Cost Reduction for Advanced Integration Heat Exchanger Technology for Microreactors

NEUP Project 21-24226

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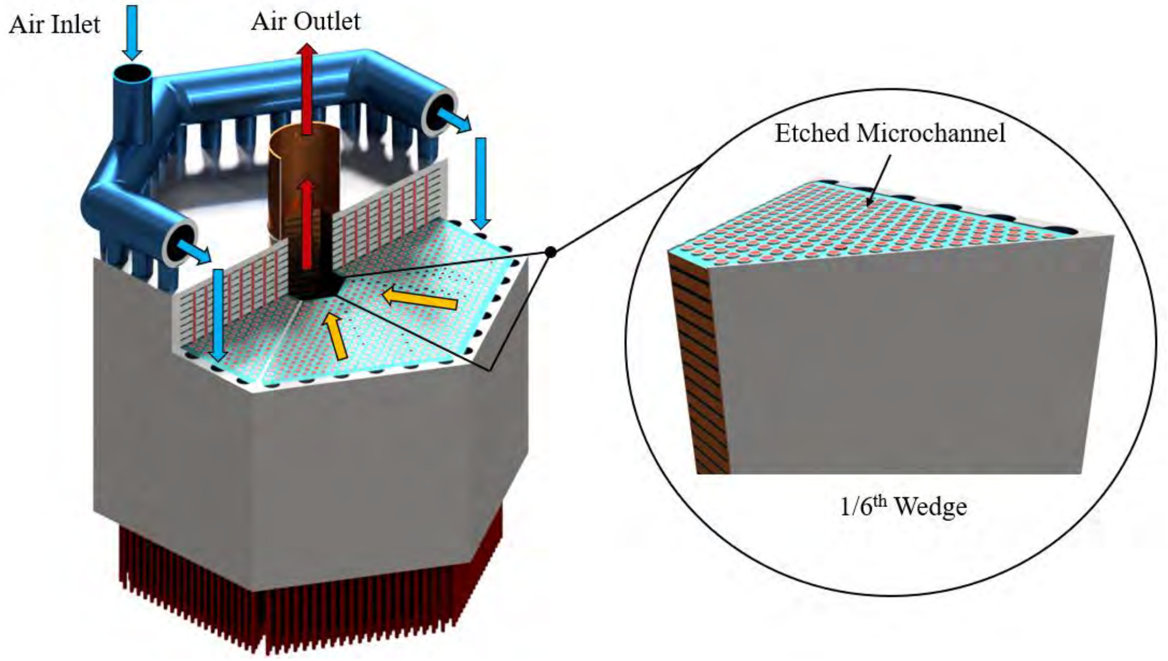
NEUP Nuclear Energy University Program
U.S. Department of Energy
Idaho National Laboratory
Westinghouse

Presentation Overview

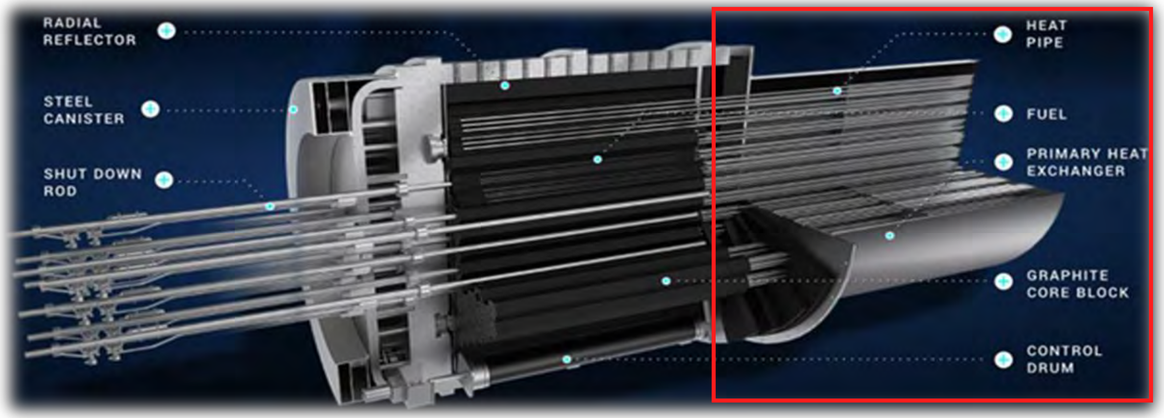
- Project background and recap
- Air Brayton testing
- sCO2 optimization
- Conclusions and future work



Project Background

Interface Heat Exchanger

- Objectives
  - o Development and validation of microreactor integration heat exchanger design tools
  - o Demonstrate potential cost-reduction/performance improvements in the context of an eVinci™-like microreactor
  - o Obtain benchmark and validation data
  - o Demonstrate sub-size PCHE-based integration HX for sCO2 and air working fluids
  - o Train several students for nuclear industry



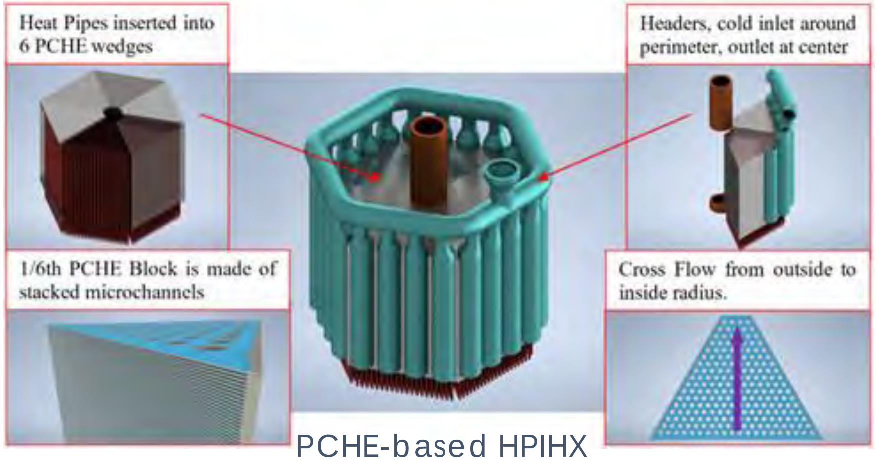
eVinci™ Micro-Reactor, Courtesy of Westinghouse Electric Company LLC

Printed Circuit Heat Exchanger

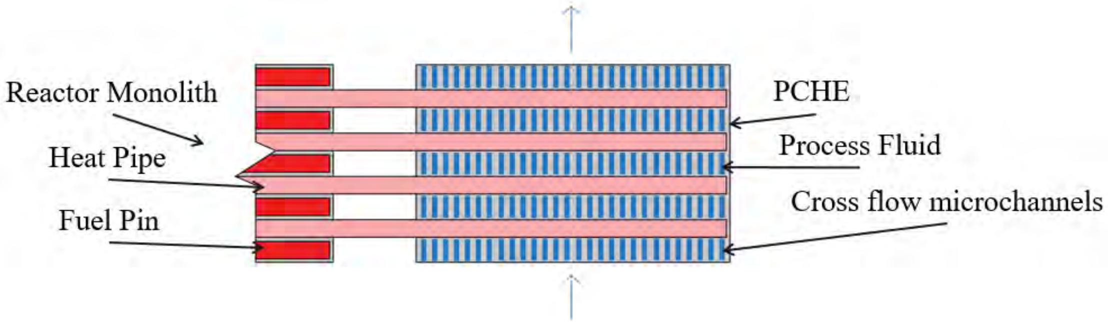
- Printed circuit heat exchanger
  - Thin metal sheets are chemically etched
  - Diffusion bonded together
  - Forms microchannels with high heat transfer area
- HPIHX PCHE
  - Single fluid, cross-flow
  - Add heat pipe holes to plates for HPIHX
  - As interlayers plates become very thin PCHE approaches cross-flow heat exchanger

Chemically etched microchannel [1]

Cutout of diffusion bonded PCHE (VPEI [2])



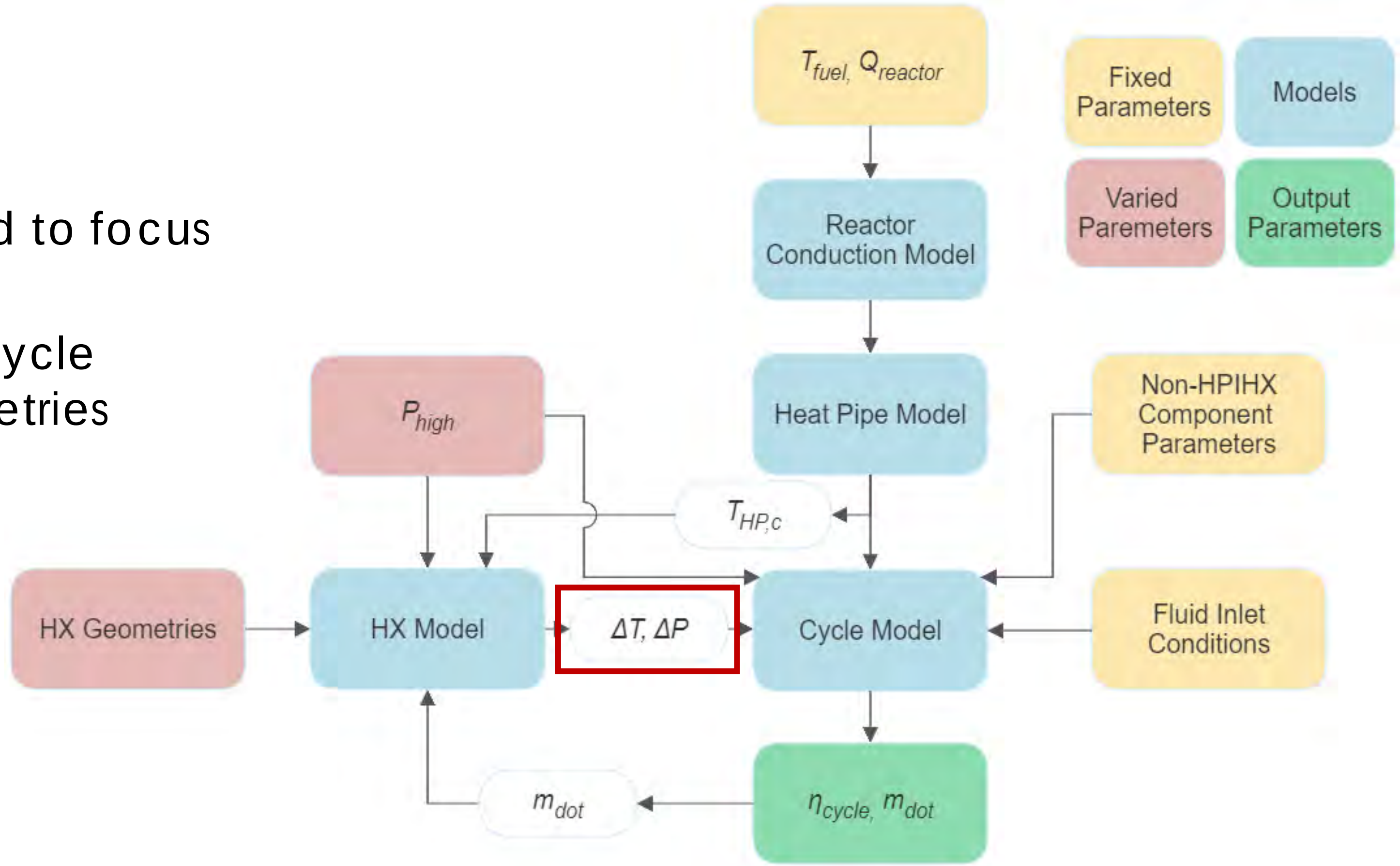
PCHE-based HPIHX



[1] "Diffusion bonded heat exchangers," Vacuum Process Engineering, https://www.vpei.com/diffusion-bonded-microchannel-heat-exchangers/ (accessed Jun. 7, 2023).
[2] "How to model a shell and tube heat exchanger," COMSOL, https://www.comsol.com/blogs/how-model-shell-and-tube-heat-exchanger/ (accessed Jun. 7, 2023).

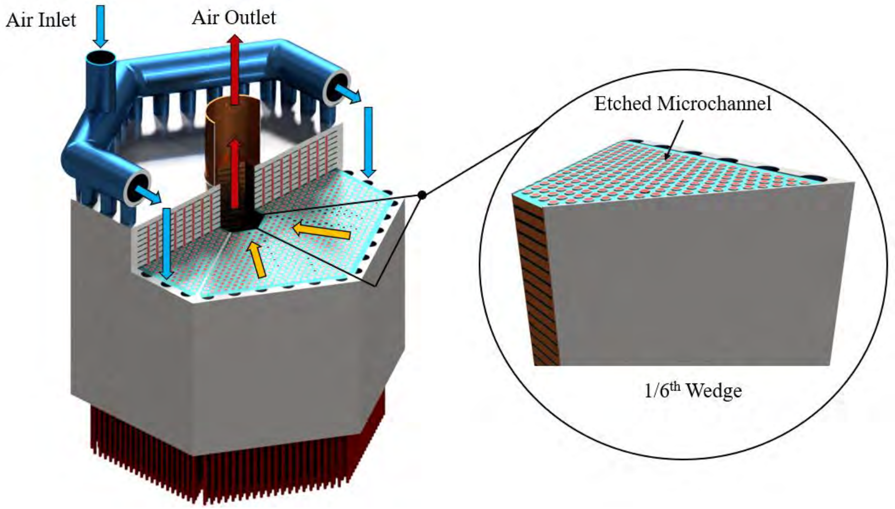
Interface Heat Exchanger Optimization

- Optimized using cycle model
  - o Reactor conduction model
  - o Heat pipe model
  - o Heat exchanger models
  - o All non-HPIHX parameters are fixed to focus analysis on the heat exchanger
  - o Vary HX geometries to maximize cycle efficiency and find optimal geometries
- AFHX and PCHE HX models
- $\Delta P = P_{in} - P_{out}$
- $\Delta T = T_{HX_{max}} - T_{fluid,out}$



Project Organization

- Air Brayton modeling
  - o Develop reactor, HX, and cycle models
  - o Optimize air Brayton HX
- Performance demonstration
  - ➡ o Design and manufacture air test specimen
  - o Demonstrate performance with N_2 at MAGNET
  - ➡ o Demonstrate performance with N_2 at UW
- sCO_2 modeling and testing
  - o Optimize sCO_2 Brayton HX
  - ➡ o Design and manufacture sCO_2 test specimen
  - o Demonstrate performance with sCO_2 at UW

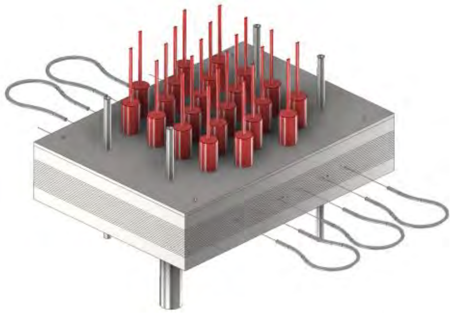


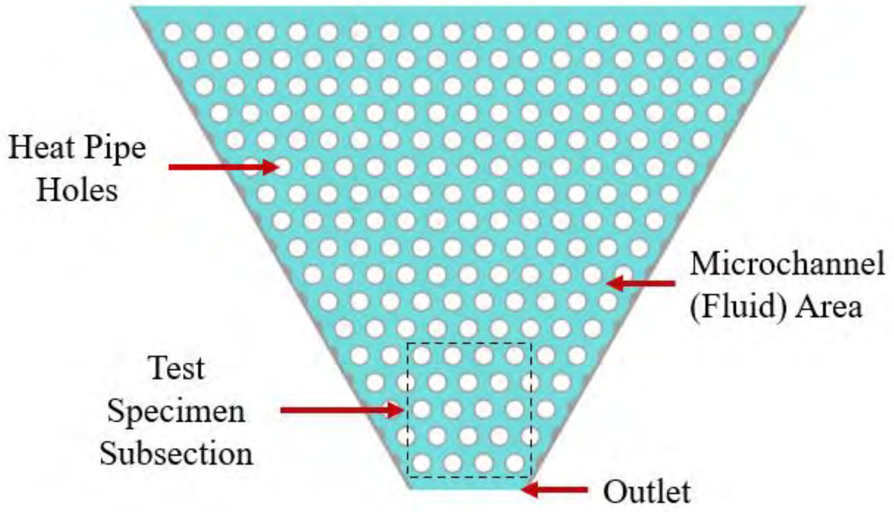
Air Brayton Testing

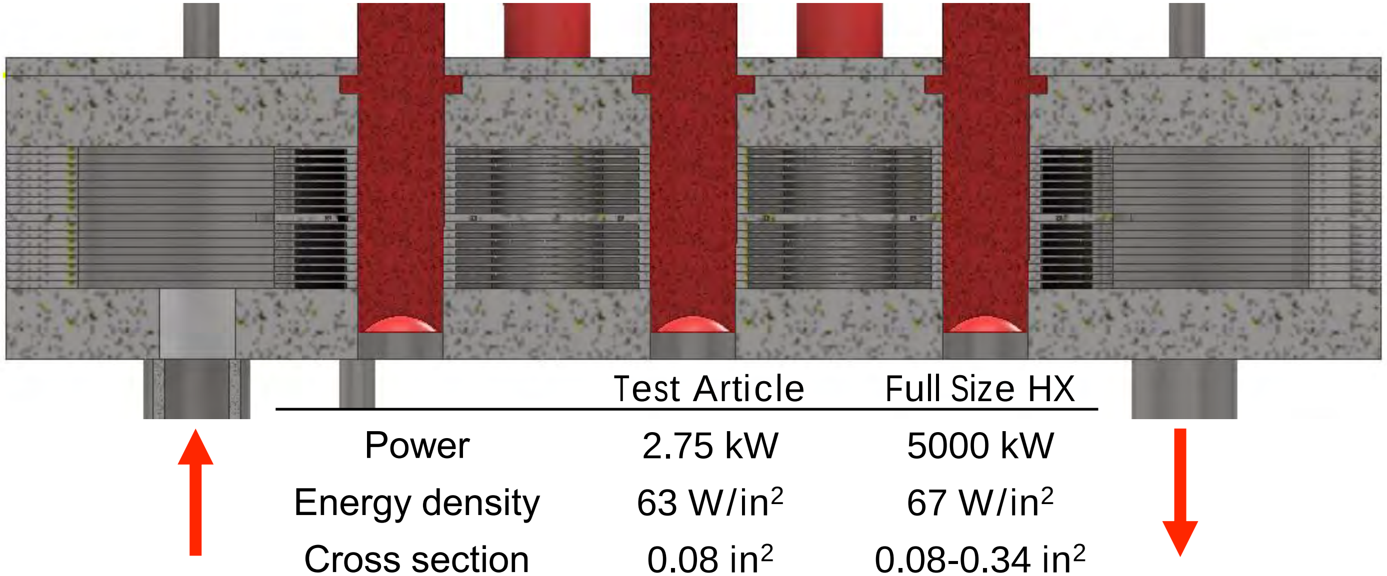
Facility, testing results, validated model

Air Brayton Test Specimen

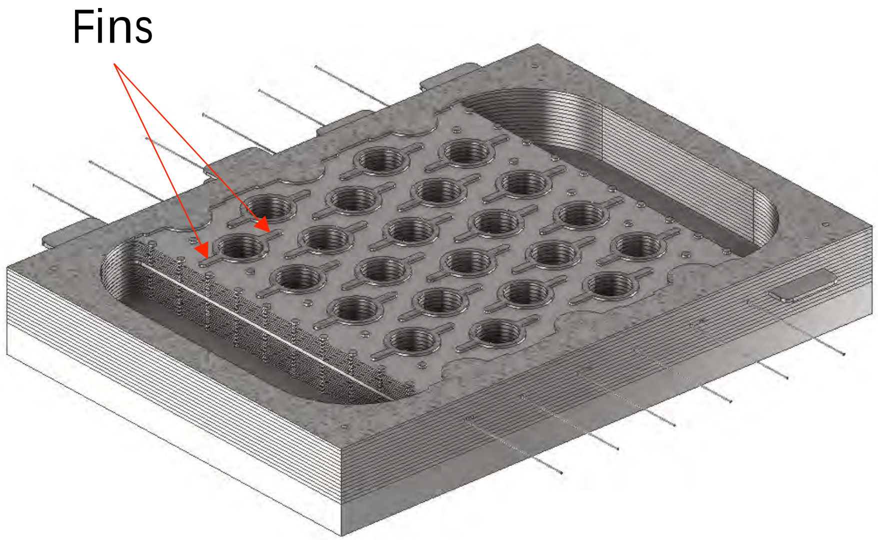
- Diffusion bonded
  - o 16 -1.5 mm 316 SS plates
  - o 1- instrumentation layer
  - o 10" x 7" x 5"
- 22-125 W cartridge heaters
- Subsection replicates conditions of the full "wedge"





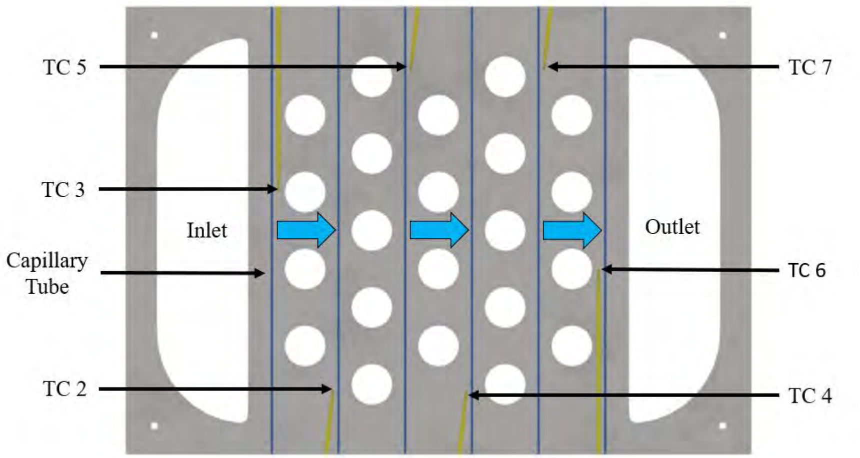


	Test Article	Full Size HX
Power	2.75 kW	5000 kW
Energy density	63 W/in^2	67 W/in^2
Cross section	0.08 in^2	0.08-0.34 in^2
Mass flow rate	0.02-0.08 kg/s	16.4 kg/s

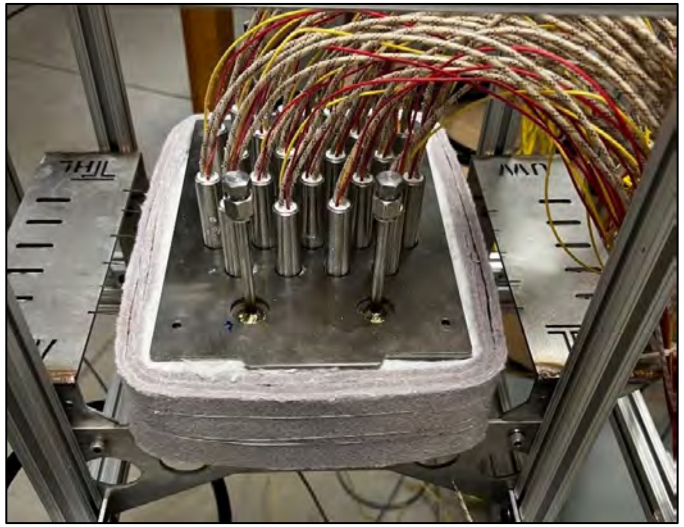


Air Brayton Test Specimen

- Instrumentation
  - 4-pressure taps (2-ΔP measurements)
  - 6-TC probes in instrument layer
  - 6-embedded capillary tubes for fiber optics
  - T_{out} initially located in the header

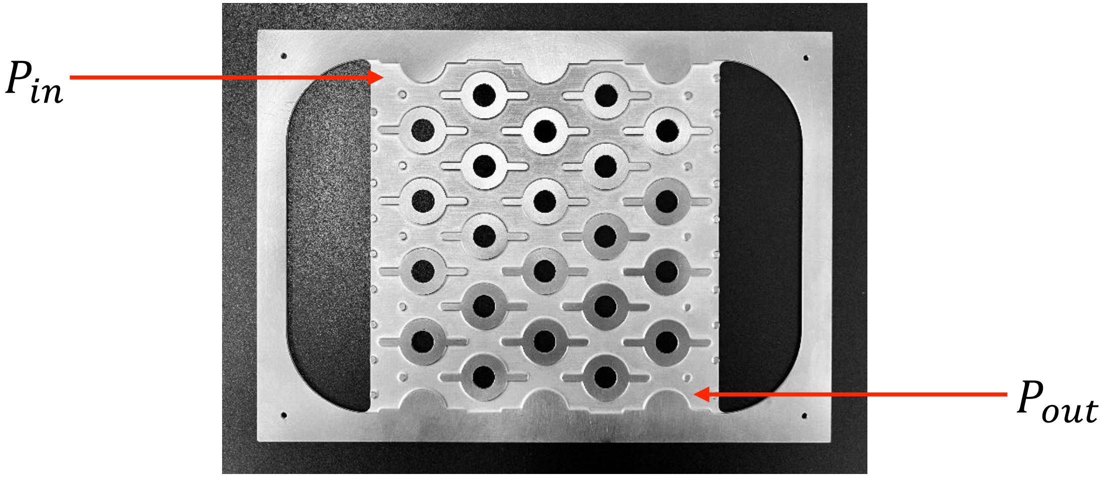


$$\Delta T = T_{hp_{max}} - T_{fluid,out} = TC_6 - T_{fluid,out}$$
$$\Delta P_{channel} = P_{in} - P_{out}$$



Cartridge heaters

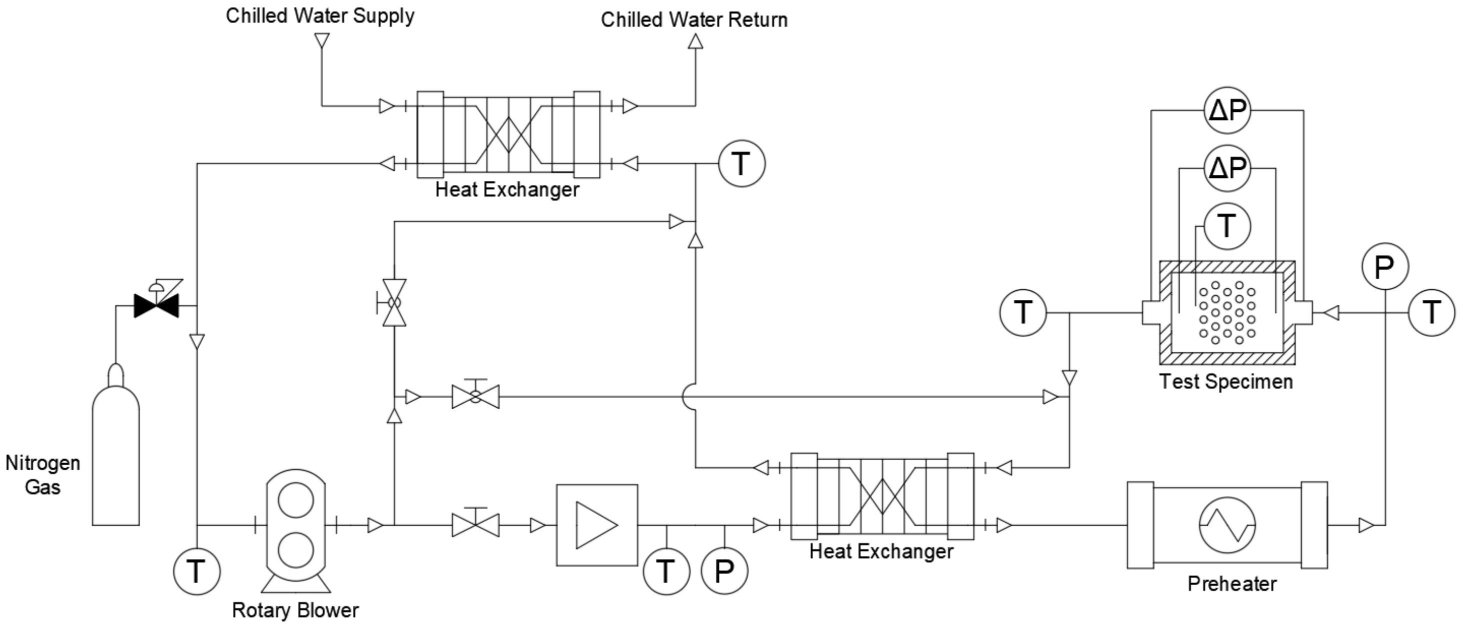
Air test specimen



Air test flow channel

UW Nitrogen Loop

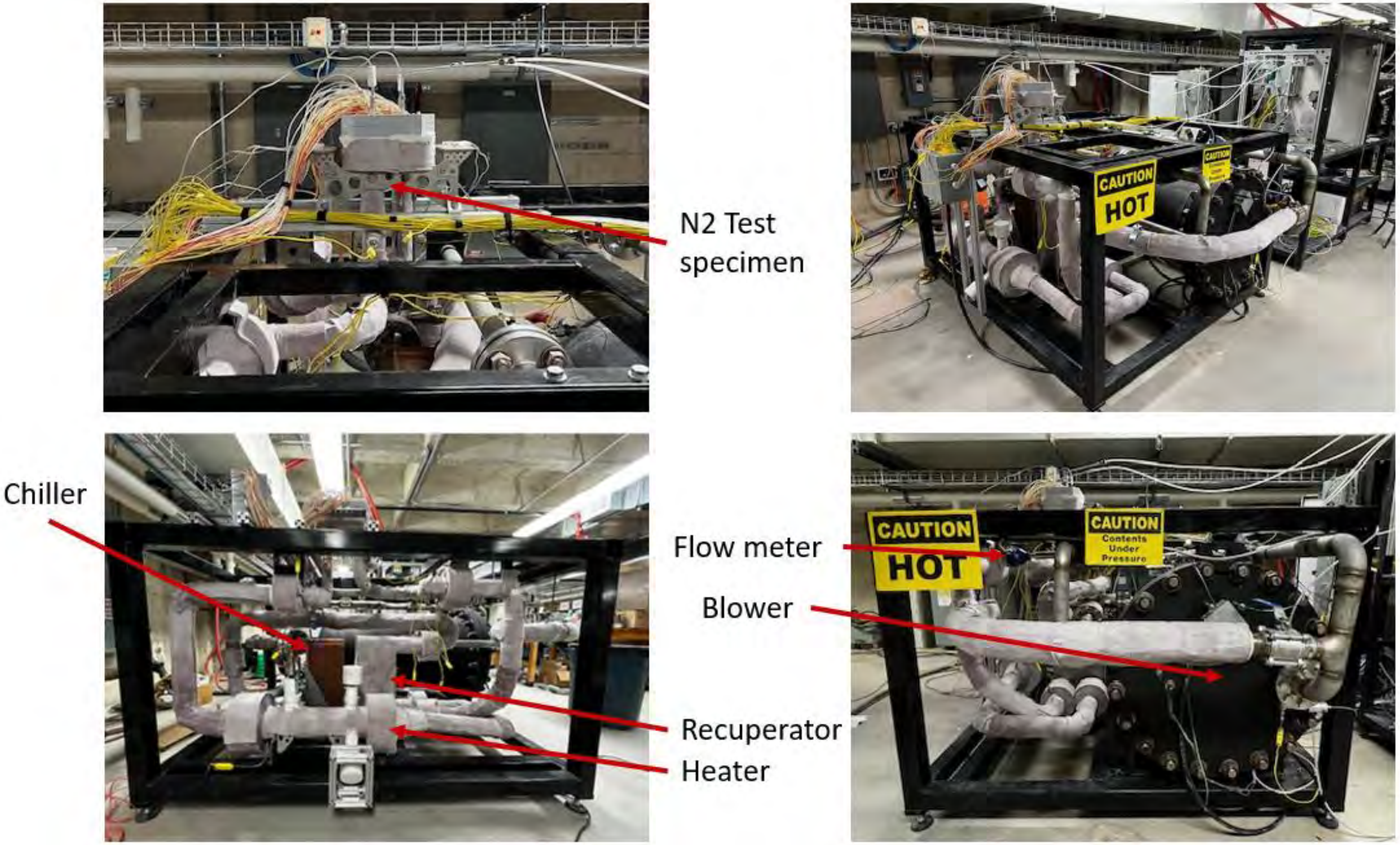
- UW designed operating conditions
  - o $\dot{m}$ ~ 0.02-0.15 kg/s
  - o T_{in} ~ 40-450°C
  - o P_{in} ~ 150-1400 kPa
- Test Matrix
  - o $\dot{m}$ = 0.02-0.1 kg/s
  - o T_{in} = 100-450°C
  - o P_{in} = 400, 550, 700 kPa
  - o $\dot{q}$ =690, 1380, 2060, 2780 W



UW-MAGNET HPIHX Schematic

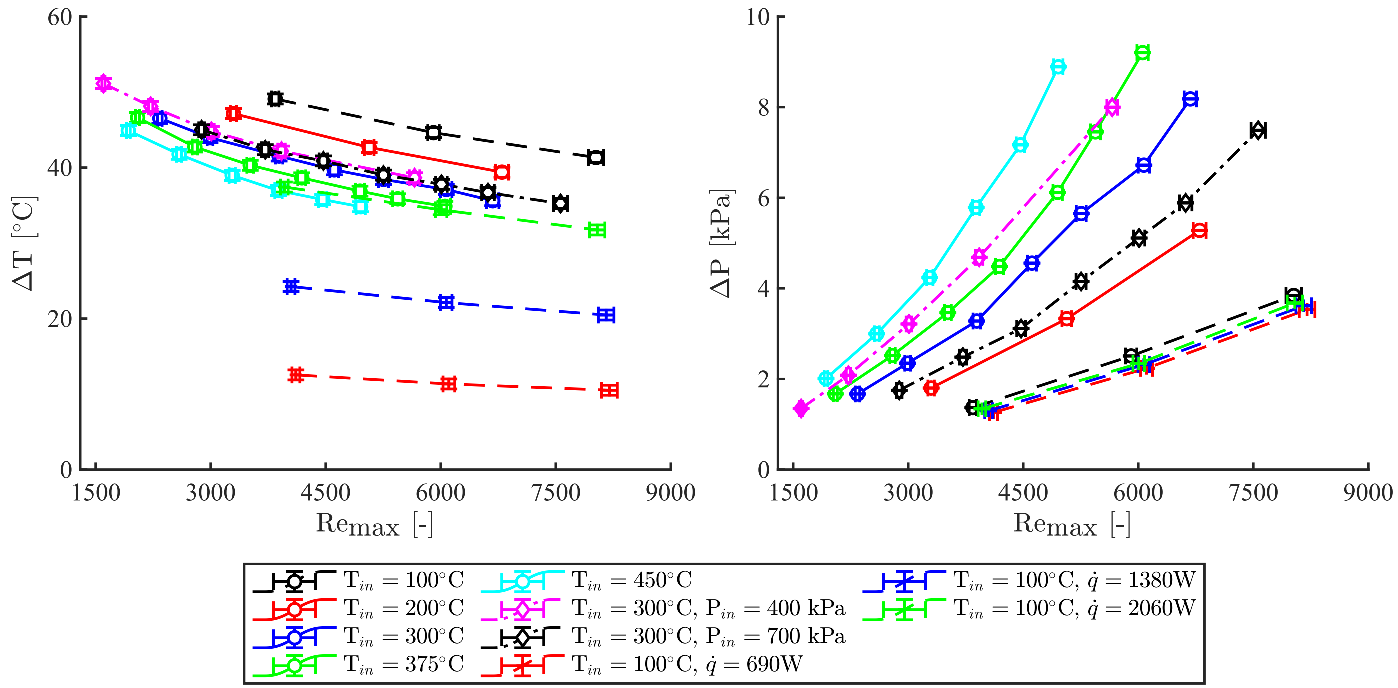
UW Nitrogen Loop

- Blower
  - o Gardner Denver,
- Motor
  - o BlackMax, 11 kW
- Flow meter
  - o Vortex Shedder
- Recuperator & chiller
  - o Kelvin, brazed plate
- Preheater
  - o Osram, 20 kW
- Controls & DAQ
  - o LabView
  - o NI compactRIO system



Testing Results

- Approach temperature vs. Reynolds
  - o Increased $\dot{q}$ → increased ΔT
  - o Increased T_{in} → decreased ΔT
  - o Varied P_{in} ~ no impact
- Pressure drop vs. Reynolds
  - o Varied $\dot{q}$ ~ no impact
  - o Increased T_{in} → increased ΔP
  - o Increased P_{in} → decreased ΔP

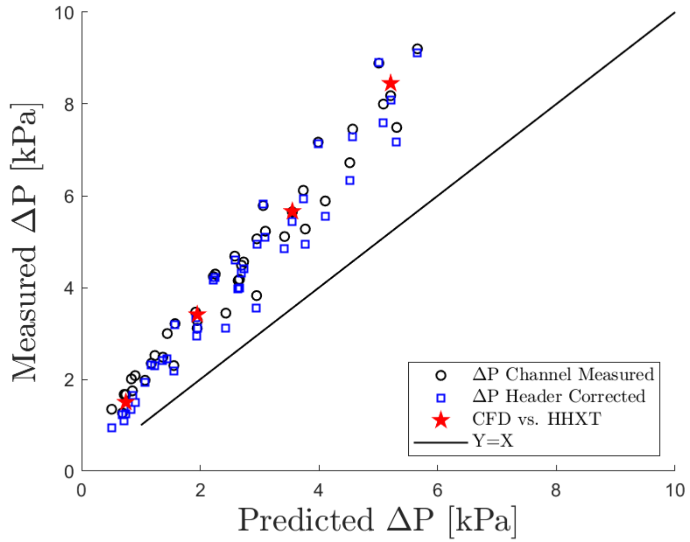


Nitrogen test results

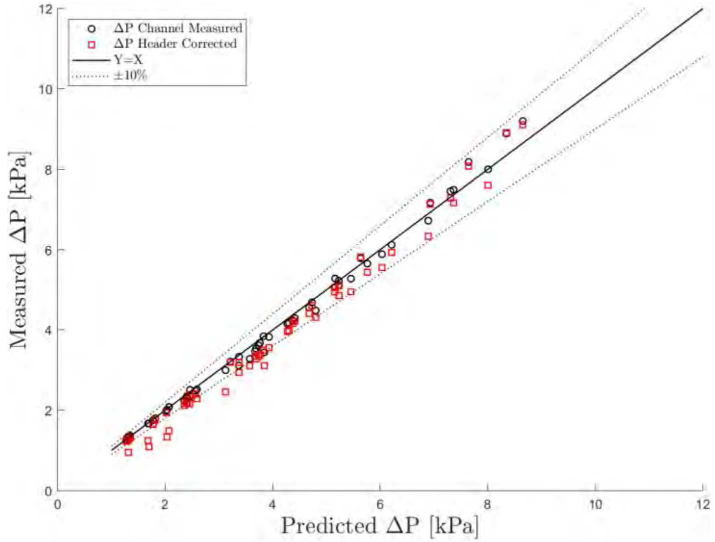
Experiment vs. Model

- Pressure drop test vs. model
  - Initial model (top) underpredicted ΔP
    - Colebrook friction factor
  - Calculated average friction factor
    - $\bar{f} = \frac{2\Delta P_{channel} D_h}{\rho v^2 L}$
  - Friction factor correlation was generated for HHXT model
    - $\bar{f}_{HHXT} = aRe_{max}^b$
    - b was fixed to maintain behavior
    - a was varied to minimize model error
  - Updated model (bottom) predicted experimental pressure drop within 10%

Initial Model



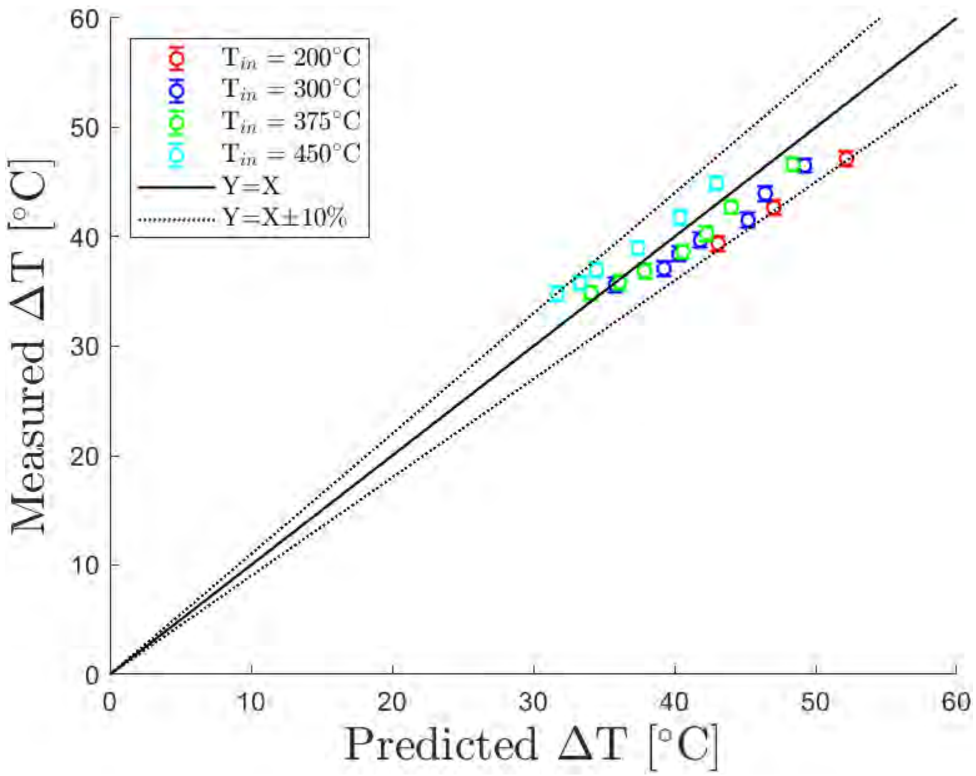
Updated Model



Approach Temp. Test vs. Model

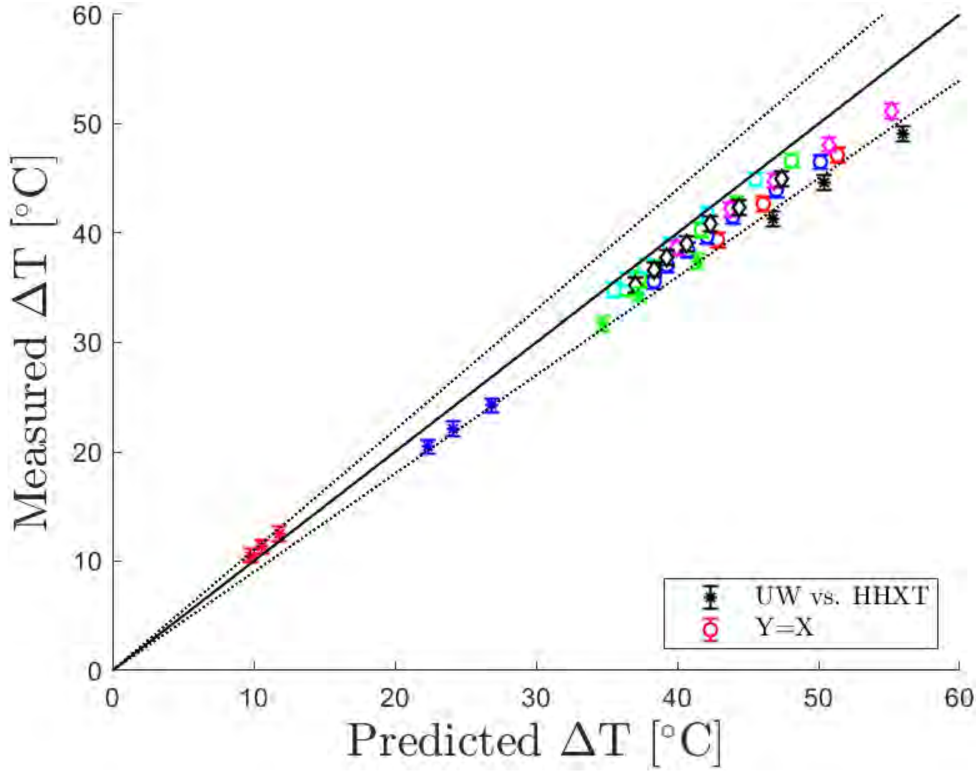
- Initial results showed general agreement within 15%
- Attributed the spread at different temperatures to heat losses
- Accounting for heat losses at elevated temperatures collapsed the points
- Relatively small change to the data results in trends agreeing between model and experiment

Initial experiment vs. model



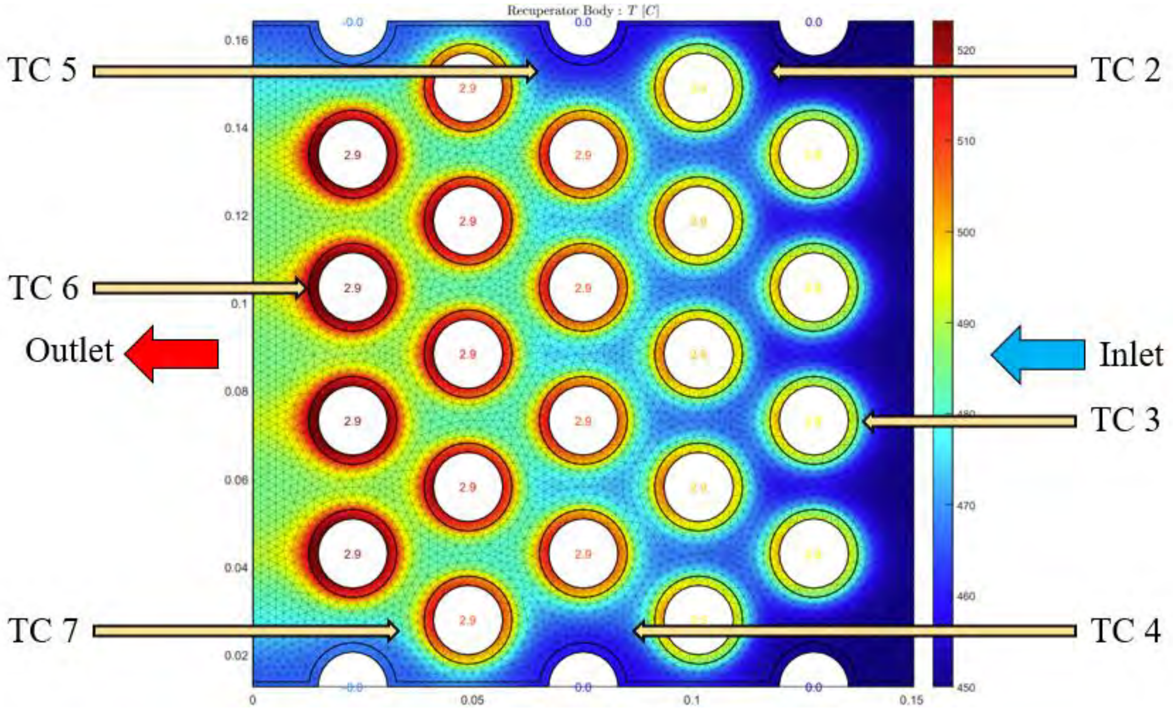
Experiment vs. Model

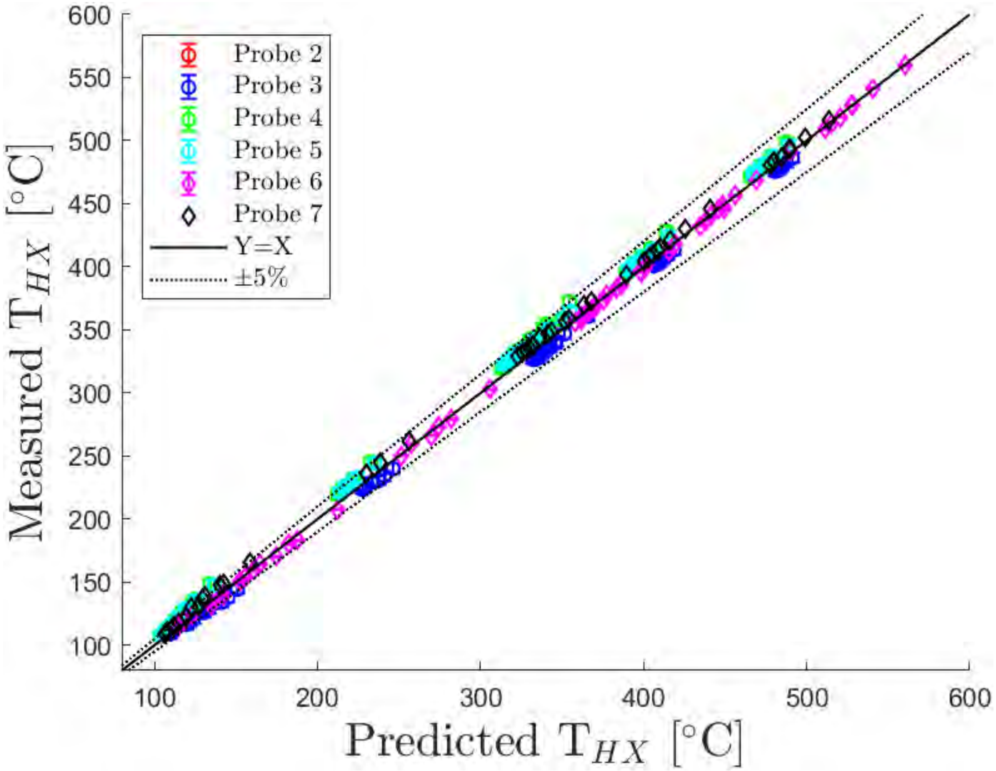
- Approach temperature test vs. model
  - After correction for heat losses all but 3 predicted values within 10% of experiment
  - Overprediction in general, partially due to fin geometry not being resolved by the model



Experiment vs. Model

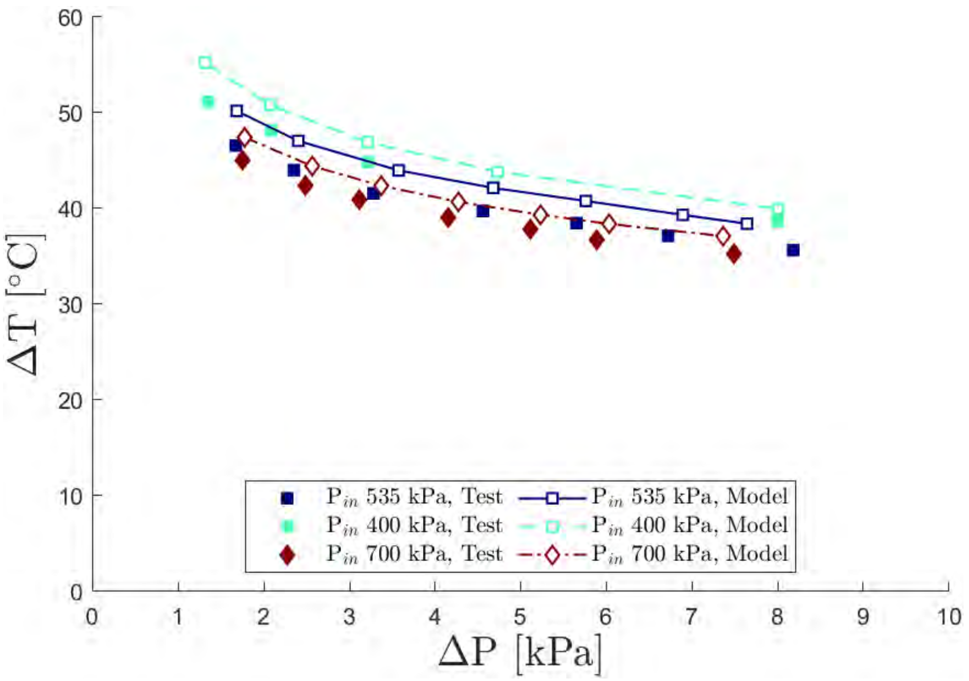
- Temperature probes versus model
  - Generally, fall within 5% of predicted value
  - TC 3 and TC 6 very close agreement (heater wall)
  - TC 2, 4, 5, 7 have fin effect from increased layer thickness of instrument layer ~(2.5 mm versus 0.5 mm)



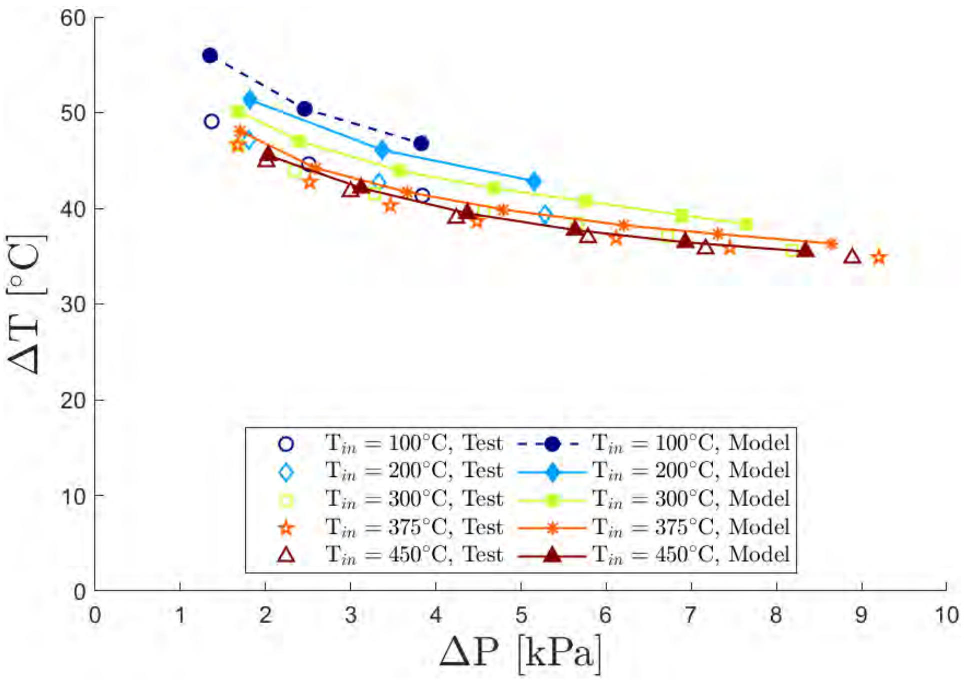


Experiment vs. Model

- Test and model, ΔT vs. ΔP
  - Varied pressures
  - Trends show agreement
- Model validation → cycle model

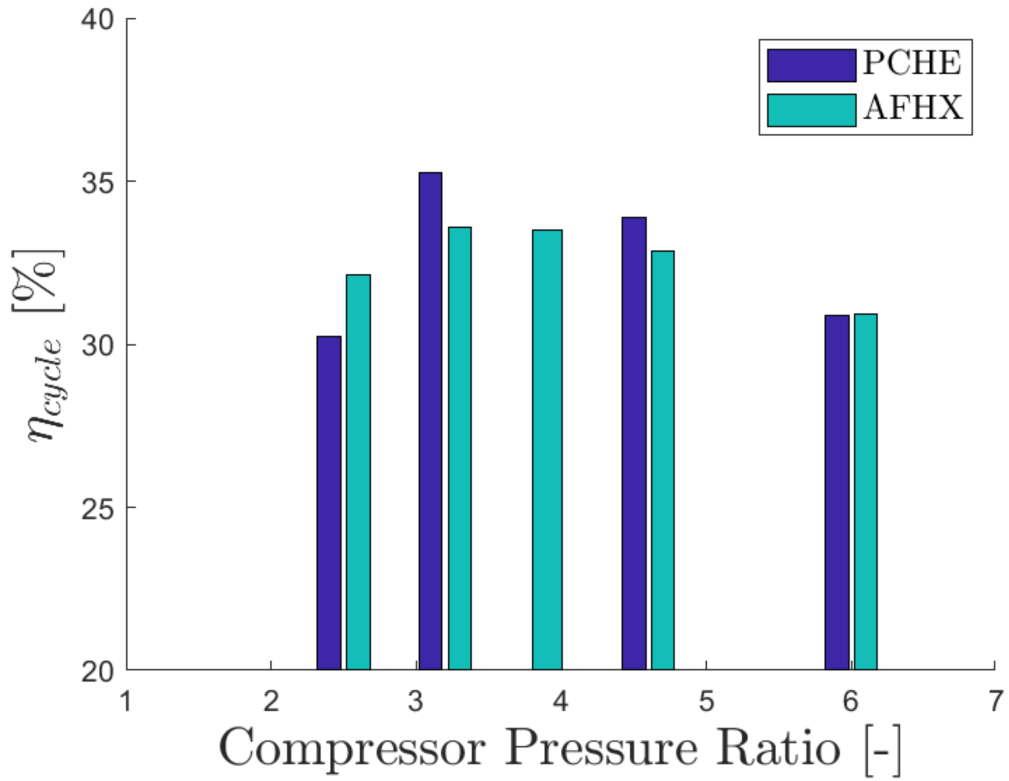


- Test and model, ΔT vs. ΔP
  - Varied temperature
  - Error (model overpredicts) as $T_{in} \downarrow$ indicates the predicted performance is conservative



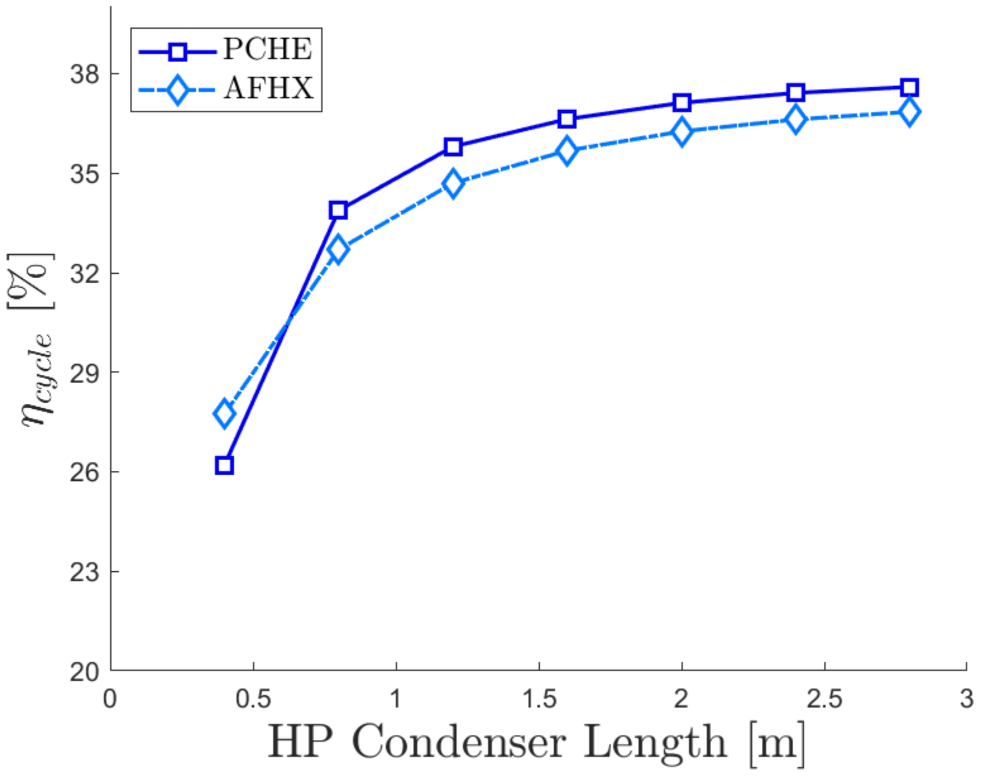
Validated Cycle Model Results

- Updated HHXT model
  - New friction factor correlation
  - General increase in pressure drop
  - Slight shift of previous optimal and decrease in efficiency (2.2% → 1%)
- AFHX and PCHE comparison
  - PCHE – 33.9% (460 kPa)
  - AFHX – 32.9% (460 kPa)
  - PCHE – 35.3% (320 kPa)
  - AFHX – 33.6% (320 kPa)



Heat Pipe Length Study

- Varied heat pipe condenser length (460 kPa)
  - Limit near 38% as condenser length increases
  - Below 0.8 m performance and cycle efficiency has significant decrease
- 3.2% increase for PCHE (0.8 m to 2.0 m)
- 3.6% increase for AFHX (0.8 m to 2.0 m)
- At 2.8 m
  - PCHE – 37.6%
  - AFHX – 36.9%
- Westinghouse has manufactured heat pipes up to 4 m

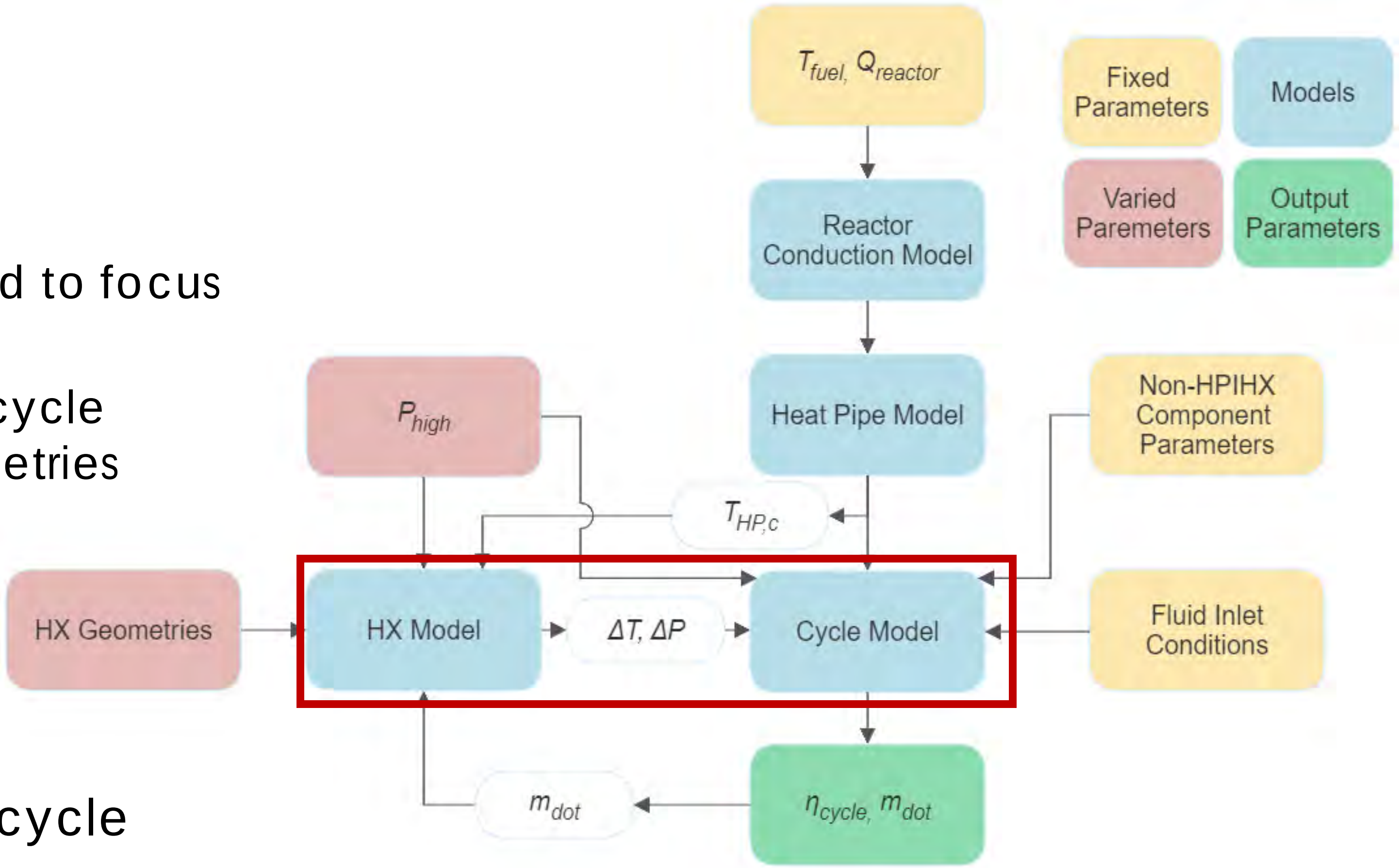


sCO_2 Optimization

Model, results, test article

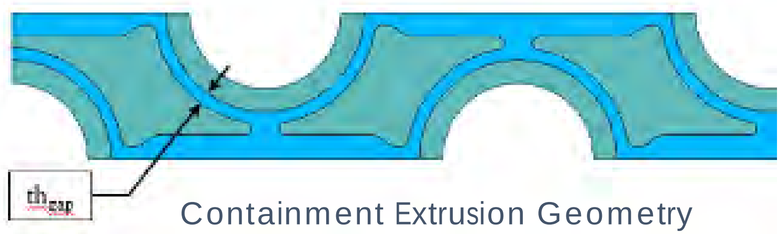
Interface Heat Exchanger Optimization

- Optimized using cycle model
  - Reactor conduction model
  - Heat pipe model
  - Heat exchanger models
  - All non-HPIHX parameters are fixed to focus analysis on the heat exchanger
  - Vary HX geometries to maximize cycle efficiency and find optimal geometries
- AFHX and PCHE HX models
- $\Delta P = P_{in} - P_{out}$
- $\Delta T = T_{hp_{max}} - T_{fluid,out}$
- Air Brayton cycle → sCO_2 Brayton cycle
- HHXT PCHE model → CFD PCHE model

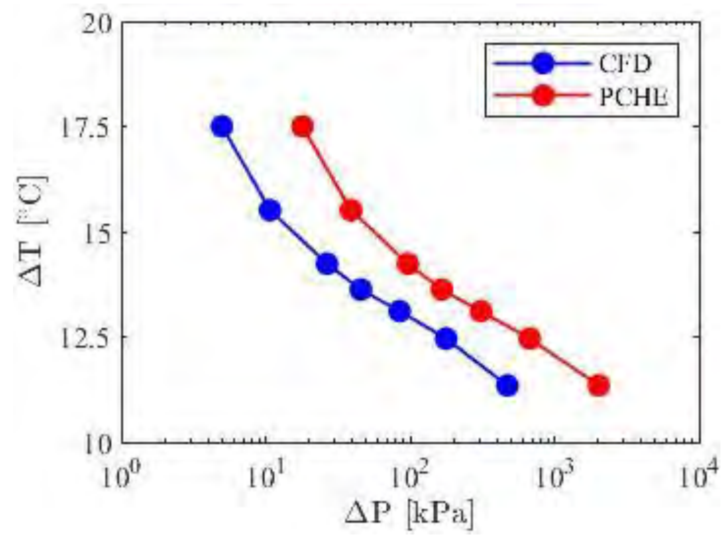


CFD Unit Cell Results

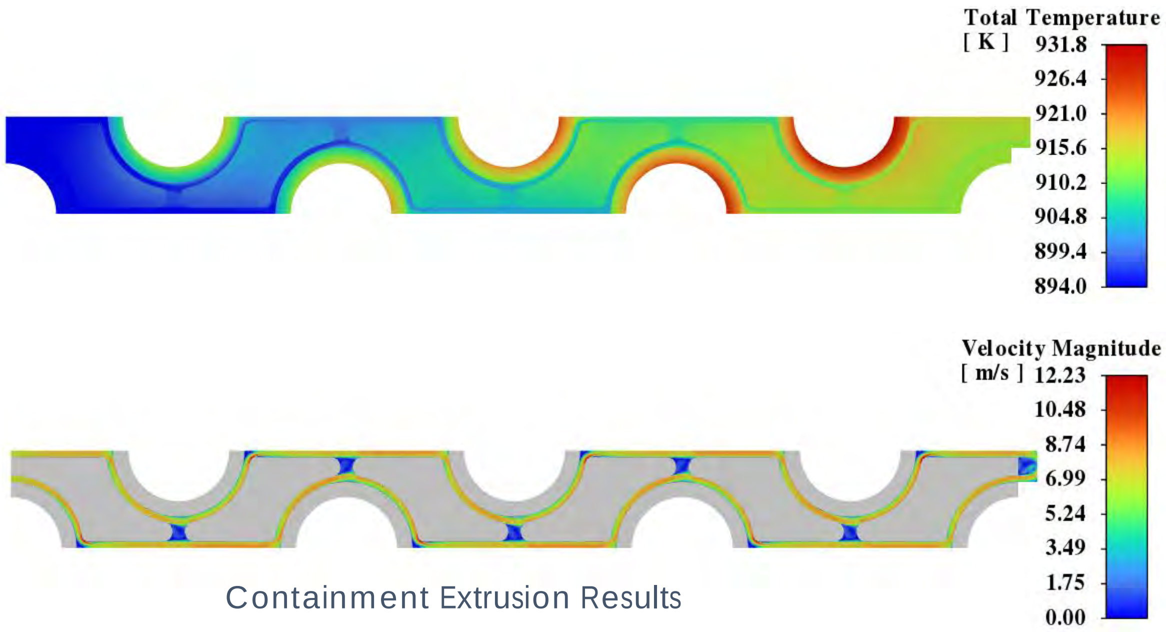
- Further refinement of best geometry
  - Channel thickness varied: $th_{gap} = 0.25 - 1.5$ [mm]
  - Openings to prevent full channel blockage
- Unit cell pressure drop used to calculate full sized PCHE pressure drop for cycle model



Containment Extrusion Geometry



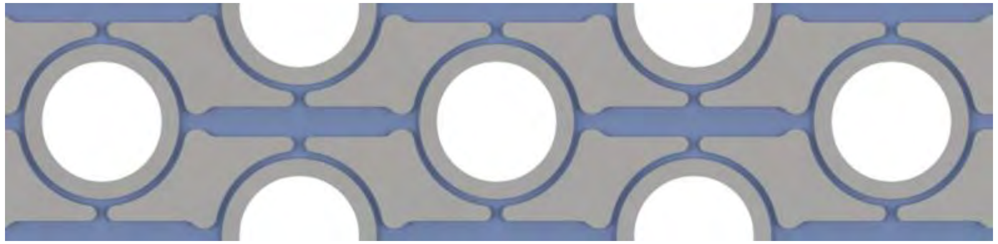
CFD unit cell approach temperature and pressure drop



Containment Extrusion Results

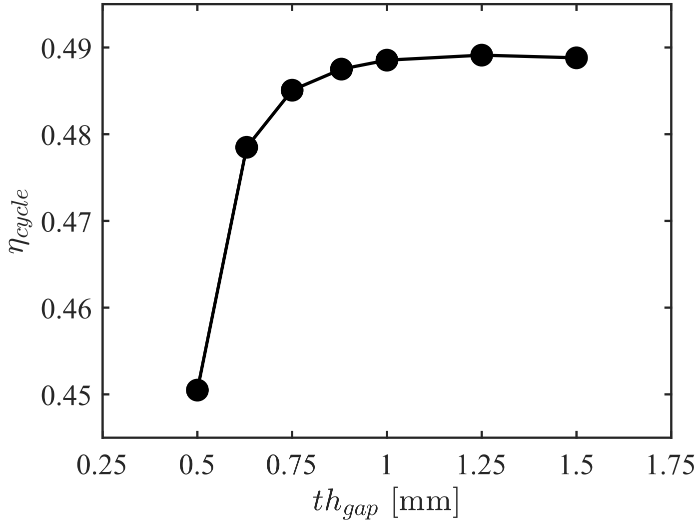
sCO_2 Cycle Analysis

- Incorporated PCHE model into sCO2 cycle
  - Solved steady-state pressure and temperature across PCHE
  - Optimized channel thickness: $\boldsymbol{th_{gap,opt} = 1.25\ mm}$
- sCO_2 Brayton cycle efficiency improved 13.3% over the air Brayton cycle



Optimized geometry

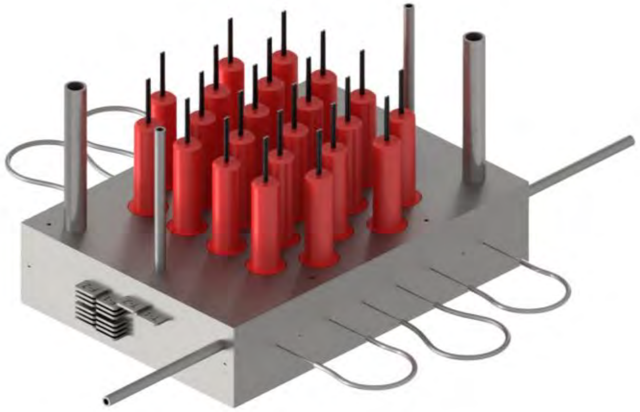
Heat Exchanger	Annular/PCHE Gap	Cycle Efficiency	**ΔP [kPa]**	**ΔT [°C]**
AFHX (air)	1.9 mm	34.3 %	32.6	51.1
PCHE (air)	1.0 mm	35.3 %	14.2	43.1
PCHE (sCO_2)	0.6 mm	48.6 %	39.0	15.5

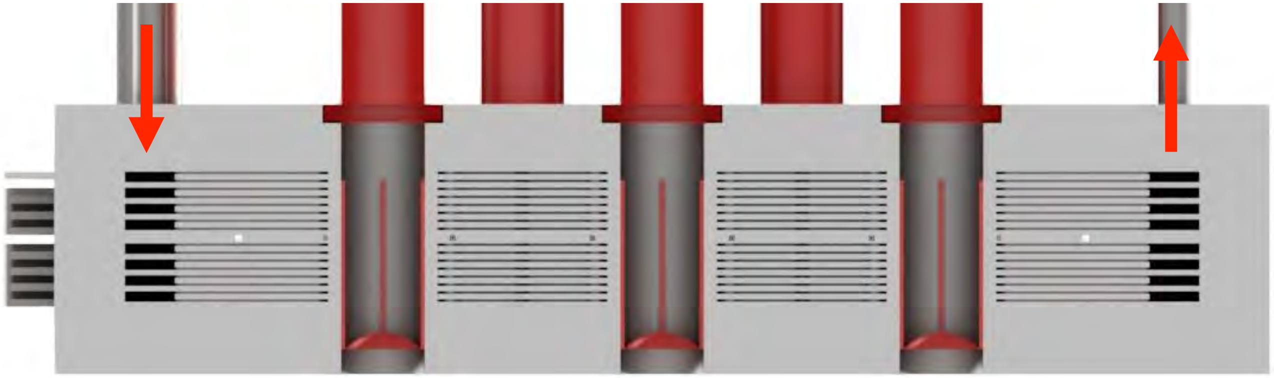


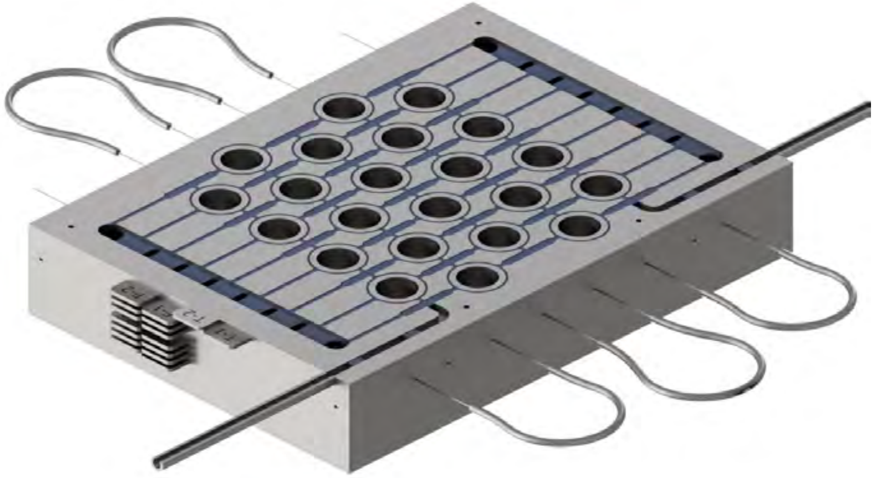
Cycle efficiency vs channel thickness

sCO_2 Brayton Test Specimen

- Design pressure 20 MPa
  - o 16 -1.5 mm 316 SS plates
  - o 1- instrumentation layer w/ TC's and FOTS
  - o 9.5" x 6.5" x 2"
- 22-130 W cartridge heaters
- Can replicate conditions of the full "wedge"



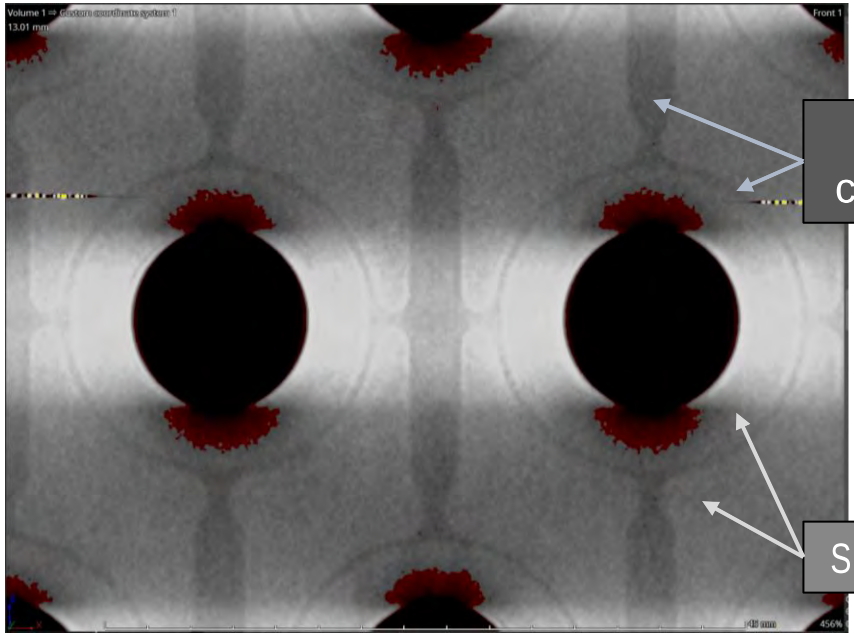


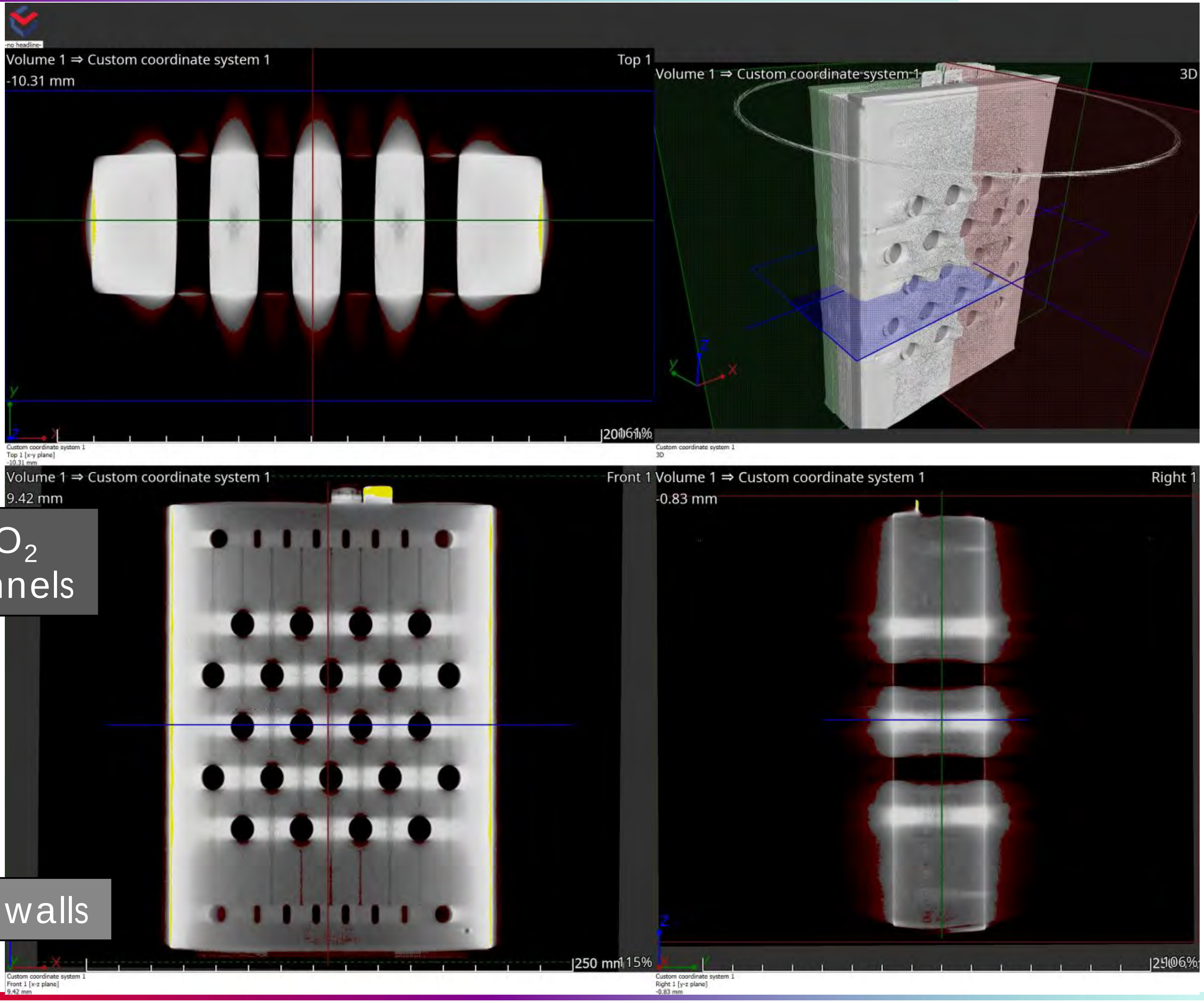


	Test Article	Full Size HX
Power	2.75 kW	5000 kW
Energy density	66 W/in^2	67 W/in^2
Cross section	0.08 in^2	0.08-0.34 in^2
Mass flow rate	0.06-0.16 kg/s	24.5 kg/s

sCO_2 Brayton Test Specimen

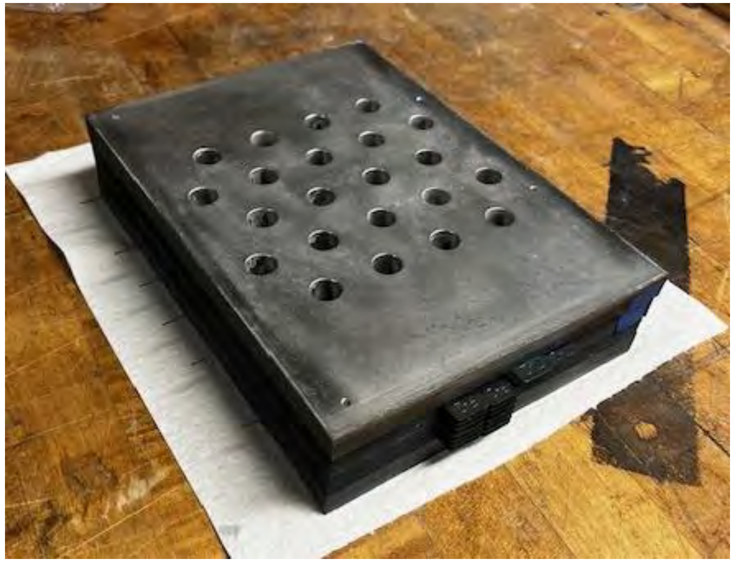
- CT Scan
- sCO_2 test specimen
- Can visualize the flow channels
- Get dimensions before machining





Next Steps – HPIHX

- Conclusions
  - o Experimental data was used to validate HHXT model for PCHE
  - o With the validated model cycle efficiency for the PCHE showed improvement over AFHX
  - o Increased heat pipe length increase efficiency ~ 3-5%
  - o PCHE channel geometry optimized for sCO_2 Brayton cycle with CFD
  - o Increased cycle efficiency over air Brayton cycle by ~ 13%
- Next steps
  - o Manufacture and test sCO_2 test article
  - o Demonstrate performance and model validity
  - o Test with fiber optic temperature sensors
  - o Final report



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Questions?

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