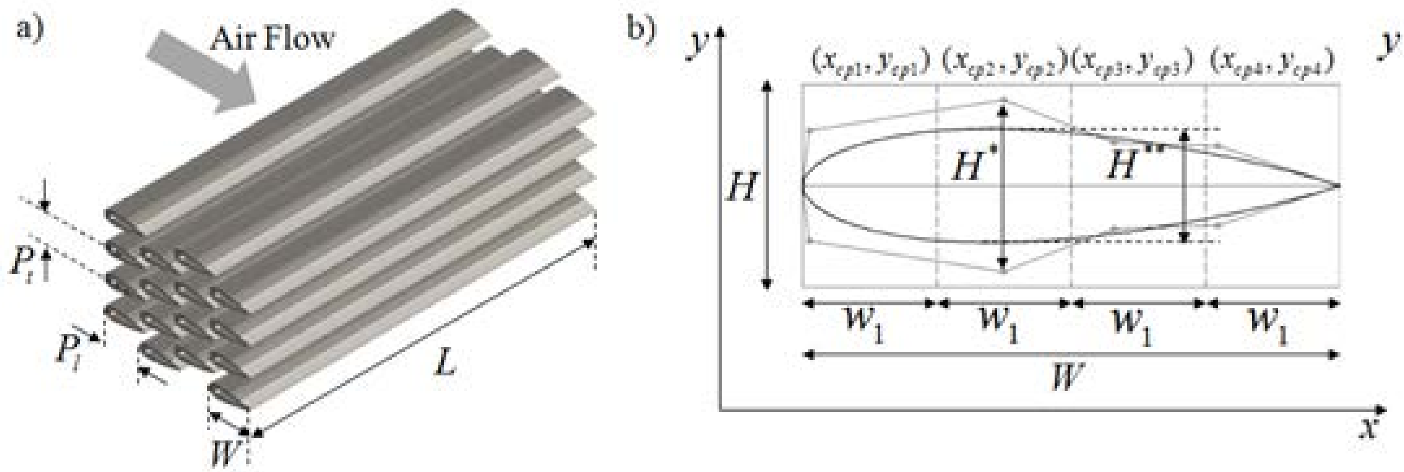
Fixed flow rates; ΔT=50K(MCHX / NGHX13); ΔT=42K (BTHX / FTHX); ΔT=40K (NTHX)

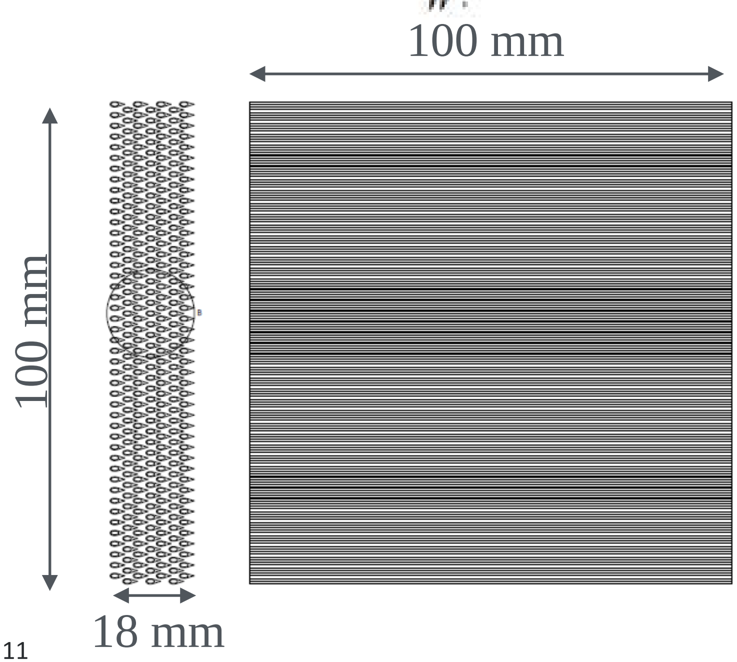


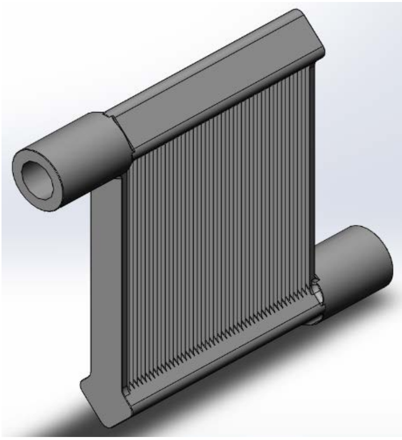


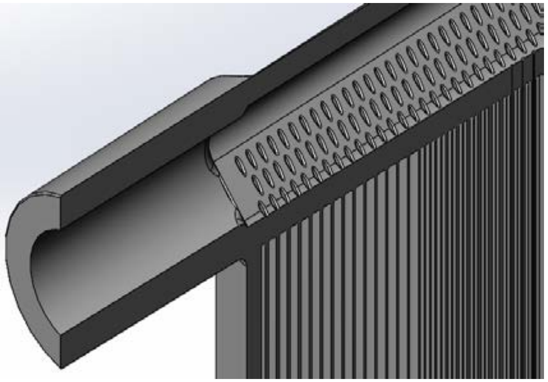
Progress and Accomplishments

- Novel multi-scale approach for tube shape optimization

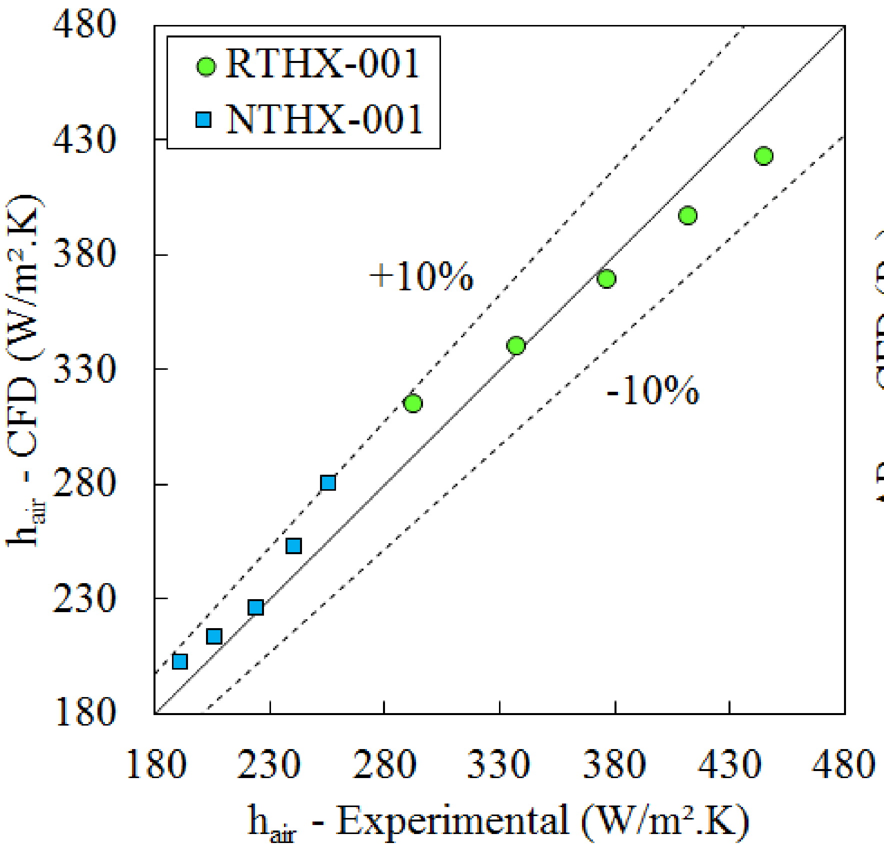


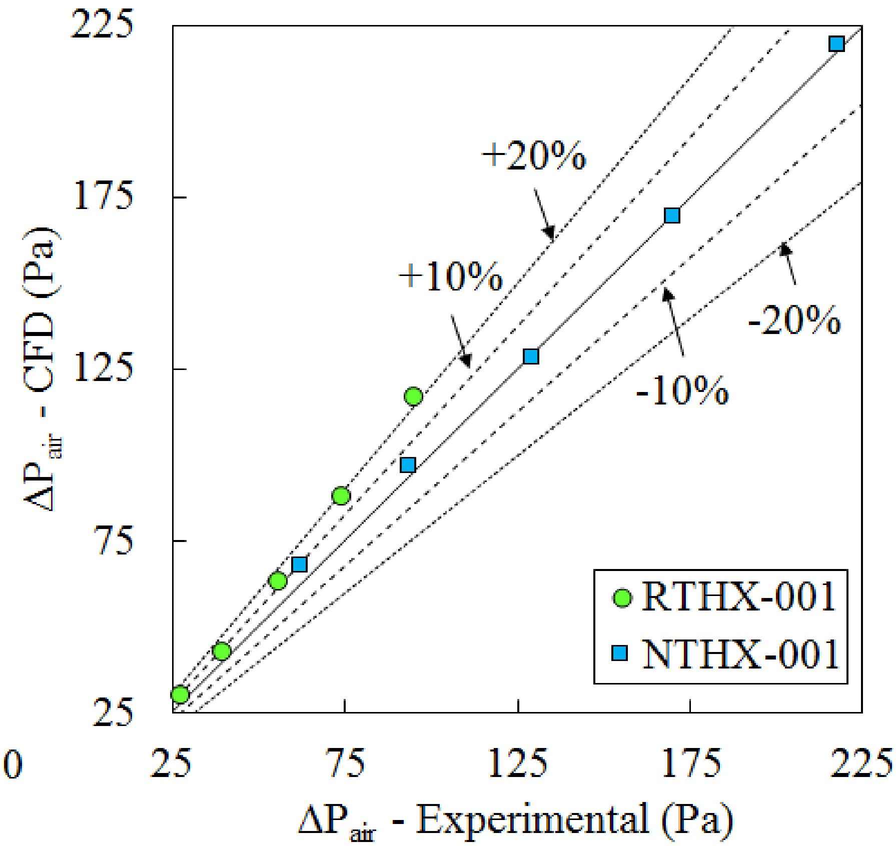






Accomplishments:



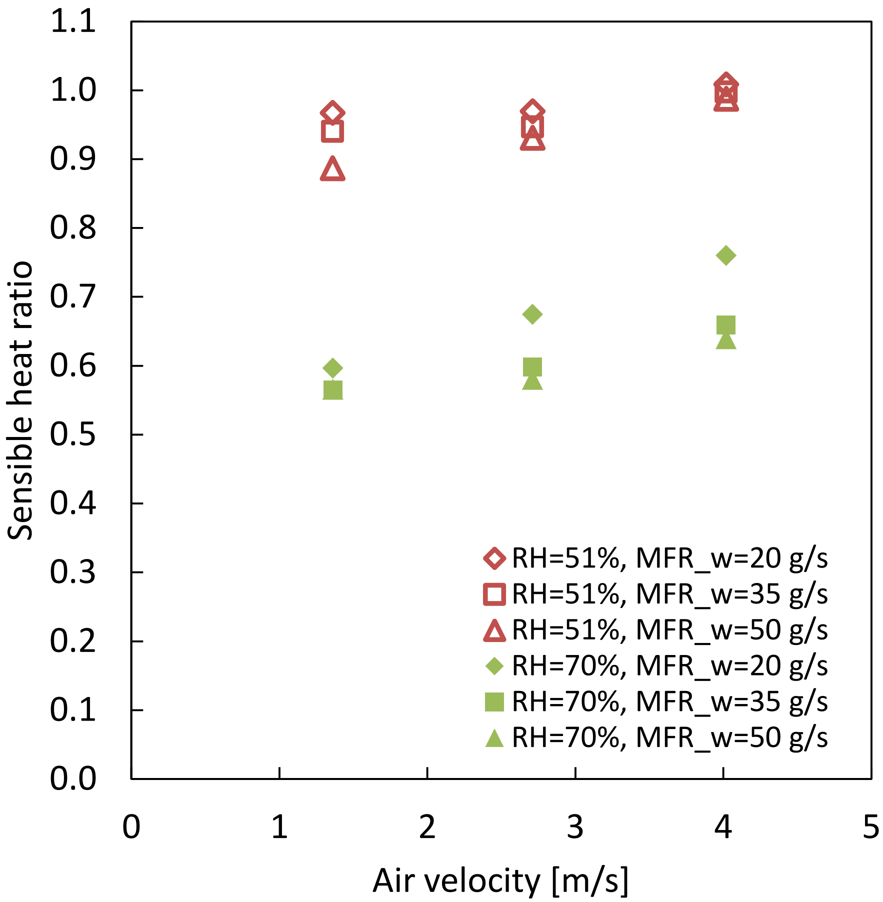


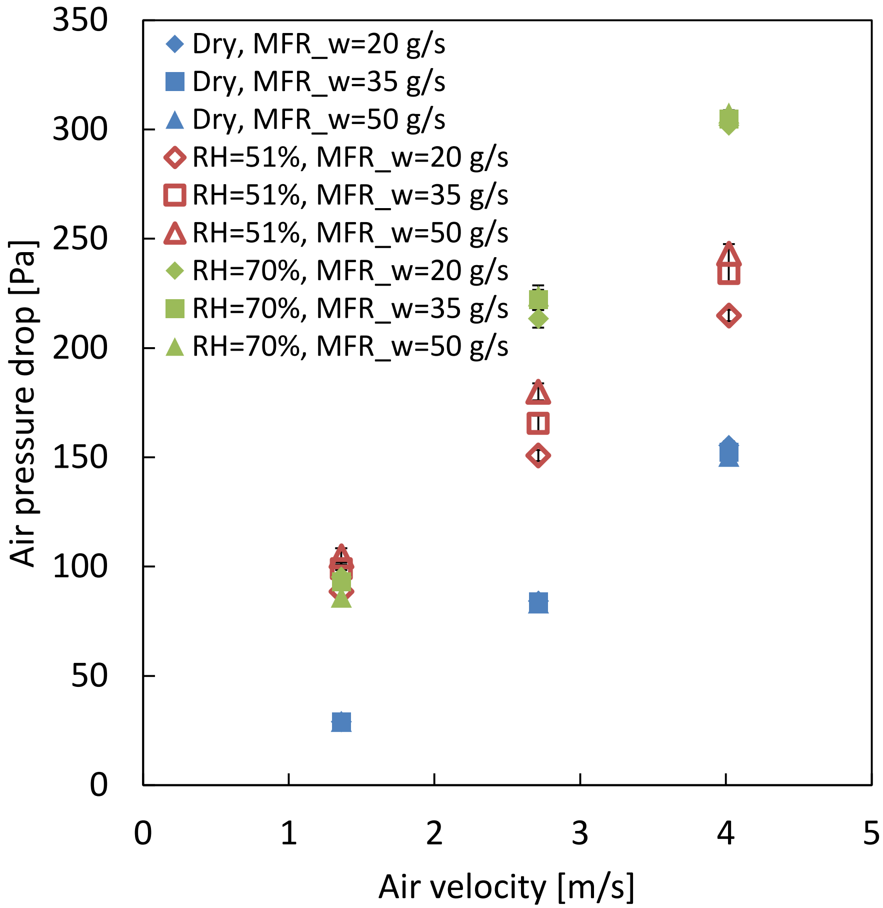
Round Bare Tubes (RTHX)

NURBS-based Tube (NTHX)

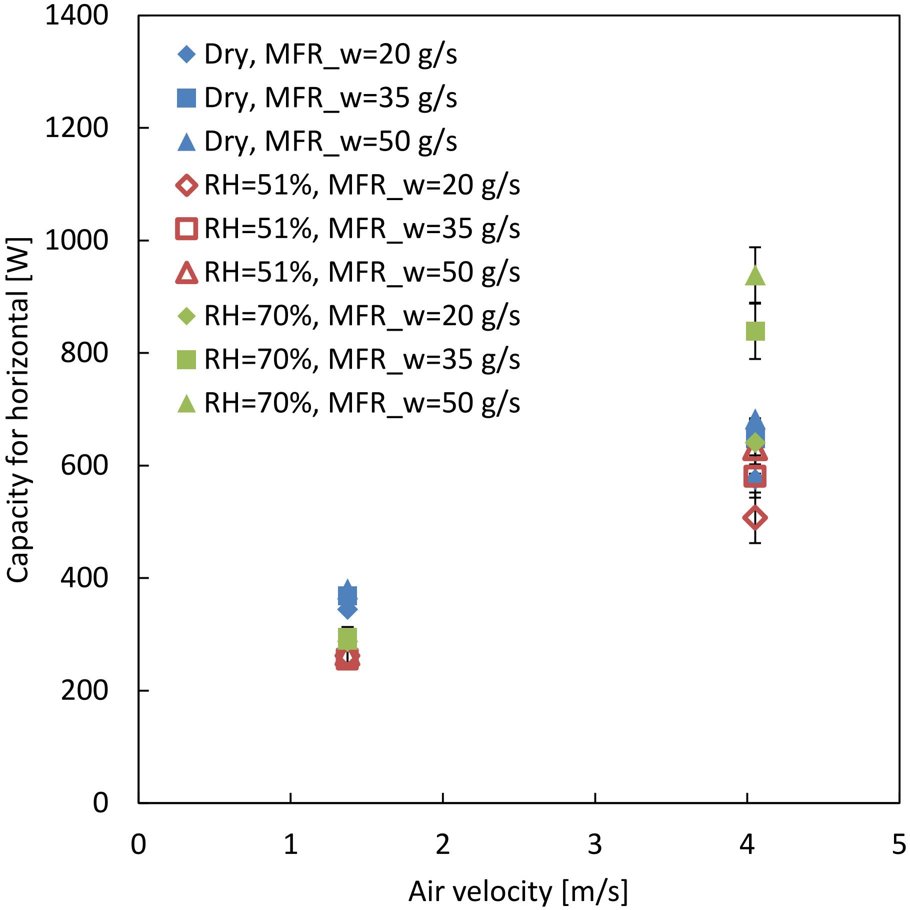
Causes for Deviation:
Air-by pass; Measurement uncertainty; Un-even tube spacing

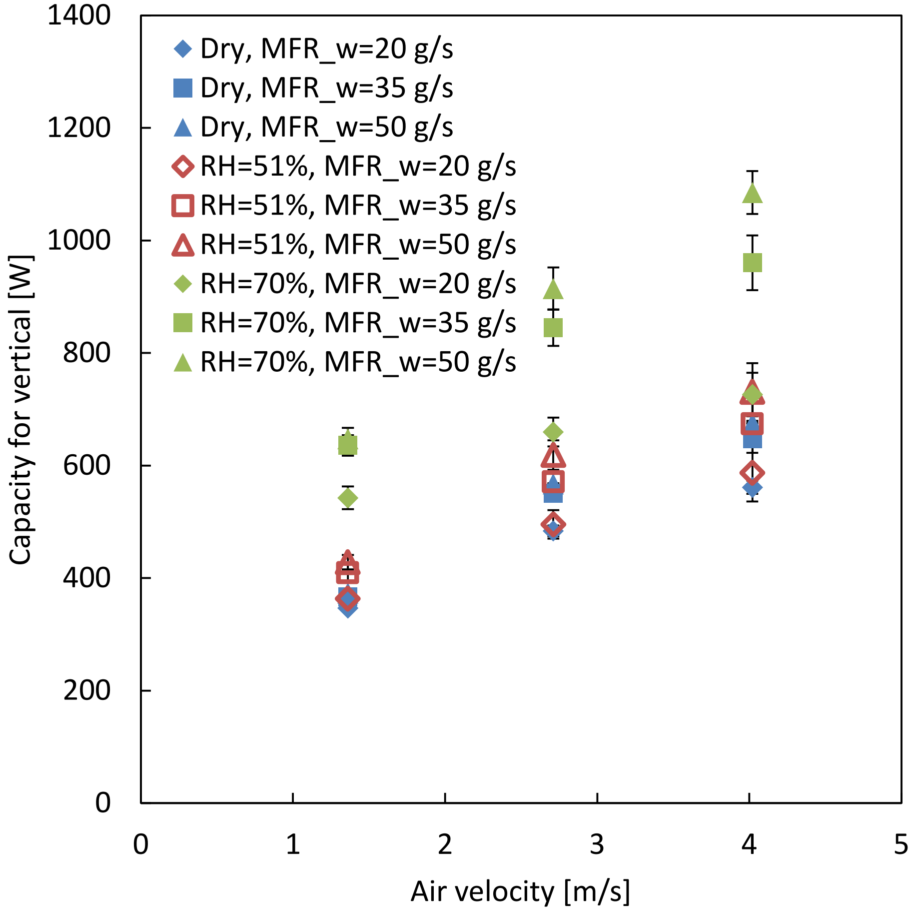
Accomplishments: Wet Tests (Vertical Orientation)



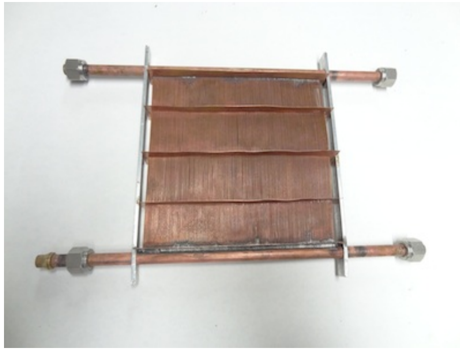


Accomplishments: Wet Tests, Horizontal vs. Vertical



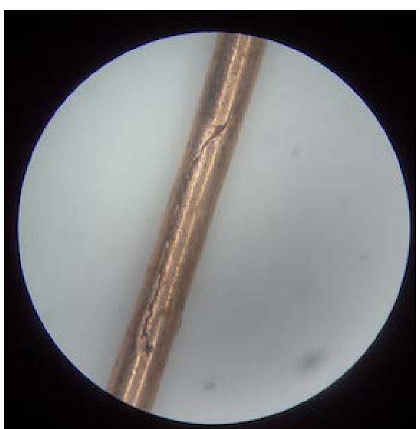


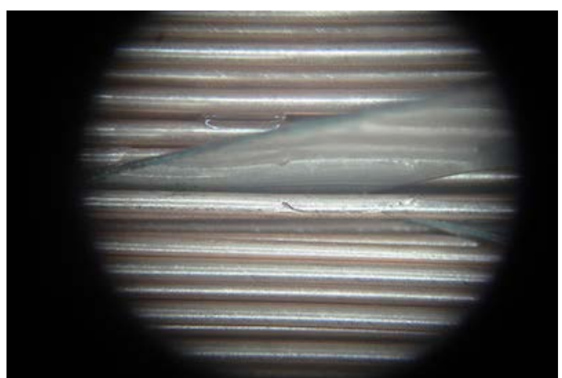
Accomplishments: 10kW Radiator Fabrication



1kW: 484 Tubes, 140mm x 150mm

10kW: 2280 Tubes, 444mm x 580mm





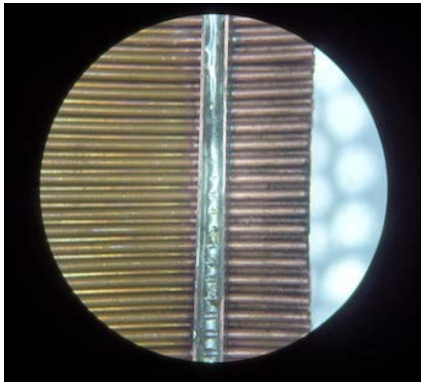
Tube Defects

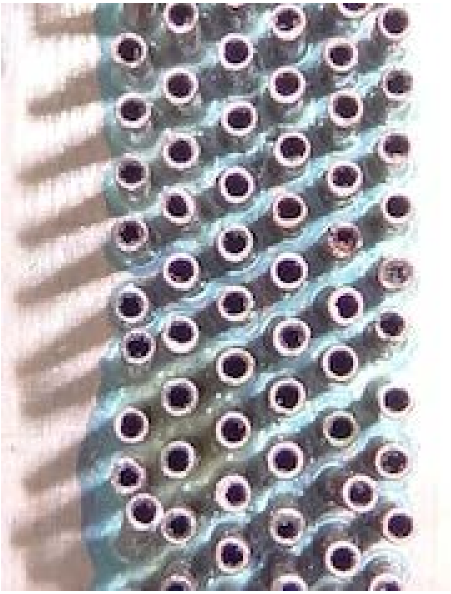
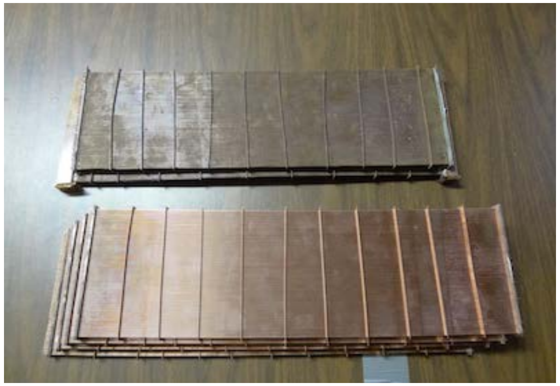
Significant tubes had fractures and leaks

Had to re-order entire batch of tubes from a different vendor

Accomplishments: Process Improvement

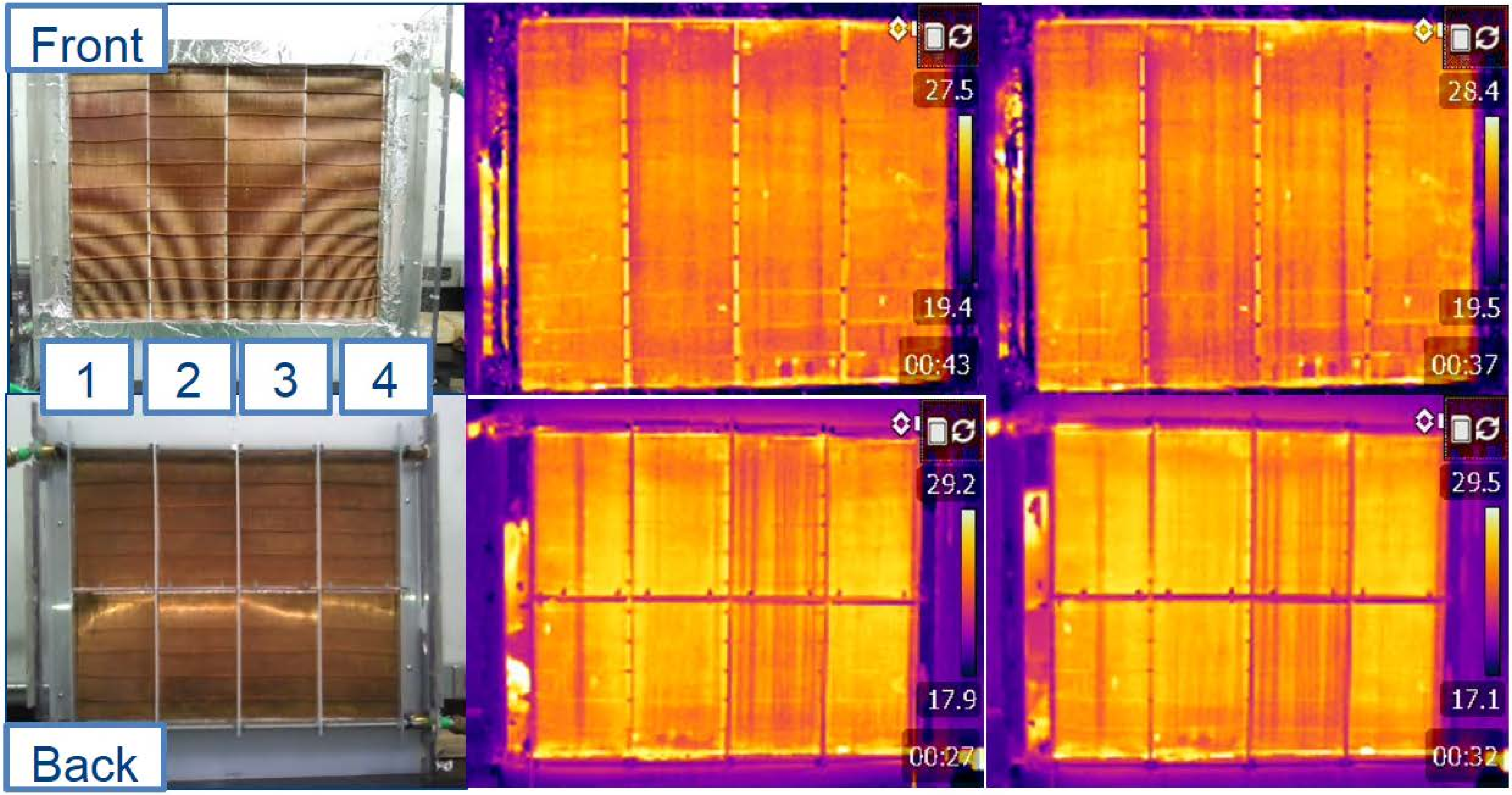
- Separate soldering process improves control and reduces complexity; New method – solder tube to header separately
- Header to manifold soldering without an oven provides cleaner appearance and allows any size HX to be made



Accomplishments: 10kW Radiator Tests

- ~25% tubes blocked in end rows
- Needs further investigation



Lessons Learned from Fabrication and Testing

- Quality control during manufacturing of small diameter tubes is critical
- Heat exchanger core needs to be flushed/cleaned before final manifold soldering; conduct single manifold flow tests
  - Material reactions could also cause blockages
- Uncertainty in latent heat load dominated by the uncertainty in humidity measurement. ASHRAE standard requirements do not guarantee 5% uncertainty for all test conditions
- Under dry conditions, the orientation of heat exchanger has no measurable impact on capacity. Under wet conditions, horizontal orientation has lower capacity than vertical orientation.
- Significant bridging effect of condensate water for bare tube heat exchangers is observed. The pressure drop penalty under wet conditions is much higher than traditional heat exchangers.
  - Need to use coatings.

3TR Evaporator and Condenser Designs

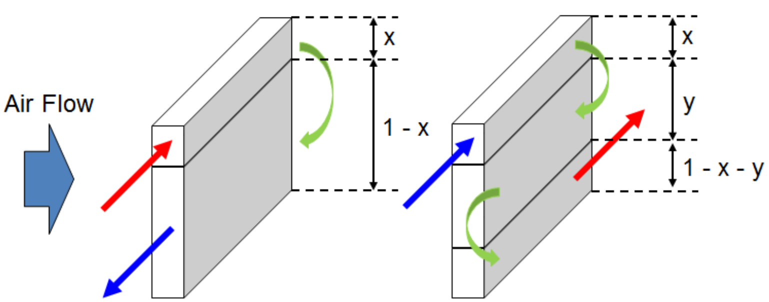
- Geometries: Round bare tubes, inline and staggered
- 3ton heat pump unit

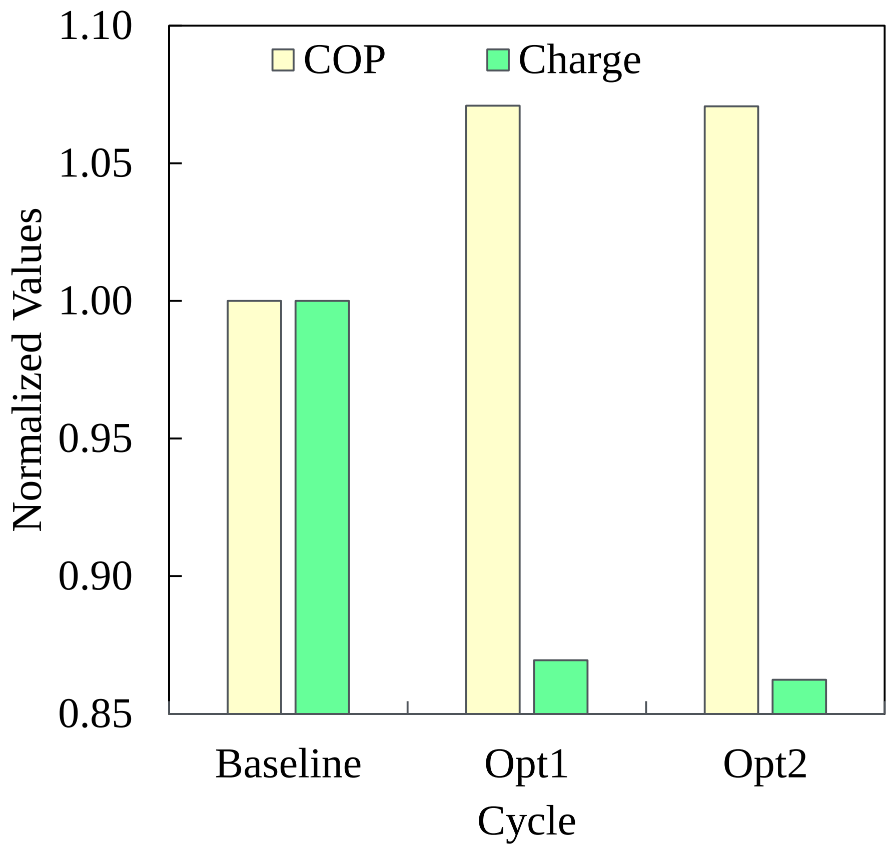
Indoor Unit (Cooling)

$$
\begin{aligned}
&\min\ f_1 = \Delta p_{air} \\
&\min\ f_2 = V_{HX} \\
&s.t. \\
&10.5 \le \dot{Q} \le 11.0kW \\
&\Delta p_{air} \le 0.8 \cdot \Delta p_{air\_baseline} \\
&V_{HX} \le 0.5 \cdot V_{baseline} \\
&0.2 \le AR \le 1.0 \\
&l \le 0.5m
\end{aligned}
$$

Outdoor Unit (Cooling)

$$
\begin{aligned}
&\min\ f_1 = \Delta p_{air} \\
&\min\ f_2 = V_{HX} \\
&s.t. \\
&13.0 \le \dot{Q} \le 13.5kW \\
&\Delta p_{air} \le 0.8 \cdot \Delta p_{air\_baseline} \\
&V_{HX} \le 0.5 \cdot V_{baseline} \\
&u_{air} \le 1.2 \text{ m/s}
\end{aligned}
$$

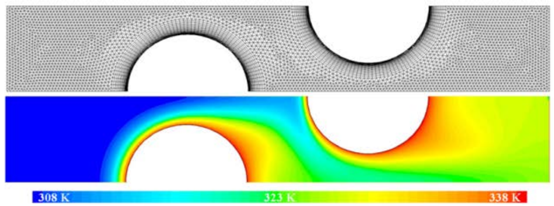


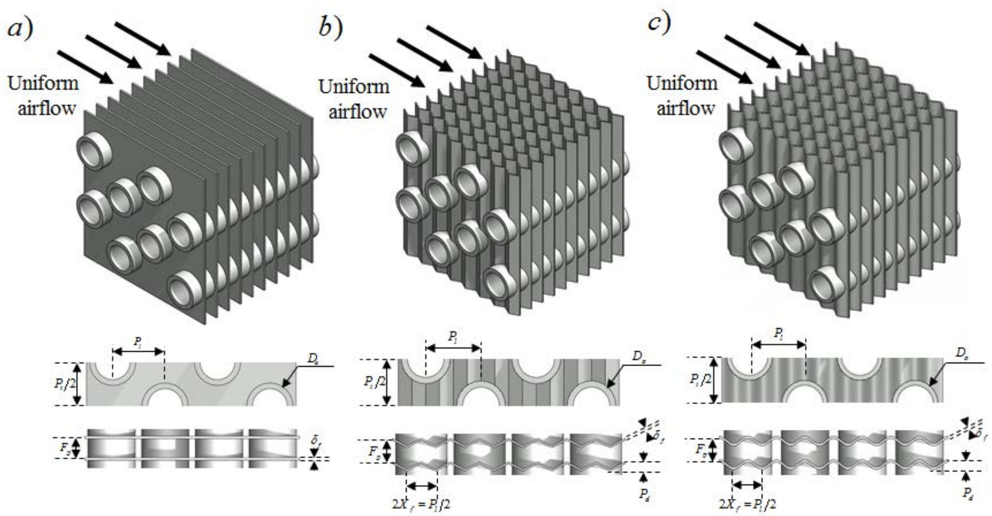


Opt1 and Opt2 are two optimized designs

Accomplishments: Design Tools for Industry

- Air-side heat transfer and pressure drop correlations





Round Bare Tube HX

Design Variable	unit	Bare Tubes	Bare Tubes	Bare Tubes
D_o	mm	2.0 to 5.0	0.5 to 2.0	0.5 to 2.0
P_t ratio (D_o)	-	1.25 to 4.0	1.2 to 4.0	1.2 to 4.0
P_l ratio (D_o)	-	1.25 to 4.0	1.2 to 4.0	1.2 to 4.0
Nt	-	2 to 20	2 to 40	2 to 40
Air face velocity	m/s	0.5 to 7.0	0.5 to 7.0	0.5 to 7.0
Arrangement	-	Staggered	Staggered	Inline

Plain Fin Tube HX

Design Variable	unit	Plain fin-and-tube
D_o	mm	2.0 to 5.0
P_t ratio (D_o)	-	1.5 to 3.0
P_l ratio (D_o)	-	1.5 to 3.0
Nr	-	2 to 10
FPI	in^{-1}	8 to 24
Air face velocity	m/s	0.5 to 7.0
Fin thickness	mm	0.115 (fixed)

Wavy Fin Tube HX

Design Variable	unit	Wavy fin-and-tube
D_o	mm	2.0 - 5.0
P_l	mm	$1.5D_o$ - $4.0D_o$
P_t	mm	$1.5D_o$ - $4.0D_o$
W_l	mm	$0.5D_o$ - $1.25D_o$
P_d	mm	$0.05W_l$ - $0.2W_l$
δ_t	mm	0.05 - 0.25
FPI	in^{-1}	5 - 50
N_t	-	2 – 10
u	m/s	0.5 - 7.5

Project Integration and Collaboration

Project Integration

- Collaboration with key project partners to identify and solve manufacturing and deployment challenges
- Collaboration with ORNL for performance testing and advanced manufacturing
- First-hand feedback from industry partners of UMD Consortium

Partners, Subcontractors, and Collaborators

- ORNL: Subcontractor; design, advanced manufacturing and testing
  - Omar Abdelaziz: Group Leader, PI; Patrick Geoghegan: Scientist
- Luvata: Industry partner; manufacturing, system integration and marketing
  - Mike Heidenreich: VP of Product Engg; Russ Cude: Director of Engg., Americans; Randy Weaver: R&D Engineer
- ICA / Heat Transfer Technologies: Industry partner; heat exchanger manufacturing process development
  - Yoram Shabtay: President; John Black: VP of Market Development
- Wieland: Industry Partner; tube manufacturer
  - Steffen Rieger, Technical Marketing Manager
- Burr Oak Tool Inc.: Specializing in machines, tools and services for HX mfg. Roger Tetzloff, Innovations Manager

Project Communications

Progress Review Meetings:

- Kick-off Meeting & Brainstorming Workshop, 22-Apr-2013, University of Maryland
- Semi-annual in-person progress review meetings (Mar and Sep), every year

IP: Invention records and provisional patent application in progress

Total Publications: 2014- 4, 2015- 3, 2016- 1, and 6 drafting

Selected Publications

1. Bacellar, D., Aute, V., Radermacher, R., **CFD-Based Correlations, with Experimental Verification, for Air Side Performance of Round Finless Tube Heat Exchangers with Diameters below 2.0mm, Intl. J. of Heat and Mass Transfer, Accepted Manuscript.**
2. Bacellar, D., Aute, V., Radermacher, R., **A Method for Air-To-Refrigerant Heat Exchanger Multi-Scale Analysis and Optimization with Tube Shape Parameterization**, 24^{th} IIR International Congress of Refrigeration, August 16 – 22, 2015 – Yokohama, Japan.
3. Bacellar, D., Aute, V., Radermacher, R., **CFD-Based Correlation Development for Air Side Performance on Finned Tube Heat Exchangers with Wavy Fins and Small Tube Diameters**, 24^{th} IIR International Congress of Refrigeration, August 16 – 22, 2015 – Yokohama, Japan.

Next Steps and Future Plans

- 1kW Prototype Wet Tests
  - Investigate the effect of coatings
- 10kW Prototype Tests
  - Investigate cause of tube blockages and improve fabrication process
- Fabricate evaporators and condensers for 3 Ton system (in-progress)
- Conduct structural and noise analysis on prototype designs
- Test evaporators and condensers in wind tunnel
- System Testing
  - Set up system test facility (complete)
  - Test evaporators and condensers as a part of complete system
- Develop and disseminate tools for heat exchanger analyses (in-progress)
- Develop and disseminate manufacturing guidelines and lessons learned (9/30/2016)

REFERENCE SLIDES

Project Budget

Project Budget: DOE Total $1050K, FY13-17 (3/1/2013 to 2/29/2016)
Variances: No change in overall budget; Higher spending in Year-2, due to prototype fabrication and test facility setup
Cost to Date: $1050K; Entire budget is expended.
Additional Funding: No additional funding for DOE is expected. Various in-kind contribution from industry partners.

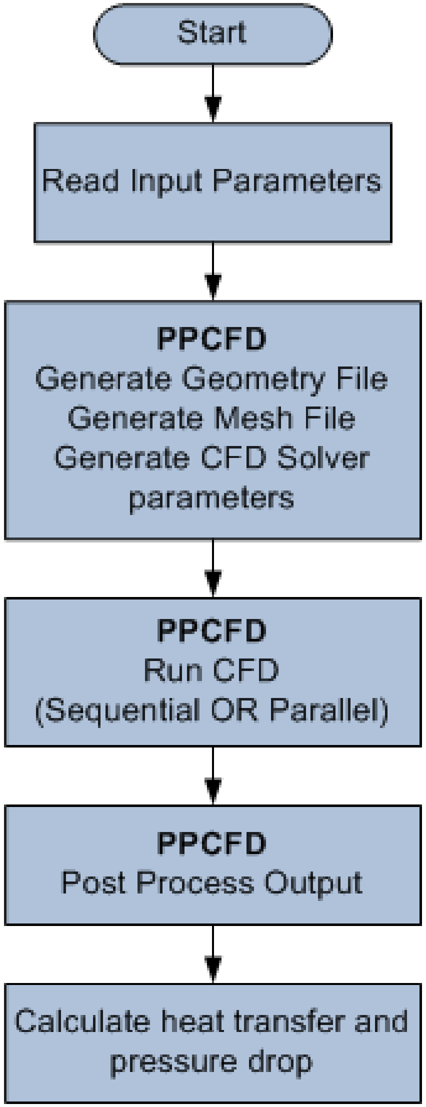
Budget History					
FY2013 – FY2014 (past)		FY2015 (Previous Year)		FY2016 (Current)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$751	NA	$130K	NA	$169K	NA

Project Plan and Schedule

Project Schedule																
Project Start: 04/15/2013		Completed Work														
Projected End: 10/30/2016		Active Task (in progress work)														
		Milestone/Deliverable (Originally Planned)														
		Milestone/Deliverable (Actual)														
	FY2013				FY2014				FY2015				FY2016			
Task	Q1 (Apr-Jun)	Q2 (Jul-Sep)	Q3 (Oct-Dec)	Q4 (Jan-Mar)	Q1 (Apr-Jun)	Q2 (Jul-Sep)	Q3 (Oct-Dec)	Q4 (Jan-Mar)	Q1 (Apr-Jun)	Q2 (Jul-Sep)	Q3 (Oct-Dec)	Q4 (Jan-Mar)	Q1 (Apr-Jun)	Q2 (Jul-Sep)	Q3 (Oct-Dec)	Q4 (Jan-Mar)
Past Work																
Finalize best designs (via optimization) for various materials																
Manufacture sample tubes, headers and investigate joining options																
Select most promising materials and techniques																
Identify preferred design and manufacturing methods																
Design and fabricate various 1 kW options																
Test various 1 kW options																
Decide on material and manufacturing approach for 10kW design																
1 kW Heat exchanger successfully tested																
Current/Future Work																
Design and fabricate 10 kW prototypes (3 HX)																
Test 10 kW prototype HX in Wind Tunnel																
Test 10kW prototypes in System																
Reporting																
Closure																

PPCFD

- Parallel Parameterized CFD (PPCFD)
- Methodology to
  - **Generate** geometries
  - **Generate** mesh files
  - **Generate** & execute CFD runs file
  - **Post process** output
- Advantages
  - Fast evaluation of parameterized geometries, ***allows topology change***
  - Applicable to most domains
  - Significant reduction in engineering time



Geometries Analyzed

Geometry		Design & Optimization					Prototyping, Experimental Testing & Development of Design Tools		
HX	**ARR**	**IA**	**PPCFD**	**UA**	**MM**	**AAO**	**PT**	**VAL**	**CORR**
BT	Inline	✓	✓	✓	✓	✓	✓	✓ *	-
BT	Staggered	✓	✓	✓	✓	✓	✓	**X**	✓
BT	Chevron	✓	-	-	-	-	-	-	-
FM	Slanted	✓	✓	✓	✓	✓	-	-	-
FM	Multiple Banks	✓	✓	✓	✓	✓	-	-	-
FT	Staggered	✓	✓	✓	✓	✓	-	-	**X**
FT	Inline	✓	-	-	-	-	-	-	-
MBT	Staggered	✓	✓						-
MBW	Staggered	✓							-
NT	Staggered	✓	✓				**X**		-
VG	N/A	X							-
WF	Staggered								-
WT	Straight	✓	✓	✓	✓	✓	**X**		-
WT	Wavy	✓	X						-
WT	Slits*								-
WT	Louver*								-

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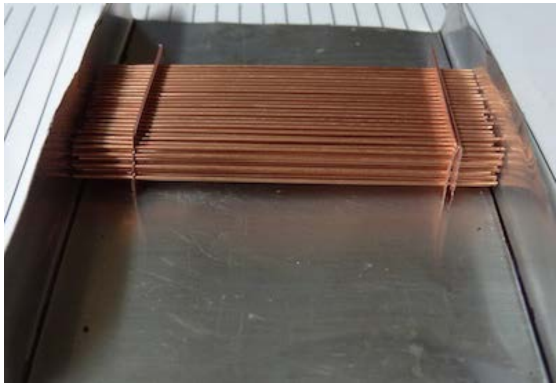
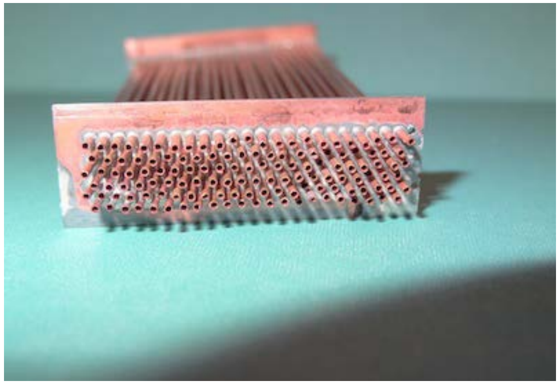
10kW Prototype Fabrication

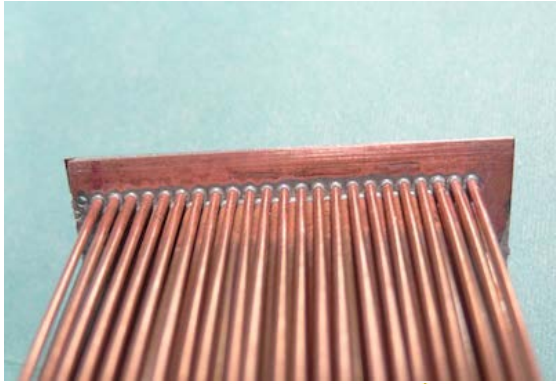
- Small sample assembly test



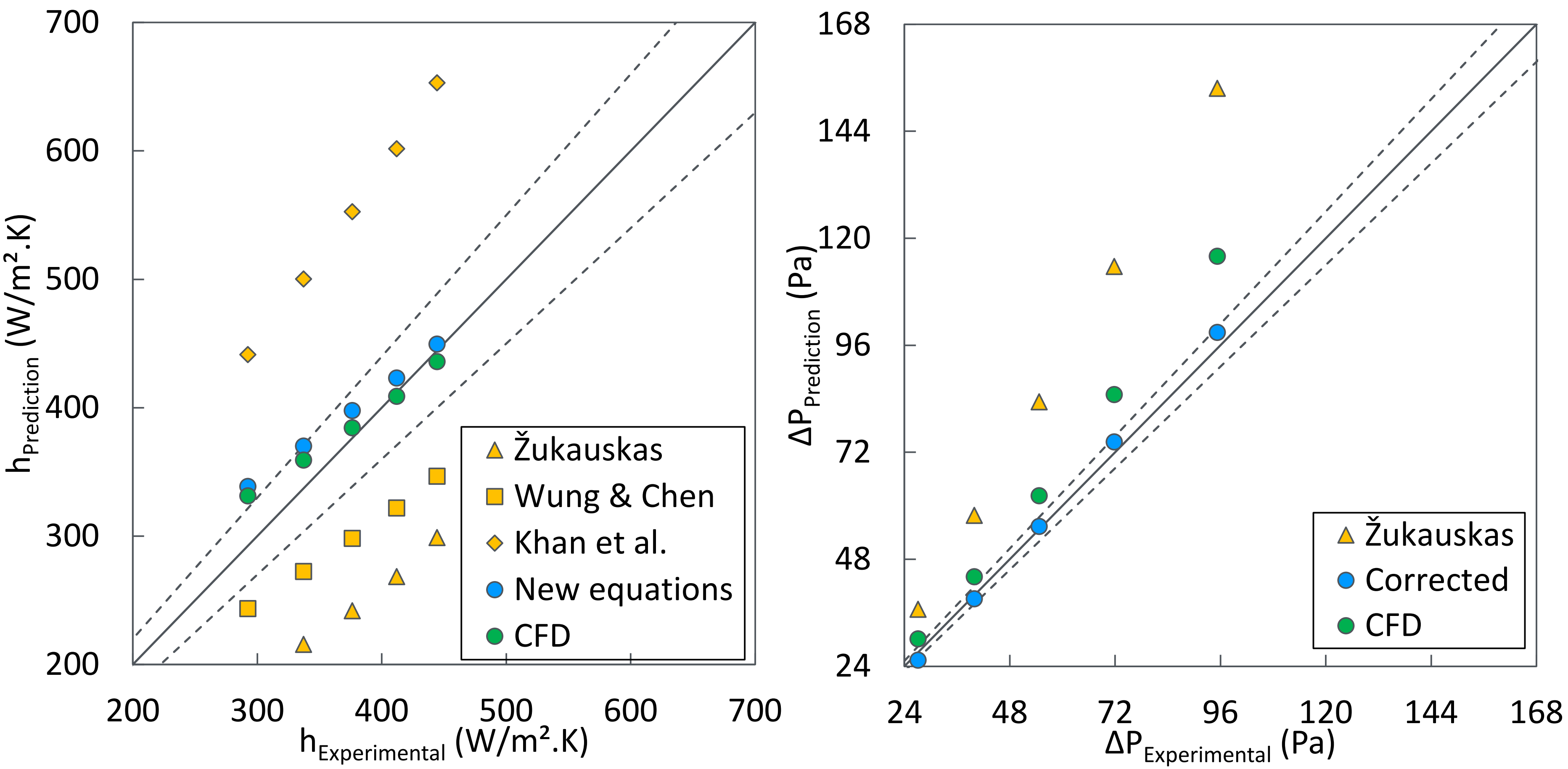
- Soldered edge spacers



- View from air-side



Need for New Correlations



Bacellar, D., Aute, V., Radermacher, R., **CFD-Based Correlations, with Experimental Verification, for Air Side Performance of Round Finless Tube Heat Exchangers with Diameters below 2.0mm**, ***(International Journal of Heat and Mass Transfer)***