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Thermohydraulic performance of a supercritical CO_2 PCHE for heat pipe microreactors

2026 sCO2 Symposium
NEUP Project 21-24226

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NEUP Nuclear Energy University Program
U.S. Department of Energy

INL Idaho National Laboratory

Westinghouse

SCL

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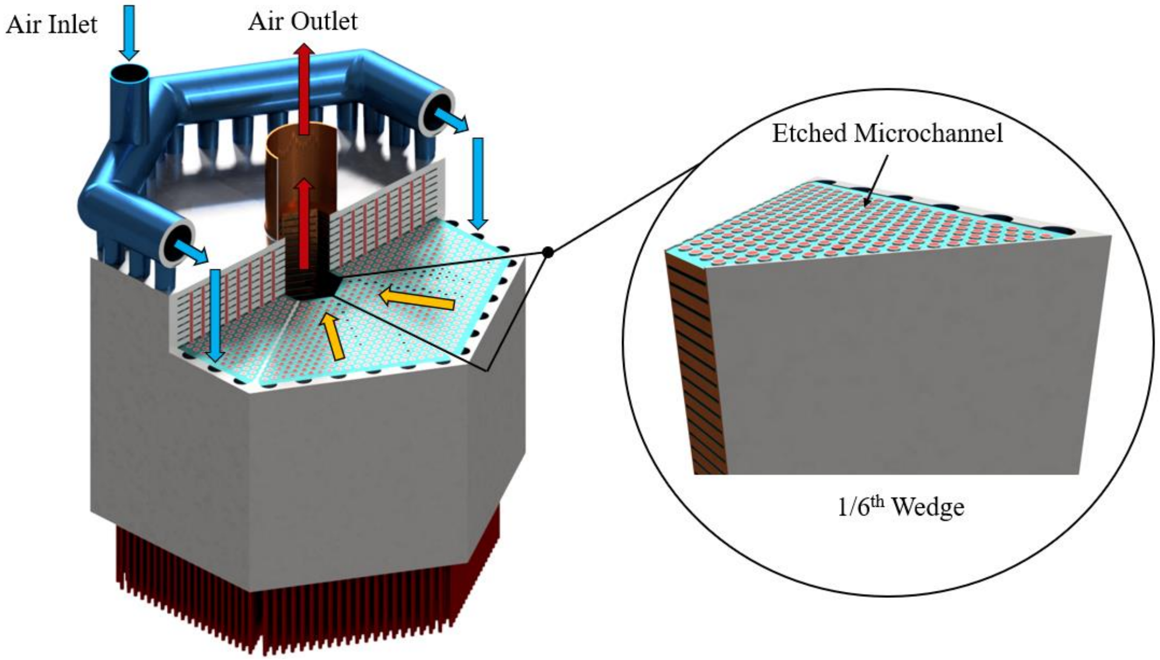
Presentation Overview

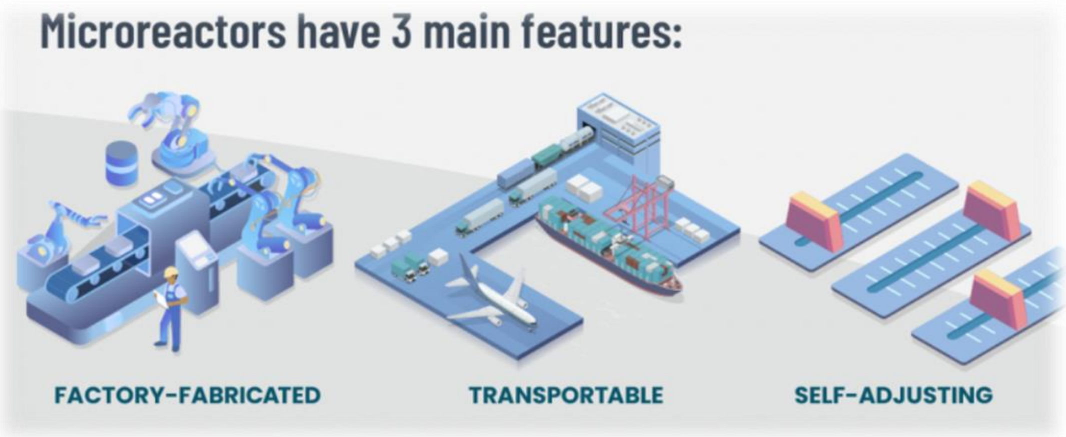
- Project background
    - Heat pipe microreactors
    - Project objectives
- sCO_2 test article manufacturing
- $WisCO_2$ facility integration
- sCO_2 testing
    - Thermohydraulic performance
    - Model comparison and validation
    - Fiber optic temperature sensor results
- Conclusions



Project Background

Microreactors

- 2050 net-zero carbon dioxide emissions target
- Nuclear power capacity in the U.S. from 100 GW to 300 GW
- Well suited to replace diesel generators (1-50 MWe)
    - Remote communities (high fuel costs)
    - Military installations (remote, fewer fuel shipments)
    - Disaster relief (emergency response, water treatment)
    - Industrial processes (mining operations, process heat)

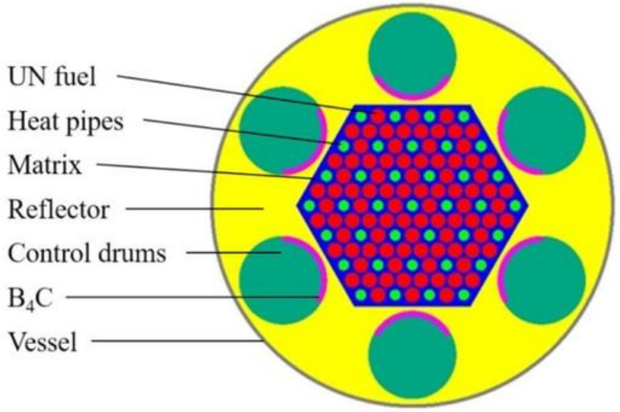


Microreactor features (INL)

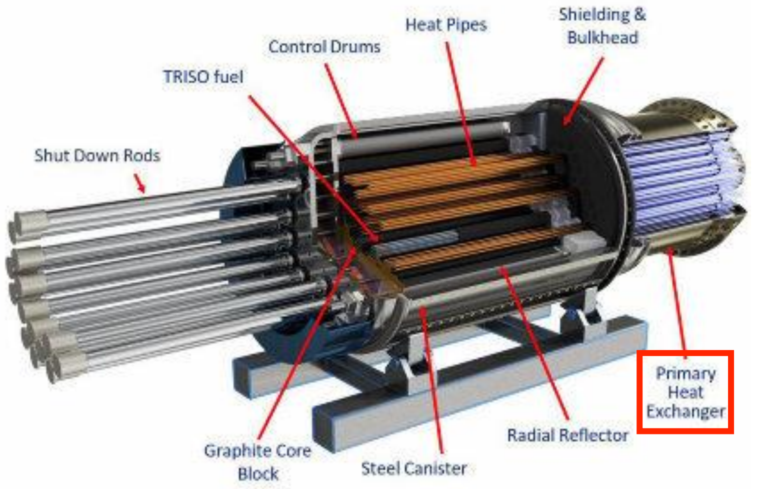
Microreactors," INL, https://inl.gov/trending-topic/microreactors/

Heat Pipe Microreactors

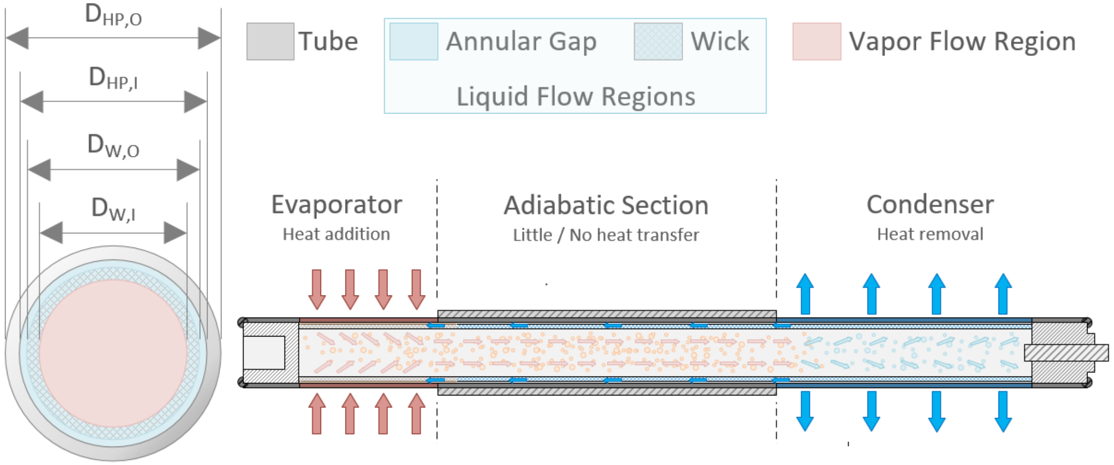
- Heat pipe microreactors
    - Fuel interspersed with heat pipes
    - “Solid state core”
    - Robust and fault tolerant
- Heat pipes
    - Working fluid is heated to evaporation
    - Vapor moves from pressure difference
    - Vapor condenses onto internal wick
    - Capillary forces move liquid back
    - High temperature HPs often use liquid metals (e.g., sodium)
- Heat pipe interface heat exchanger
    - HPIHX, interfaces heat pipe condenser end with process fluid (primary HX)



HPMR schematic [1]



eVinci™ microreactor rendering (Westinghouse [2])



Heat pipe schematic

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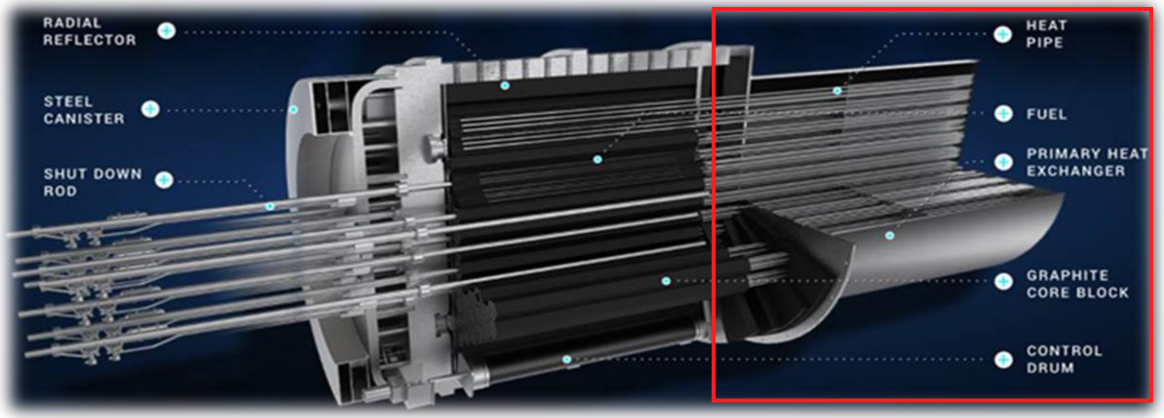
[1] H. Sun, C. Wang, X. Liu, W. Tian, S. Qiu, and G. Su, “Reactor Core Design and Analysis for a Micronuclear Power Source,” Front. Energy Res., vol. 6, Mar. 2018, doi: 10.3389/fenrg.2018.00014.

[2] “eVinci™ Microreactor | Westinghouse Nuclear.” https://westinghousenuclear.com/energy-systems/evinci-microreactor/

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

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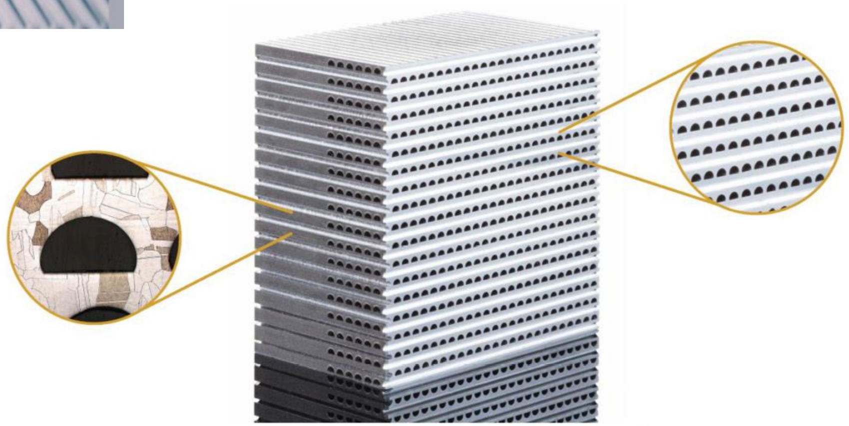
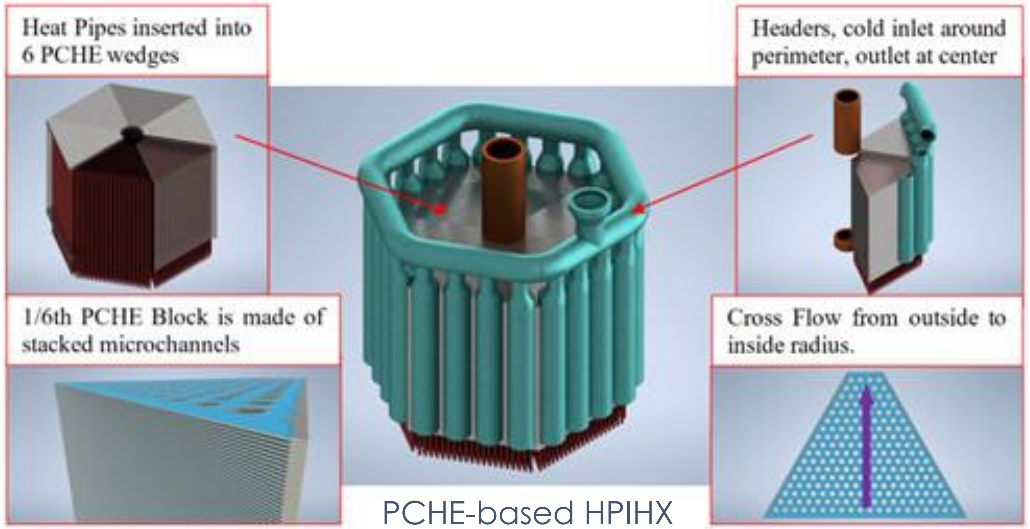
Printed Circuit Heat Exchanger

- 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

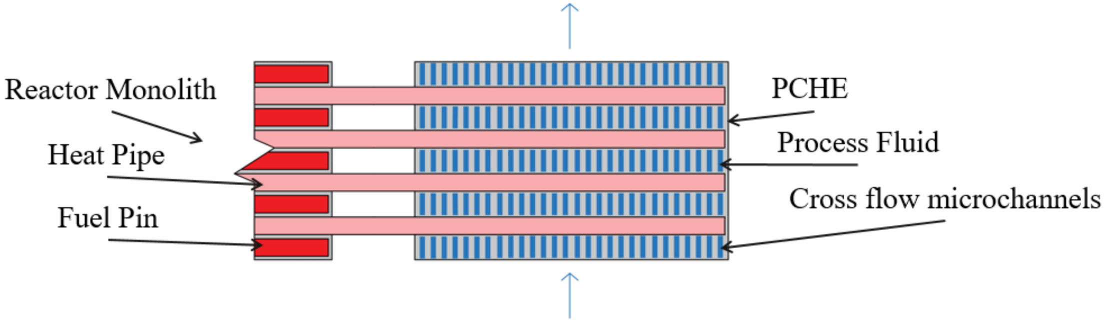
Chemically etched microchannel [1]



Cutout of diffusion bonded PCHE (VPEI [2])



PCHE-based HPIHX



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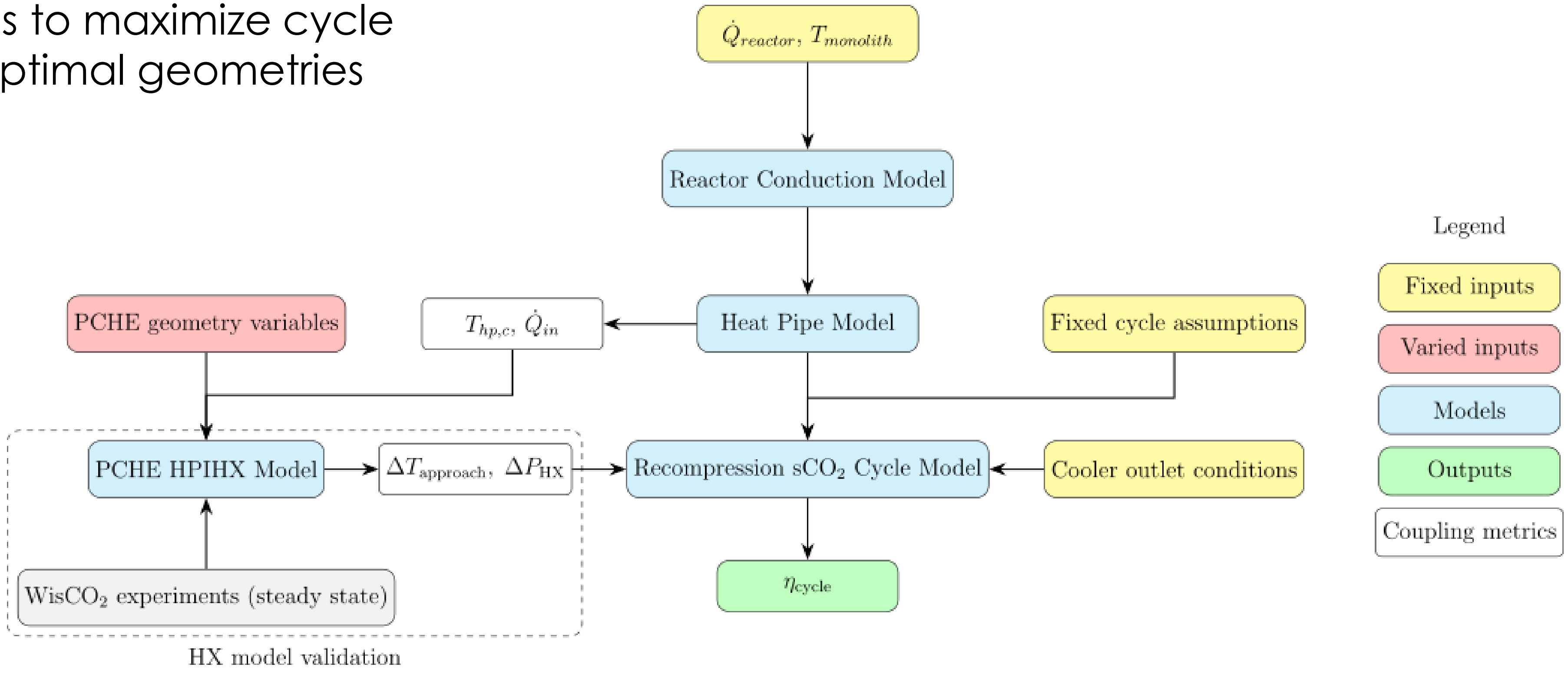
[1] "Diffusion bonded heat exchangers," Vacuum Process Engineering, https://www.vpei.com/diffusion-bonded-microchannel-heat-exchangers/ (accessed Jun. 7, 2023).
[2] "How to model a shell and tube heat exchanger," COMSOL, https://www.comsol.com/blogs/how-model-shell-and-tube-heat-exchanger/ (accessed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

Interface Heat Exchanger Optimization

- Optimized using cycle model
  - Varied HX geometries to maximize cycle efficiency and find optimal geometries
- PCHE HX models
- $\Delta P = P_{in} - P_{out}$
- $\Delta T = T_{hp_{max}} - T_{fluid,out}$
- sCO$_2$ Brayton cycle
- CFD PCHE model


$\dot{Q}_{reactor}$, $T_{monolith}$

Reactor Conduction Model

PCHE geometry variables

$T_{hp,c}$, $\dot{Q}_{in}$

Heat Pipe Model

Fixed cycle assumptions

PCHE HPIHX Model

$\Delta T_{\mathrm{approach}}$, ΔP_{HX}

Recompression sCO$_2$ Cycle Model

Cooler outlet conditions

WisCO$_2$ experiments (steady state)

η_{cycle}

HX model validation

Legend

Fixed inputs

Varied inputs

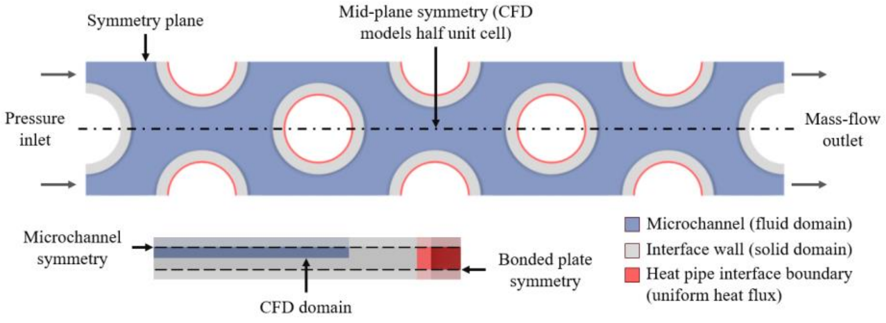
Models

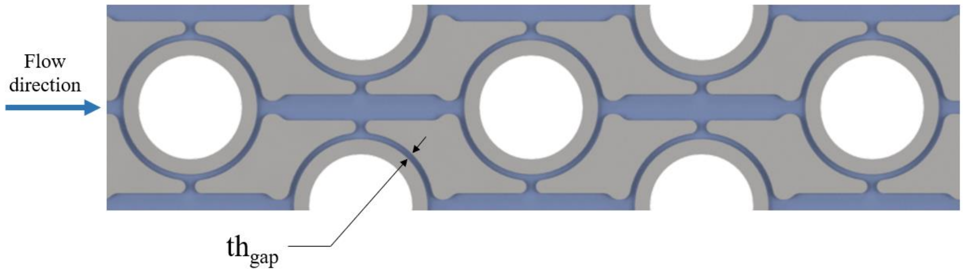
Outputs

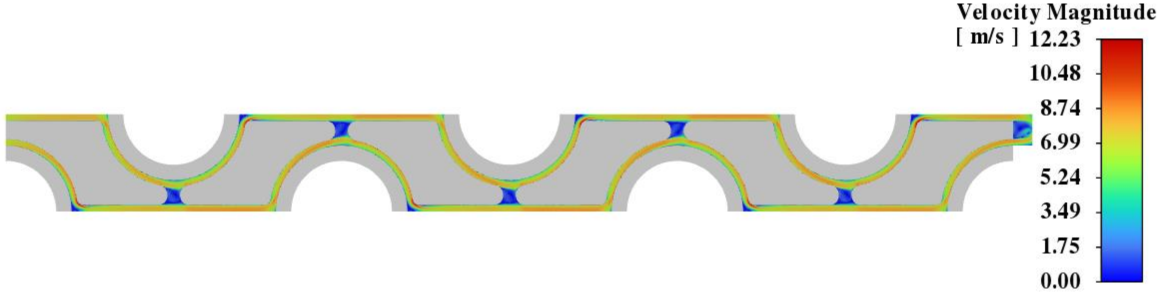
Coupling metrics

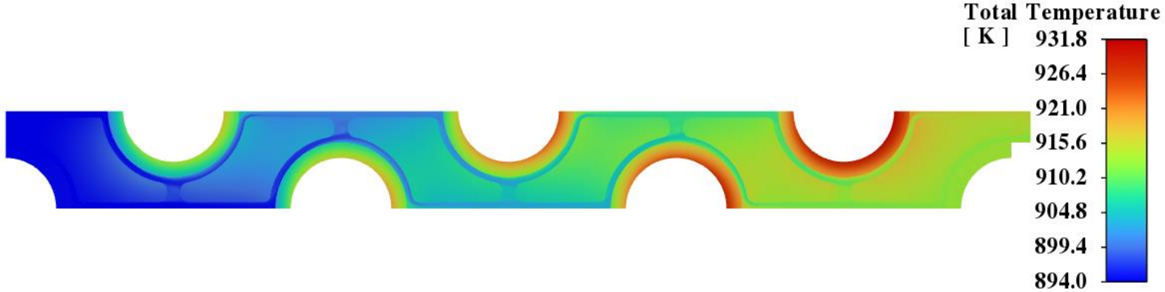
CFD Microchannel Optimization

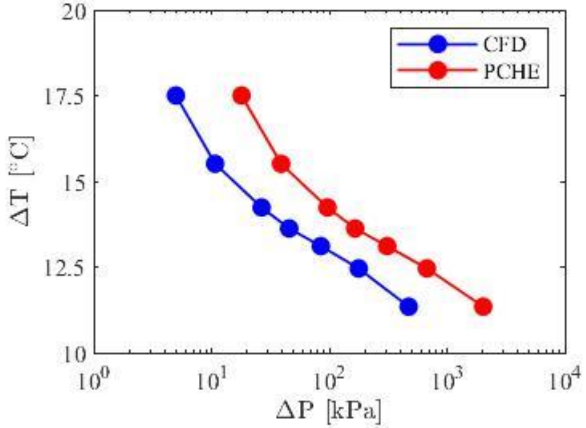
- CFD “unit-cell” microchannel model developed
    - Evaluated geometry families to arrive at “containment” geometry
- Optimized characteristic geometry through cycle efficiency (through $\Delta T_{approach}$, ΔP)
- Matched $\Delta T_{approach}$ to unit cell, ΔP_{PCHE} from minor loss factors determined from CFD











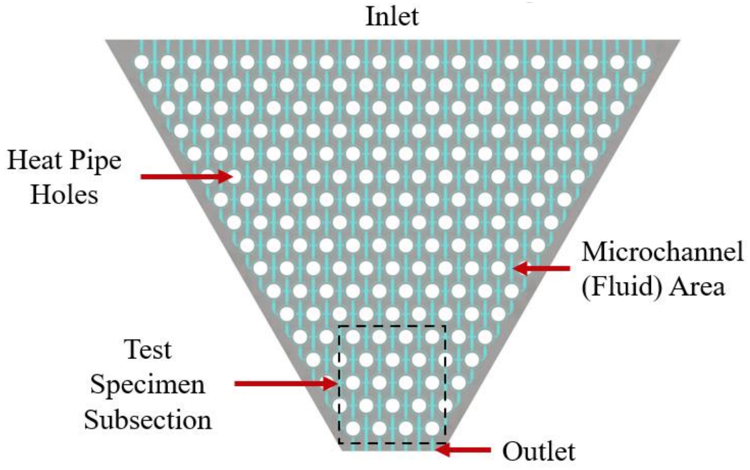
CFD unit cell approach temperature and pressure drop

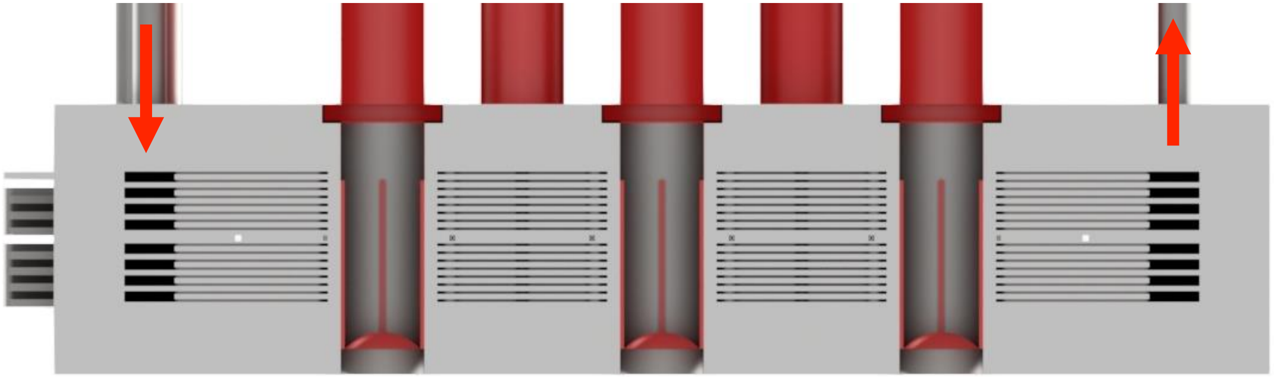
sCO_2 Test Article

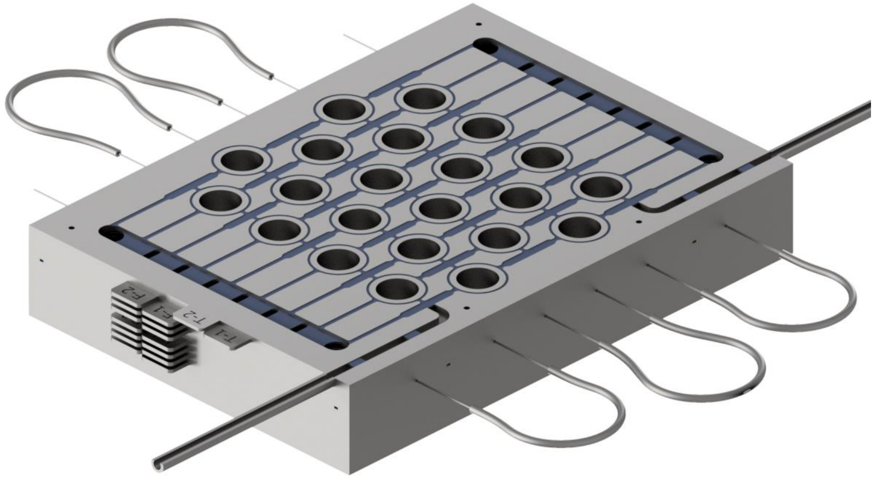
Manufacturing and instrumentation

sCO$_2$ Brayton Test Specimen

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



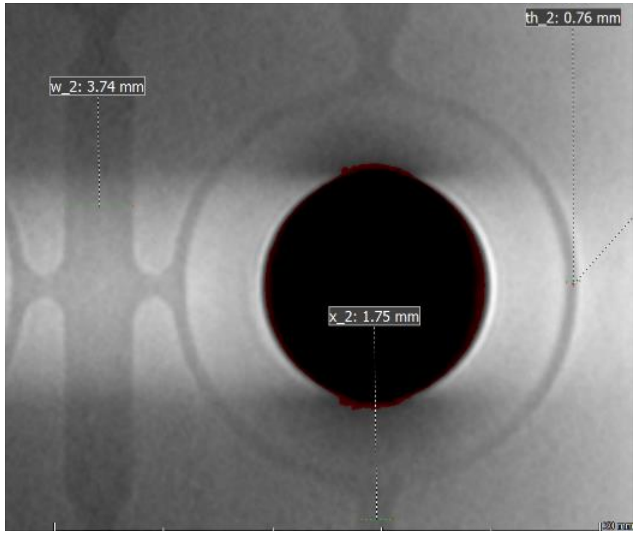


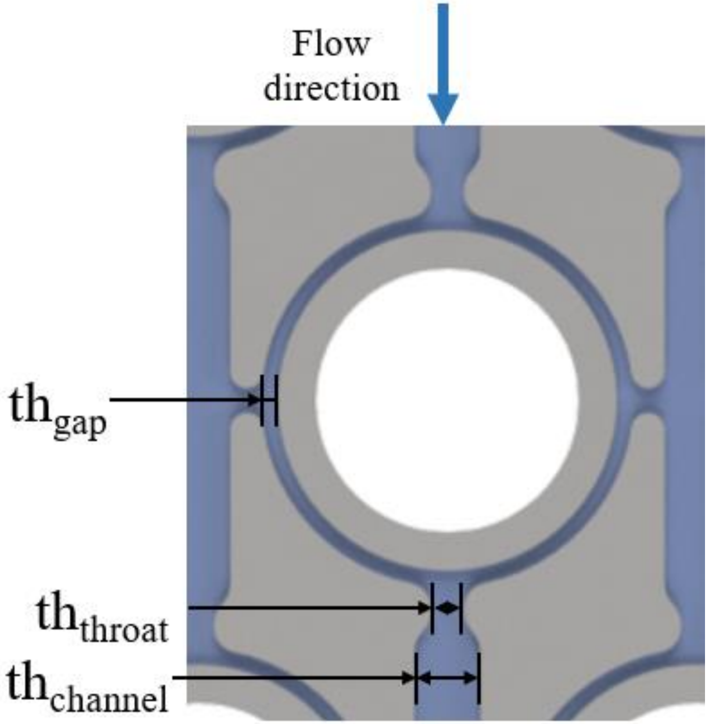


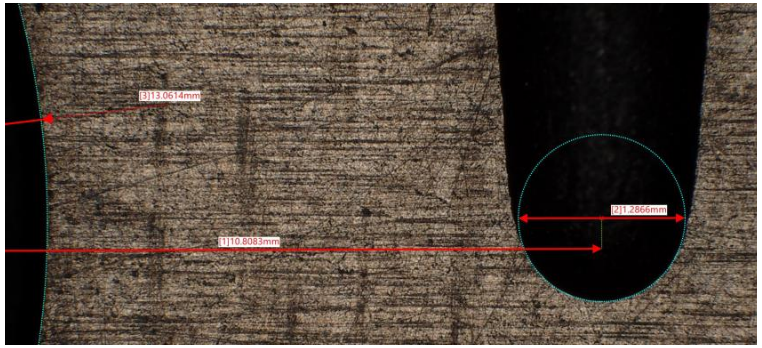
	Test Article	Full Size HX
Power	2.75 kW	5000 kW
Energy density	66 W/in^2	67 W/in^2
Cross section	0.08 in^2	0.08-0.34 in^2
Mass flow rate	0.06-0.16 kg/s	24.5 kg/s

sCO_2 Test Specimen Characterization

- CT scan of channel geometry
- Resulting dimensions
  - Heater gap (th_{gap}) ~ 0.76 vs. 1 mm
  - Relief channel ($th_{channel}$) ~ 3.75 vs. 4 mm
  - Throat thickness (th_{throat}) ~ 1.75 vs. 2 mm
- Approximately 0.24 mm narrow
  - 0.12 mm shallow on etch (2x)
  - Etch depth ~ 0.38 vs. 0.5 mm
- Etch uncertainty ~ 0.15 mm (10% mat th)
- Optical measurements
  - TC probe locations

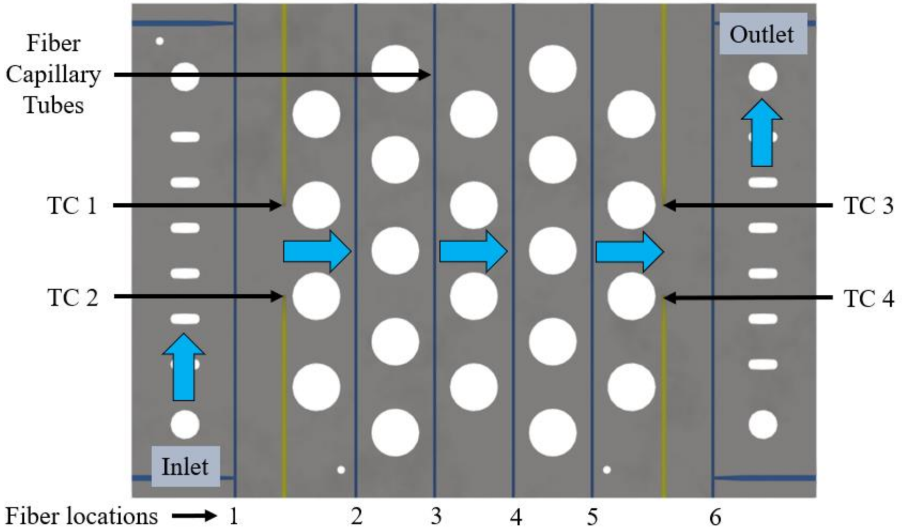


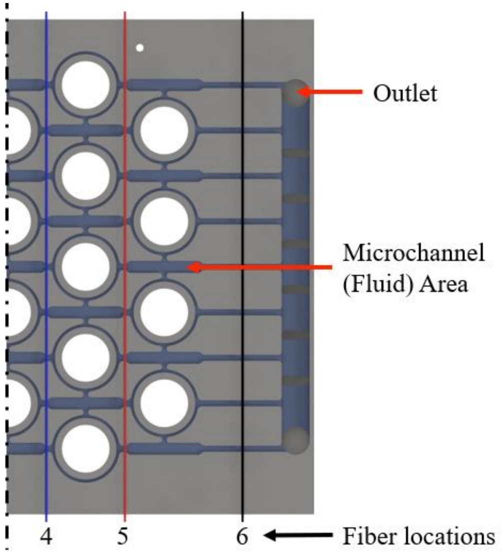


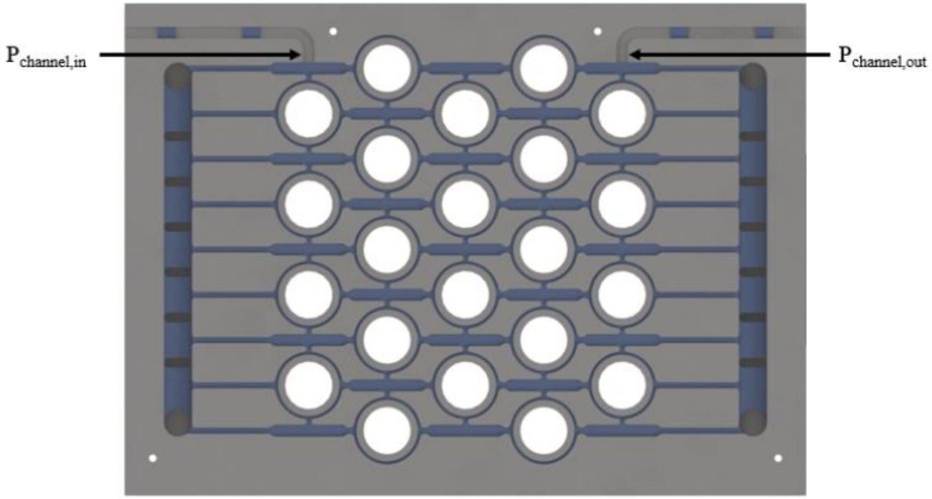


Instrumentation

- 4 – embedded TCs
- 6 – fiber optic temperature sensor passes
- Inlet and outlet fluid TCs
- Inlet and outlet pressure
  - Channel and test specimen
- Key parameters
  - $\boldsymbol{\Delta T_{approach}} = \frac{\mathrm{TC_3+TC_4}}{2} - \mathrm{TC_{out}}$
  - $\boldsymbol{\Delta P_{channel}} = P_{channel,in} - P_{channel,out}$



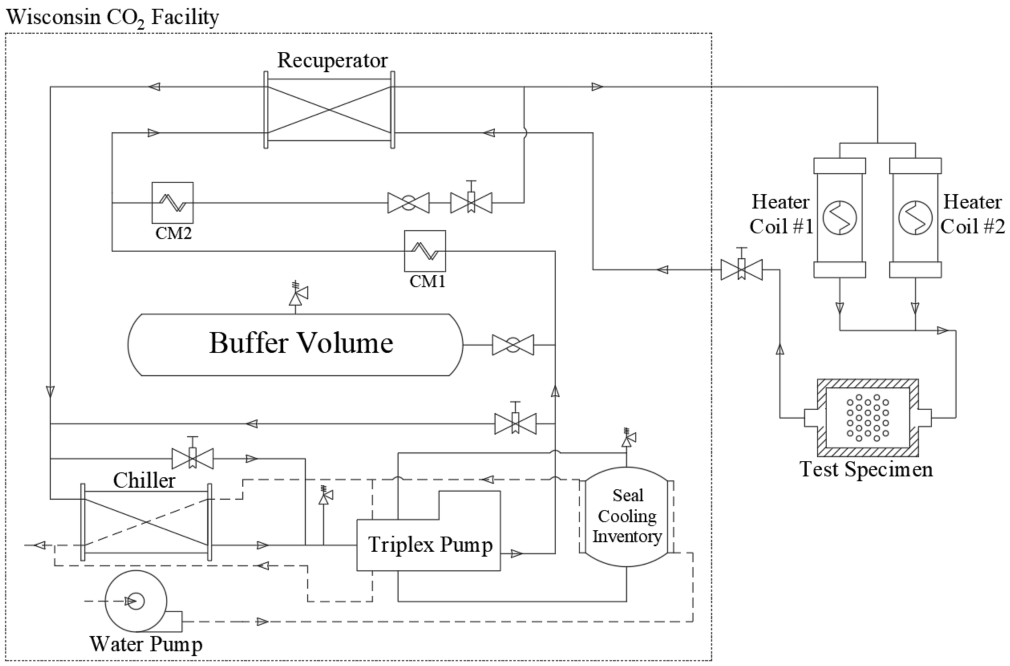


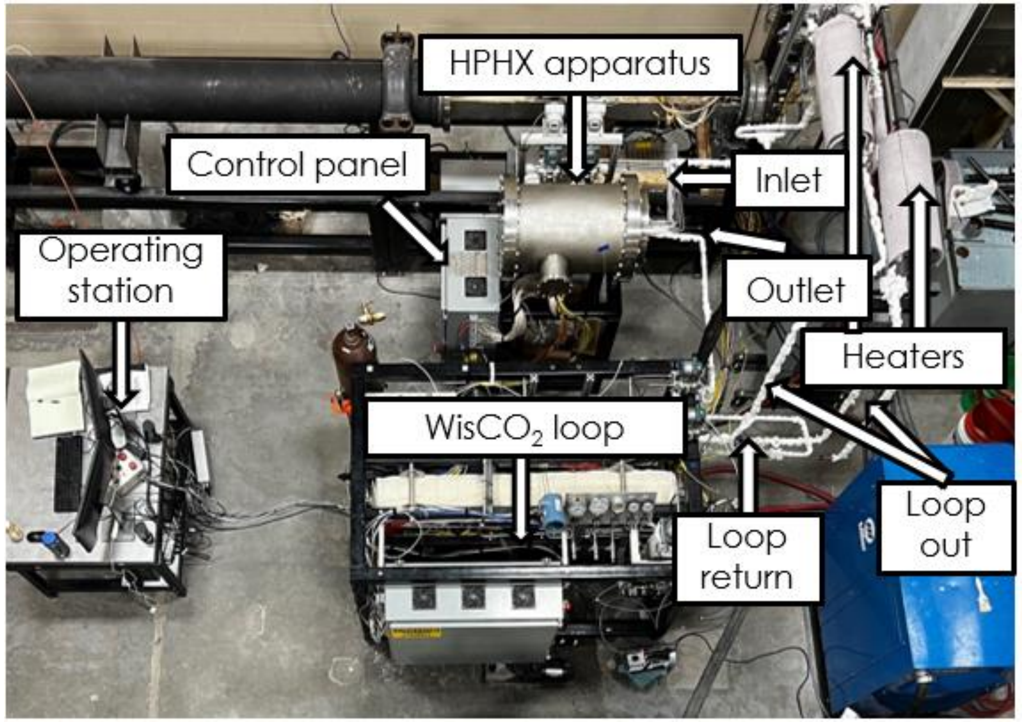


WisCO$_2$ Facility

Facility and integration

WisCO$_2$ Facility





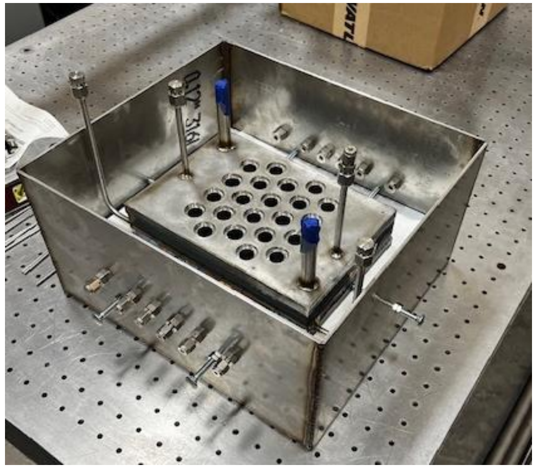
WisCO$_2$ facility layout

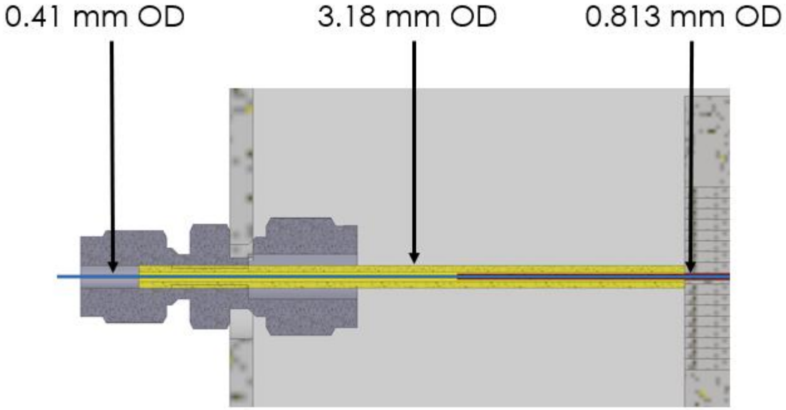
- Facility operating region
  - Operating pressure up to ~25 MPa
  - Mass flow rate ~ 0.02–0.6 kg/s
  - Inlet temperature up to ~ 500 C (current configuration)

Test	Pressure	Temperature	Mass Flux [kg/m^{2}s]	Heater Power
1-7	10 MPa	75°C	260, 400, 530, 660, 800, 930, 1060	100%
8-14		200°C		
15-21		325°C		

Test Specimen Integration

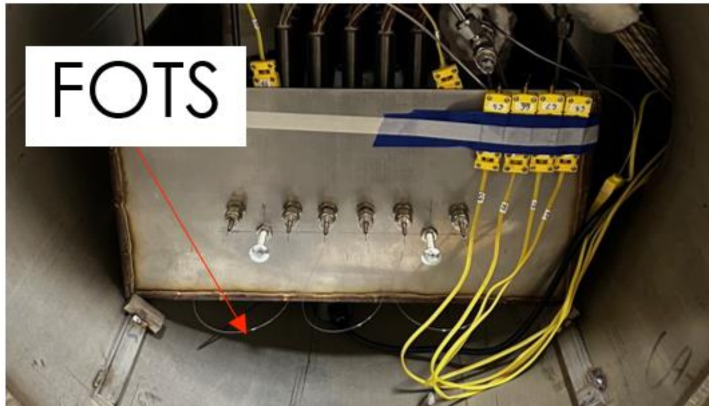
- Insulation tray
    - Minimize heat losses
    - Feedthroughs support fiber optic sensor
- Test apparatus
    - SS chamber provides biological shield
    - CO_2 detector monitors for leaks
    - Heater control and DAQ panel


Test specimen insulation tray



FOTS feedthroughs


Instrumented and insulated test specimen



Installed fiber optic temperature sensor


Heat exchanger test apparatus

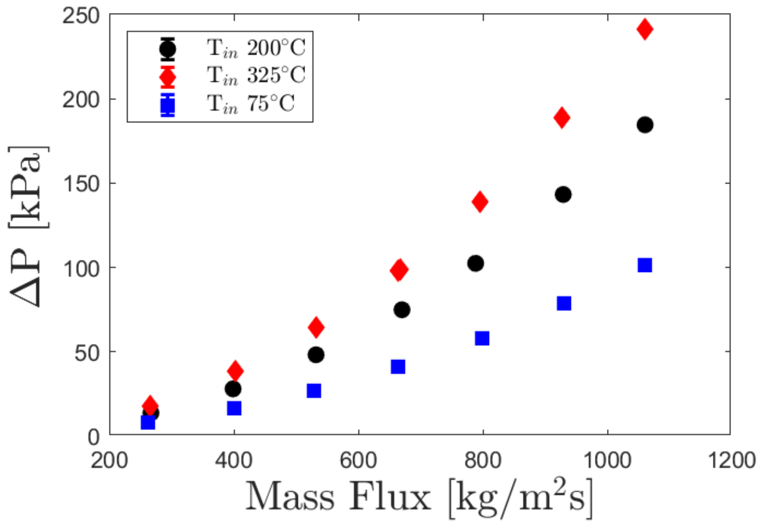
sCO_2 Testing

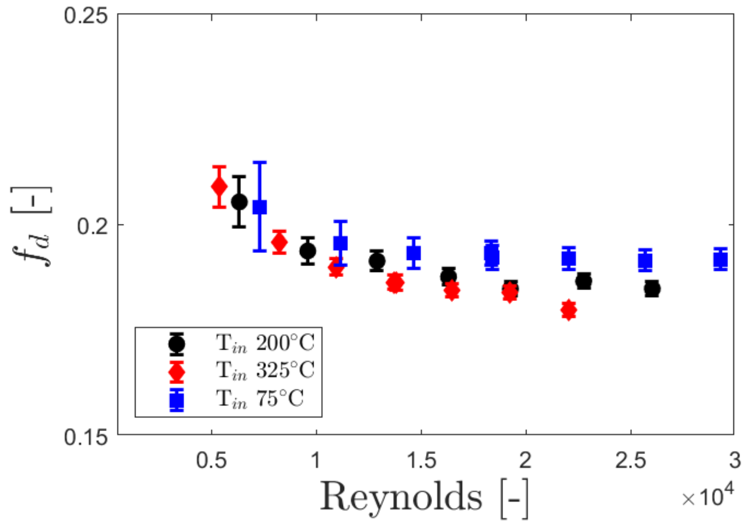
Model validation and FOTS

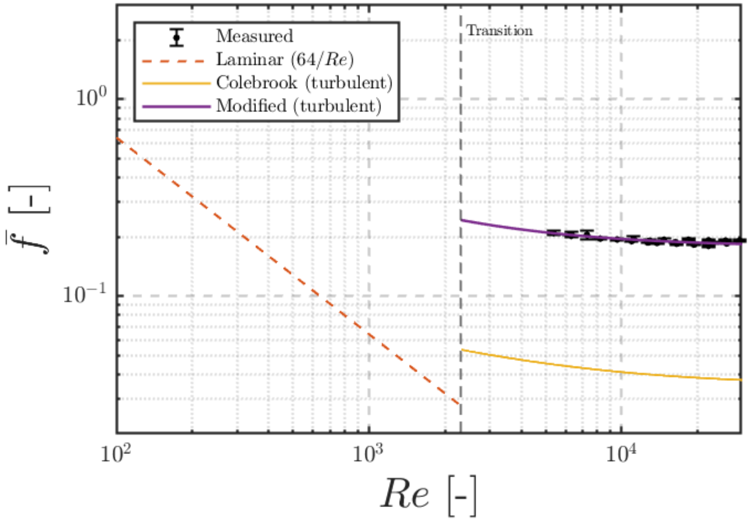
sCO_2 Pressure Test Results

- Pressure drop increases with flow rate and temperature
  - Higher flow rates and lower densities result in increased velocities
- An apparent friction factor begins to collapse with Reynolds
- Increased $\bar{f}$ result from minor-loss contributions (form drag)

- $\bar{f} = \frac{2\Delta P_{channel} D_h}{\rho L v^2}$
- $\bar{f}(Re) = f_0 + f_{cb}(Re)$
- $\frac{1}{\sqrt{f_{cb}}} = -A \log_{10}\left(\frac{RR}{B} + \frac{C}{Re\sqrt{f_{cb}}}\right), A = 2, B = 0.1816$
- $C = 34.10, f_0 = 0.0410, RR = 0.0081$





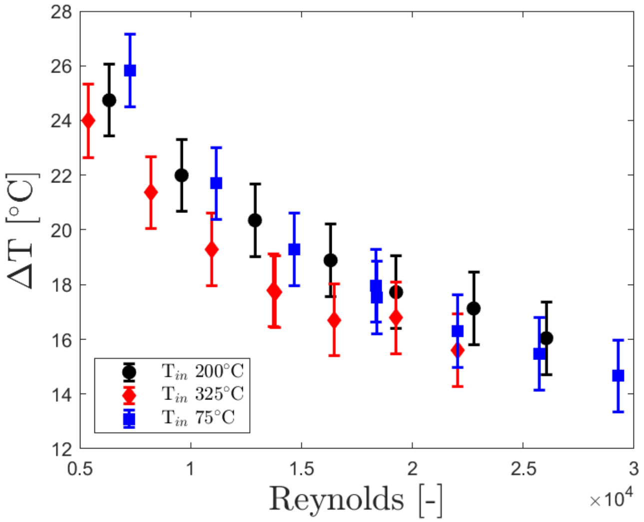


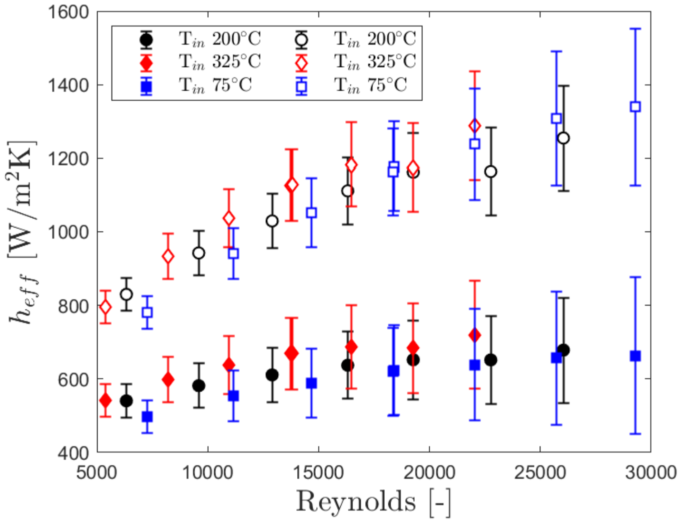
sCO_2 Thermal Test Results

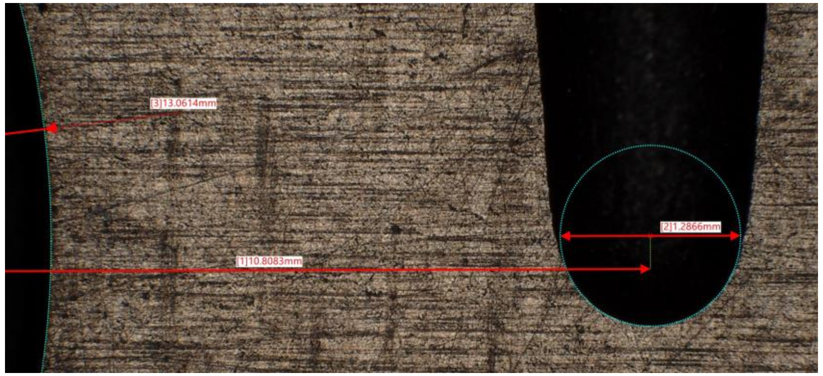
- Approach temperature decreases with Reynolds (HTC increases)
- Temperature increase from 200 to 325°C lowers approach temperature (conductivity increases)
- Non-monotonic from 75 to 200 °C due to property variations near the pseudocritical region below 100°C (Cp is ~2x at 75°C)

- Effective heat transfer coefficient vs Reynolds
  - $\Delta T_{approach} = T_{TC} - T_{out}$ (white markers)
  - $\Delta T_{approach} = T_{interface} - T_{out}$ (radial cond. inferred $T_{interface}$)
- TC based h_{eff} dependent on Reynolds
- Interface temperature shows resistance dominated by conduction through interface solid wall

$$h_{eff,row} = \frac{\dot{Q}_{row}}{A_{s,row}\Delta T_{approach}}$$

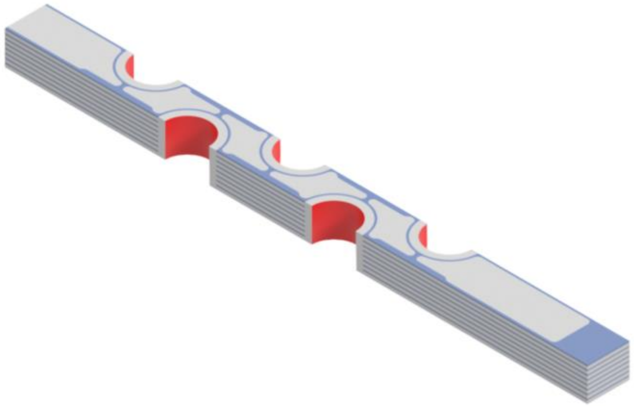


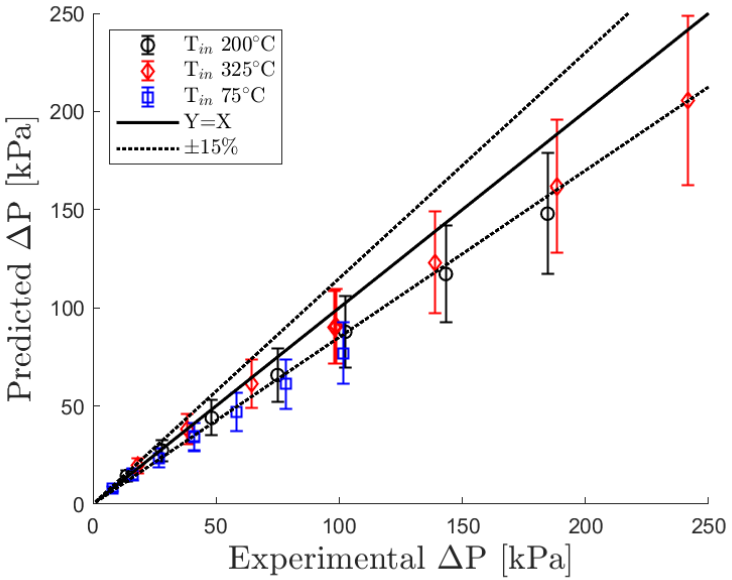


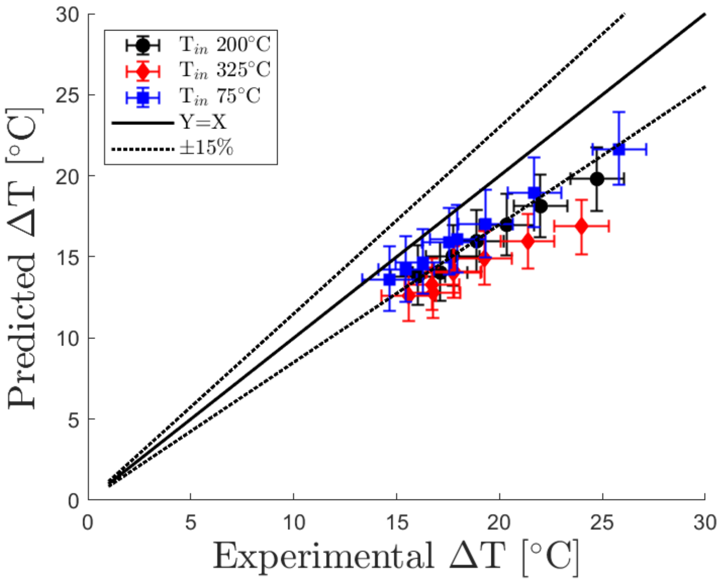


Model Comparison

- Model comprised of unit cell with 8 channels and instrument layer
- Uniform heat flux heater boundary condition
- Close agreement with trends and approximately 15% under predicted both pressure drop and approach temperature
- Error bars for predicted values are primarily from etch depth (±0.02 mm) and TC location (±0.3 mm) uncertainty

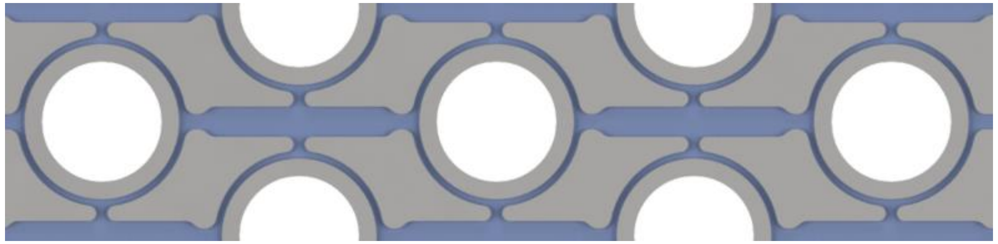






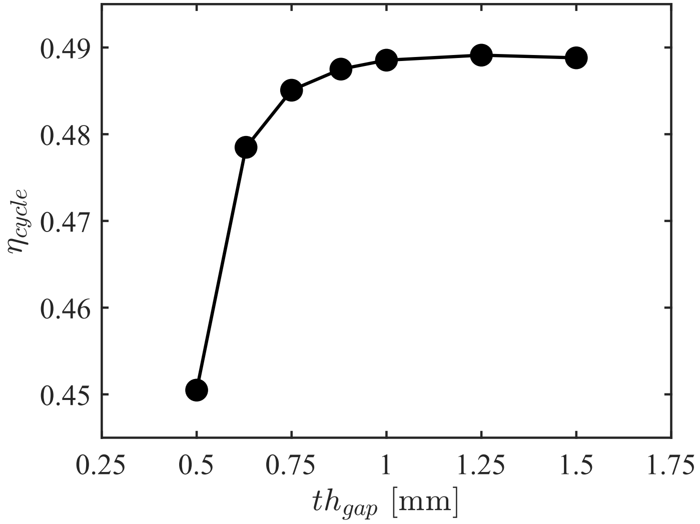
sCO_2 Cycle Analysis Impact

- Correction factors integrated into system-level
  - Pressure drop – 1.15
  - Approach temperature – 1.2
- Cycle efficiency decreased ~0.1%
- Add in in etch uncertainty when selecting optimal channel thickness
- Shift towards 1.3 mm to account for ± 0.3 mm uncertainty



Optimized geometry

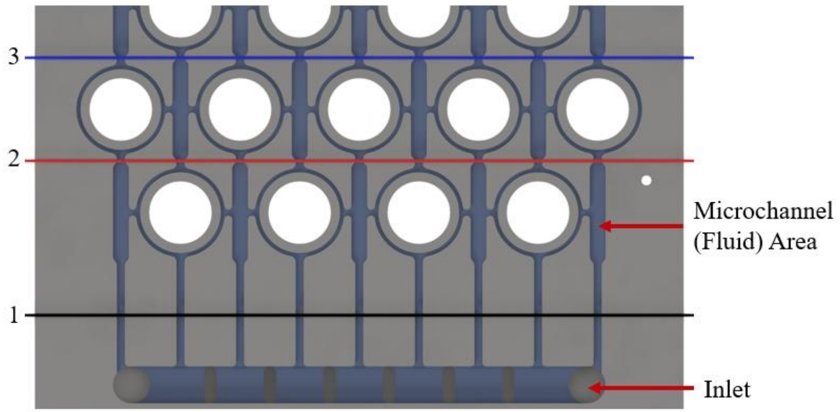
Heat Exchanger	**Annular/PCHE Gap**	**Cycle Efficiency**	**ΔP [kPa]**	**ΔT [°C]**
AFHX (air)	1.9 mm	34.3 %	32.6	51.1
PCHE (air)	1.0 mm	35.3 %	14.2	43.1
PCHE (sCO_2)	1.2 mm	48.5 %	39.0	15.5

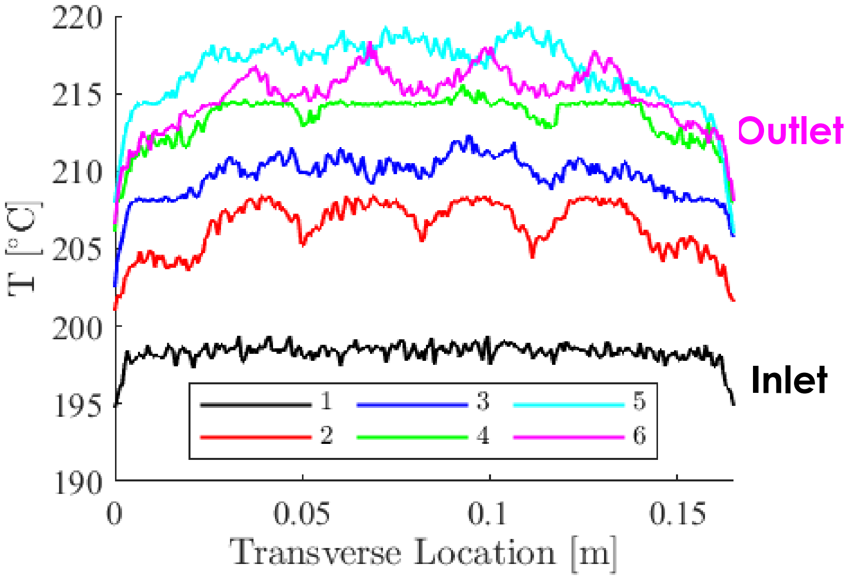


Cycle efficiency vs channel thickness

Fiber Temperature Measurements

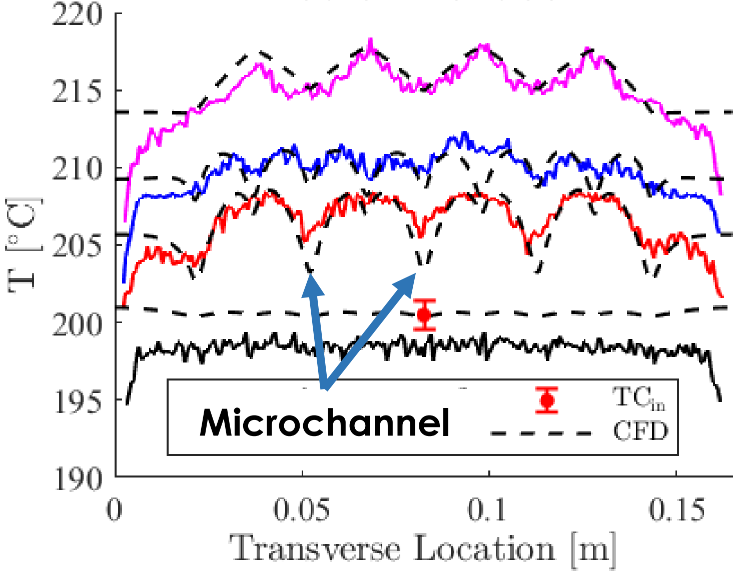
- Near-inlet profile nearly uniform, confirming minimal upstream thermal influence from downstream heaters
- Distinct temperature peaks align with heater interface locations, validating spatial alignment and geometric fidelity of the PCHE instrumentation
- Downstream profiles show increasing baseline temperature due to cumulative heat addition, while preserving transverse temperature structure
- Slight peak reduction near outlet, consistent with reduced solid–fluid temperature difference as bulk fluid temperature rises





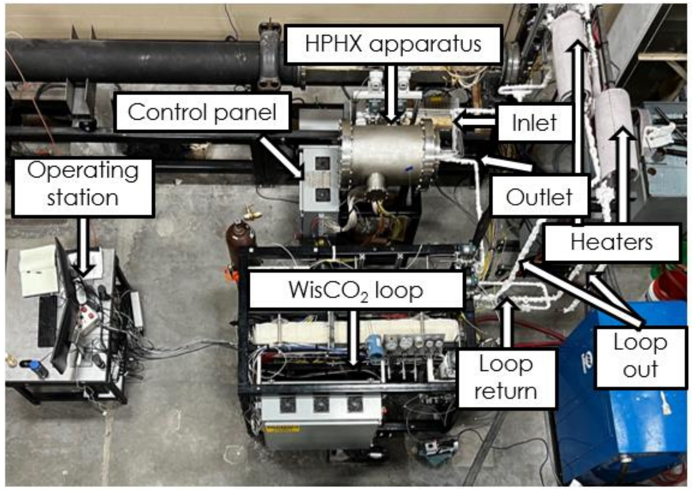
$T_{in} = 200$ C°

$\dot{m} = 0.16$ kg/s


Heater Interface

Conclusions – HPIHX

- Conclusions
    - PCHE based HPIHX test specimen was manufactured and experimentally demonstrated using supercritical sCO_2
    - Experimental data was used to validate sCO_2 model for PCHE
    - With the validated model cycle efficiency decreased ~ 0.1% showing substantial improvement over air Brayton
    - High resolution distributed fiber optic temperature measurements showed microchannel characteristics
    - Demonstrating potential for performance monitoring (channel blockage or failed heat pipe)
- Recommended future work
    - Higher temperature and pressure testing
    - Transient investigations
    - Heat pipe to PCHE interface improvement



THL Thermal Hydraulics Laboratory

sCO2

Questions?

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