Topology Optimized Heat Exchangers: Their Potential and Design and Manufacturing Challenges

Reinhard Radermacher
Minta Martin Professor, Director CEEE
University of Maryland
Department of Mechanical Engineering
College Park, MD 20742-3035
Email: raderm@umd.edu | Tel: 301 405 5286 | www.enme.umd.edu/ceee/

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13	Guentner	26	Honeywell		

Carrier Center of Excellence
Ford Motors, GE Global Research, ORNL, DOE, ARPAe, MIPS, PNU
Energy Innovation Fund

The Vision

IEA: 1.6 Billion Air-conditioners Worldwide Today

5.6 Billion Air-conditioners Worldwide in 2050

CEEE at UMD: To help Transform an entire Industry to Manufacture 5.6 billion air-conditioners that are

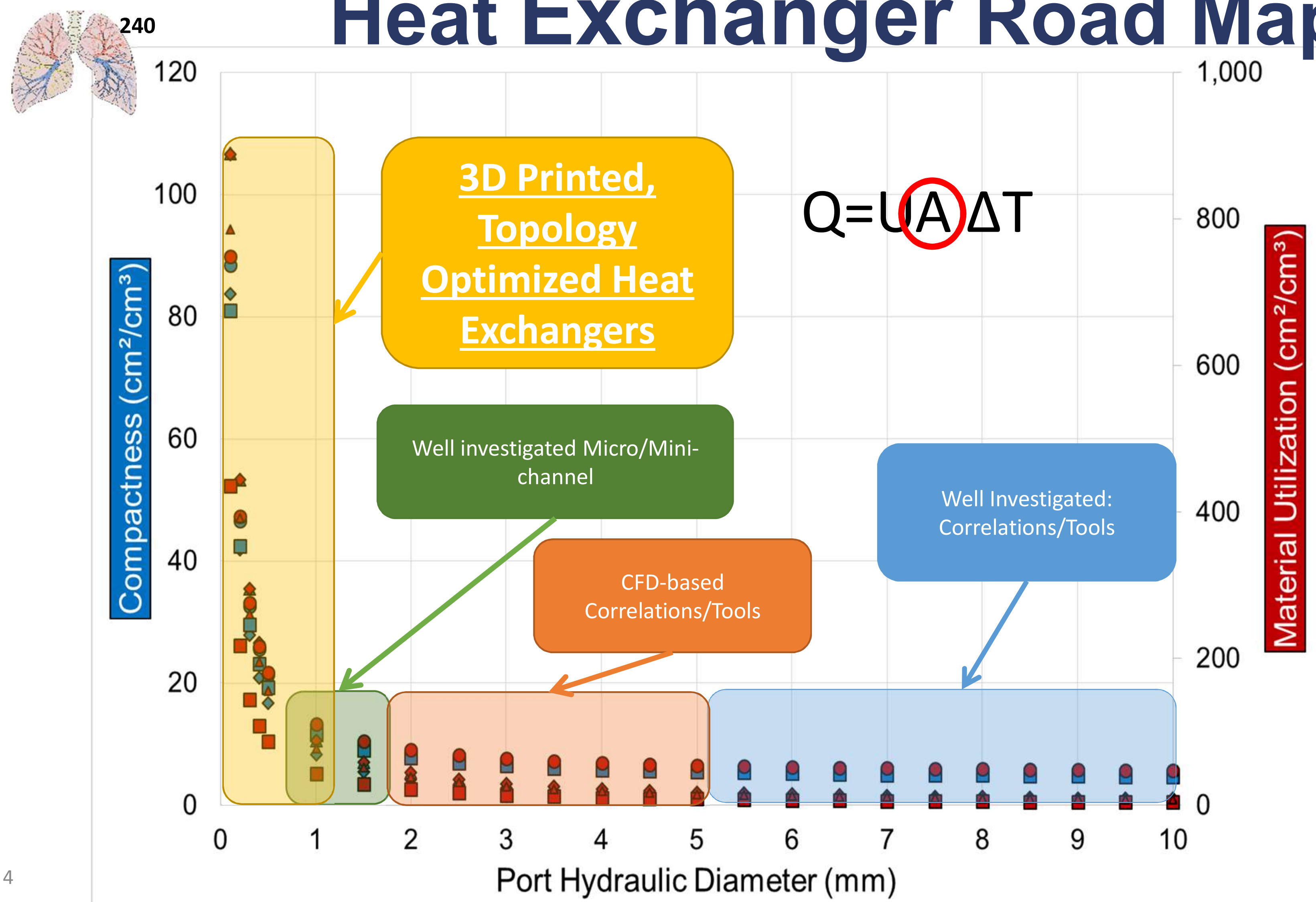
Much smaller,

Much less resource-intensive than today and

Operate in buildings with no net energy consumption.

HEAT EXCHANGERS ARE A BIG PART OF THE CHALLENGE!

Heat Exchanger Road Map



Bacellar, D., Aute, V., Huang, Z., and Radermacher, R., 2016, Airside friction and heat transfer characteristics for staggered tube bundle in crossflow configuration with diameters from 0.5 to 2.0mm, Technical Note, Intl J. of Heat and Mass Transfer, Vol. 98, pp. 448-454

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Optimization Formulations

Objectives	Constraints	Design Variables
Min. of HX volume	Heat capacity	Tube geometric parameters
Min. of HX weight	Pressure drop	Tube layout pattern
Min. of life cycle cost	Life cycle net cost	Number of circuits
Min. of capital cost	Capital cost	Circuitry connection
Min. of HT area	Fan width vs. tube length	Total number of tubes
Max. of heat capacity	Length-diameter ratio	Fin geometric parameters
Min. of pressure drop	Tube geometric parameters	Fan model
Min. of capital cost	Fin geometric parameters	Fan count
Max. of effectiveness	Shell geometric parameters	Shell geometric parameters
Max. of exergy efficiency	Baffle geometric parameters	Baffle geometric parameters
Min. of entransy dissipation	Baffle spacing	Fluid states
Min. of entropy generation	HX dimensions	
Min. of Nusselt number	HX weight	
Min. of Friction factor	Vibration	
Max. of cycle COP		

Table Source: Aute et al., CH-15-039, ASHRAE 2015 Winter Conference
25+ quantitative metrics for comparing heat exchangers can be found in the literature

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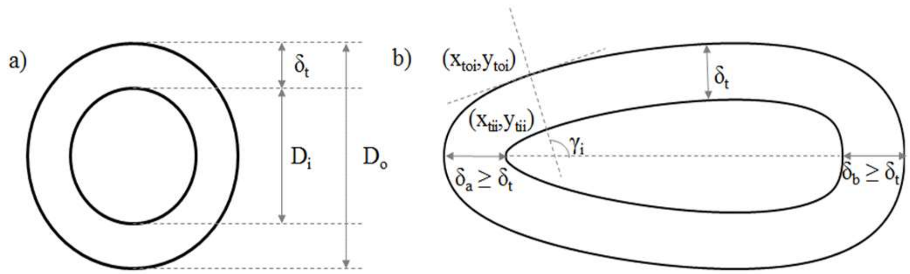
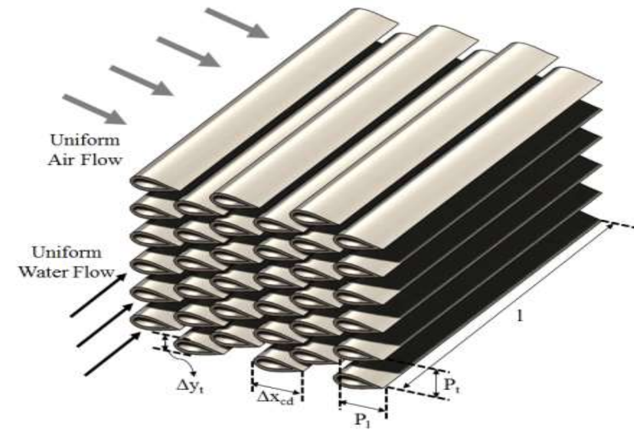
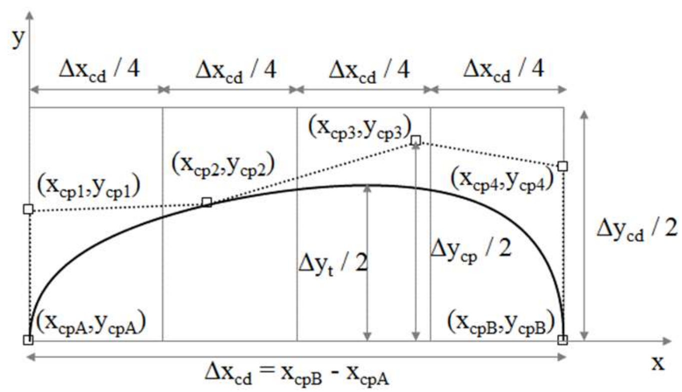
NURBS Tube HX (NTHX)







Design Variable	Unit
Δy_{cd}	mm
Δx_{cd}	mm
P_t	mm
P_l	mm
L	mm
N_r	-
N_t	-
x_{cp_i}	mm
y_{cp_i}	mm

i = 1…15

NURBS = <u>N</u>on-<u>U</u>niform <u>R</u>ational <u>B</u>-<u>S</u>plines

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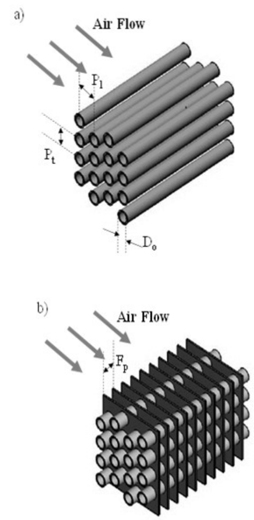
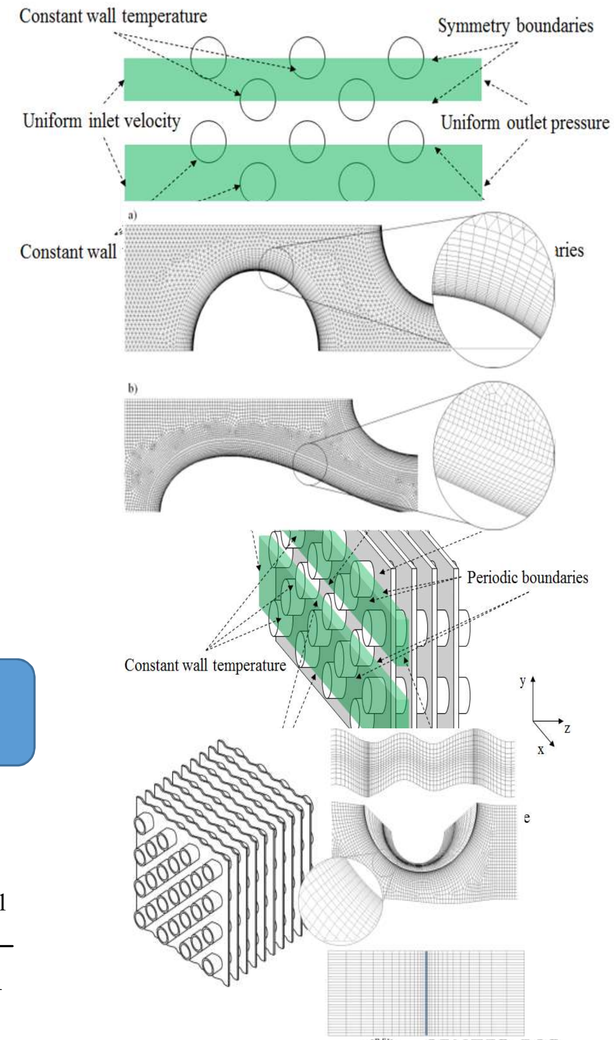
Airside CFD Model

- Platform
  - Geometry and Mesh: Gambit 2.4.6
  - Simulations: ANSYS Fluent 14.5
- Assumptions
  - Airside only → constant wall temperature
  - Dry air
  - Steady-state flow
  - Non-existent energy and mass sources nor external forces
  - Negligible gravitational effects
  - Polynomial curve fit for thermophysical properties
  - Negligible pressure work and kinetic energy
- Settings
  - Turbulence model: k-ε Realizable / k-kl-w
  - Solver: coupled pressure-velocity
- Mesh
  - Mapped growing elements (1.2) near wall, Pave (core)
- Uncertainty Analysis with Grid Convergence Index (GCI)
- Data reduction: UA-LMTD



Similar Effort Needed for FEA

$$GCI_{fine}^{21} = \frac{F_s \cdot e_a^{21}}{r_{21}^{p} - 1}$$



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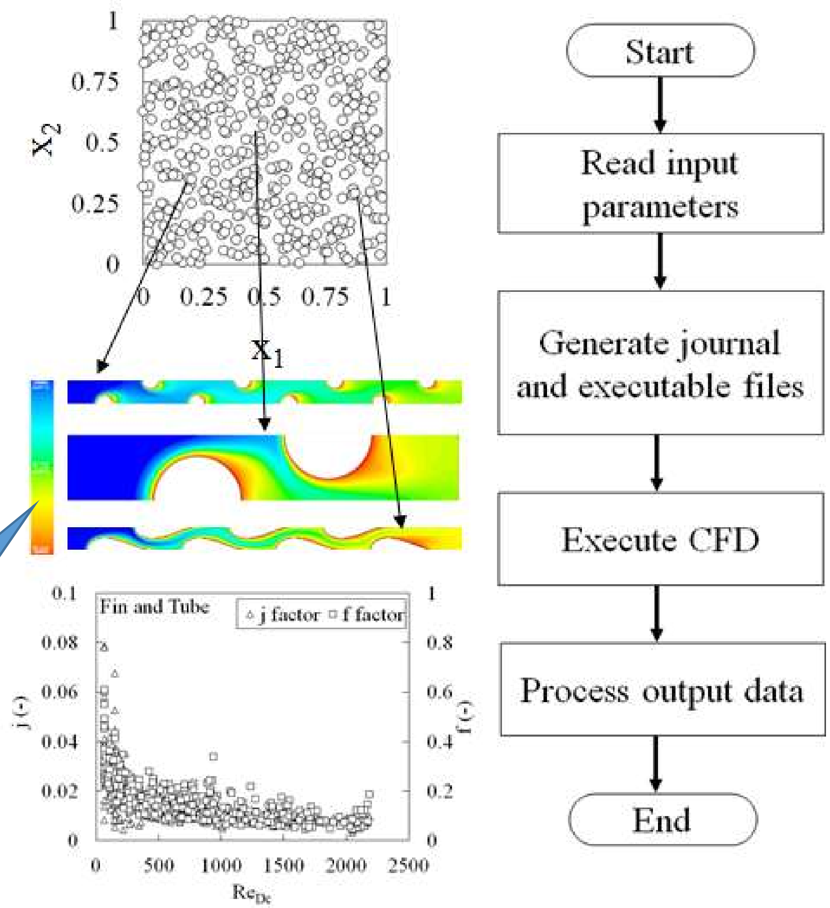
Parallel Parameterized CFD+FEA (PP-CFD-FEA)

- Methodology to
  - **Generate** geometries
  - **Generate** mesh files
  - **Execute** CFD and FEA
  - **Post process** output
  - **Goto next geometry**
- Advantages
  - Fast evaluation of parameterized geometries
  - ***Allows shape and topology change***
  - Applicable to most domains
  - **Significant reduction in engineering ti… 90%)**

Framework allows for simultaneous shape and topology change



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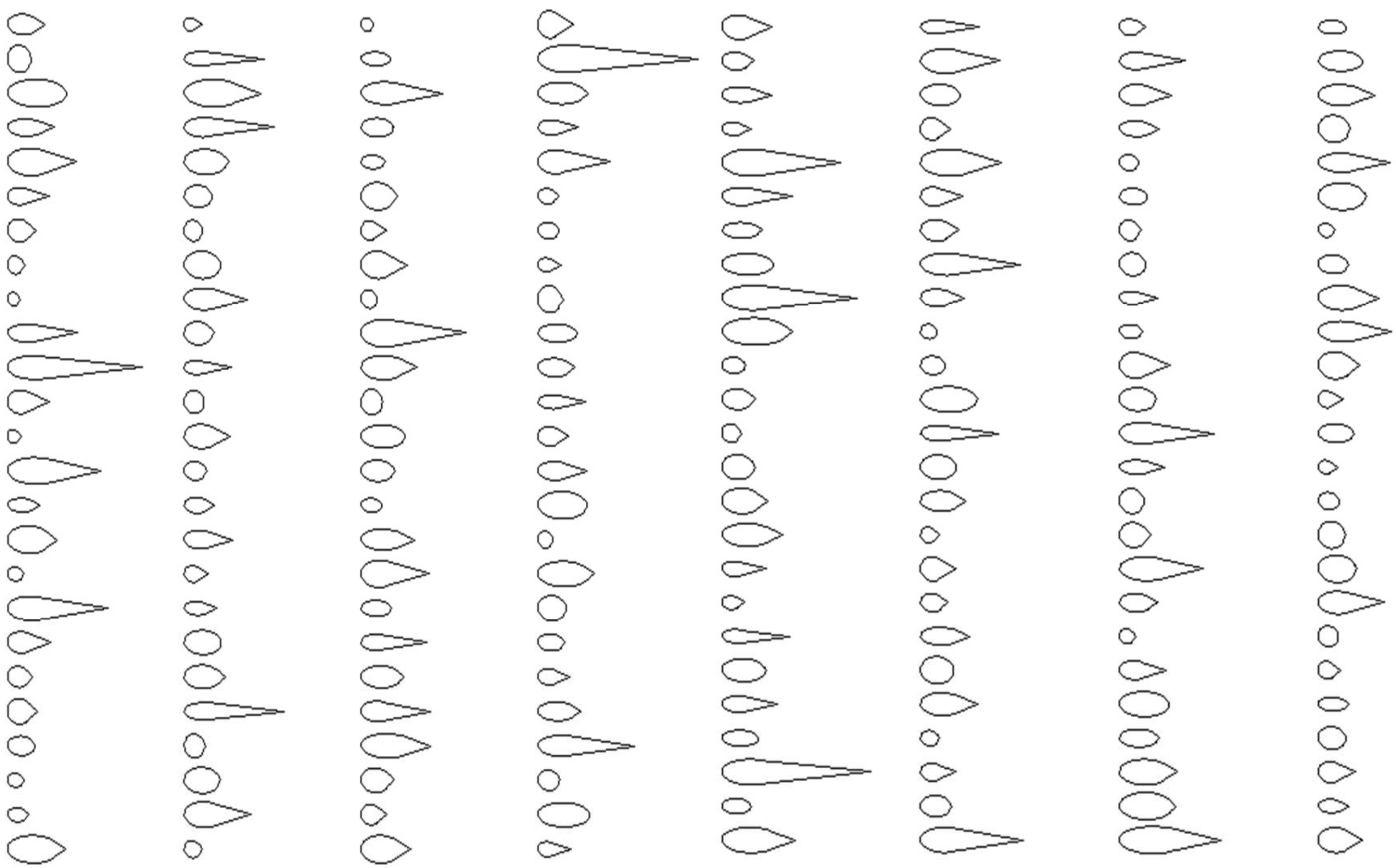
Typical Tube Shape Population



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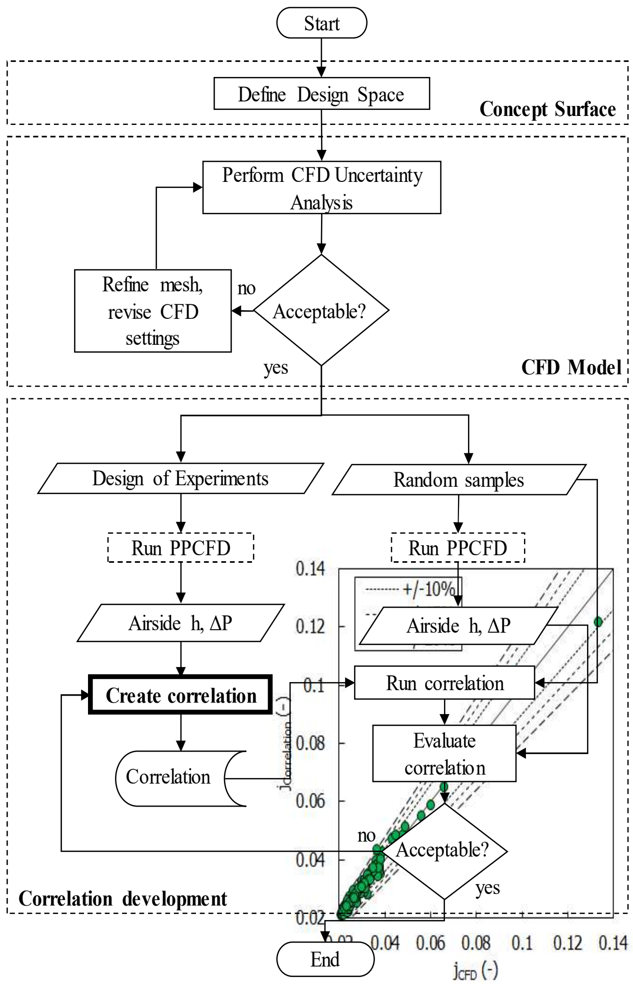
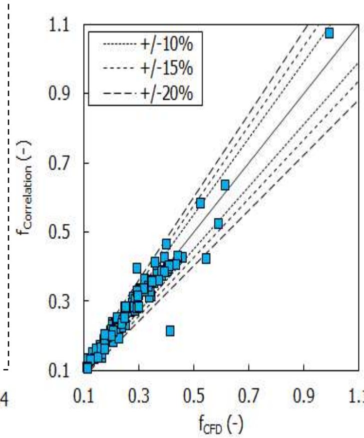
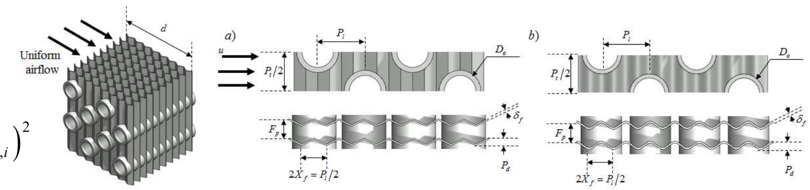
Correlation Framework



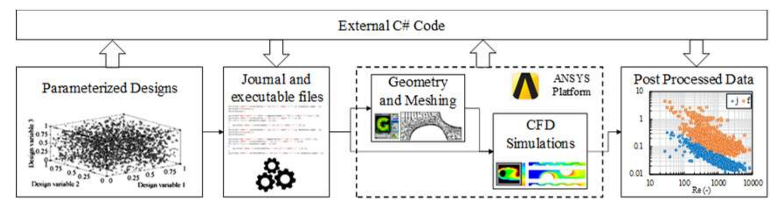


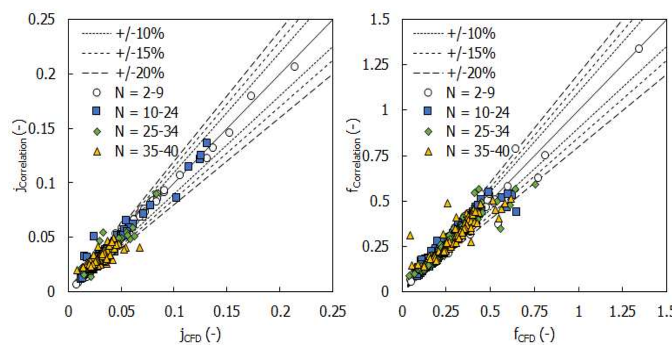
$$f(\underset{\sim}{x}) = \sum_{i=0}^{n} \left(\phi_{corr,i}(\underset{\sim}{x}) - \phi_{CFD,i} \right)^2$$

$$\min f(\underset{\sim}{x})$$
$$s.t.$$
$$\underset{\sim}{x}_{lb} \le \underset{\sim}{x} \le \underset{\sim}{x}_{ub}$$



D_o (mm)	P_t/D_o (-)	P_l/D_o (-)	F_p (mm)	P_d/X_f (-)	δ_f (mm)	N (-)	u (m/s)
2.0 - 5.0	1.25 – 4.0	1.25 – 4.0	0.5 – 2.5	0.088 – 0.84	0.05 – 0.1	2 - 20	0.5 – 7.0





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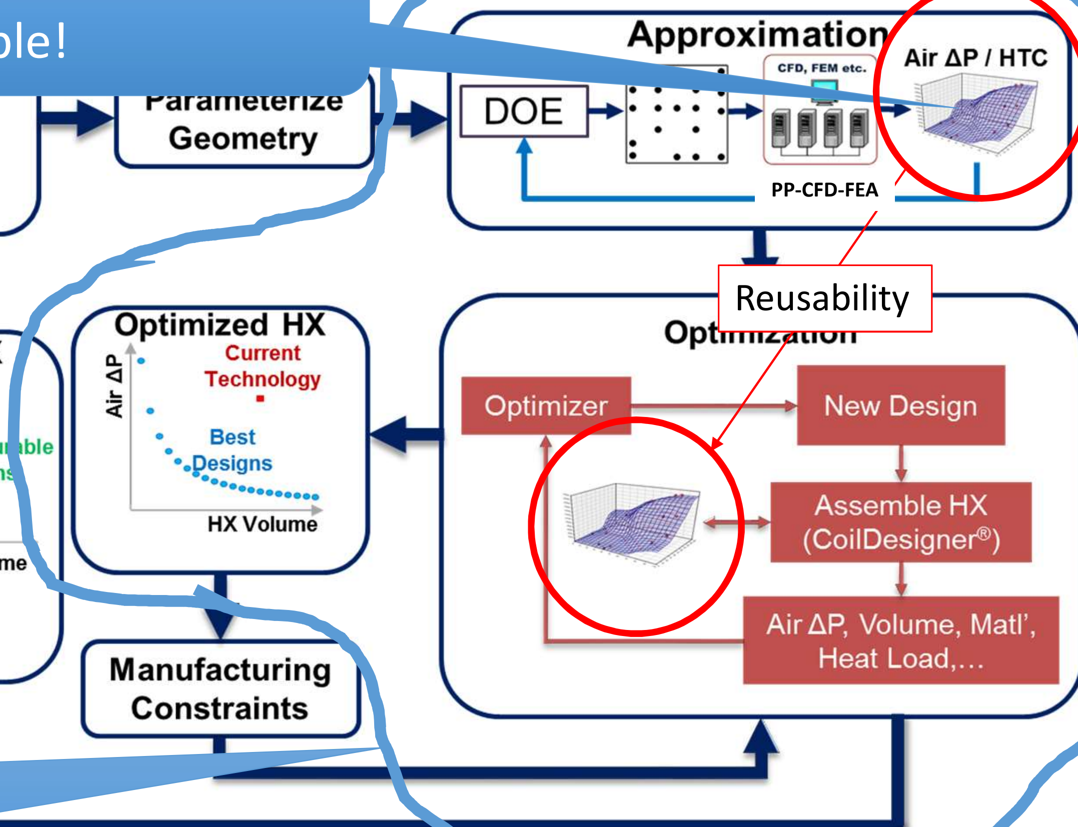
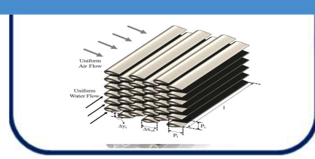
Optimization Framework

Metamodel = New HT, dP Correlation!
It is reusable!



Prototypes



Automated!
90% Reduction
in Engineering
Time

Abdelaziz, O., Aute V ... ximation Assisted Optimization For Novel Compact Heat Exchanger Designs, HVAC&R Research, Vol 16 , No. 5, pp. 707-728.

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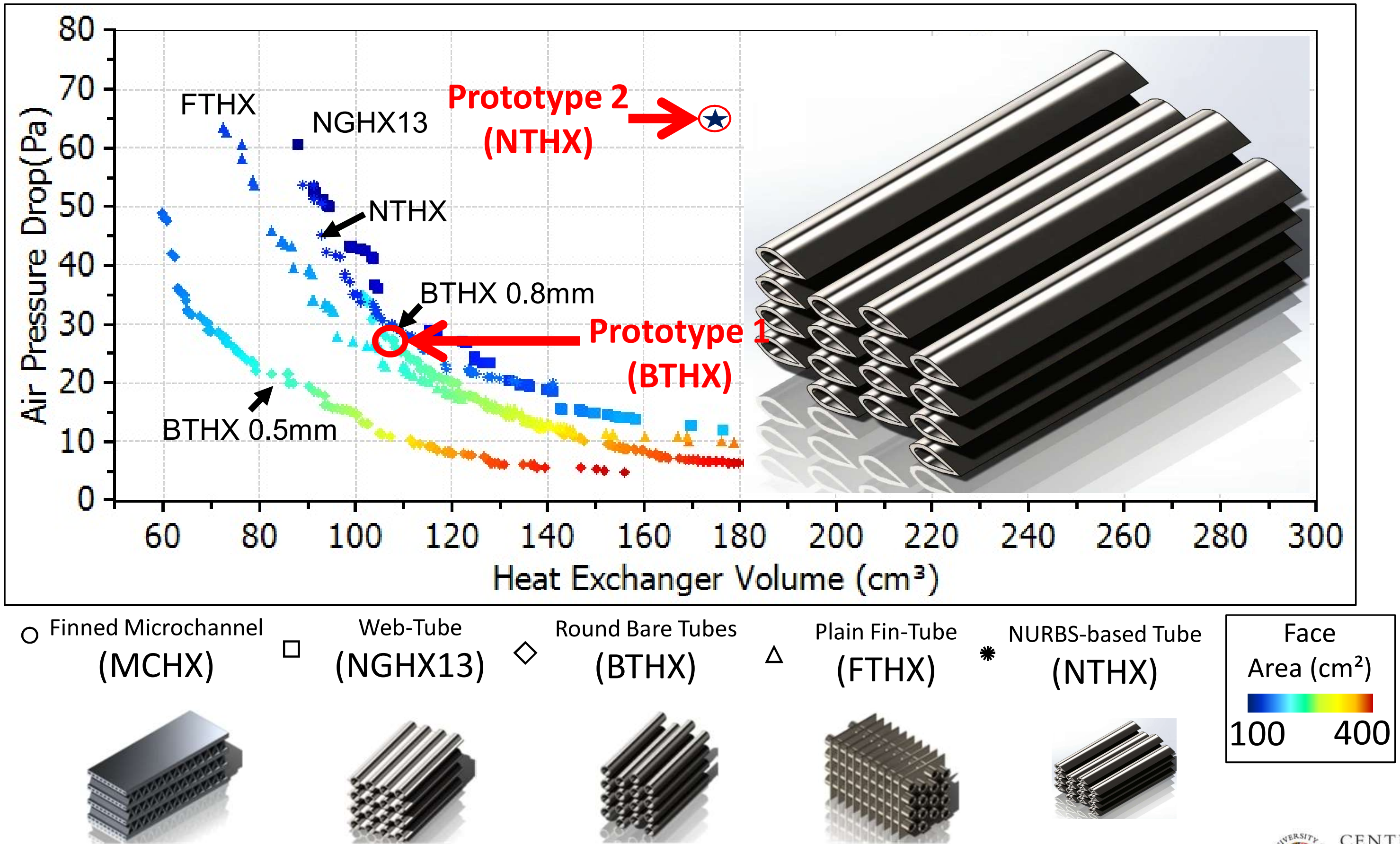
Optimized HX Geometries for 1 kW Radiators

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



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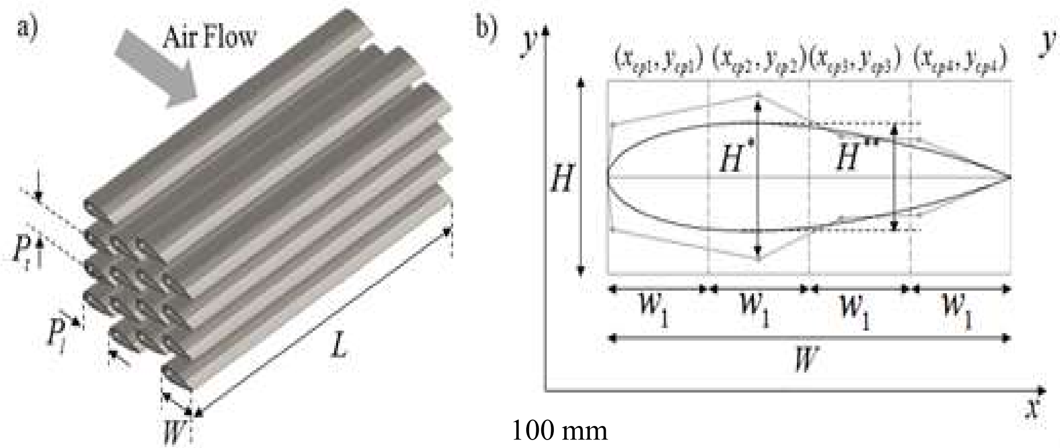
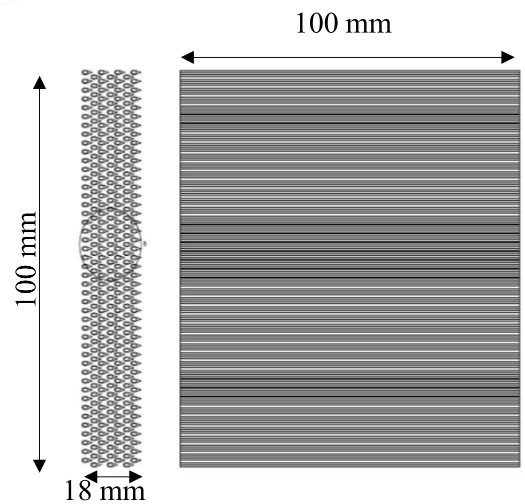
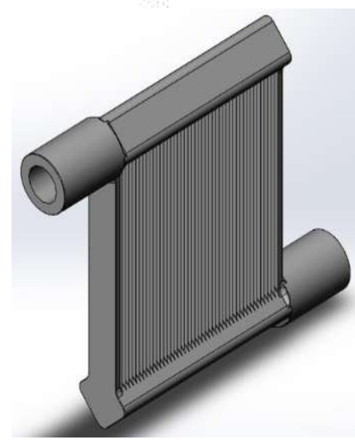
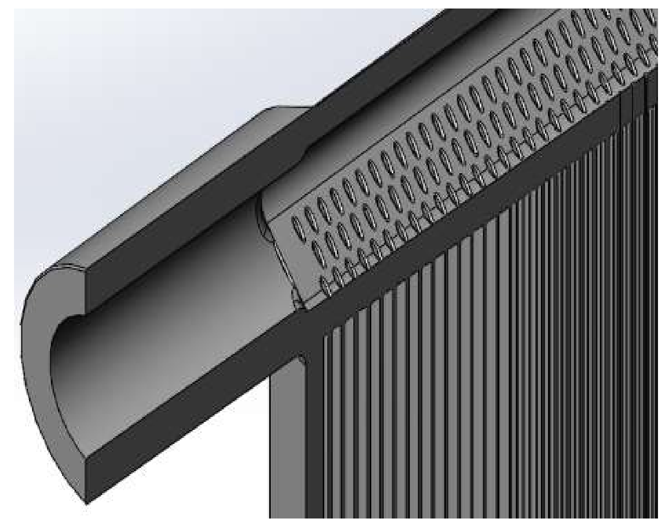
Tube Shape Optimization



Geometry and Topology Optimized in 2 Dimensions!







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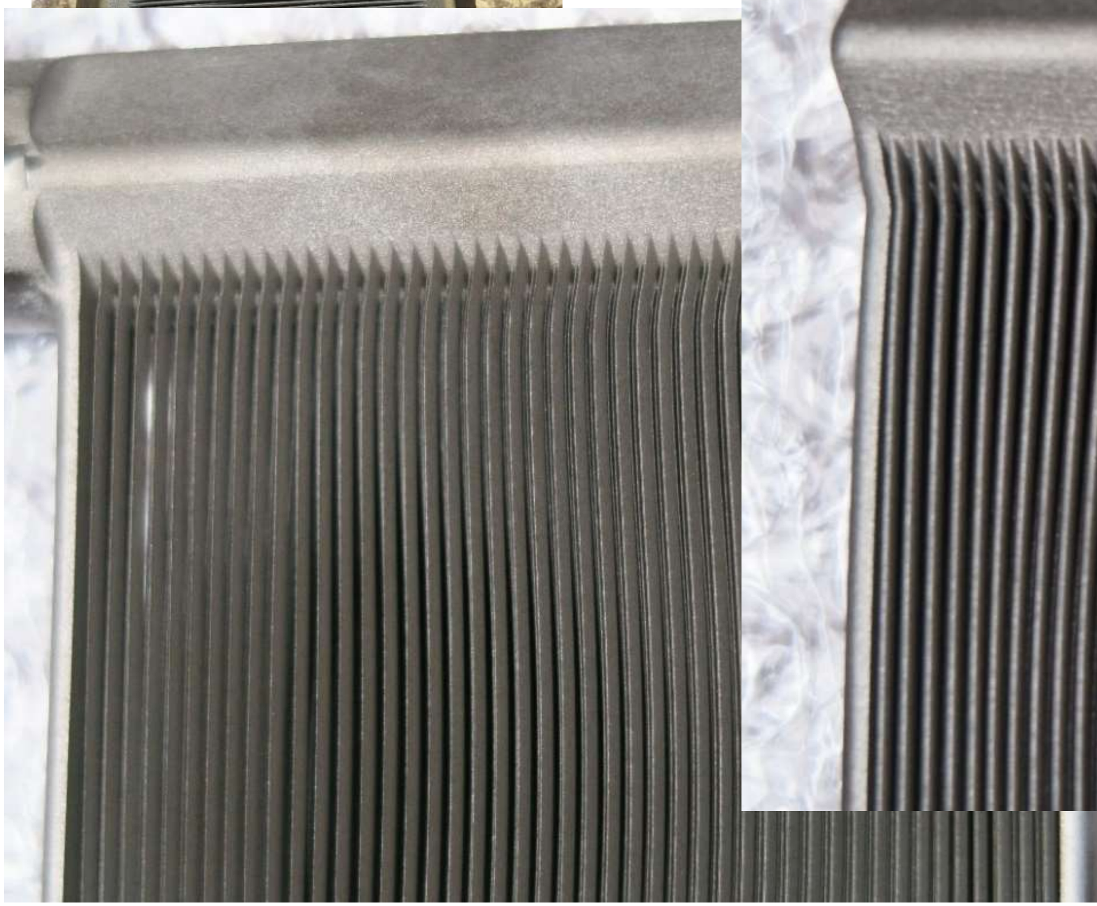
NURBS-Tube HX



Validation

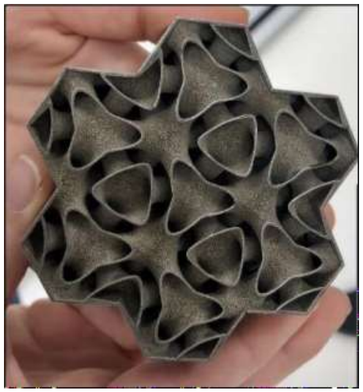
Energy Balance ±2.5%

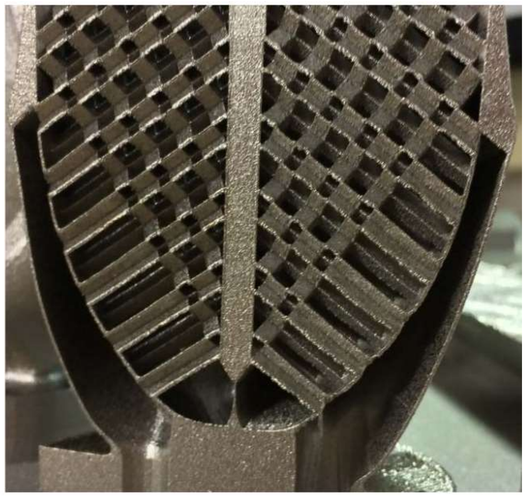
Heat Capacity ±7%

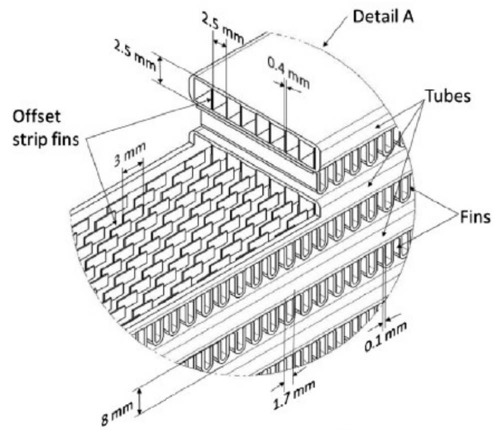
Air-side pressure drop ±12%

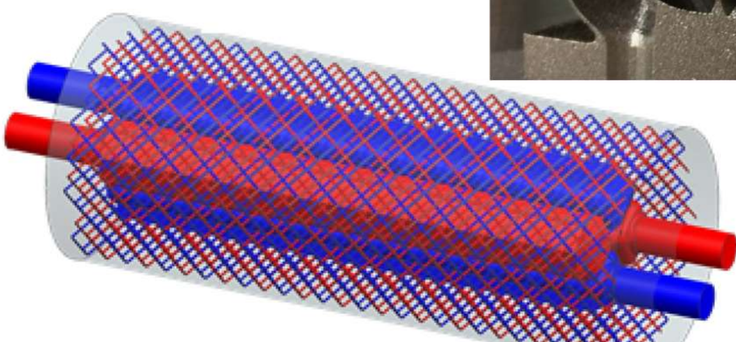
No fitted parameters

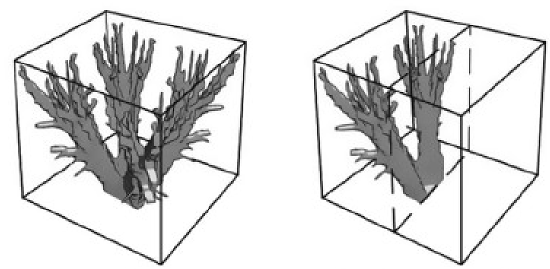
Higher Performance Heat Exchanger Examples











Isometric View   Sectional Isometric View

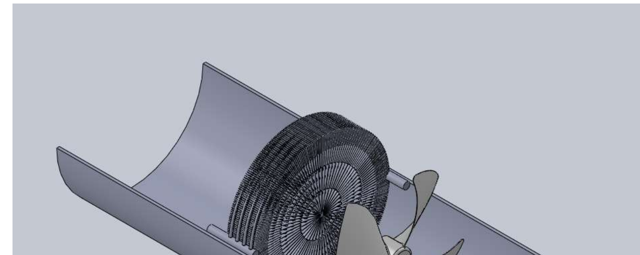
The need for next generation Thermal System Modeling, Peter de Bock, Ph. D. – GE Research, Itherm 2019; Gerstler & Erno, 2017, IEEE ITHERM Conference
Design and characterization of an additive manufactured hydraulic oil, Cooler, Brandon J. Hathaway, Kunal Garde, Susan C. Mantell, Jane H. Davidson, IJHMT 117 (2018) 188–200
Design and Validation of Topology Optimized Heat Exchangers , Kimberly R. Saviers, Ram Ranjan1, and Reza Mahmoudi, *United Technologies Research Center, East Hartford, CT, 06108, USA,* AIAA SciTech Forum, 2019
F.H. Burger, J. Dirker, J.P. Meyer, Three-dimensional conductive heat transfer topology optimisation in a cubic domain for the volume-to-surface problem, Int. J. Heat Mass Transf. 67 (2013) 214–224.

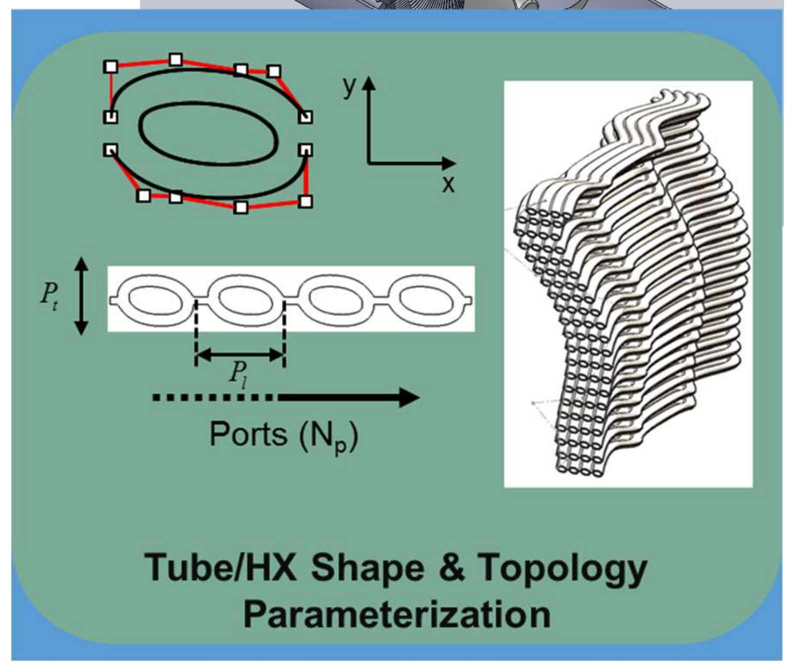
Challenges for 3D Printed HX

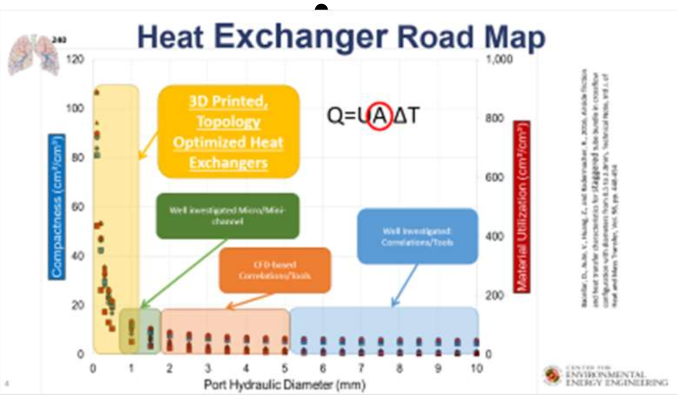
- Performance Prediction for Shapes that Never Existed Bef
  - Multi-scale, Multiphysics ad Process Analysis
  - Parallel Parameterized CFD and FEA Optimization of Topology a
  - Header Integration, Minimization of Header Volume, Pressure Dr Charg
- Smallest Possible Feature Size (Ports, Wall Thickness)
  - Simultaneous Optimization of Heat Transfer, Pressure Drop, Strengths, for Two (or more) Fluids Streams
  - Increasing Pressure Drop → Multiple Parallel Ports
  - Flow Distribution Issues → Phase Separation, Microfluidic Valves
  - Purity of Fluids → Filters
- Tuning of Machine Parameters, Design of Support Stru
- Reproducibility
  - Surface Roughness Correlations
  - Influence on Heat Transfer for Single-phase Flow, Two(Multi)-Phase Flow
- Predicting Performance Accurately Before First Prototype is Fabricated

Opportunities for 3D Printed HX

- Unparalleled Compactness
- Hybrid Manufacturing
- Shape Conforming Designs
  - Oil Cooler Integrated with Jet Engine
  - Car Radiator Follows Shape of Hood
  - Heat Exchanger Integrated into Existing Duct







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Ultimate Heat Exchanger Design Goal

Taking Lungs as Example:

- ~ 800,000 Operating Hours
- 100% Uptime
- Self Repairing
- Integrated, Self-cleaning Filter
- Heat Exchanger and Fan Tightly Integrated
- Heat Transfer and Energy Supply by the Same Fluid Stream

Thank you!

Questions?

Reinhard Radermacher, raderm@umd.edu

Backup Slides

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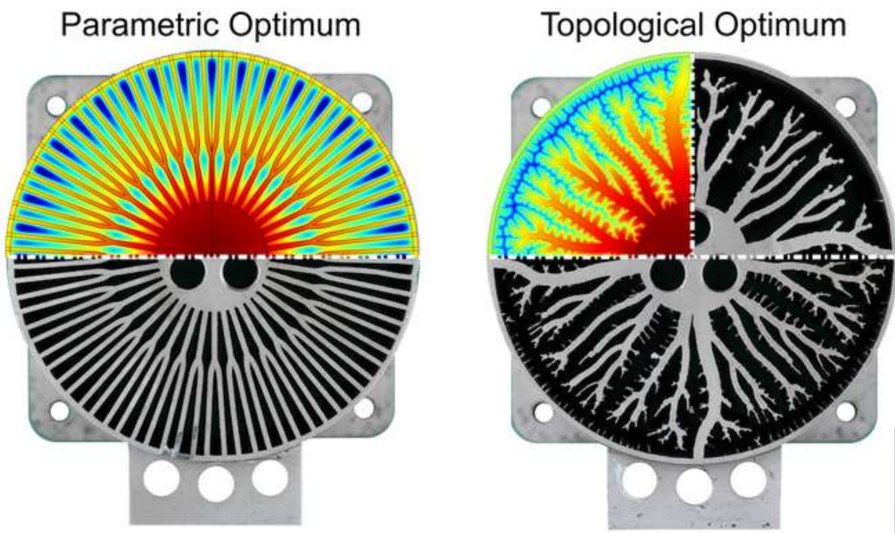
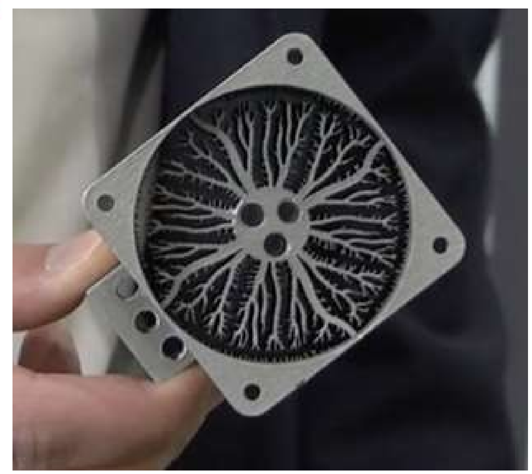
Topology Optimized Heat Sink





Lange et al., 2018, COMSOL Conference, Lausanne

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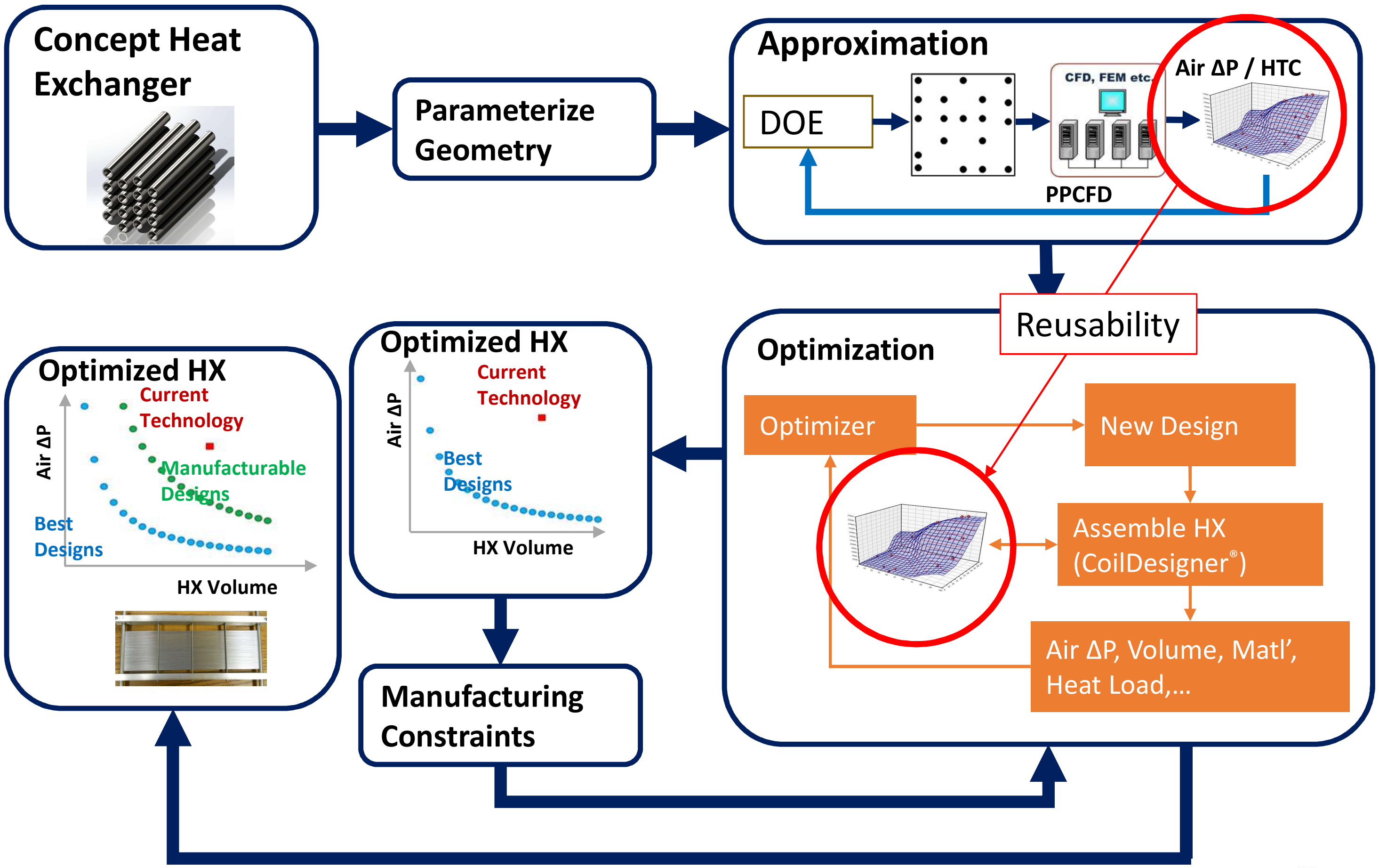
Design and Optimization Methodology



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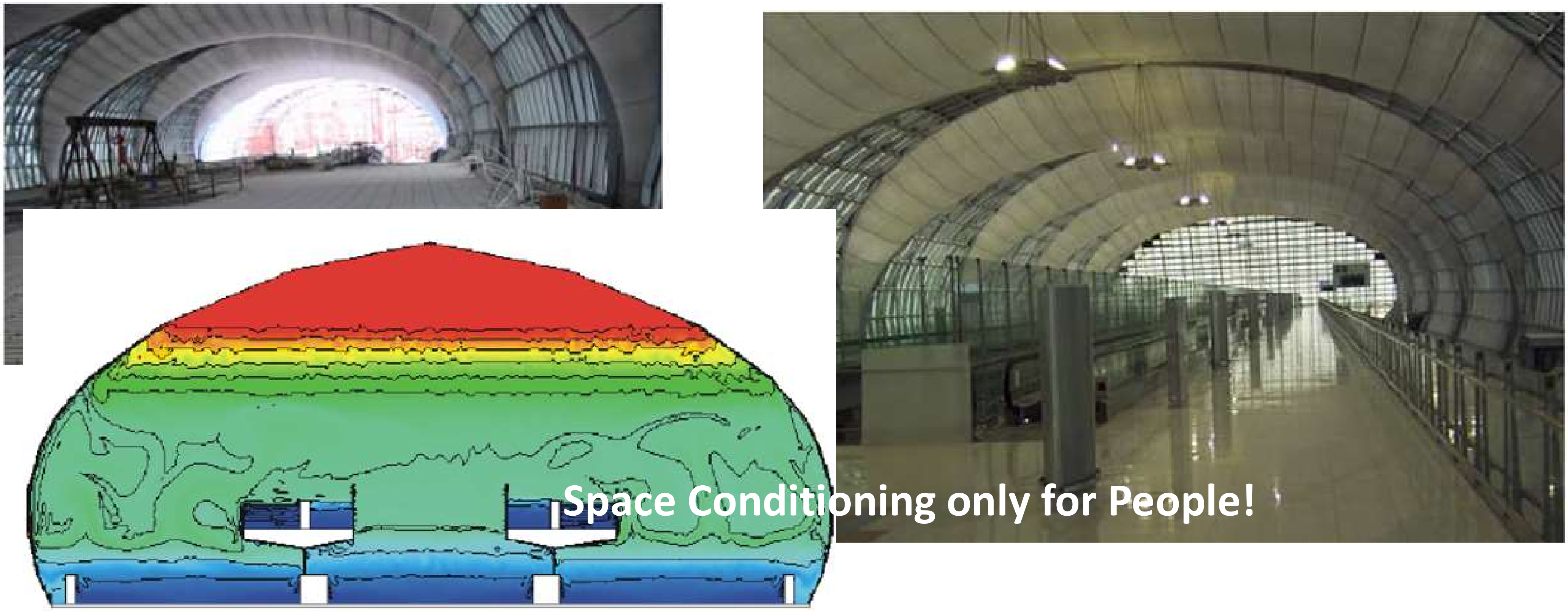
Adjoint-Based Optimization

- Powerful technique for gradient-based shape optimization
- Allows us to answer:
  - What is the impact of changing boundary/channel-shape on my flow field?
  - How to change the boundary/shape to min./max. this impact
- Uses concept of Adjoints
  - From Optimal control, Lions et al. (1971)
  - Fast evaluation of a perturbation (e.g., gradient or sensitivity)
  - Carried out at flow equation level; tightly integrated with the solvers
- Now available in most commercial tools

Giles, MB., Pierce, NA., 2000, An Introduction to the Adjoint Approach to Design, Flow, Turbulence and Combustion, Vol. 65, pp. 393-415.

Airport in Bangkok, Cooled Floors



Space Conditioning only for People!

Olesen B., 2009, Low temperature radiant heating – high temperature radiant cooling, ASHRAE, Louisville

Future of Heat Exchangers

- Much smaller dimensions
- Conform to irregular shapes – f-the-way
- Filters increasingly important
- Oil-free compressors requirec
- Transformation of design and manuracturing metnods
- Heat exchangers may not be product of traditional HVAC manufacturers
- **Lots of room for creativity!**

It will **NOT** be 'business-as-usual'.

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Half the Volume, Third of the Weight…

	Conventional Technology	Proposal
Compressor Weight (kg)		
Heat Exchangers (kg)		
Balance of Plant (kg)		
Total (kg)		

Industry-leading Design Software

Validation of Our Own Software

<u>Inventing</u> New, Optimized Heat Exchangers

2x smaller Volume
3x lower Weight
Workshop Sept. 18-20, 2019

Backup

Outlook

- Greatest energy savings: minimize use!
- Major system components may not be products o manufacturers
- Increasing energy efficiency in Bldgs. → less HVAC
- Renovation is a ***huge*** opportunity!
- Future of Vapor Compression Heat Pumps: **Great!**

It will **NOT** be 'business-as-usual'.

Smaller, Better, Lower cost

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