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Cost Reduction for Advanced Integration Heat Exchanger Technology for Microreactors

Microreactor Program Review
NEUP Project 21-24226

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

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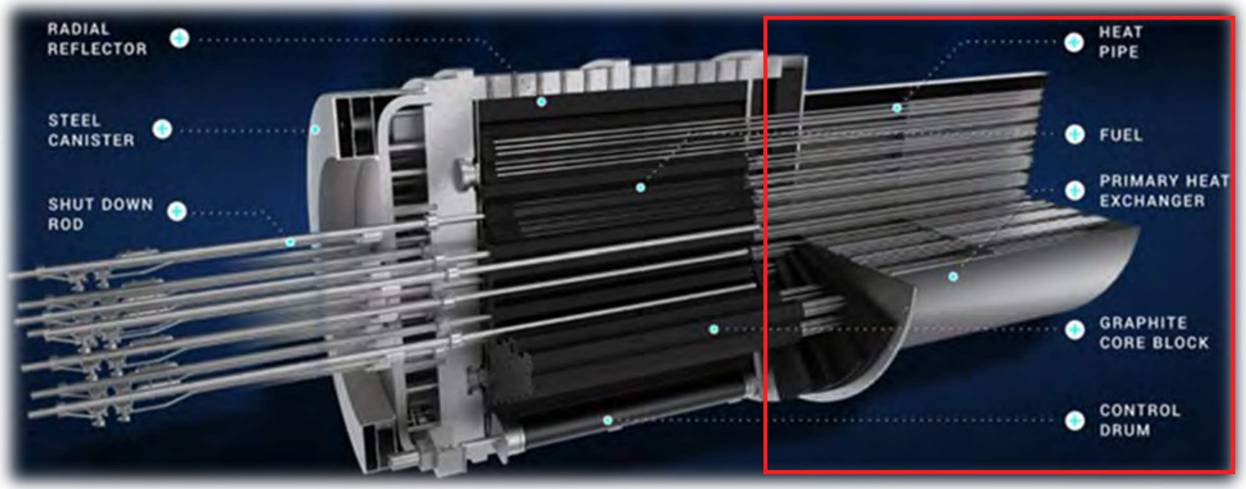
Presentation Overview

- Project background and organization
- Previous work
- Air Brayton test specimen testing
- sCO_2 HX design optimization
- Heat pipe manufacturing, imaging, and testing

Interface Heat Exchanger

Objectives

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

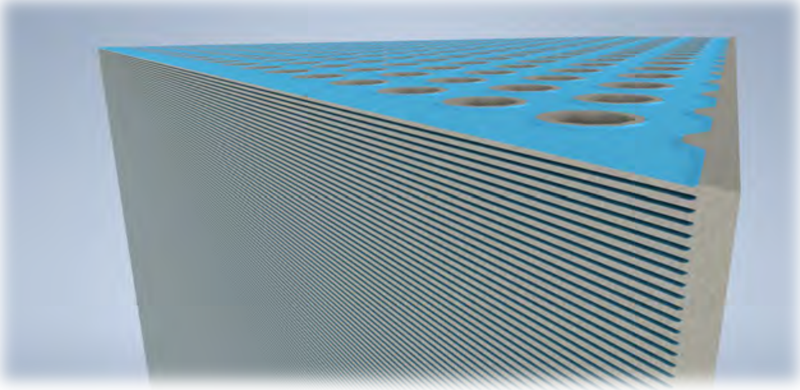


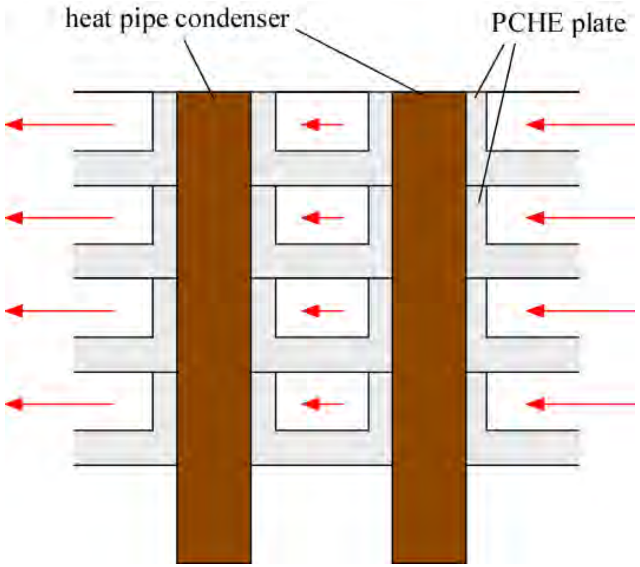
eVinci™ Micro-Reactor, Courtesy of Westinghouse Electric Company LLC

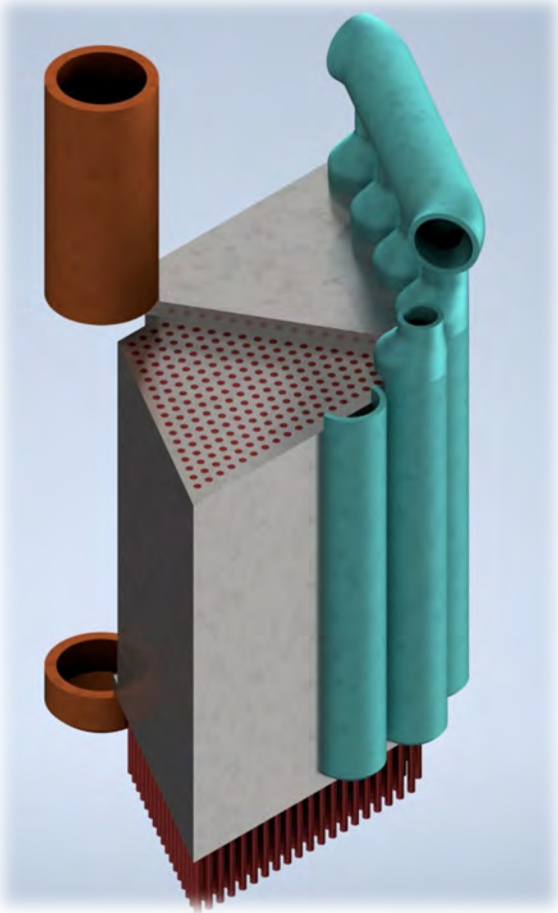
PCHE-Based Interface Heat Exchanger

Potential advantages (Morton, 2020 [1])

- Mature technology.
- Additional geometric degrees of freedom.
- Plates provide additional surface area
- Low susceptibility to single channel blockage.
- Reduced axial temperature gradient.
- Uniform condenser temperature (per heat pipe) takes advantage of the entire condenser section.
- High pressure capability of PCHE geometry.





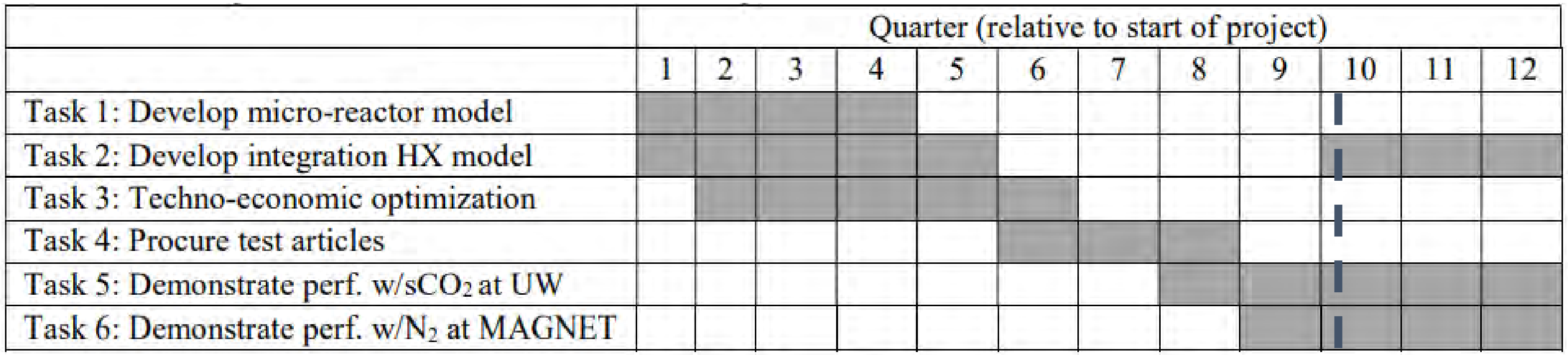


Concept of a PCHE-based integration heat exchanger

[1] Morton, T.J., *Integrated Energy Systems Development*, INL/MIS-20-59847D, Sep. (2020).

Project Organization

- Phase I
    - o Develop reactor, HX, and cycle models
    - o Optimize air Brayton HX
- Phase II
    - o Design and manufacture air test specimen
    - o Demonstrate performance with N_2 at MAGNET
- Phase III
    - o Optimize sCO_2 Brayton HX
    - o Design and manufacture sCO_2 test specimen
    - o Demonstrate performance with sCO_2 at UW



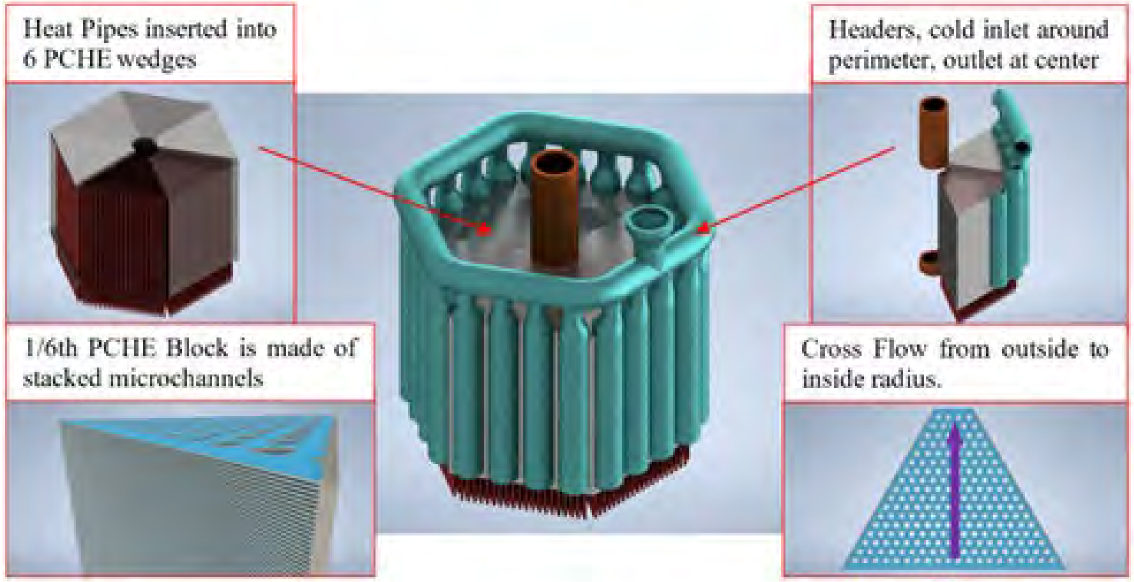
	Quarter (relative to start of project)											
	1	2	3	4	5	6	7	8	9	10	11	12
Task 1: Develop micro-reactor model	▨	▨	▨	▨								
Task 2: Develop integration HX model	▨	▨	▨	▨	▨					▨	▨	▨
Task 3: Techno-economic optimization		▨	▨	▨	▨	▨						
Task 4: Procure test articles						▨	▨	▨				
Task 5: Demonstrate perf. w/sCO_2 at UW								▨	▨	▨	▨	▨
Task 6: Demonstrate perf. w/N_2 at MAGNET									▨	▨	▨	▨

PHASE I Work

Modeling and Optimization

Previous Work (Design)

- PCHE design
  - 5 MW Special Purpose Reactor [2]
    - 1224 heat pipes
  - 6-diffusion bonded blocks
  - 533 microchannels (0.8 m)
    - Etched into 1.5 mm thick plates

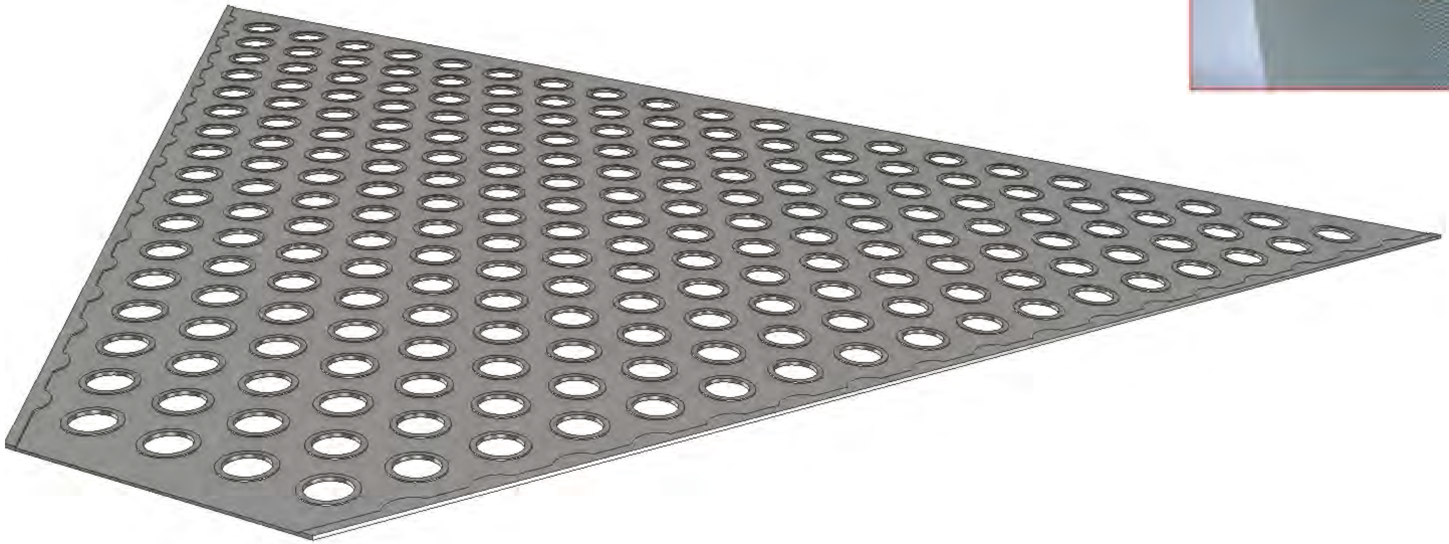


Heat Pipes inserted into 6 PCHE wedges

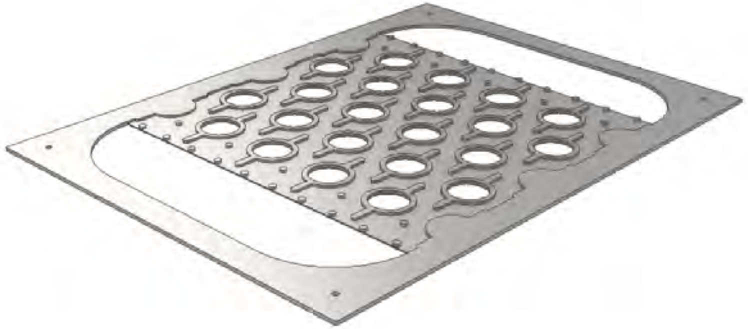
Headers, cold inlet around perimeter, outlet at center

1/6th PCHE Block is made of stacked microchannels

Cross Flow from outside to inside radius.



PCHE microchannel



Test specimen microchannel

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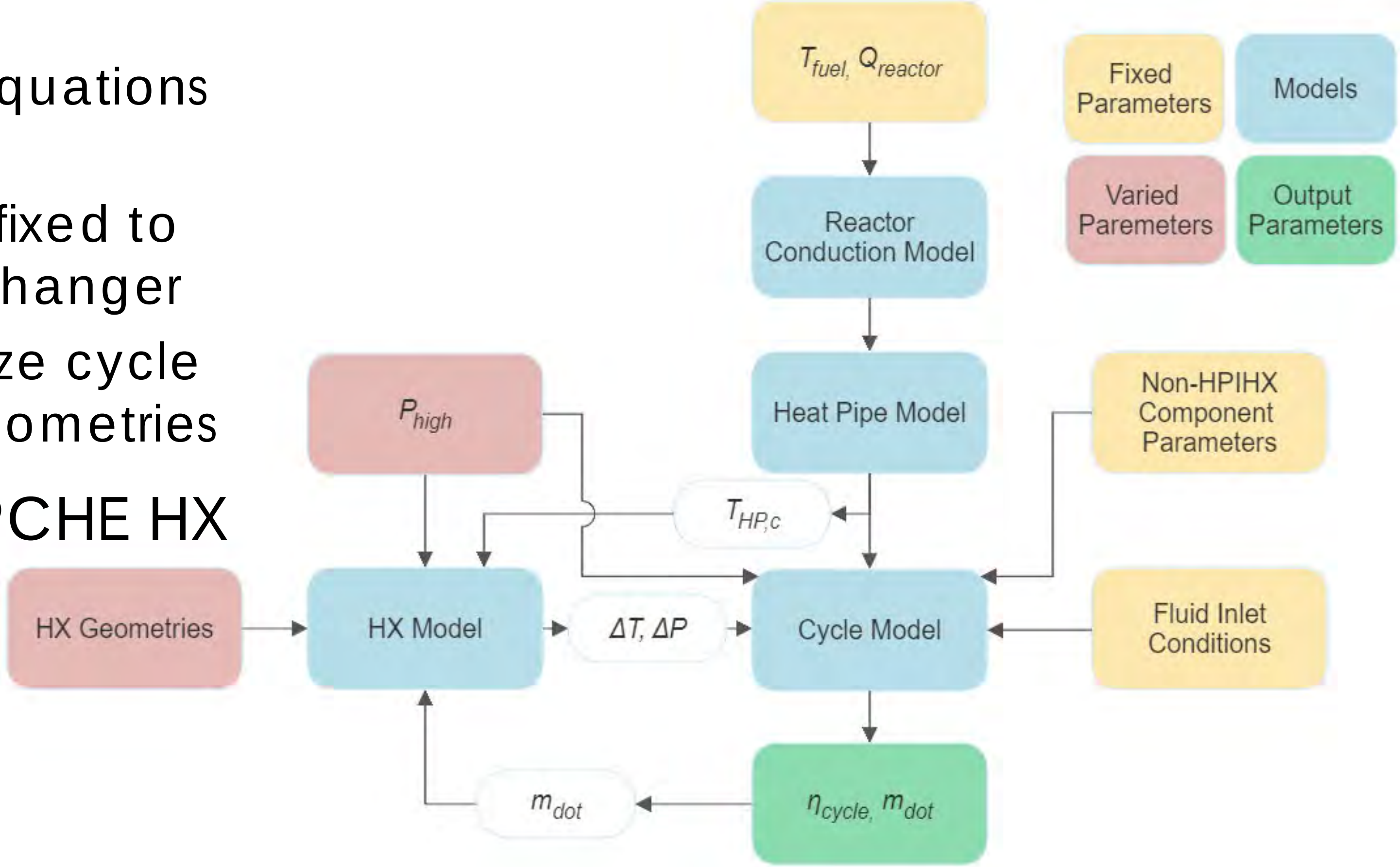
[2] J. W. Sterbentz, et al., “Special purpose nuclear reactor (5 MW) for reliable power at Remote Sites Assessment Report,” 2017.

Previous Work (Modeling)

- Cycle model
  - Implemented in Engineering Equations Solver (EES) [3]
  - All non-HPIHX parameters are fixed to focus analysis on the heat exchanger
  - Vary HX geometries to maximize cycle efficiency and find optimal geometries
- Performed using AFHX and PCHE HX models



[3] Klein, S.A., *EES – Engineering Equation Solver*, Version 11.303, F-Chart Software, https://fchartsoftware.com

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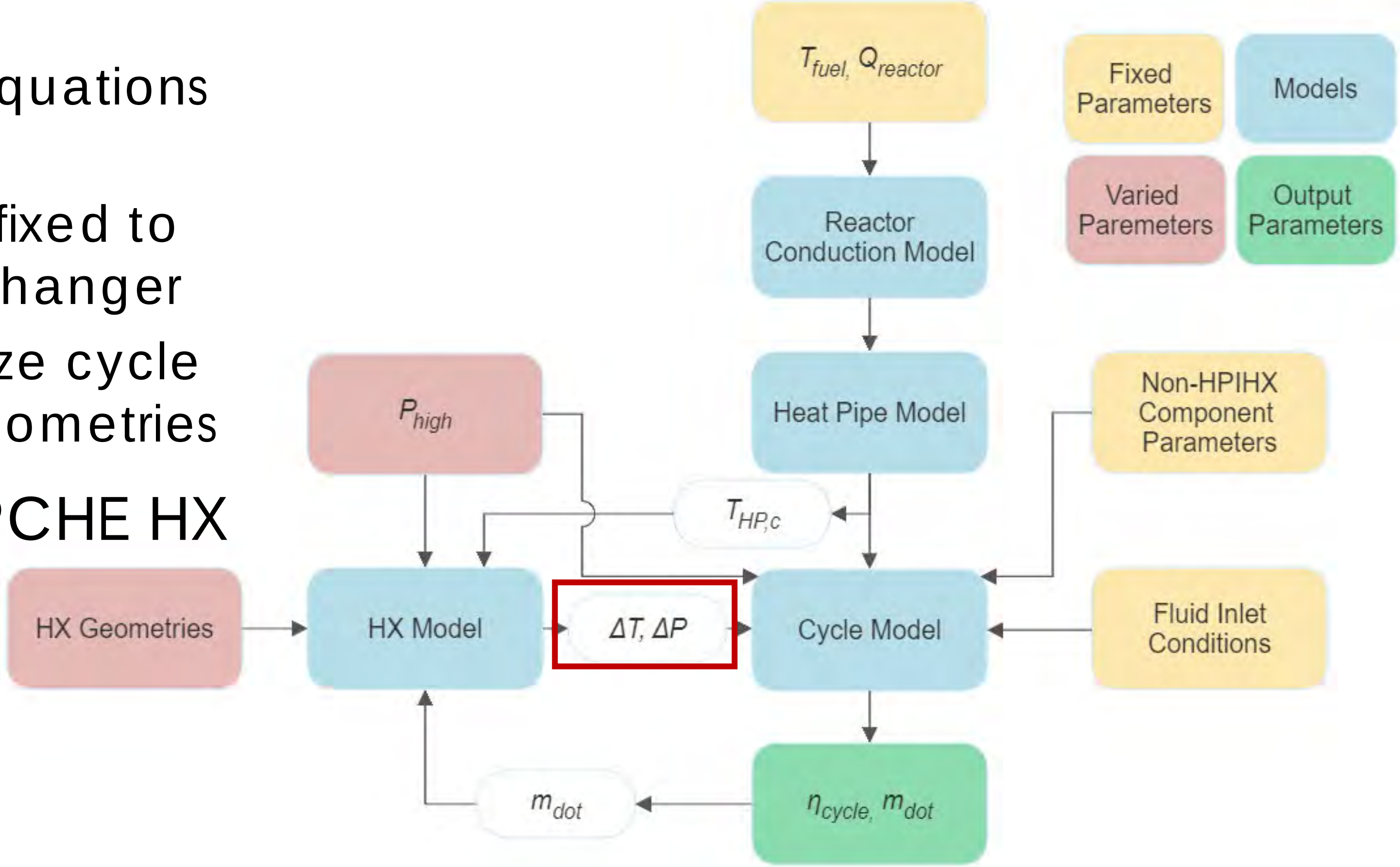
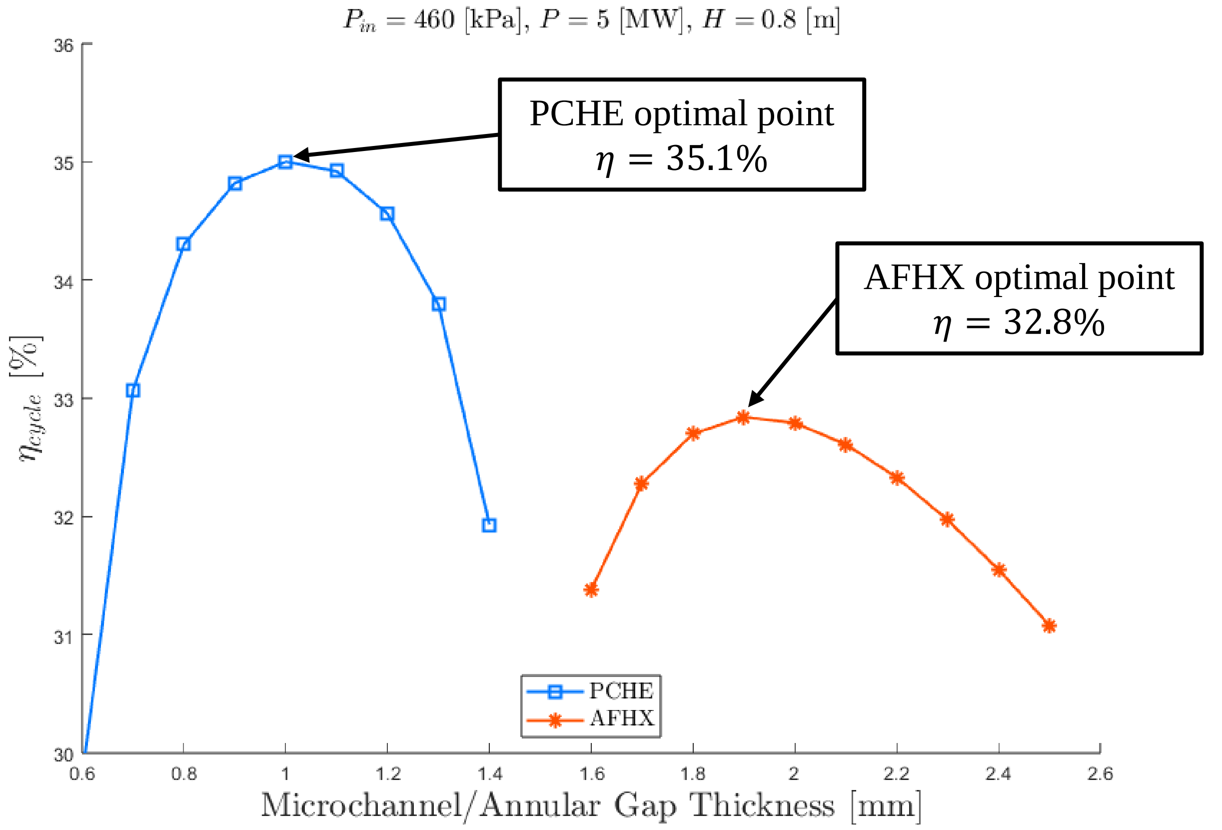


[3] Klein, S.A., *EES – Engineering Equation Solver*, Version 11.303, F-Chart Software, https://fchartsoftware.com

Previous Work (Results)

- Optimized HX geometries
  - Based on cycle efficiency
- Microchannel thickness
  - 1.0 mm
- Annular Gap
  - 1.9 mm
- PCHE increased cycle efficiency
  - Due to lower approach temperature and lower pressure drop



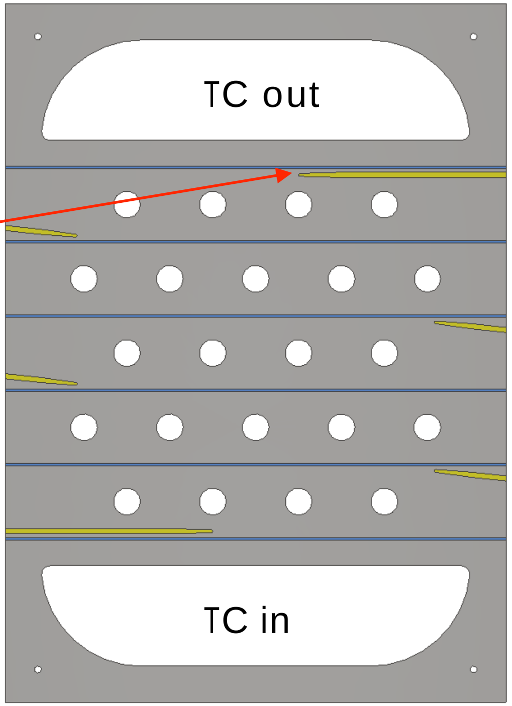
PHASE II Work

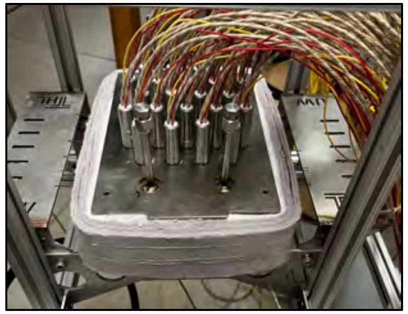
Air Brayton Test Specimen

Air Brayton Test Specimen

- Diffusion bonded
  - o 16 -1.5 mm 316 SS plates
- Machined heater holes
  - o Heater OD + 0.001”
- Instrumentation
  - o 4-pressure taps (2-ΔP measurements)
  - o 2-TC’s (1 in each header plenum)
  - o 6-TC probes in
- Heaters
  - o 22-125 W cartridge heaters (69 $\mathrm{W/in^2}$)

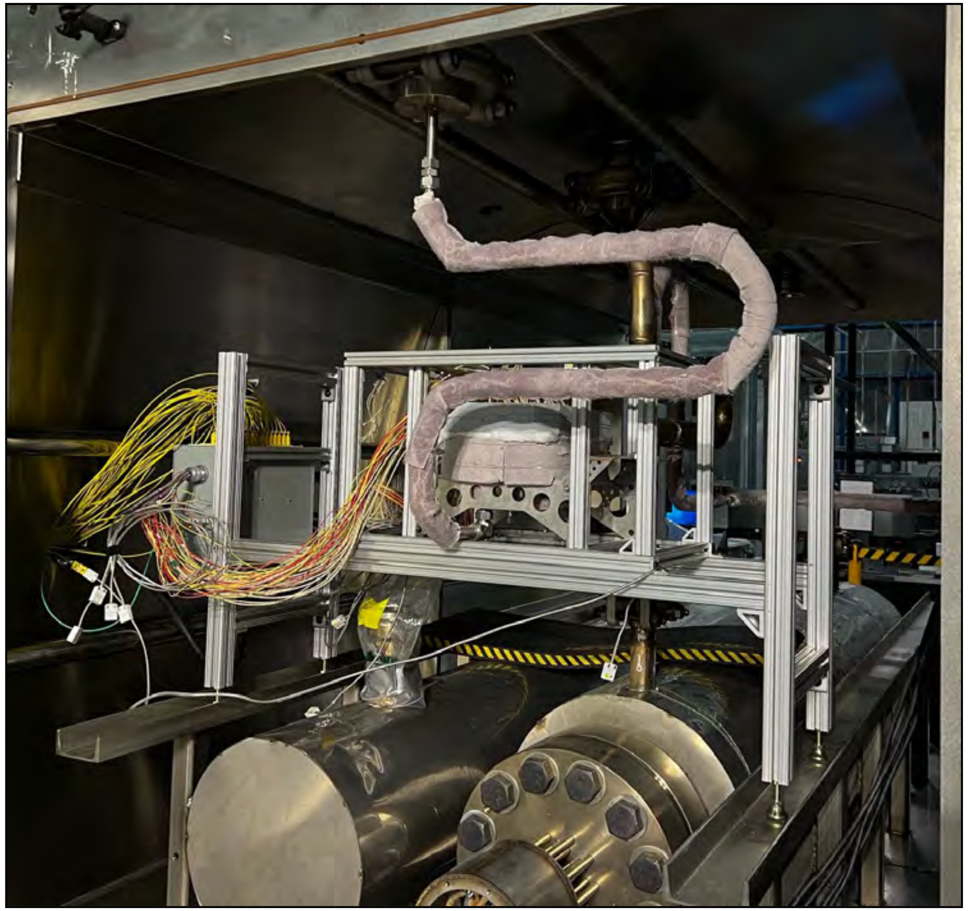

Air test specimen




Cartridge heaters

Integration with MAGNET

- UW control panel
  - o Test specimen heater control
  - o Test specimen data acquisition
- MAGNET facility
  - o $\dot{m}, T_{in}, P_{in}$ control
  - o $\dot{m}$ data acquisition

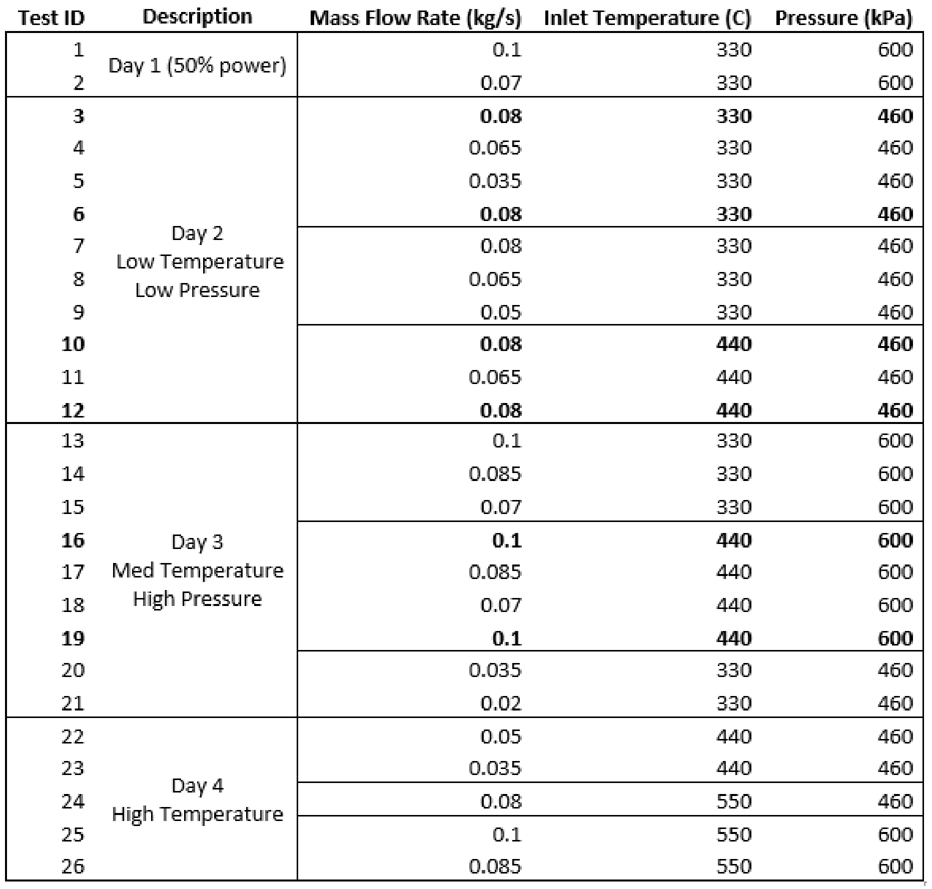


Test specimen in the MAGNET chamber

UW control panel

Testing Conditions

- Mass flow rate
  - o 0.02-0.1 kg/s
- Inlet temperature
  - o 330-550 C°
- Inlet pressure
  - o 550 and 680 kPa
- Test specimen
  - o Max temperature 650 C°

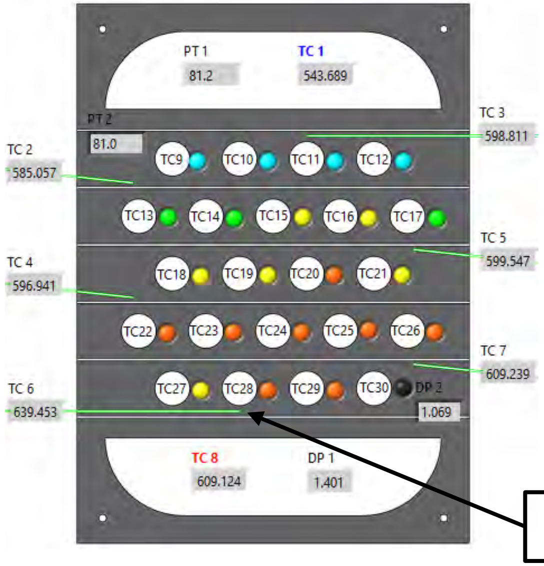


Test ID	Description	Mass Flow Rate (kg/s)	Inlet Temperature (C)	Pressure (kPa)
1	Day 1 (50% power)	0.1	330	600
2		0.07	330	600
3	Day 2 Low Temperature Low Pressure	**0.08**	**330**	**460**
4		0.065	330	460
5		0.035	330	460
6		**0.08**	**330**	**460**
7		0.08	330	460
8		0.065	330	460
9		0.05	330	460
10		**0.08**	**440**	**460**
11		0.065	440	460
12		**0.08**	**440**	**460**
13	Day 3 Med Temperature High Pressure	0.1	330	600
14		0.085	330	600
15		0.07	330	600
16		**0.1**	**440**	**600**
17		0.085	440	600
18		0.07	440	600
19		**0.1**	**440**	**600**
20		0.035	330	460
21		0.02	330	460
22	Day 4 High Temperature	0.05	440	460
23		0.035	440	460
24		0.08	550	460
25		0.1	550	600
26		0.085	550	600

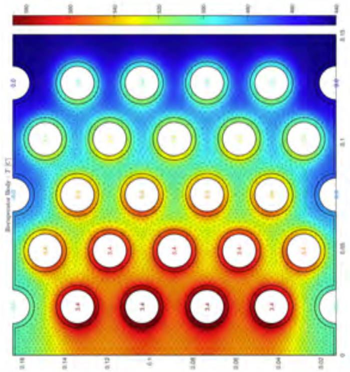
UW-MAGNET HPIHX Test Matrix

Heat Transfer Performance

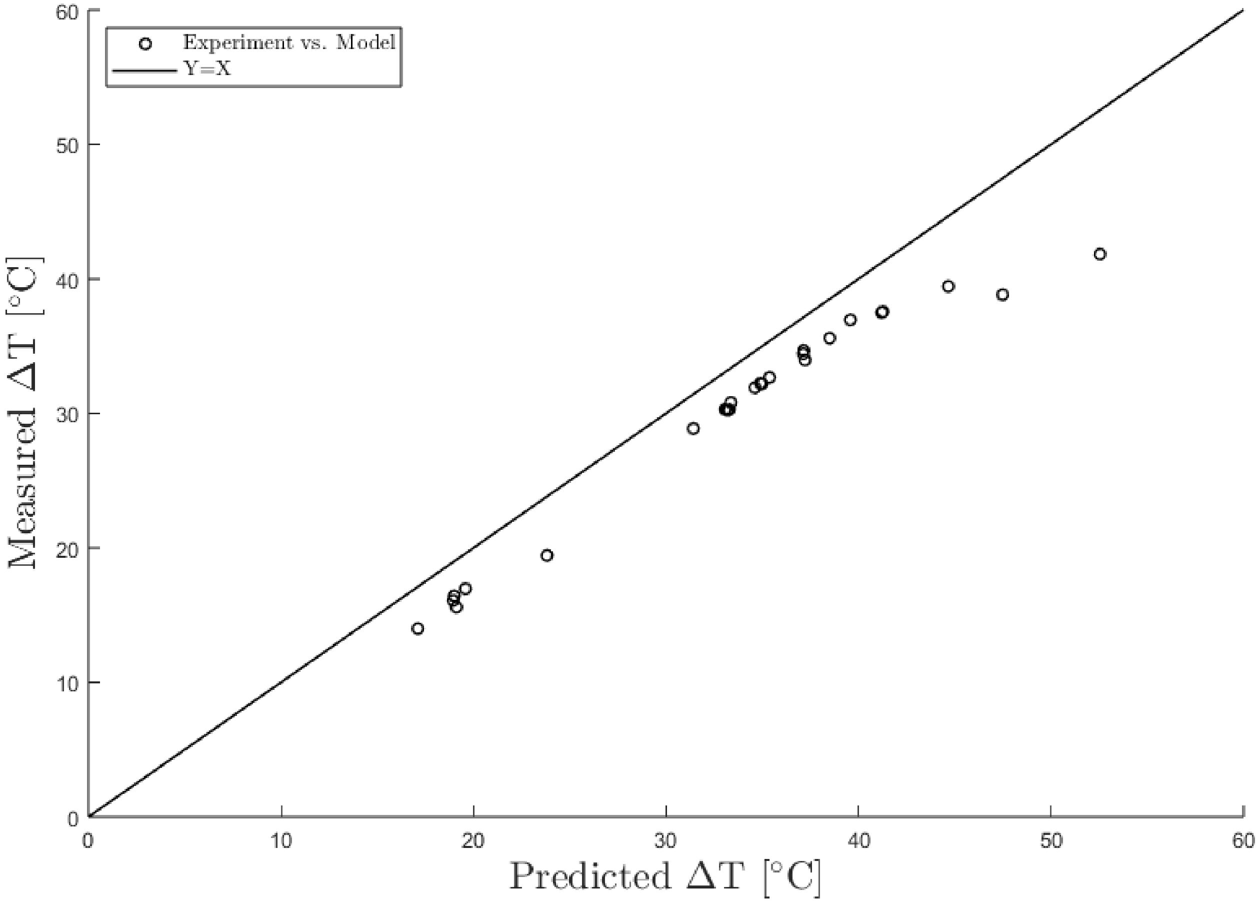
- Approach Temperature
  - o $\Delta T = T_{HP_{max}} - T_{out}$
  - o Percent difference 12%
- HX performance versus model prediction


PT 1 81.2
TC 1 543.689
PT 2 81.0
TC 2 585.057
TC 3 598.811
TC 4 596.941
TC 5 599.547
TC 6 639.453
TC 7 609.239
DP 2 1.069
TC 8 609.124
DP 1 1.401

$TC\ 6 = T_{HP_{max}}$

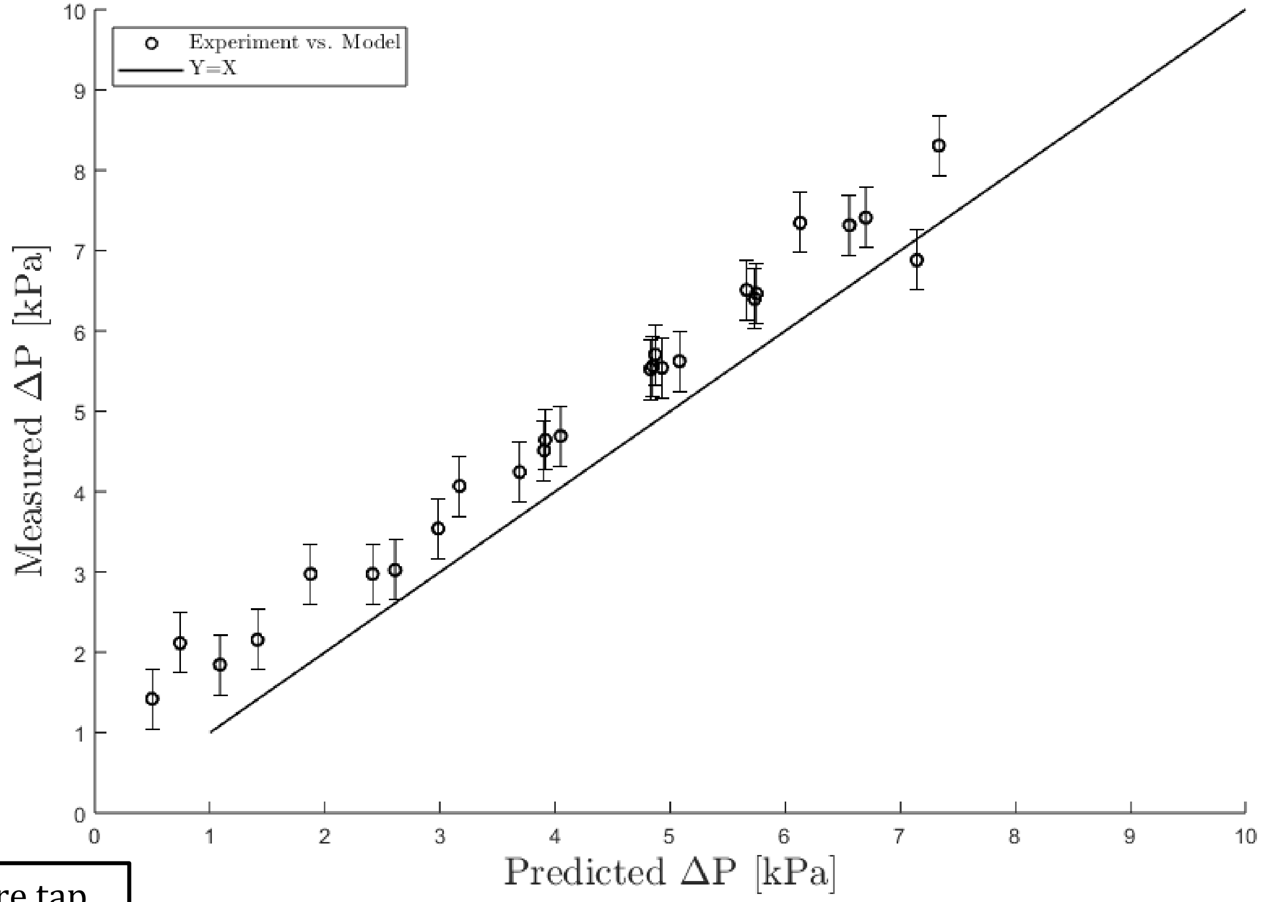


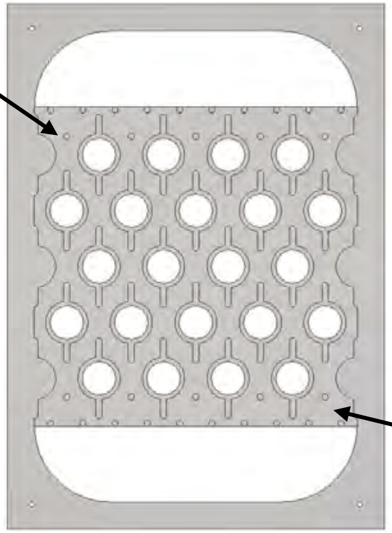
HHXT model



Pressure Drop Performance

- Pressure drop performance versus model prediction
- Channel pressure drop
- Percent difference 20%



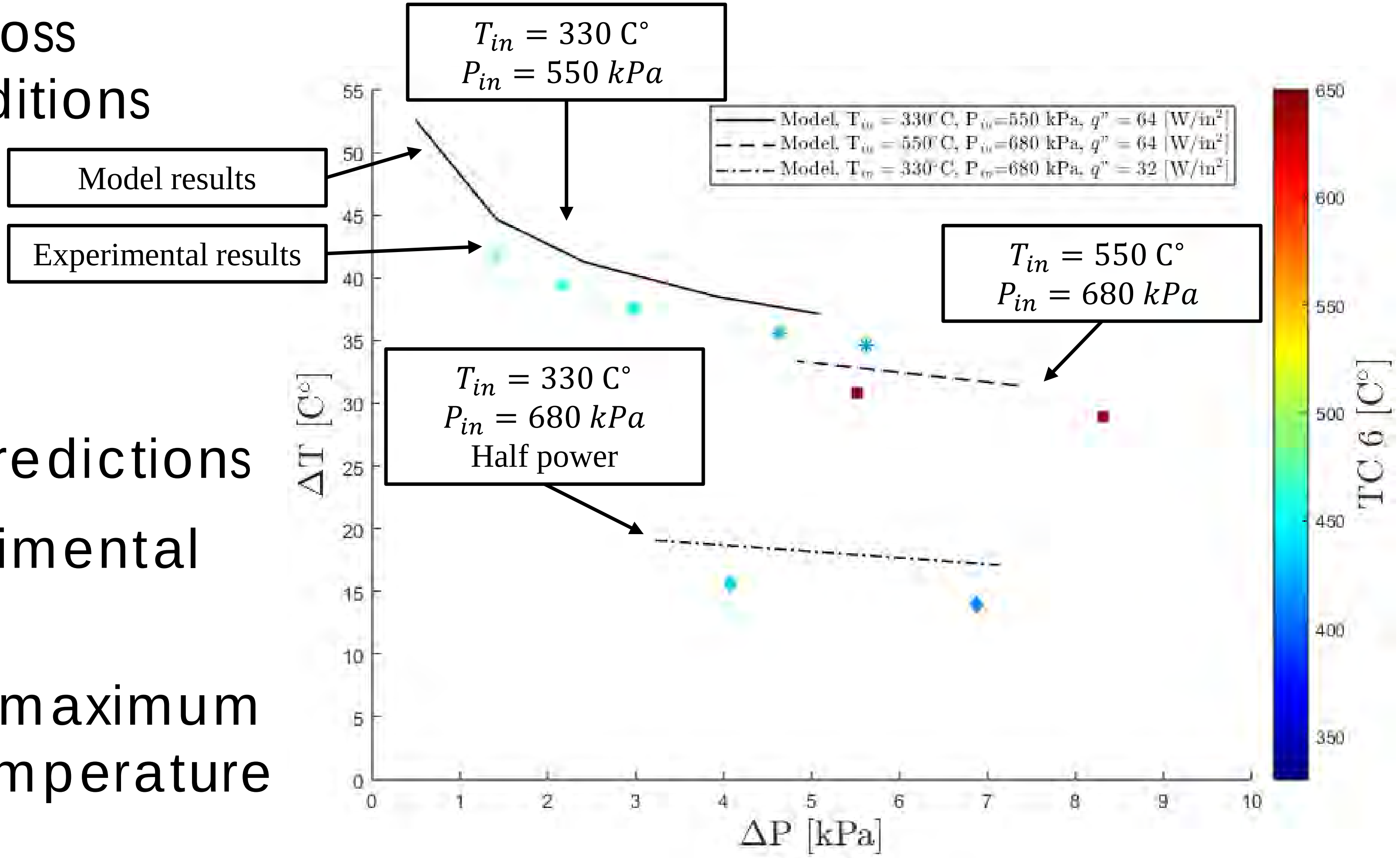


P_{high} pressure tap

P_{high} pressure tap

Approach Temp. vs. Pressure Drop

- General agreement across different operating conditions
  - o Inlet temperature
  - o Inlet pressure
  - o Heater power
  - o Mass flow rate
- Lines represent model predictions
- Markers represent experimental data
- Marker color represents maximum measured test article temperature



T_{in} = 330 C°
P_{in} = 550 kPa

Model results

Experimental results

T_{in} = 550 C°
P_{in} = 680 kPa

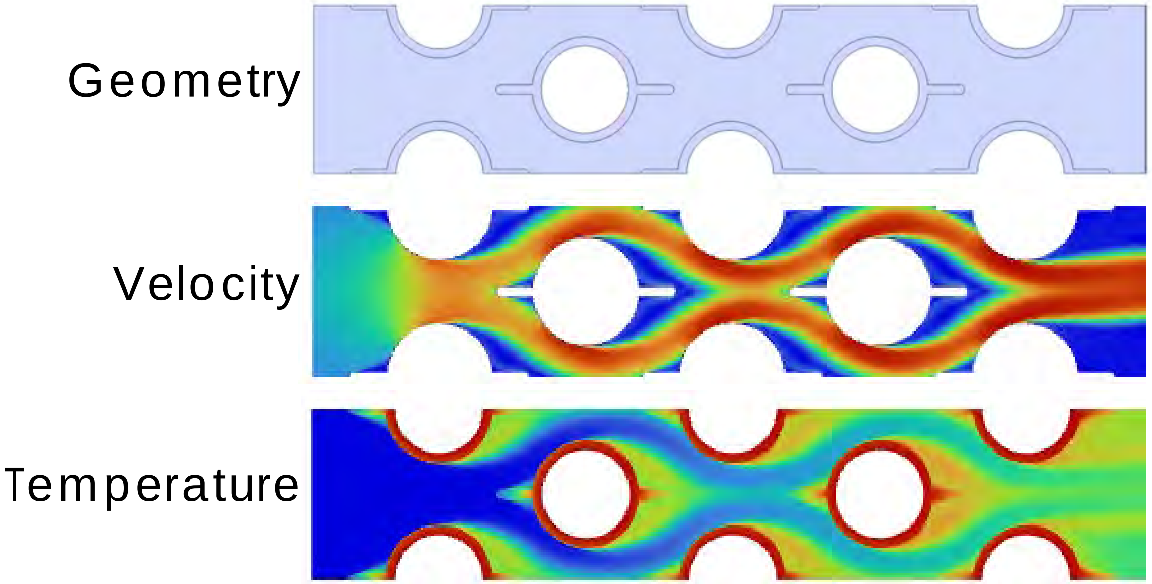
T_{in} = 330 C°
P_{in} = 680 kPa
Half power

PHASE III Work

sCO_2 Brayton Cycle HX

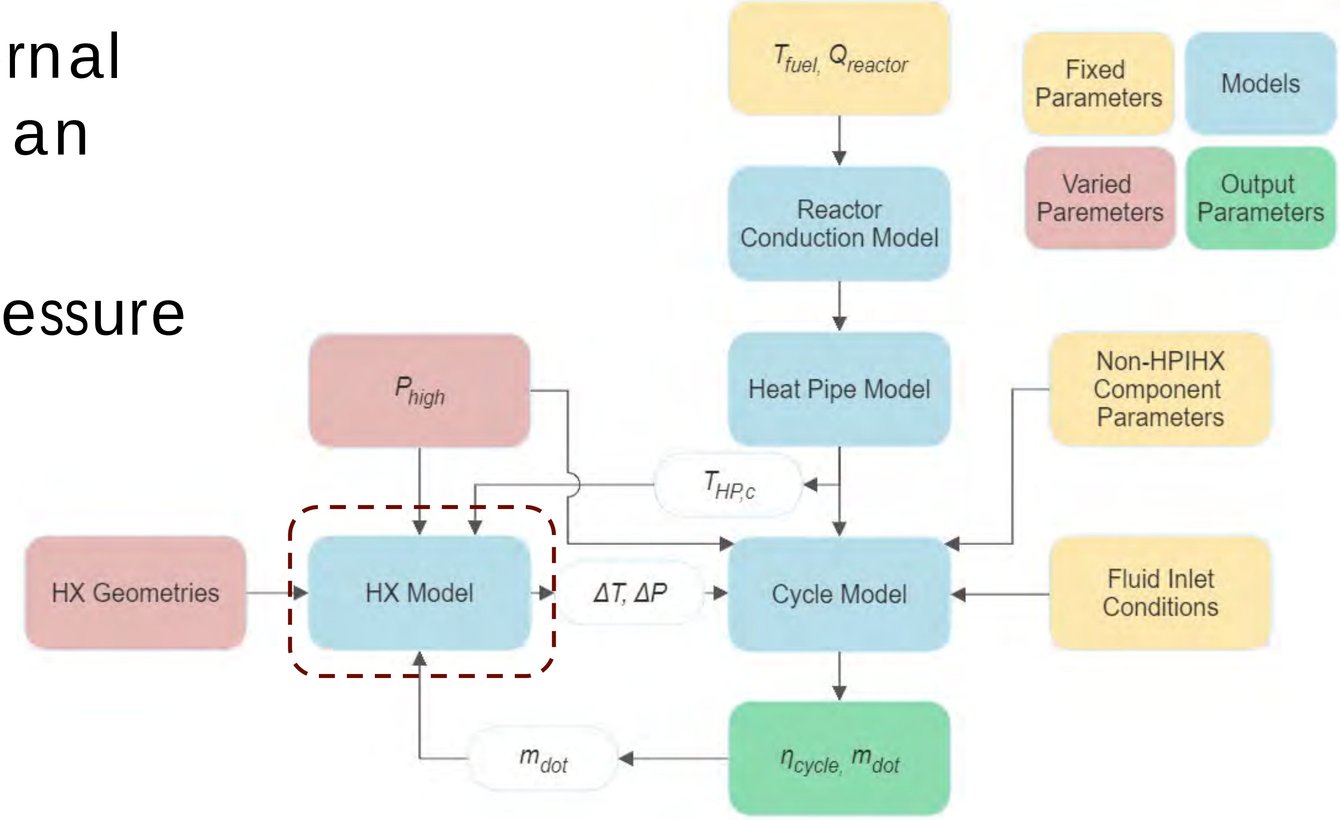
sCO$_2$ Brayton Cycle HX Design

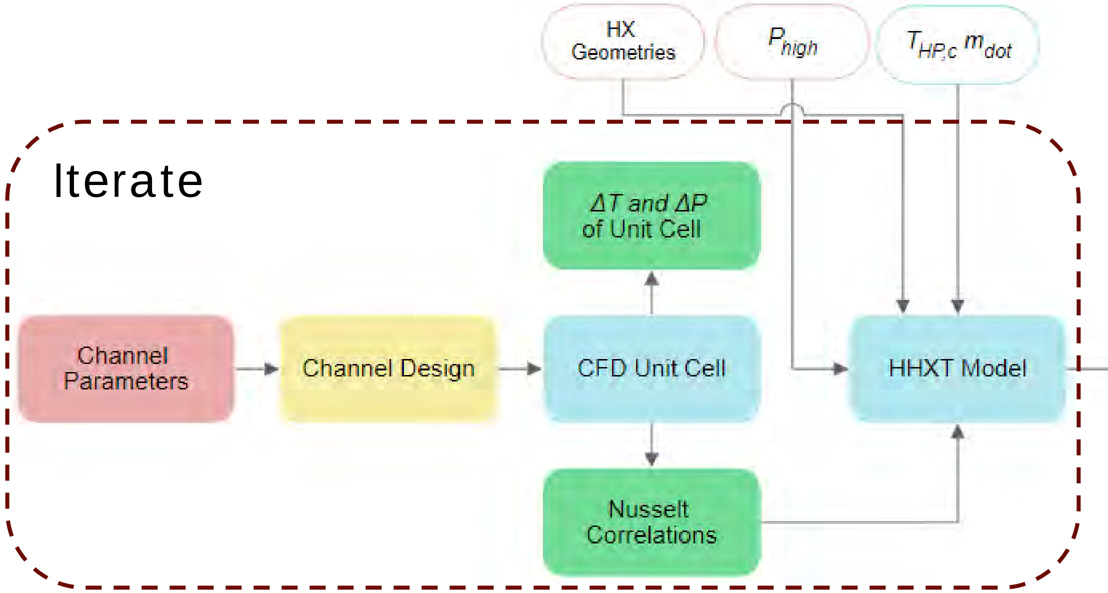
- Limitations of Air Brayton design
  - o Cycle efficiency was highly dependent on pressure drop
  - o Limited channel geometry and heat transfer
  - o Stagnation regions and low Reynolds number
- sCO$_2$ HX design freedom
  - o High operating pressure (~20 MPa)
    - o Increased density → lower pressure drop
    - o $\Delta P = \frac{1}{2} f_D \frac{L}{D_h} \rho v^2$
    - o $\dot{m} = \rho v A_c$
    - o $\Delta P = \frac{1}{2} f_D \frac{L}{D_h} \frac{1}{\rho} \left(\frac{\dot{m}}{A_c}\right)^2$



sCO_2 Brayton Cycle HX Optimization

- Parameterize and optimize the internal channel geometry of the HPIHX for an sCO2 Brayton cycle
- Maximize heat transfer, minimize pressure drop

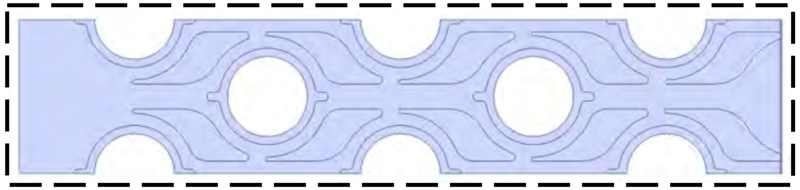


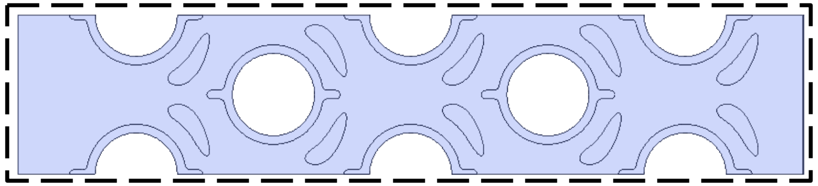


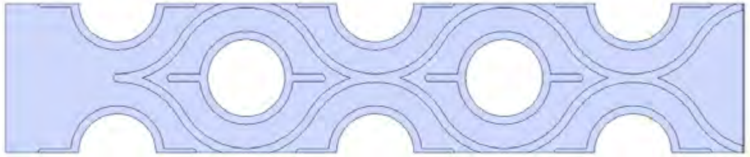
Channel Parameterization

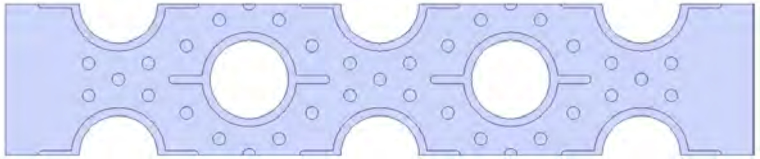
- Create families of channel designs to parameterize
- Goals of internal channel geometries:
  1) Facilitate fluid movement towards the heat pipe wall to maximize heat transfer
  2) Be as nonrestrictive to the fluid flow as possible to avoid pressure losses
  3) Avoid stagnation points (sharp corners, void geometrical areas)

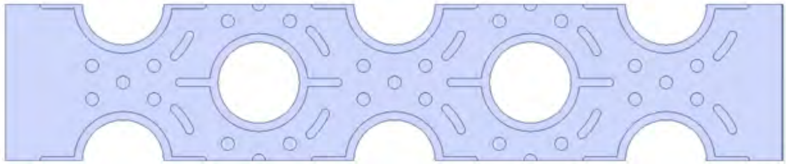

Bare Finned (baseline)


Containment


Airfoil

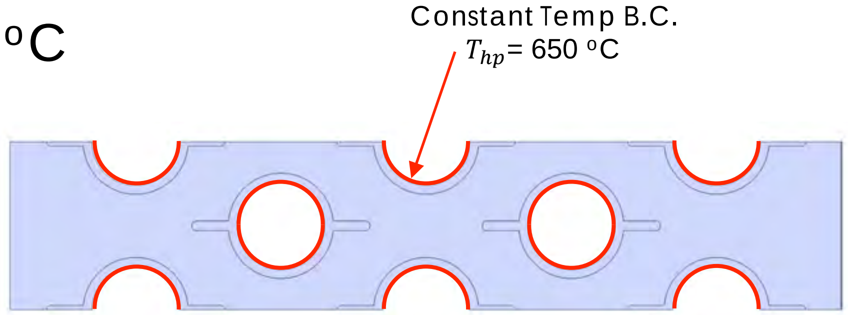

Swoosh


Pegs

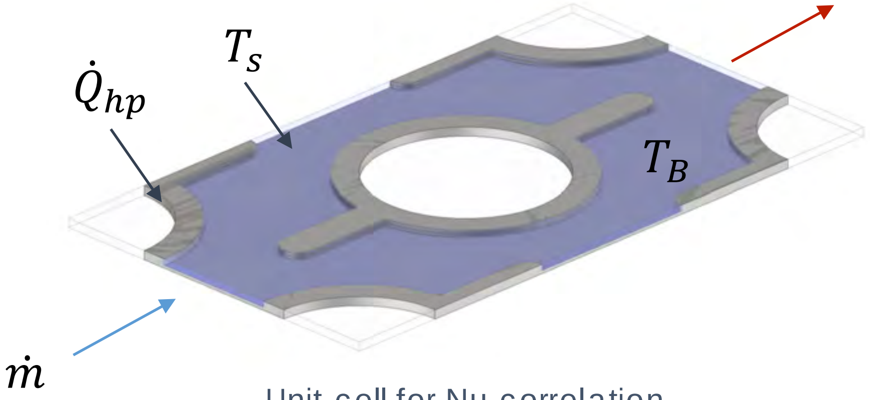

Pegs with Fins

CFD Model (ANSYS FLUENT)

- Obtain approach temperature difference and pressure drop values for a parameterized unit cell
  - o Boundary condition: constant temperature, $T_{hp} = 650$ °C
  - o Inlet conditions:
    - o $P_{in} = 20$ MPa, $T_{in} = 470$ °C
    - o Constant mass flow rate
- Calculate Nusselt correlation, $Nu = f(Re)$
  - o Hydraulic Diameter: $D_h = \frac{4V_f}{A_s}$
  - o Reynolds number: $Re = \frac{\rho v_D D_h}{\phi_f \mu} = \frac{\dot{m} D_h}{A_{in} \phi_f \mu}$
  - o Heat transfer coeff.: $h = \frac{\dot{Q}}{A_s(T_s - T_b)}$
  - o Nusselt number: $Nu = \frac{h D_h}{k}$



CFD Geometry

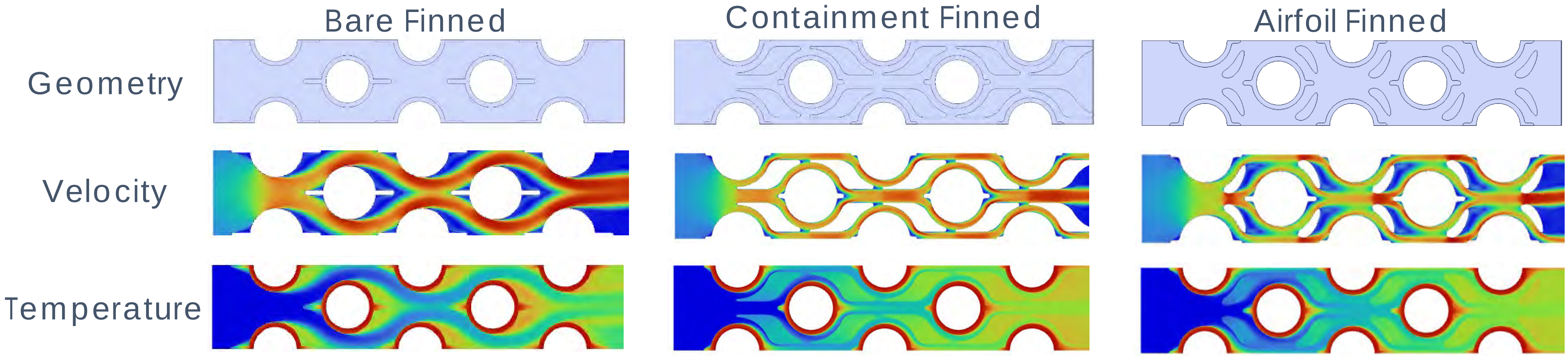


Unit cell for Nu correlation

Preliminary CFD Results

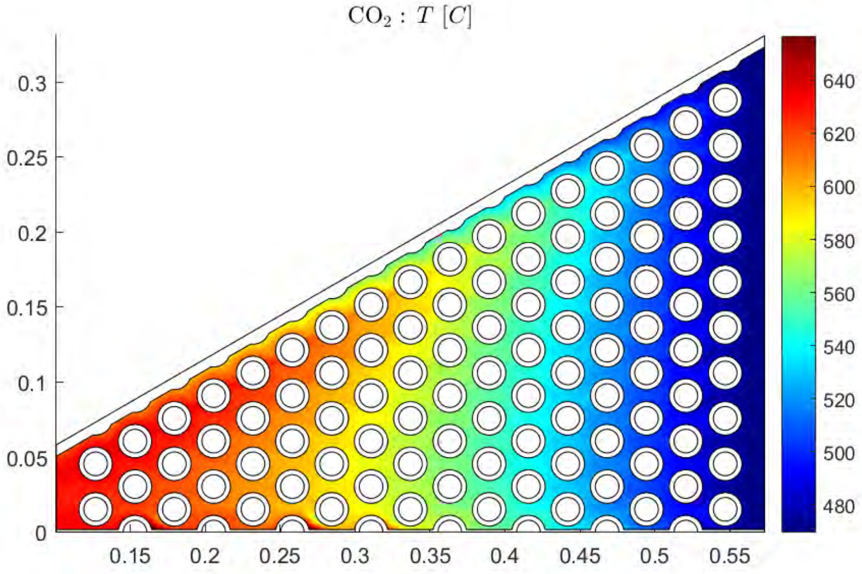
- The baseline design is a bare-finned internal geometry
- Ran a dozen preliminary designs to prove their performance

Geometry	Approach Temp^1 (^{o}C)	Pressure Drop^1 (kPa)	Max Solid Temp (^{o}C)
Bare Finned	101.6	0.284	554.3
Containment Finned	78.4	0.432	521.4
Airfoil Finned	82.0	0.411	524.8



Next Steps – sCO$_2$

- Model and optimize
  - o Import CFD correlations
  - o Run model for different HX and sCO2 cycle configurations (th$_i$, H, P$_{in}$, $\dot{m}$)
  - o Obtain optimal heat exchanger geometries
- Test specimen
  - o Design for 20 MPa
  - o Utilize advanced channel geometry
  - o Investigate heat pipe heat exchanger interface
  - o Test with UW manufactured sodium heat pipe



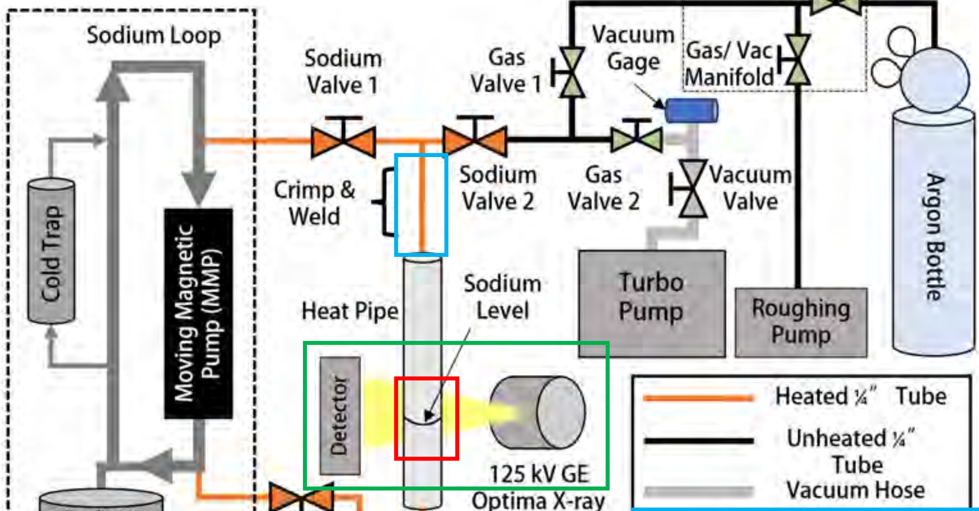
Overview of UW Heat Pipe Work

Manufacturing process development; testing and imaging HPs

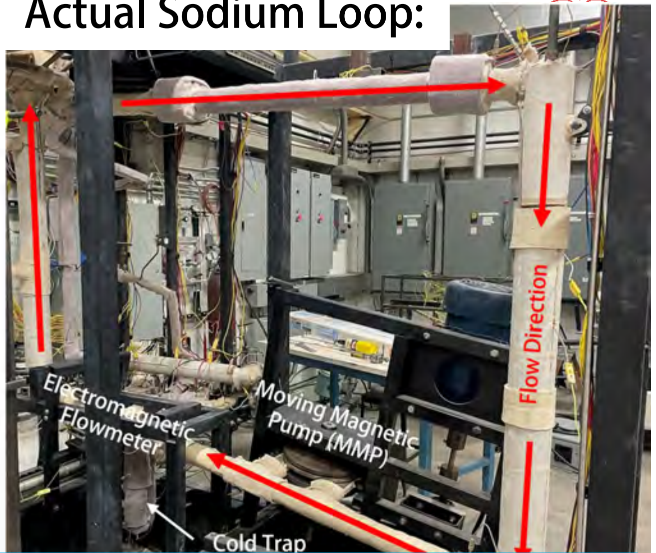
HP Fill Process

1. Vacuum bake-out HP at 800 ℃ and 1E-05 torr
2. Circulate sodium at 400 ℃ through HP using cold trap to control oxide concentration (<5 ppm)
3. Slowly drain HP of sodium and use X-ray system to monitor sodium level
4. Crimp/weld upper fill tube to seal
5. Pull turbo vacuum (1E-05 torr) on heat pipe
6. Crimp/weld lower fill tube for final seal
7. Use XRCT to verify fill volume

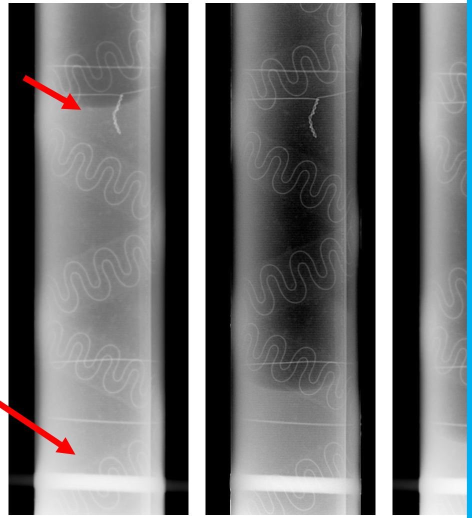
Fill Process Schematic:

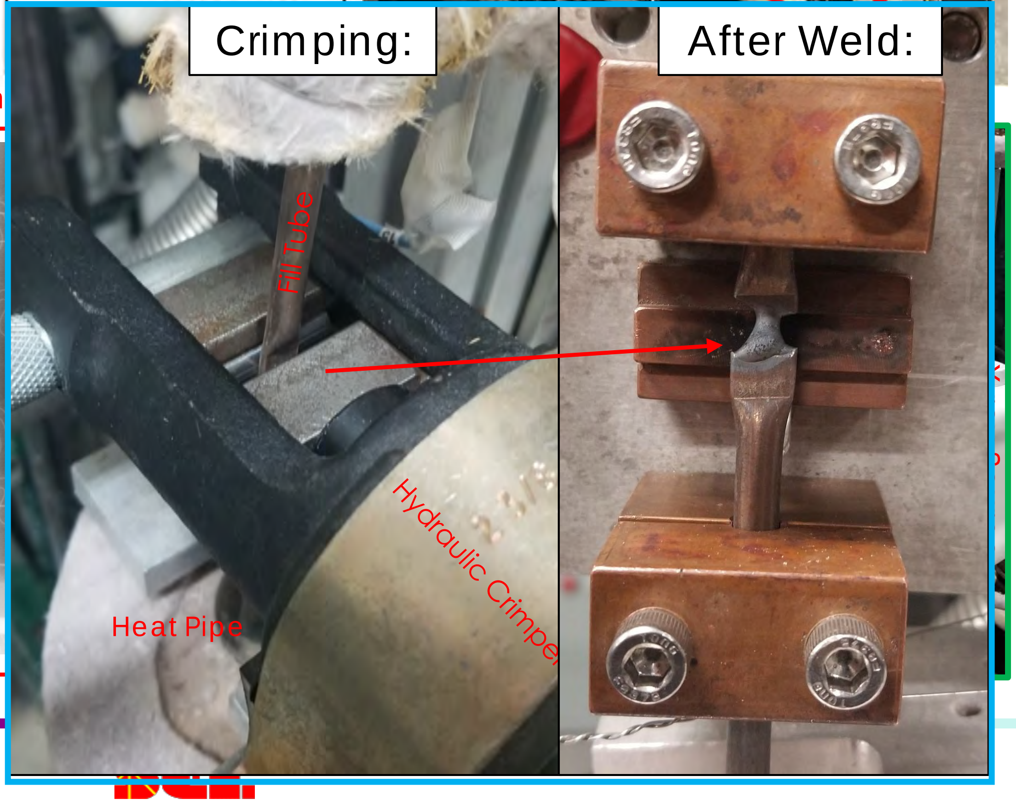


Actual Sodium Loop:



X-ray Images of Sodium

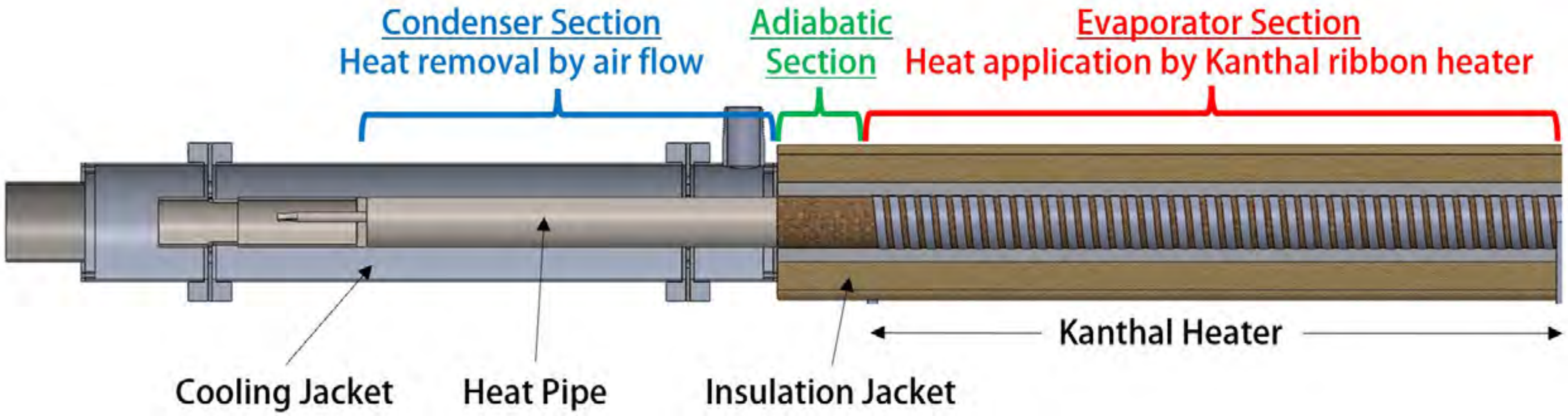


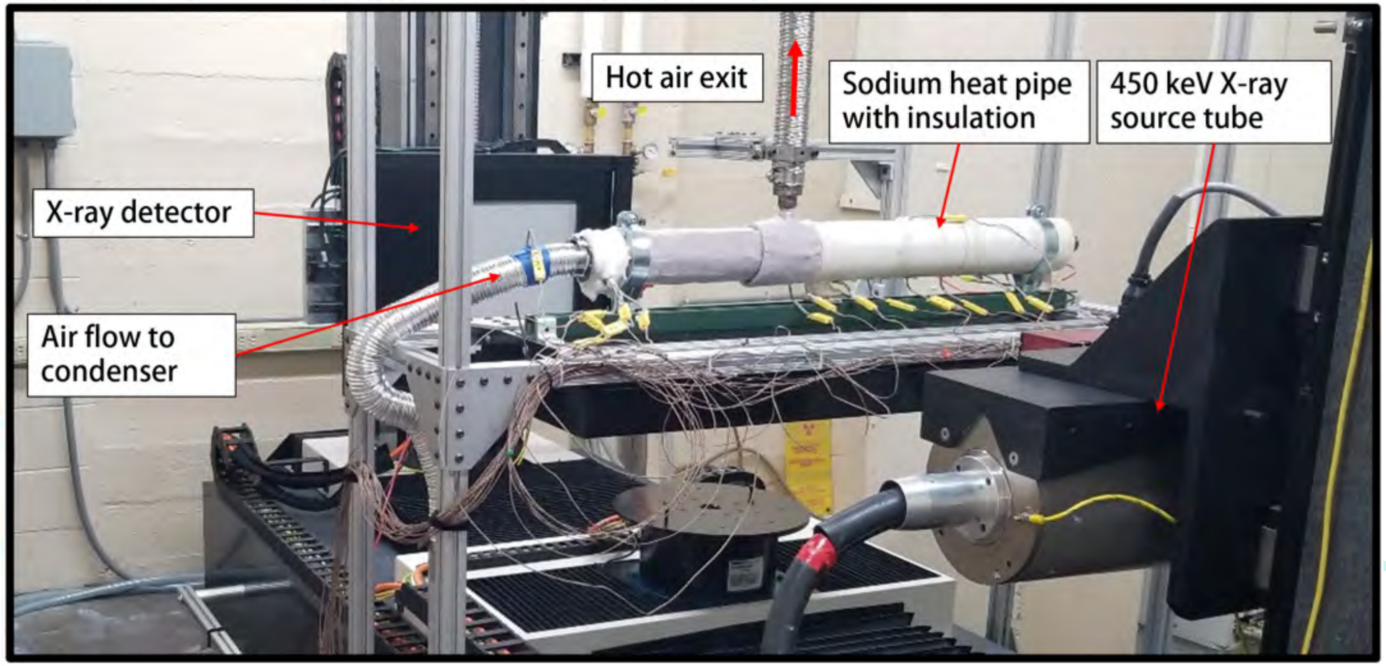


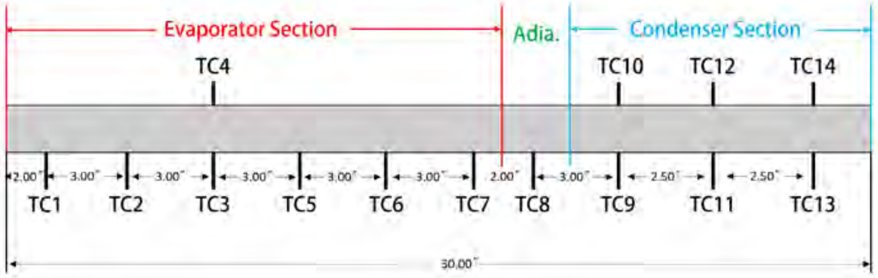
Thermal Hydraulics Laboratory

Heat Pipe Testing Facility

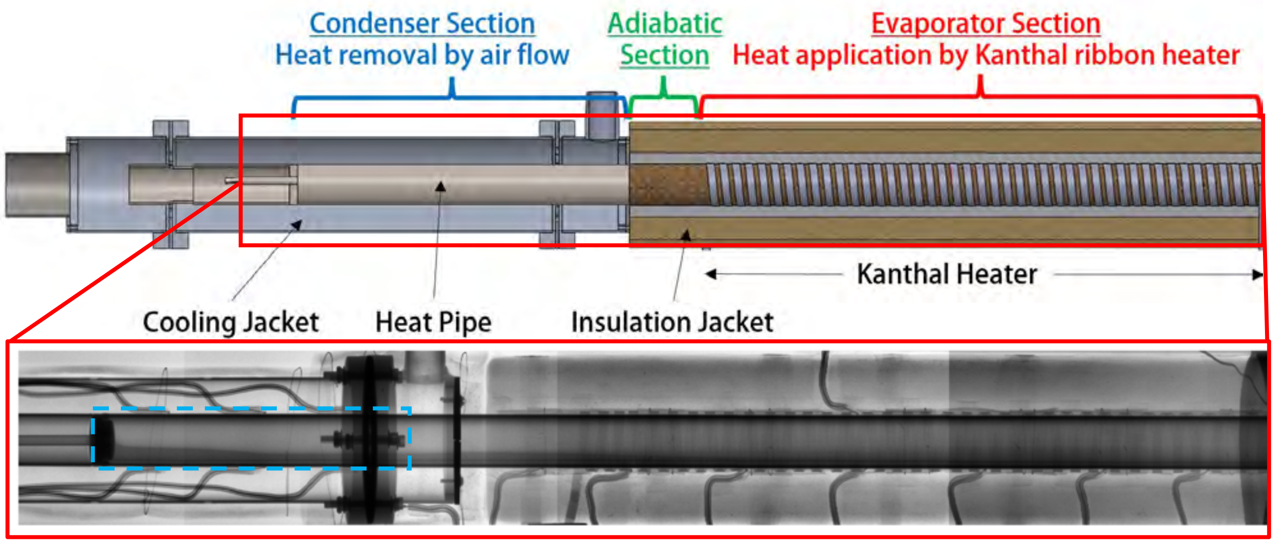
- Heat is applied to evaporator by resistive heating of Kanthal (FeCrAl) ribbon
- Blower drives air flow through a cooling jacket to remove heat from condenser
- Heat pipe installed on 450 kV X-ray machine for imaging
- Detector can record up to 30 fps with 0.4mm resolution
- Externally-attached thermocouples measure temperature:







HP Testing & Imaging



Area of Detail

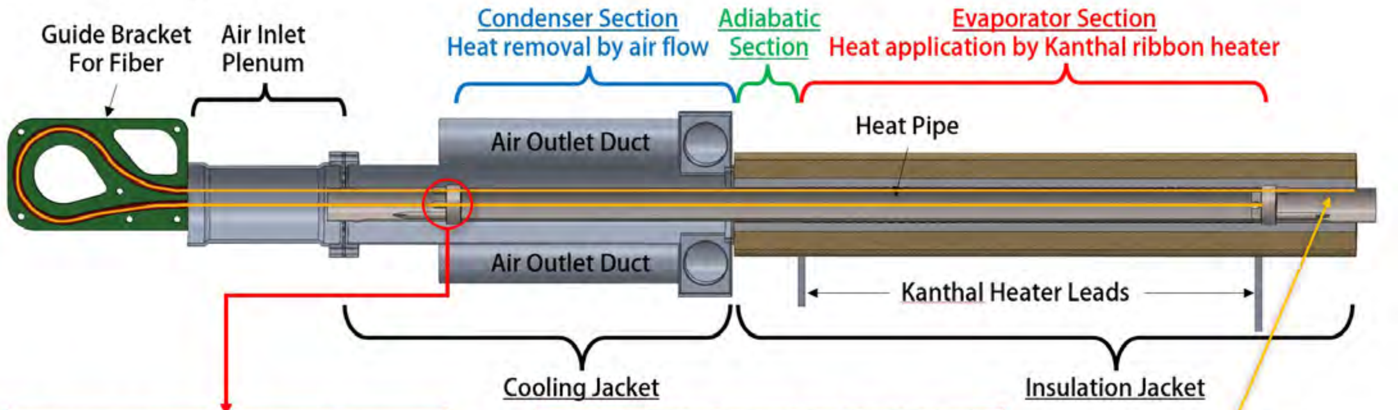
Heat Pipe condenser during start-up: 5x speed, 1500W

Condenser after heater is shut down: 5x speed

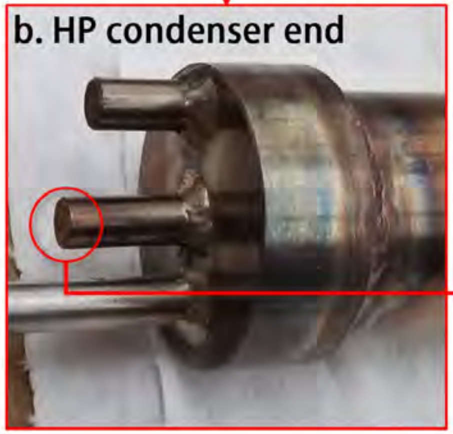
Progress

- Designed new HP to incorporate capillary tubes to house FODTS
  - Optimized laser welding process to seal capillaries into HP ends
- Developed process for manufacturing HP wicks
  - Characterize wicks using bubble test
  - Communicating with vendors to produce wicks for us at scale
- Redesigned testing facility
- New HP is completed; currently working setting up for testing with FODTS installed

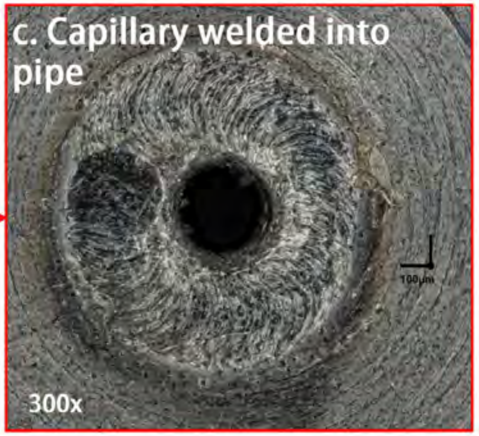
a. HP testing & instrumentation diagram



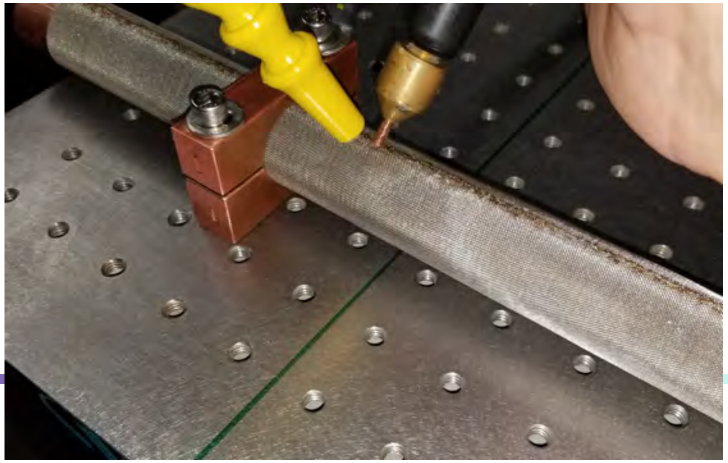
Fiber optic sensor (FODTS) highlighted in orange



b. HP condenser end

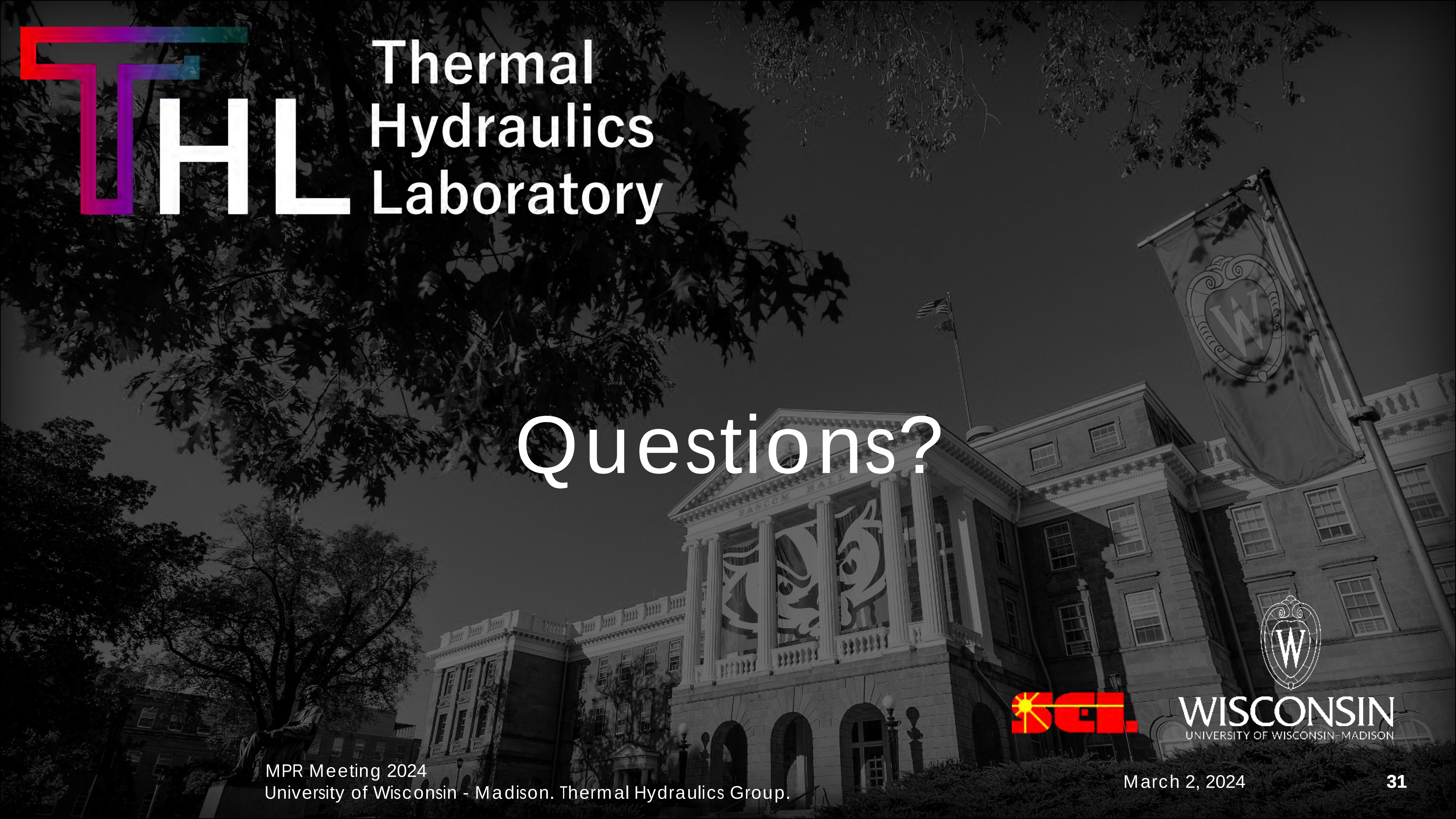


c. Capillary welded into pipe



Next Steps

- Goals of present research:
  - Match high-resolution FODTS measurements to x-ray images to better understand heat pipe transient phenomena
  - Optimize radiography techniques & apply Dual-Energy Material Decomposition to determine void fraction in the wick
  - Operate HP in gravity-adverse conditions to induce dryout event in evaporator; capture dryout with x-ray images and FODTS measurements
- Future research goals:
  - Investigate optimization of HP, including wick geometry, sodium fill volume, and effect of non-condensing species
  - Characterize HP failure modes
  - Integrate sodium HPs with sCO2 heat exchangers for testing



THL Thermal Hydraulics Laboratory

Questions?

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