Cost Reduction for Advanced Integration Heat Exchanger Technology for Microreactors

University of Wisconsin-Madison
Greg Nellis and Mark Anderson, Professors
Ian Jentz, Scientist
Curtis Foster and Erik Tillman, Graduate Students

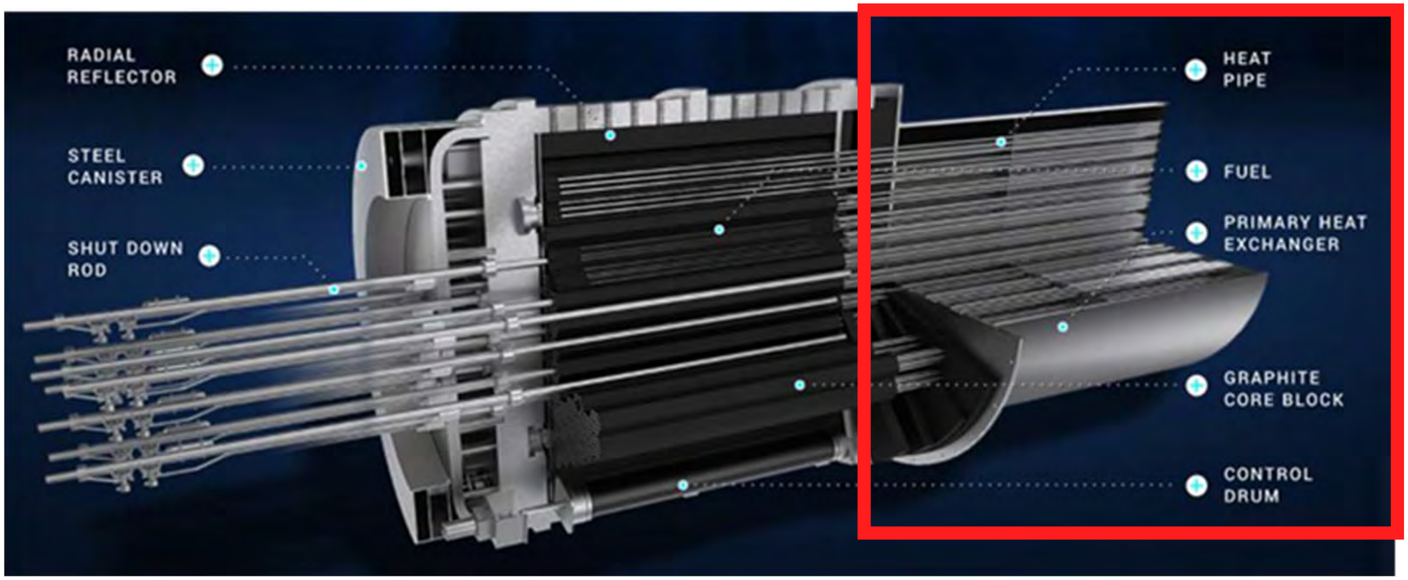
Overview

- Introduction to project and organization
- Work on Tasks 1-3
  - Air Brayton cycle
  - HPIHX models
  - Results
  - Air Brayton cycle with reheat
  - Future work
- Work on Tasks 4-6
  - Test specimen design
  - Instrumentation
- Heat pipe work

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



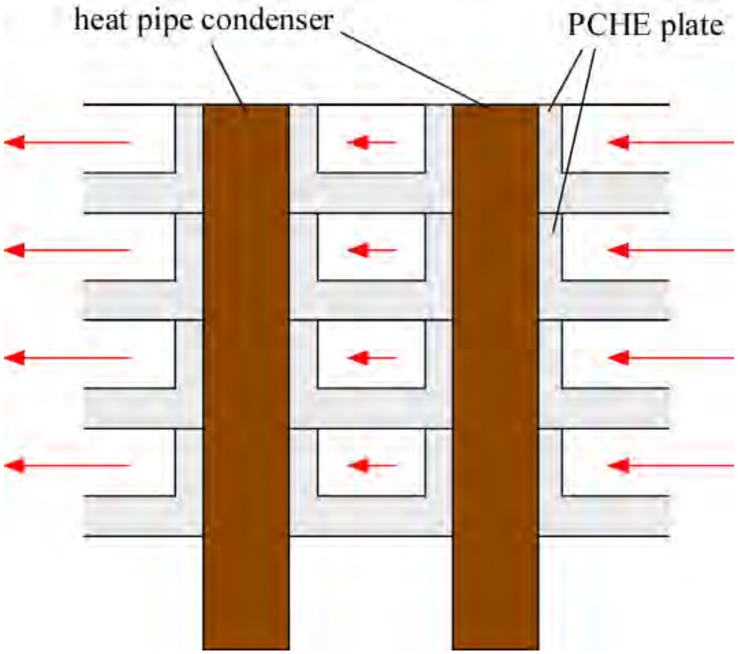
eVinci^{TM} Micro-Reactor, Courtesy of Westinghouse Electric Company LLC

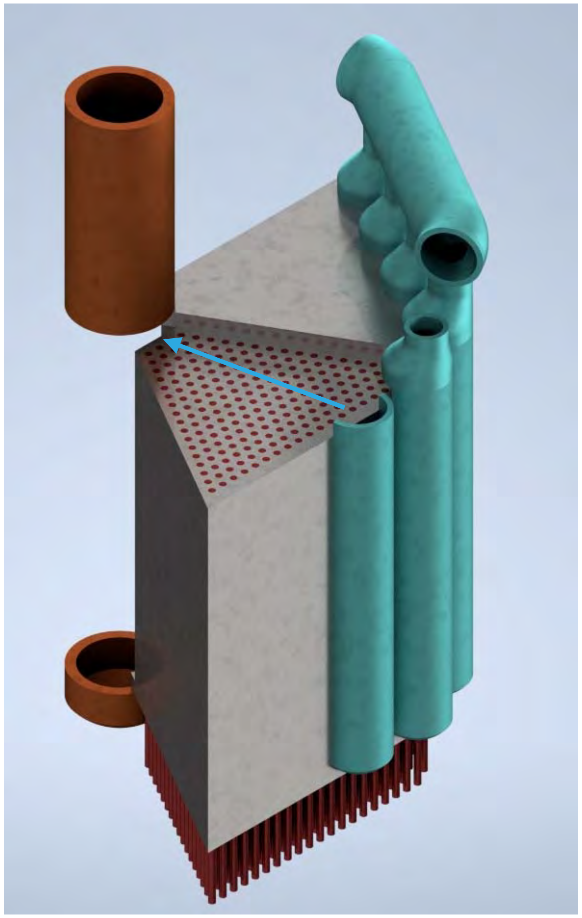
MRP Microreactor Program

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

Project Organization

Task 1: Develop balance of system models (Q1-Q4)

- Develop low-level models of the components affected by the integration heat exchanger
- Microreactor: fuel and monolith in order to predict limiting reactor hot spots and coupling between heat pipes
- Heat pipe: sodium heat pipe in order to predict thermal resistance and performance limits
- Cycle: end-use application in order to provide insight into the value of improved interface heat exchanger performance

Task 2: Develop model of PCHE-based integration heat exchanger (Q1-Q5)

- High fidelity model of the heat exchanger capable of carrying out design studies.
- Used to optimize heat exchanger subject to constraints related to loading and operating conditions.
- Develop detailed design for heat exchangers for air- and sCO_2-Brayton applications.

Task 3: Techno-economic optimization of integration heat exchanger (Q2 – Q6)

- Assess the value of PCHE-based integration heat exchanger in the context of two end-uses: air-Brayton and sCO_2-Brayton power cycles.
- Compare with alternative integration heat exchanger.
- Extension of the Economics-by-Design approach discussed in INL/EXT-21-63067 [2]

Project Organization

Task 4: Procure test articles (Q6-Q8)

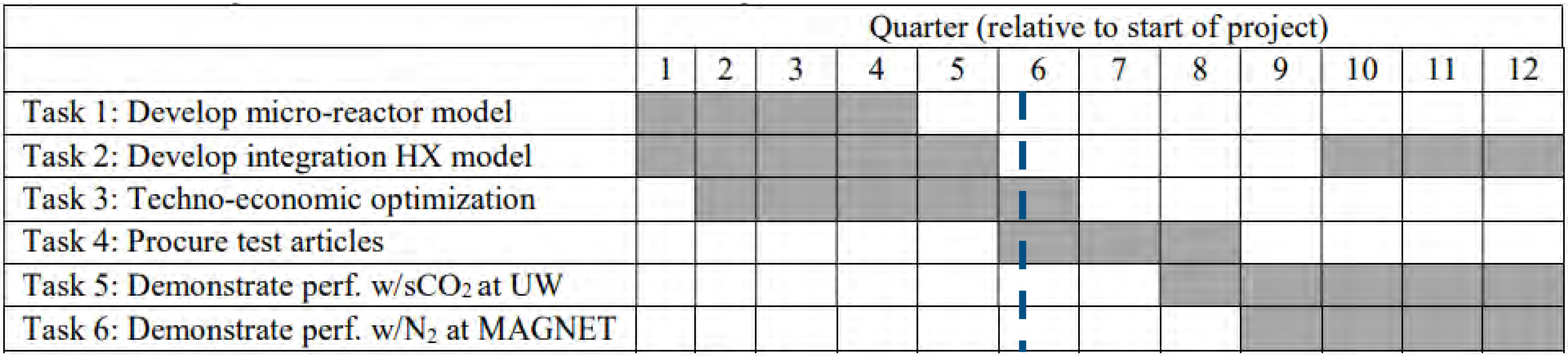
- Sub-size test articles corresponding to the two designs (air and sCO_2) developed in Task 2.

Task 5: Demonstrate performance using sCO_2 at UW (Q8-Q12)

- Instrument sCO2 test article in order to characterize thermal-hydraulic performance.
- Optical sensors will be used to obtain details regarding temperature distribution along plates.
- Install in sCO_2 loop at UW.

Task 6: Demonstrate performance using N_2 in MAGNET facility (Q9 – Q12)

- Instrument air test article at UW and deliver to MAGNET facility for integration and test.



	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									▨	▨	▨	▨

MRP Microreactor Program

Interface Heat Exchangers

Annular flow heat exchanger (AFHX)

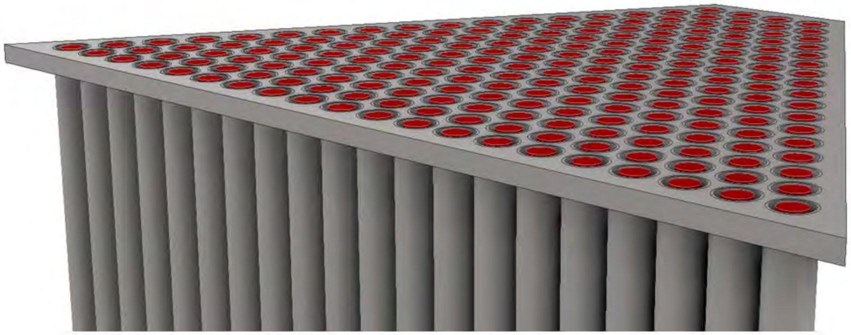
- LANL's eBlock37 electrical demonstration unit [3]

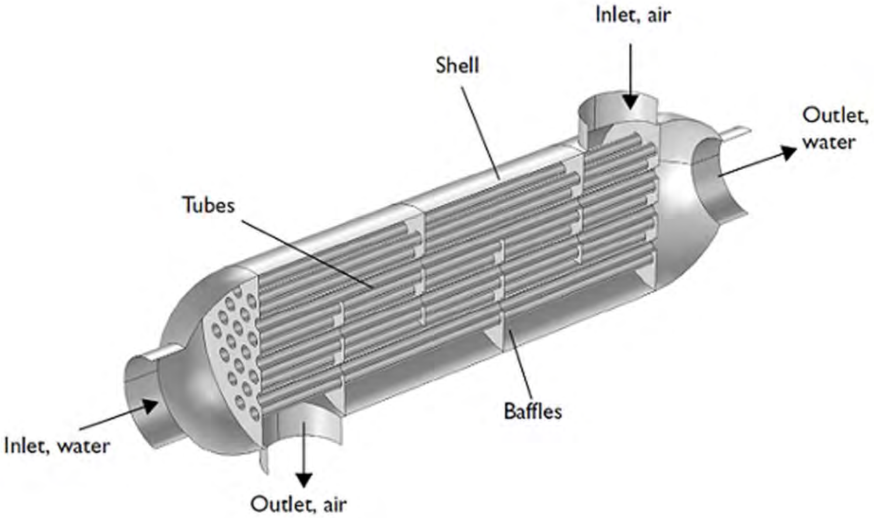
Shell and tube heat exchanger

- Cross-flow style similar to eVinci™

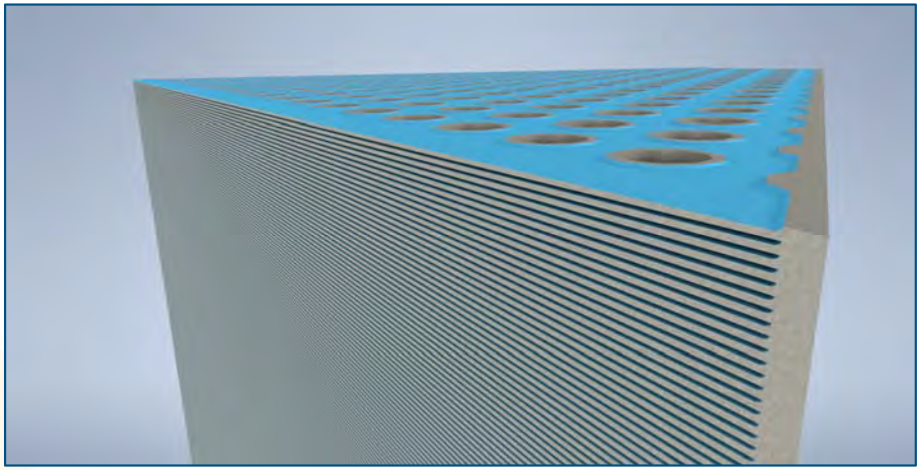
Printed circuit heat exchanger (PCHE)

- As interlayer plates become very thin PCHE approaches cross-flow heat exchanger


AFHX concept design



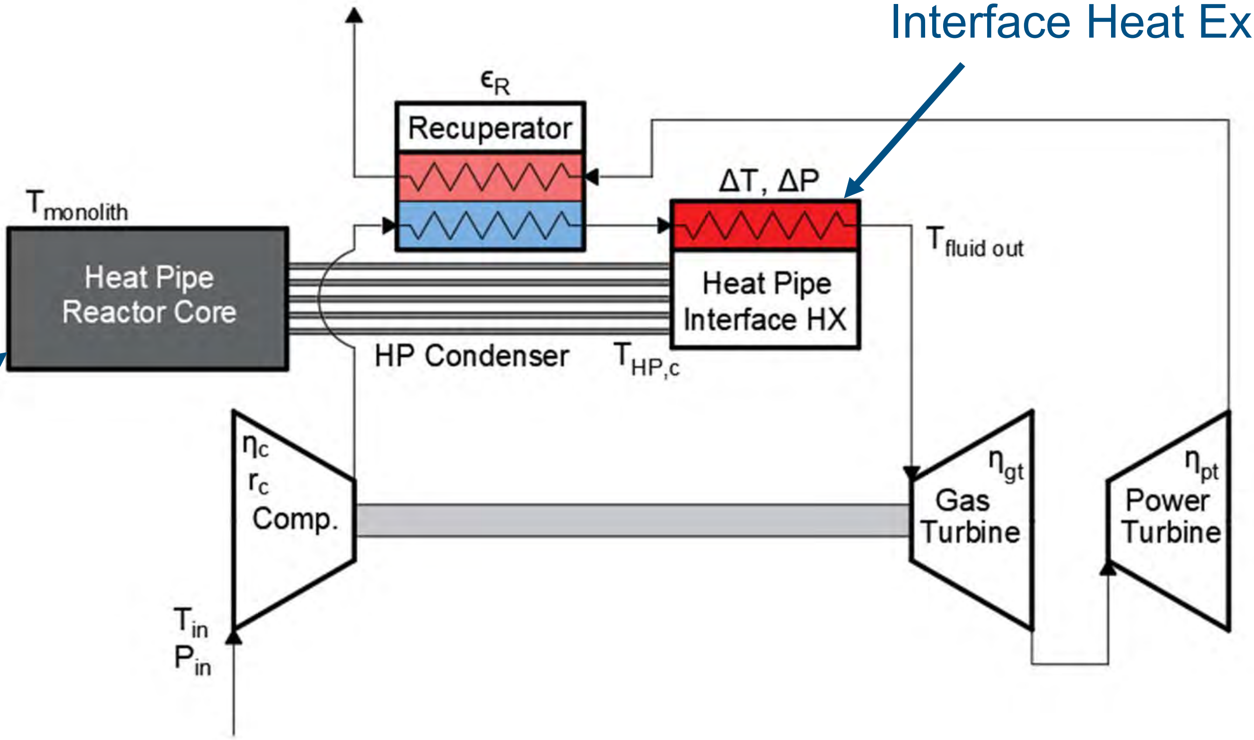
Shell and Tube HX [4]


PCHE cross section

Recuperated Air Brayton Cycle Model

Single heating stage

- We will return to the Brayton cycle with reheat later



Interface Heat Exchanger

Heat Pipe Microreactor Core

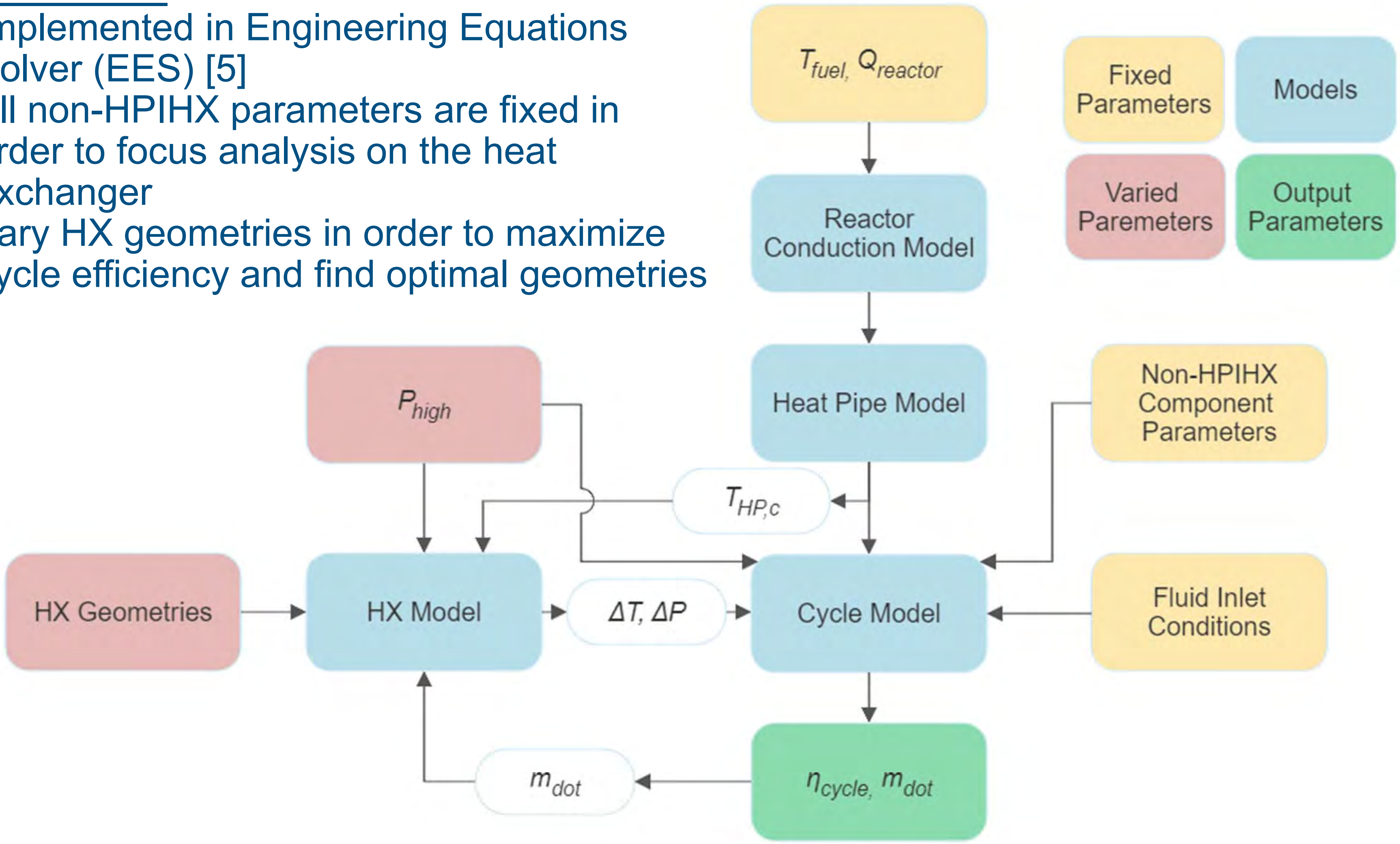
Component Parameter	Value
Compressor isentropic efficiency, η_c	89.5%
Compressor ratio, r_c	4.6
Power turbine isentropic efficiency, η_{pt}	93.9%
Gas turbine isentropic efficiency, η_{gt}	93.9 %
Recuperator effectiveness, ϵ_R	0.95
Recuperator pressure drop	1%

Key Variables	Symbol
Approach temperature	ΔT
HX pressure drop	ΔP

Recuperated Air Brayton Cycle Model

Cycle model

- Implemented in Engineering Equations Solver (EES) [5]
- All non-HPIHX parameters are fixed in order to focus analysis on the heat exchanger
- Vary HX geometries in order to maximize cycle efficiency and find optimal geometries



Fixed Parameters

Models

Varied Paremeters

Output Parameters

$T_{fuel,}$ $Q_{reactor}$

Reactor Conduction Model

Heat Pipe Model

Non-HPIHX Component Parameters

P_{high}

$T_{HP,c}$

HX Geometries

HX Model

ΔT, ΔP

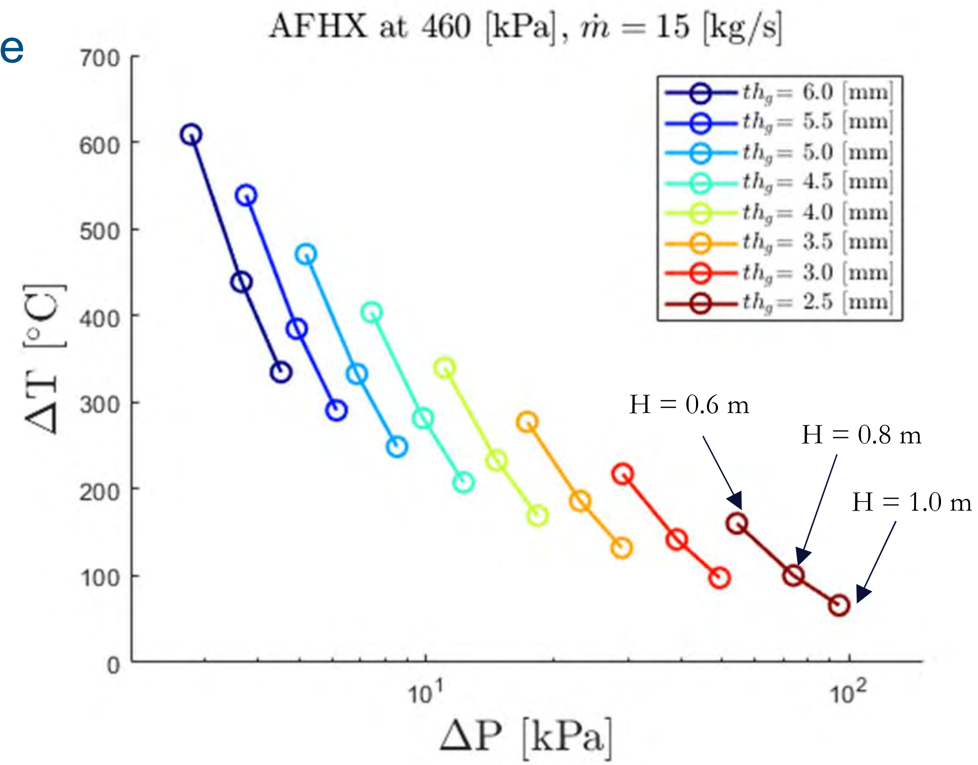
Cycle Model

Fluid Inlet Conditions

m_{dot}

$\eta_{cycle,}$ m_{dot}

Thermodynamic Evaluation: AFHX Model



Heat transfer

- 1-D convection model for single heat pipe

Assumptions

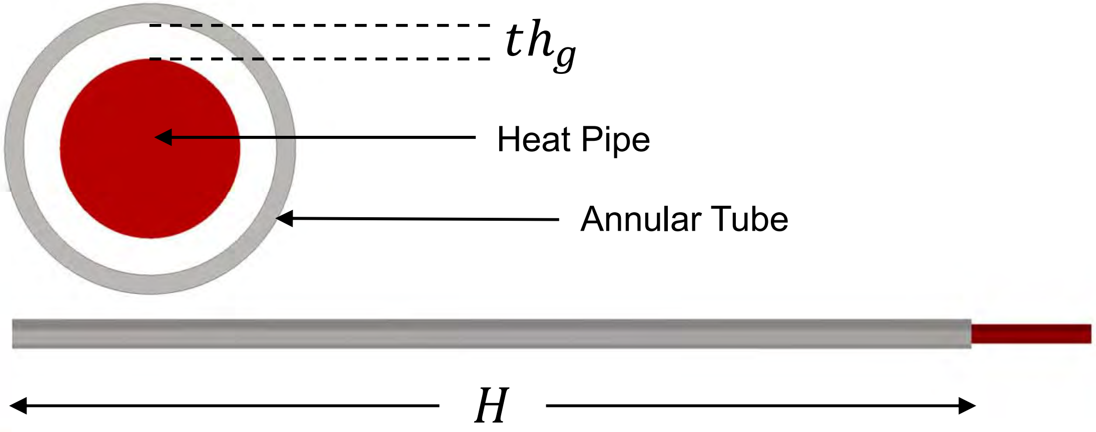
- Isothermal heat pipe temperature
- Adiabatic outer wall
- 316 stainless steel

Average heat transfer coefficient

- Gnielinski (1975) Nusselt correlations [6]

Friction factor correlation

- Offor (2016) [7]

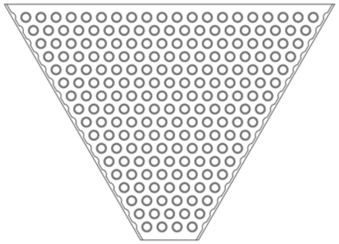


Feature	Identifier
HX length	markers
Annular Gap	lines

Thermodynamic Evaluation: PCHE Model

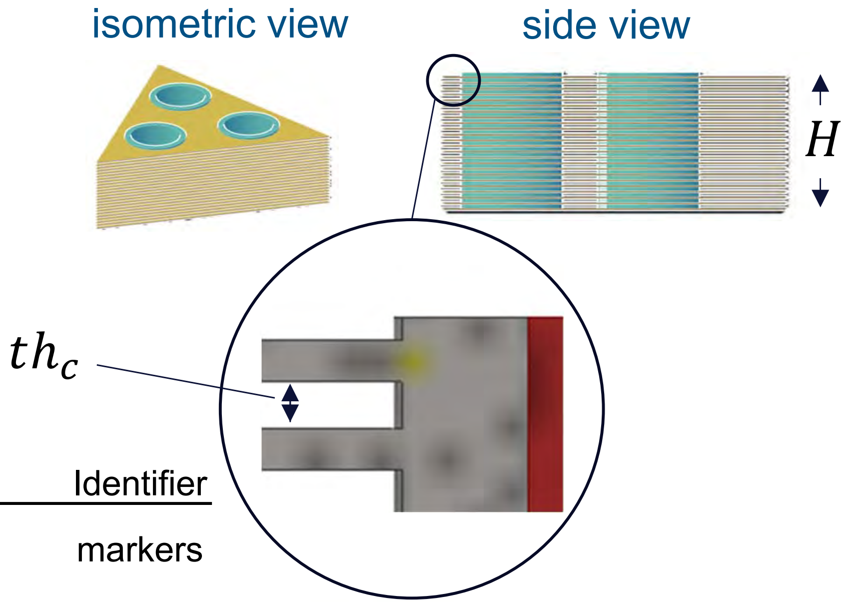
Heat transfer and hydraulic modeling

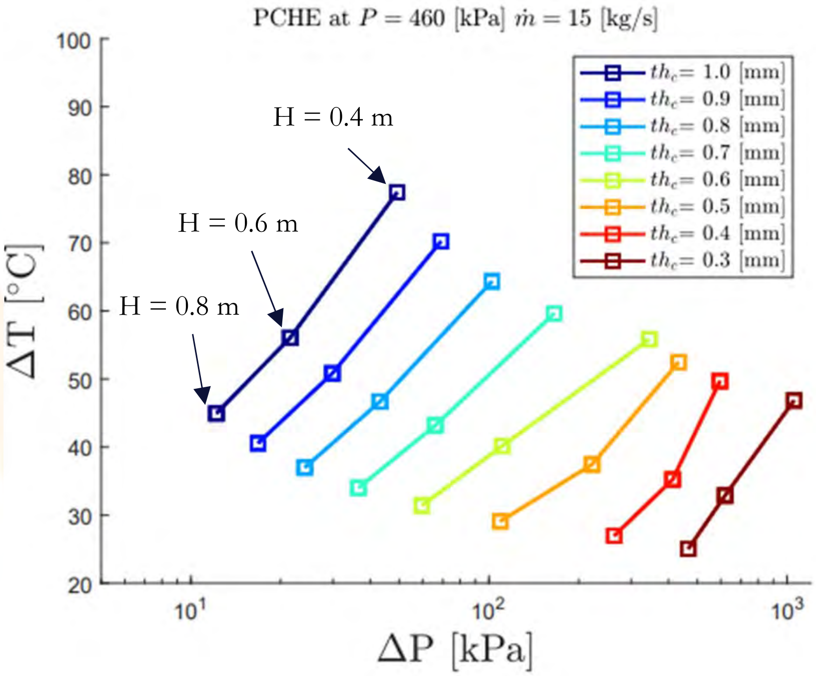
- Homogenized Heat Exchanger Thermohydraulic modeling environment developed by Jentz & Anderson (2021) [8]
- Nusselt correlations from Kays & London (1984) for finned circular tube geometries, which resemble the flow passages in the PCHE [9]
- Pressure drop calculated using the Colebrook flow equation



Assumptions

- Uniform 4 kW heat transfer rate from each heat pipe
- Cross flow through micro-channel structure



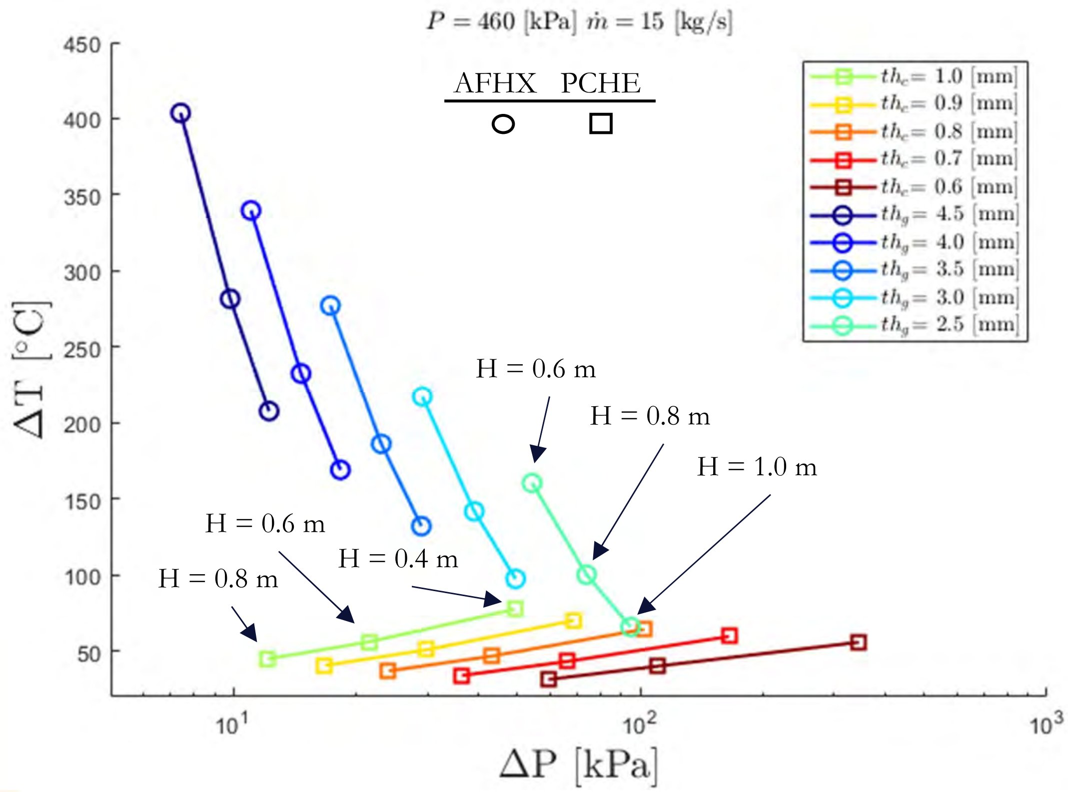


Feature	Identifier
HX length	markers
Channel thickness	lines

Thermodynamic Evaluation: HX Comparison

AFHX and PCHE

- Restricted to top performing geometries for each HX model
- PCHE achieves a lower approach temperature in the low pressure drop region (~10-50 kPa)



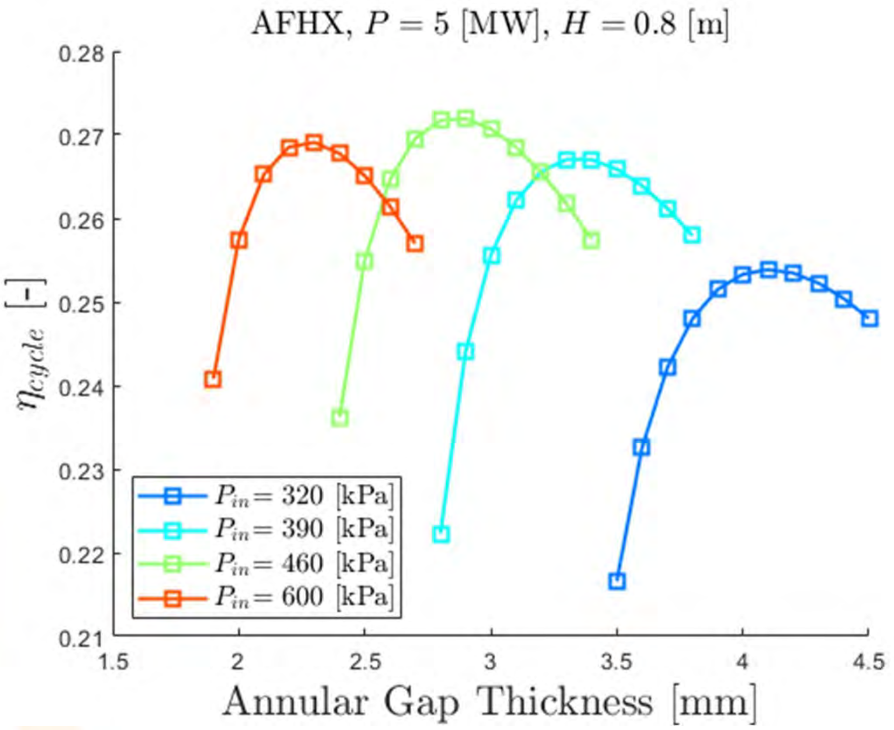
Approach temperature comparison for a given pressure drop

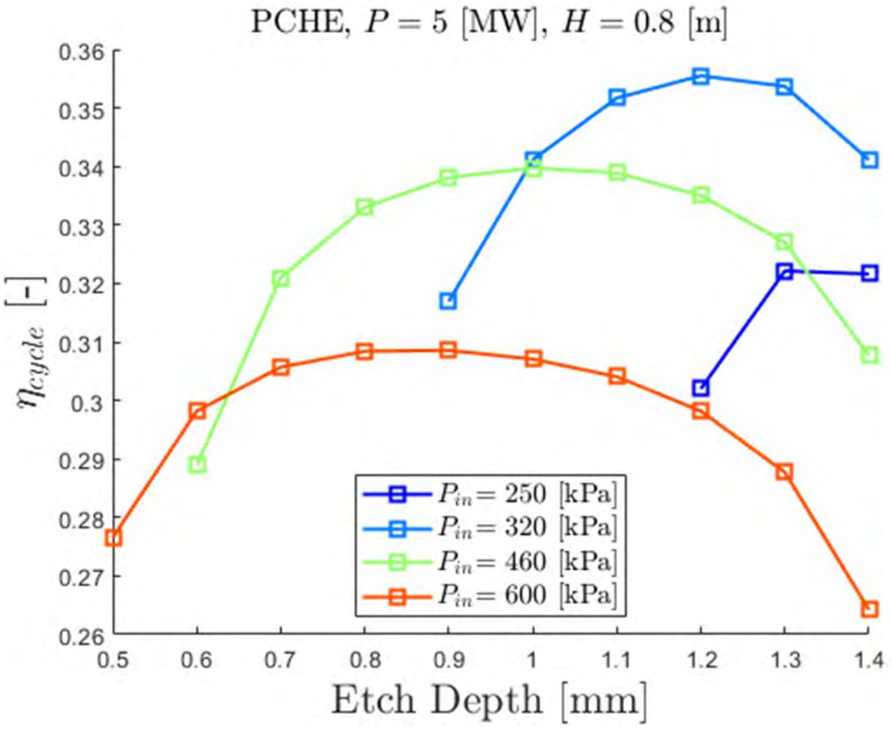
ΔP [kPa]	ΔT PCHE [C]	ΔT AFHX [C]
95	35	65
15	45	275

Design Optimization Results

Cycle optimization

- As P_{in} increased the optimal flow volume decreased for both HX's
- Optimal operating was 460 kPa pressure for AFHX and 320 kPa for PCHE
- Cycle efficiency decreases as PCHE interlayer $\longrightarrow$ 0 (approximately cross-flow HX)





Comparison of optimal geometries at 460 kPa (design pressure)

Heat Exchanger	Air Gap/Etch Depth	Cycle Efficiency	ΔP [kPa]	ΔT [°C]
AFHX	2.9 mm	27.2 %	46.2	120.3
PCHE	1.0 mm	34.0 %	13.7	44.6

MRP Microreactor Program

Air Brayton Cycle with Reheat

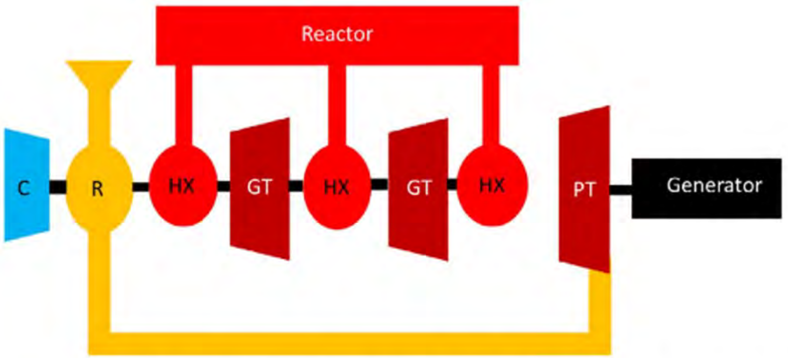
Guillen & McDaniel (2021) evaluated microreactor power conversion systems [10]

- Suggested a recuperated air Brayton cycle with 3 reheat cycles
- Found multiple heating cycles to increase efficiency

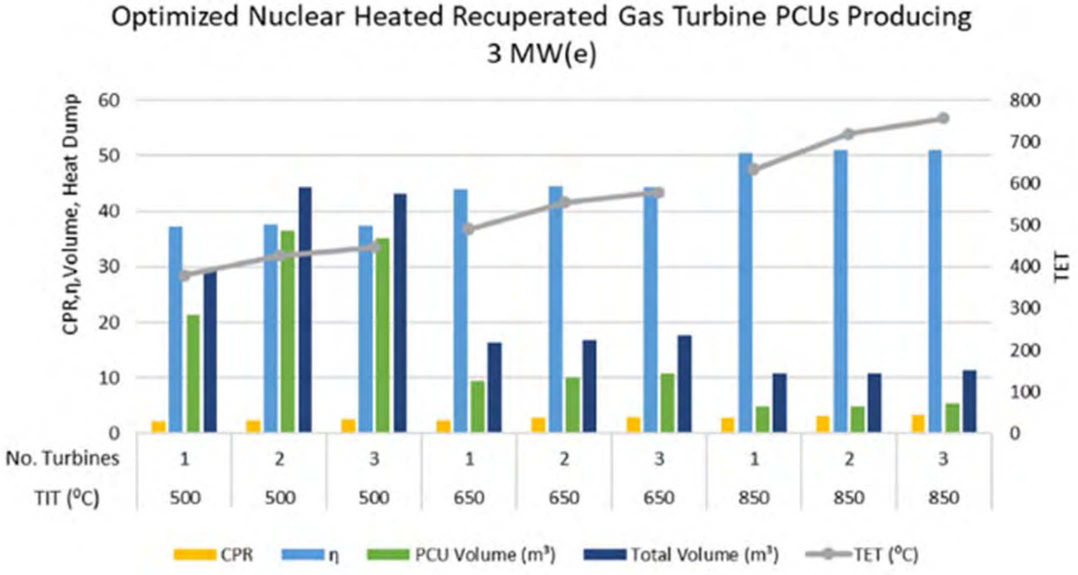
Primary heat exchanger assumptions

- Effectiveness of 0.95
- Pressure drop of 1%
- This assumes that size and space are not a constraint

- HPIHX is constrained by heat pipe geometry



Optimized nuclear heated recuperated gas turbine cycle. C=Compressor, R = Recuperator, PT=Power Turbine, HX=Heat Exchanger, GT = Gas Turbine.



Optimized nuclear heated recuperated gas turbine PCUs producing 3 MW(e).

Schematic and figure image credit from Guillen & McDaniel [10]

Air Brayton Cycle with Reheat

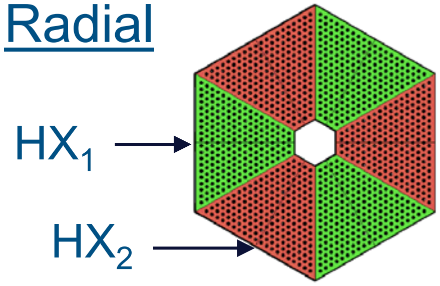
Heat exchanger distribution

- Heat pipe (HP) condenser end area is limited
- Radial HX distribution - fraction of total number of HPs, full length
- Axial HX distribution – all HPs, fraction of the total HP length

Reheat cycle modeling

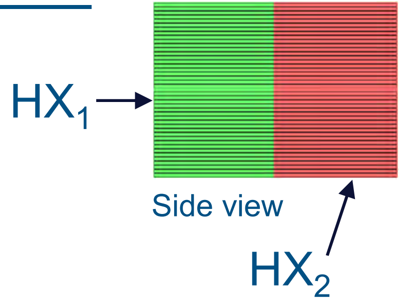
- Models developed in EES with 2 and 3 stages of heating
- For the PCHE, radial and axial distribution have the same performance as the fluid flow length and cross section are constant

Radial



Front view

Axial



Reheat cycle efficiencies for optimal PCHE and “Ideal” HXs, ϵ_R= 0.95

Heating Stages	Ideal HX η_{cycle}	ΔP	$\overline{\Delta T}$ [°C]	PCHE η_{cycle}	ΔP	$\overline{\Delta T}$ [°C]
One	42.3 %	3.2 kPa	33.9	35.4 %	15 kPa	45.5
Two	44.1 %	4.7 kPa	33.9	33.8 %	39 kPa	55.2
Three	44.5 %	7.1 kPa	33.9	26.9 %	97 kPa	52.3

Reheat cycle efficiencies for optimal axial and radial AFHX configurations, ϵ_R= 0.95

Heating Stages	Radial AFHX η_{cycle}	ΔP	$\overline{\Delta T}$ [°C]	Axial AFHX η_{cycle}	ΔP	$\overline{\Delta T}$ [°C]
One	27.2 %	46 kPa	120.3	27.2 %	46 kPa	120.3
Two	21.3 %	92 kPa	153.7	27.6 %	52 kPa	126.0
Three	20.4 %	97 kPa	175.4	27.8 %	56 kPa	134.2

PCHE

- As HXs were added, ΔP increased, decreasing efficiency

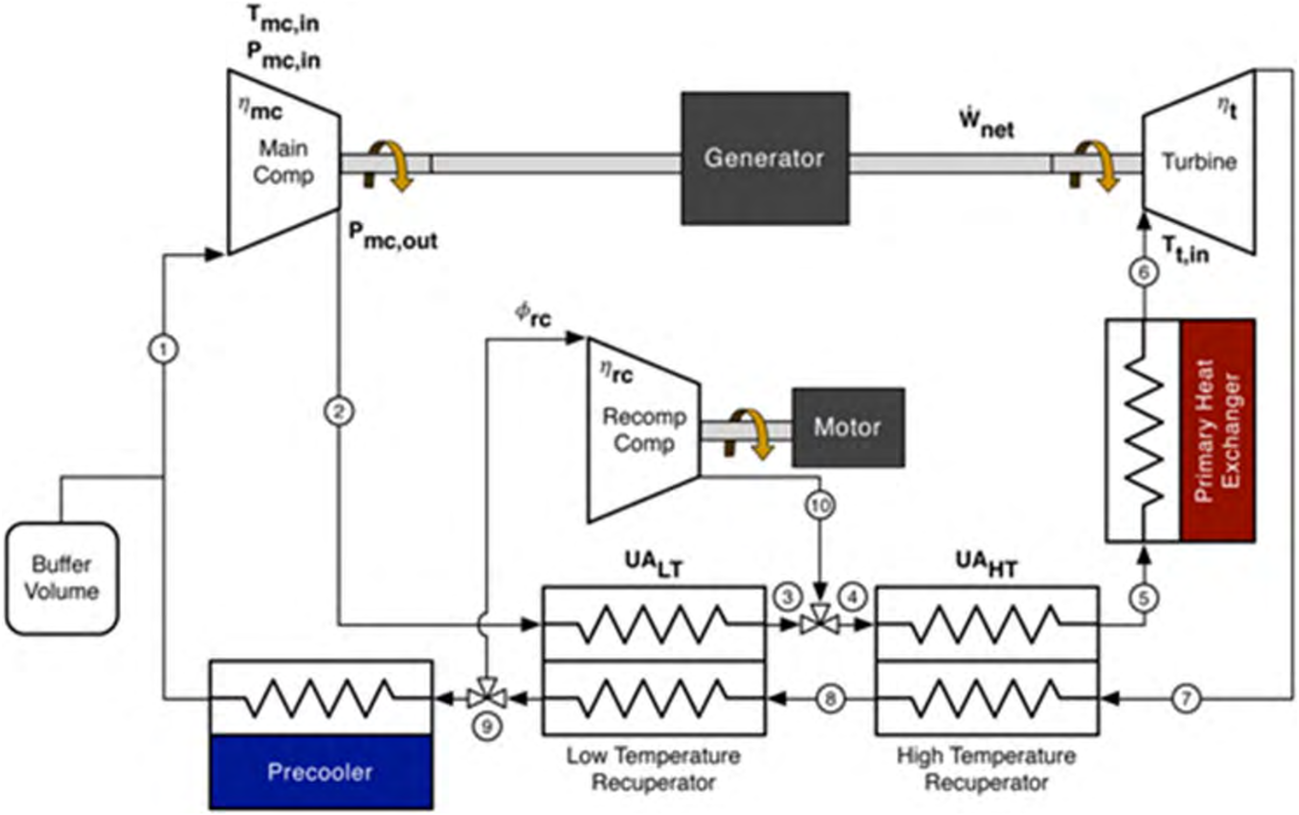
AFHX

- As HXs were added, ΔT increased
- Radial split: decreased cycle efficiency
- Axial split: optimized towards single HX (9:1 split) and resulted in negligible increase to efficiency

Future Modeling Work

Future work

- sCO_2 cycle has been developed in EES
- Evaluate PCHE model with sCO_2 working fluid
- Repeat design optimization for the PCHE with sCO_2 Brayton cycle

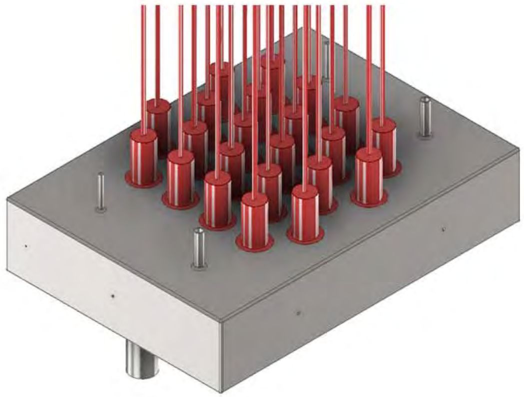


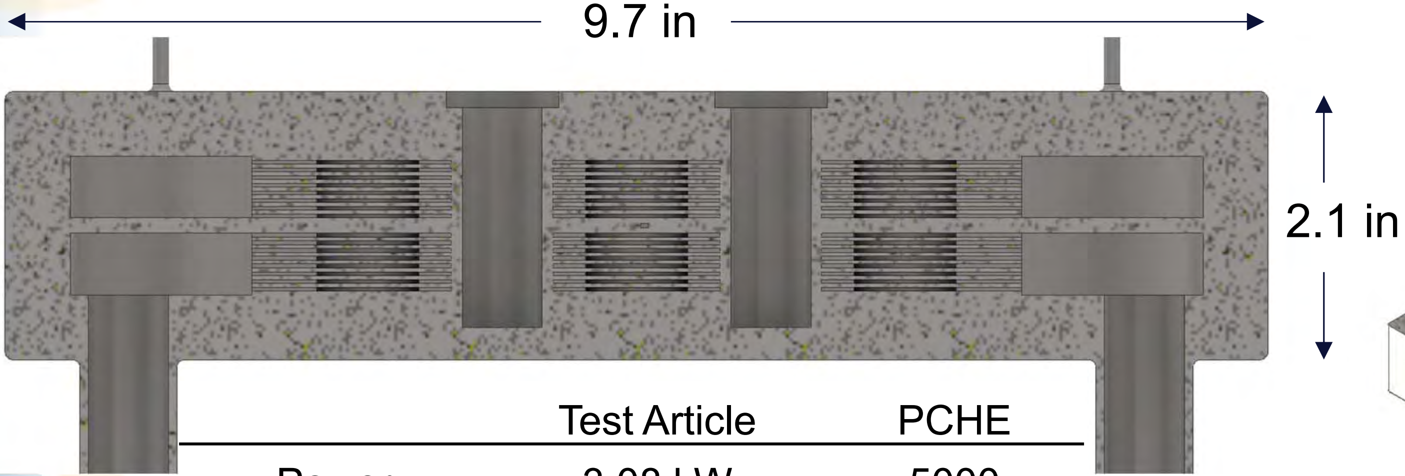
Schematic of recompression sCO_2 cycle, from Dyreby et al., (2014) [11]

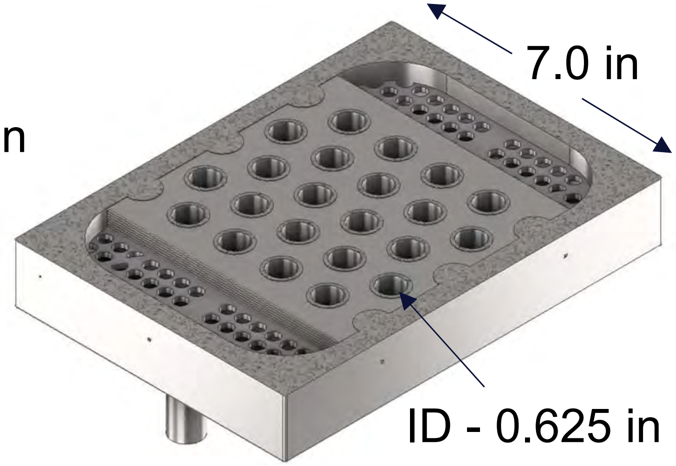
Air Test Specimen Design

Design Specifications

- Up to 3.08 kW with 22 conduction cartridge heaters (~140 W each)
- 9.7” x 7.0” x 4.8” (with headers and heaters)
- 36 - 1.5 mm 316 stainless steel sheets
- 16 – “flow” layers etched to 1 mm depth
- Matches cross section at the wedge exit





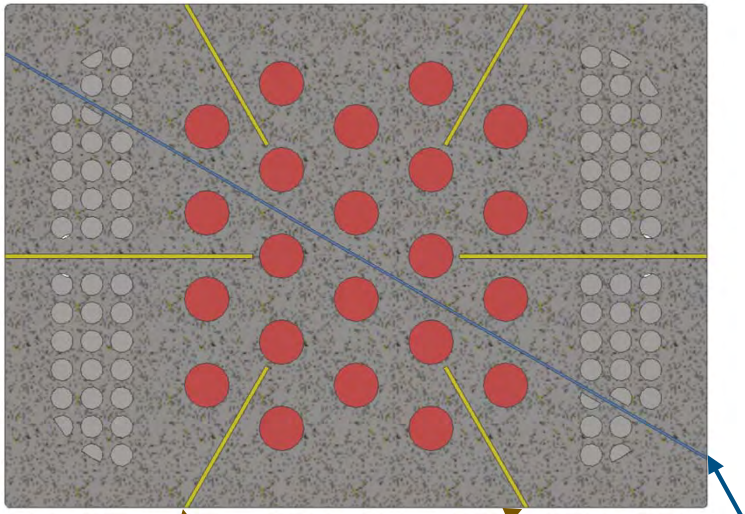


	Test Article	PCHE
Power	3.08 kW	5000
Energy density	69 W/in^2	67 W/in^2
Cross section	0.080 in^2	0.08-0.34 in^2
Mass flow rate	0.002-0.08 kg/s	16.4 kg/s

Instrumentation

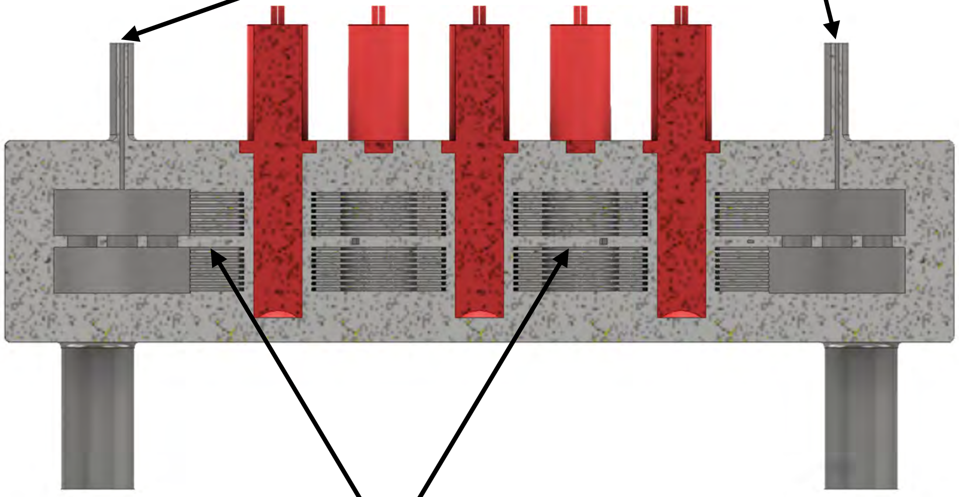
Proposed instruments

- Thermocouples (TCs) at inlet/outlet plenums
- Thermocouples at heat pipe walls
- Differential pressure transducer at inlet/outlet plenums
- Fiber-optic temperature sensor for body temperature



Thermocouple probes

Fiberoptic temperature sensor



Pressure transducer and TC ports

Instrumentation plate

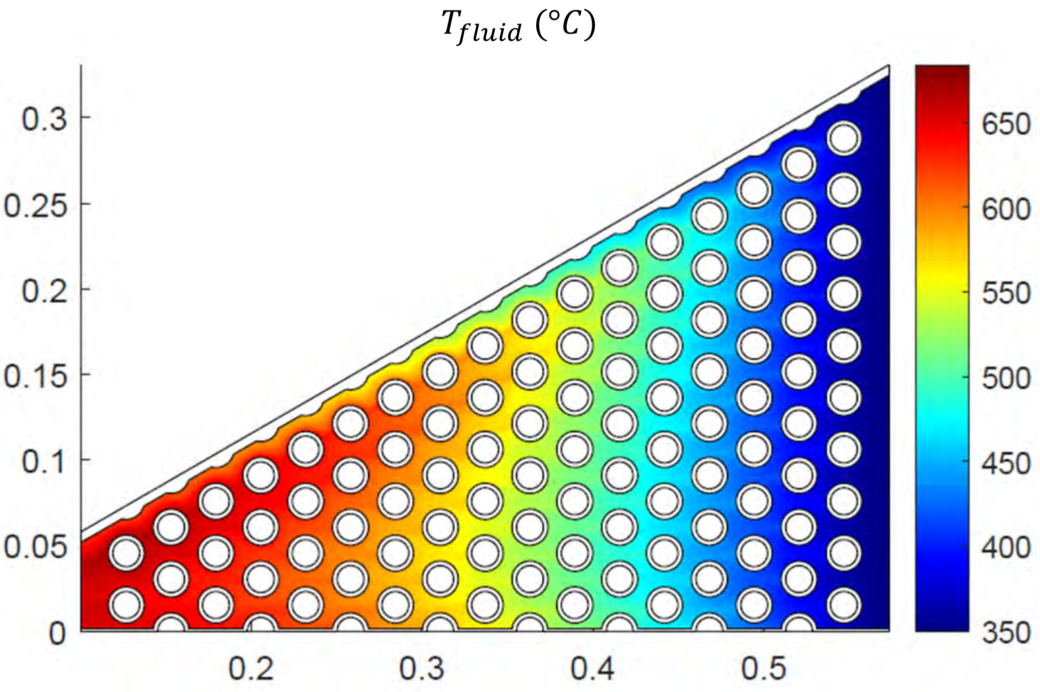
Anticipated Measurements and Testing

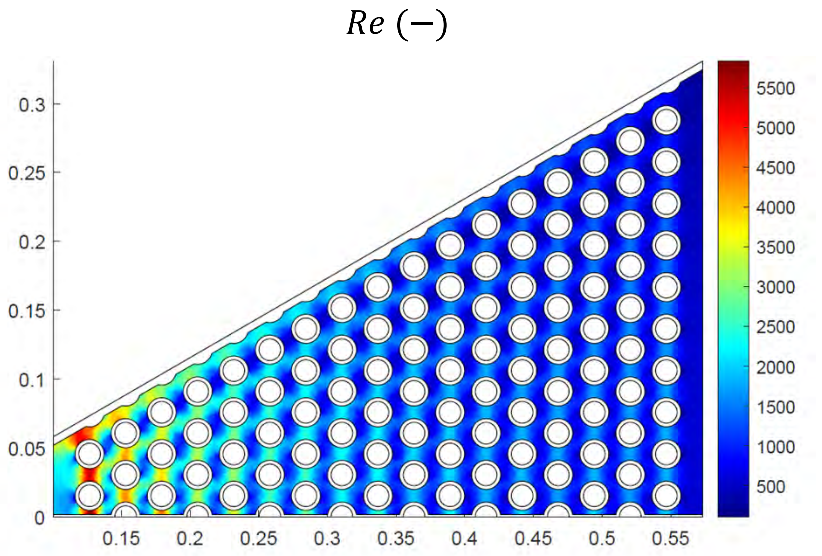
Instrument measurements

- Inlet/outlet TC's → fluid temperature change
- Heat pipe TC's → heater wall temperature
- Fiber-optic sensor → *body temperature gradient*
- Pressure transducer → *pressure drop*
- Testing will vary T_{in}, P_{in}, and $\dot{m}$ to simulate wedge conditions

approach temperature

	PCHE Entrance	PCHE Exit
Temperature	345 °C	620 °C
Pressure	460 kPa	447 kPa
Reynolds	1420	5959

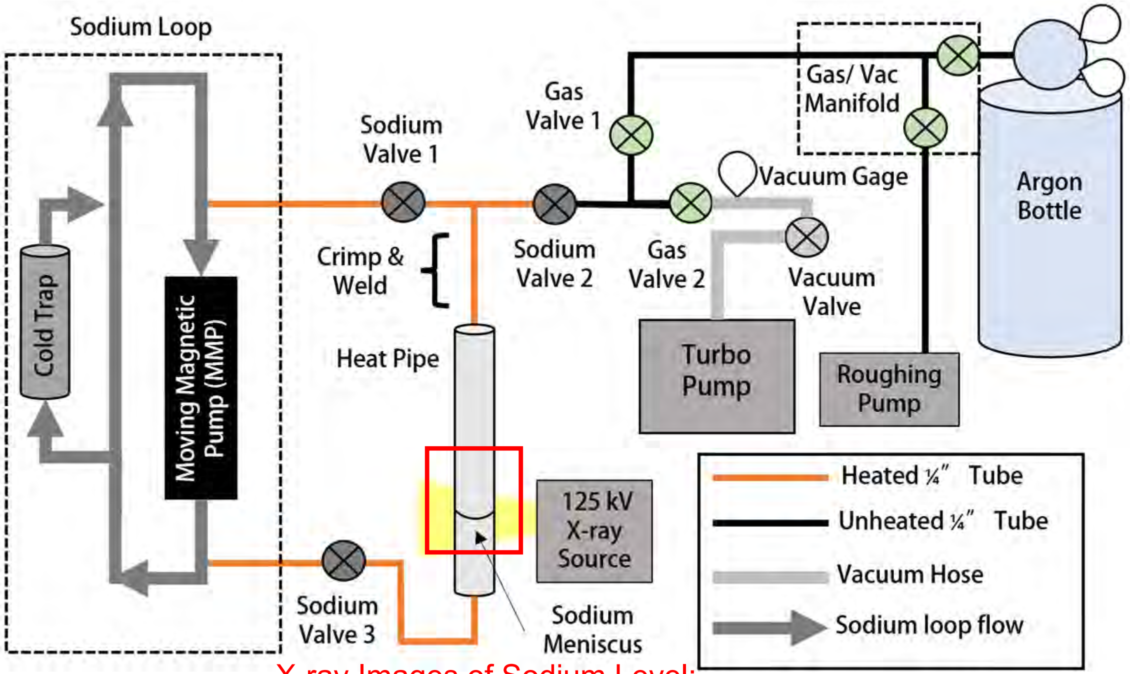




MRP Microreactor Program

Heat Pipe Fill

1. Run sodium at 400 ℃ through vertical pipe (upflow) for 3 hours
2. Drain the loop of sodium
3. Pulse Sodium Valve 3 open/closed and periodically take an X-ray image to look for sodium meniscus
4. Crimp & weld upper fill tube
5. Allow sodium to freeze and flip heat pipe upside-down
6. Remelt to transfer sodium to the bottom and refreeze
7. Pull turbo vacuum (~1E-05 torr) on the heat pipe overnight
8. Crimp and weld upper fill tube for the final seal



X-ray Images of Sodium Level:

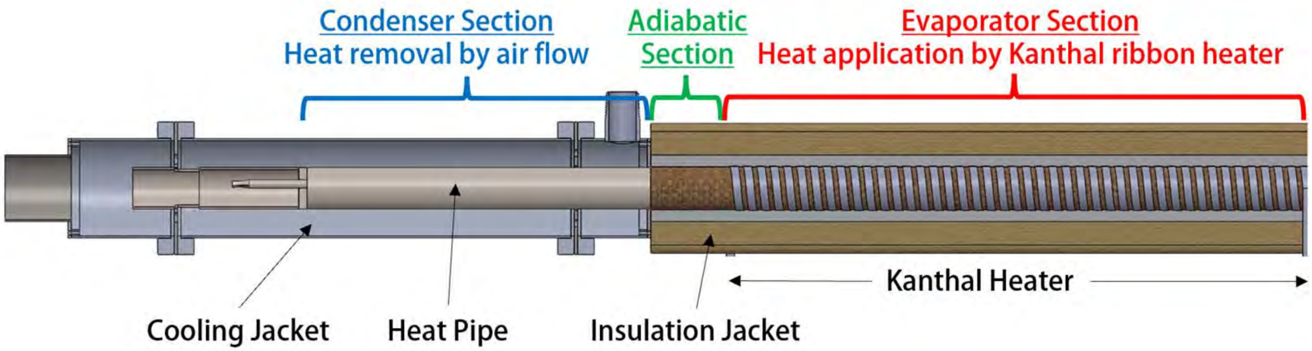
Liquid sodium meniscus

Indicates target fill level

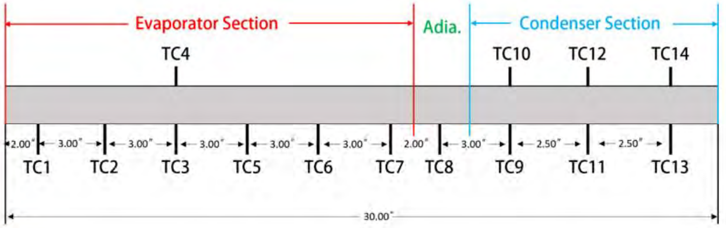
Bar removed to show final level:

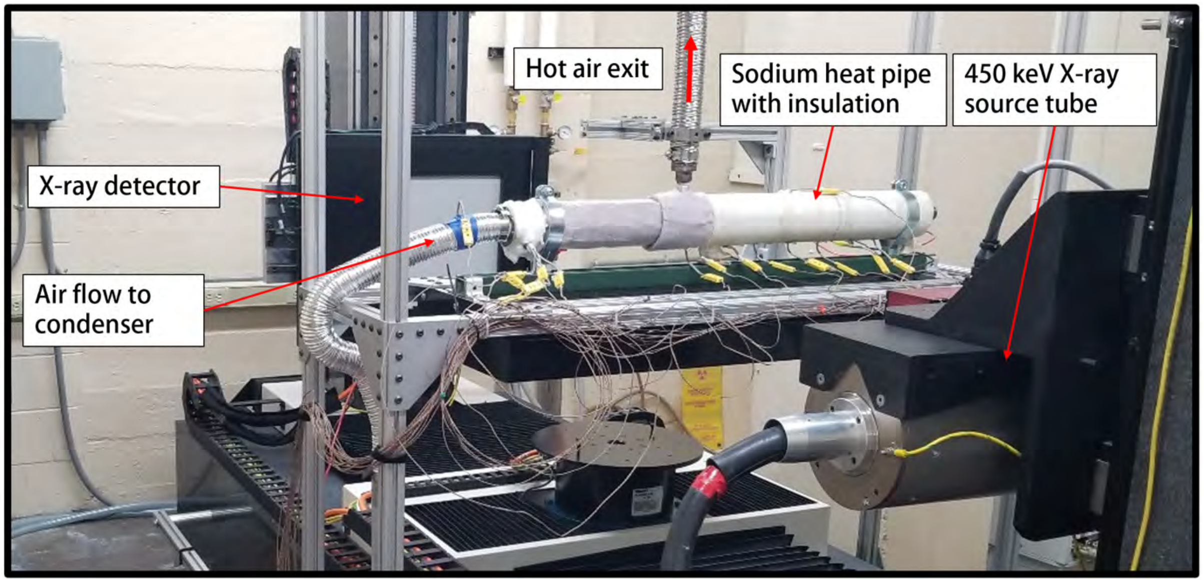
MRP Microreactor Program

Testing Facility

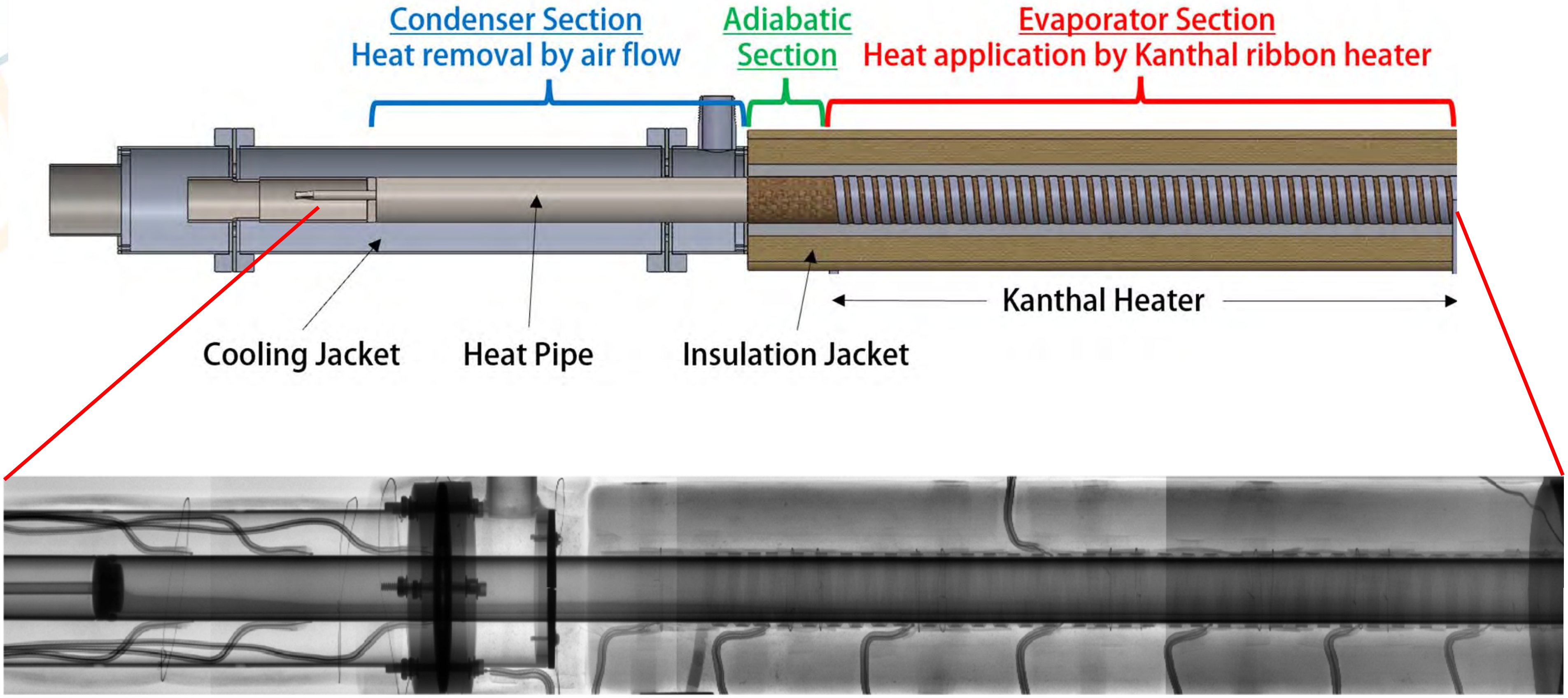


- Heat is applied to evaporator by resistive heating of Kanthal (FeCrAl) ribbon
- Blower drives air flow through a cooling jacket to remove heat
- Heat pipe installed on 450 kV X-ray machine for imaging
- Detector can record up to 30 fps with 0.4mm resolution
- 7 evaporator, 1 adiabatic, 6 condenser thermocouples measure temperature:

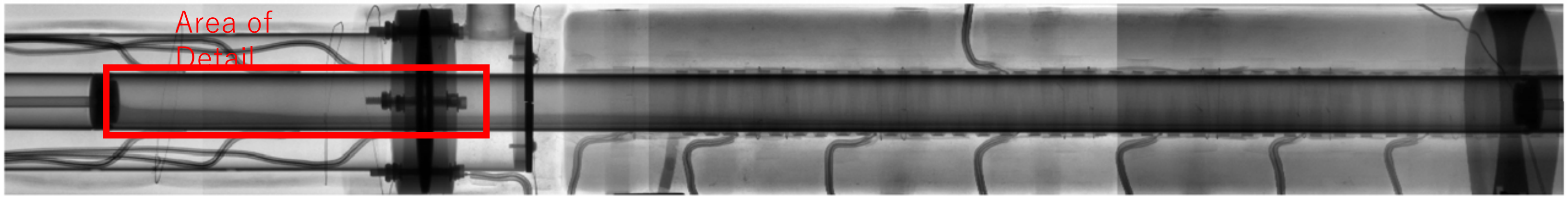




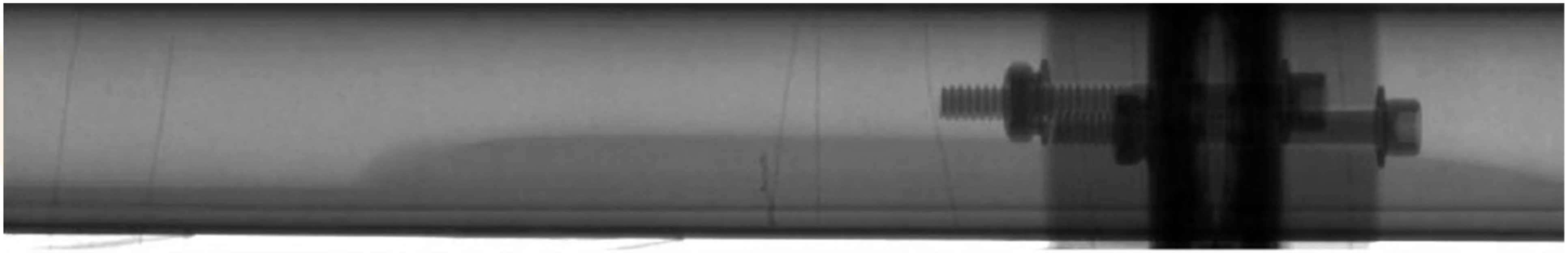
Heat Pipe Imaging



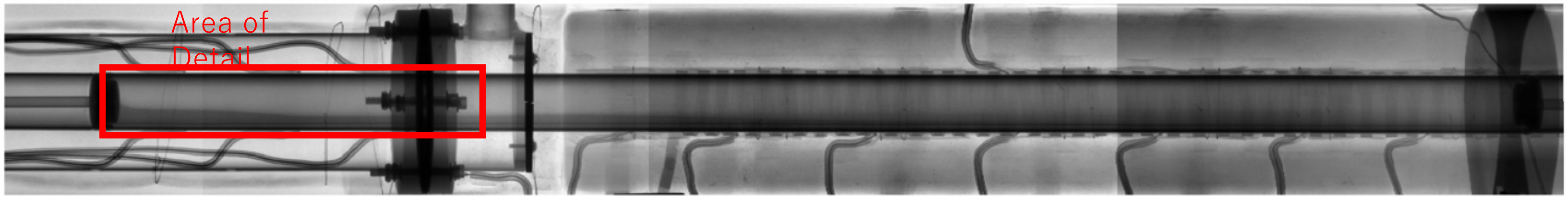
Condenser Startup



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



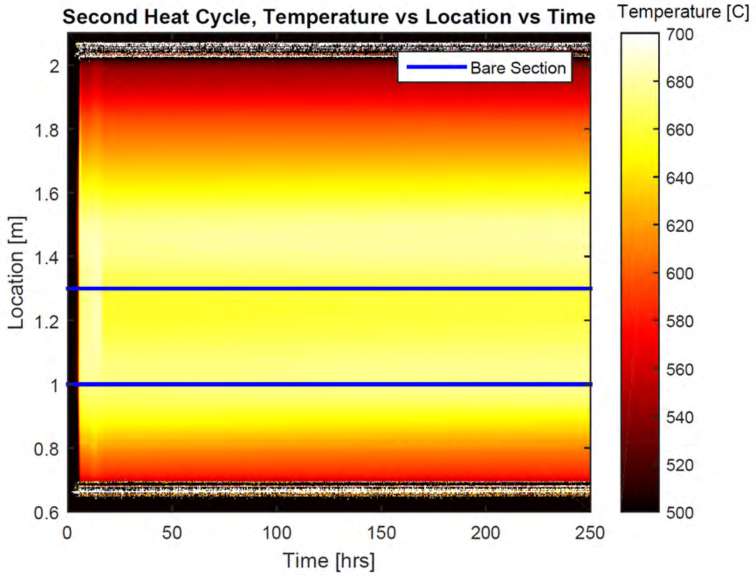
Condenser Shutdown



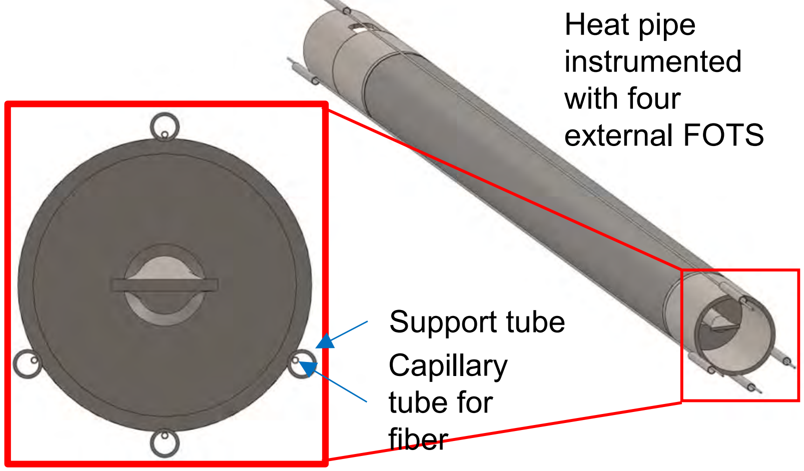
Heat Pipe condenser after heater is shut down: 5x speed, 500 W

Next Steps

- Instrument the current heat pipe with external Fiber Optic Temperature Sensors
- Manufacture next-iteration heat pipe with internal FOTS for more accurate temperature measurements
- Optimize imaging methods
- Apply Dual-Energy Material Decomposition to get some indication of sodium void fraction in the wick
- Capture evaporator dryout event with time-resolved X-ray imaging



Example of FOTS showing spatial and temporal resolution



Heat pipe instrumented with four external FOTS

Support tube

Capillary tube for fiber

References

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

[2] Abou-Jaoude, A., A. Foss, Y. Arafat, and B. Dixon, *An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept*, INL/EXT-21-63067 (2021).

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