



Thermohydraulic performance of a supercritical CO₂ PCHE for heat pipe microreactors

2026 sCO₂ Symposium
NEUP Project 21-24226



March 2, 2026

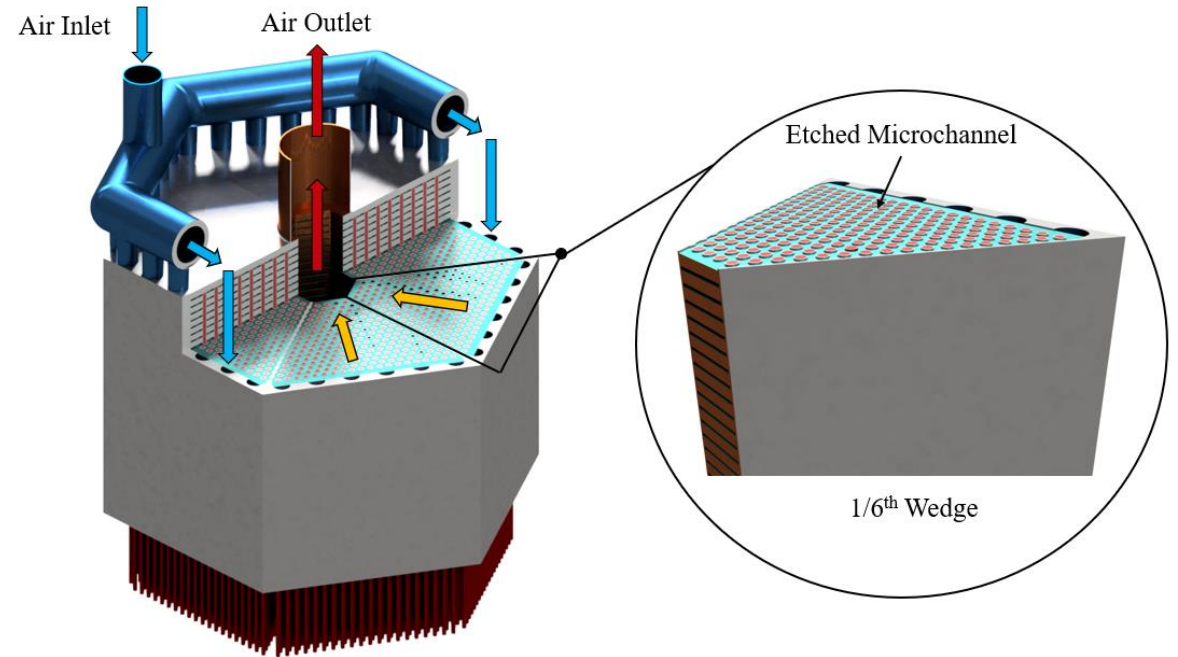


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Presentation Overview



- Project background
 - Heat pipe microreactors
 - Project objectives
- sCO₂ test article manufacturing
- WisCO₂ facility integration
- sCO₂ 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)

Microreactors have 3 main features:



Microreactor features (INL)



Heat Pipe Microreactors



- Heat pipe microreactors

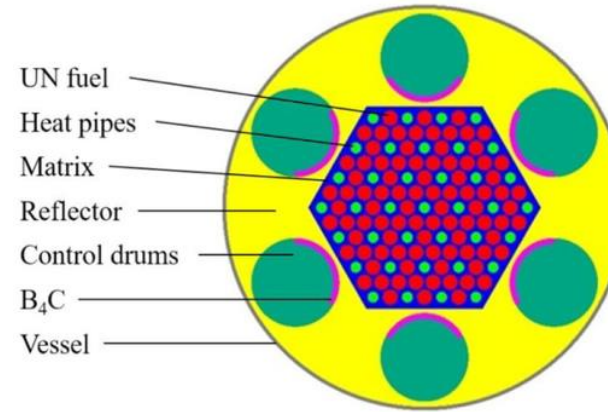
- Fuel interspersed with heat pipes
- “Solid state core”
- Robust and fault tolerant

- Heat pipes

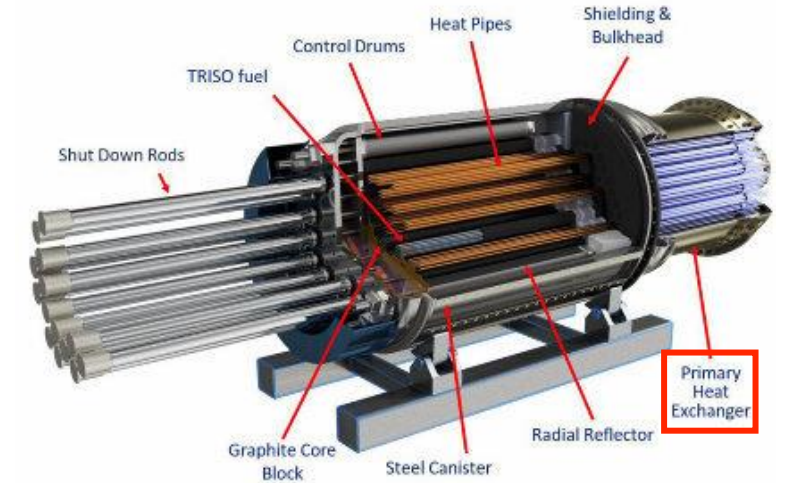
- Working fluid is heated to evaporation
- Vapor moves from pressure difference
- Vapor condenses onto internal wick
- Capillary forces move liquid back
- High temperature HPs often use liquid metals (e.g., sodium)

- Heat pipe interface heat exchanger

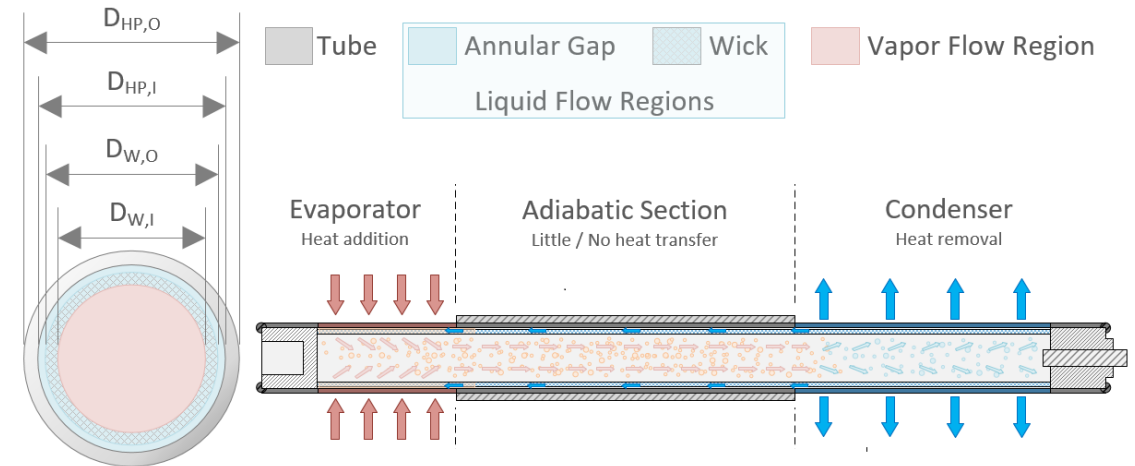
- HPIHX, interfaces heat pipe condenser end with process fluid (primary HX)



HPMR schematic [1]



eVinci™ microreactor rendering (Westinghouse [2])



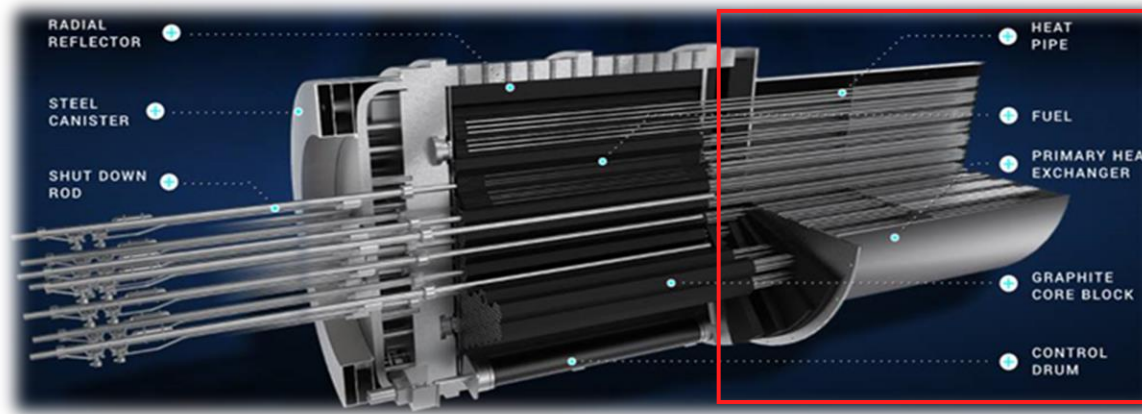
Heat pipe schematic

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



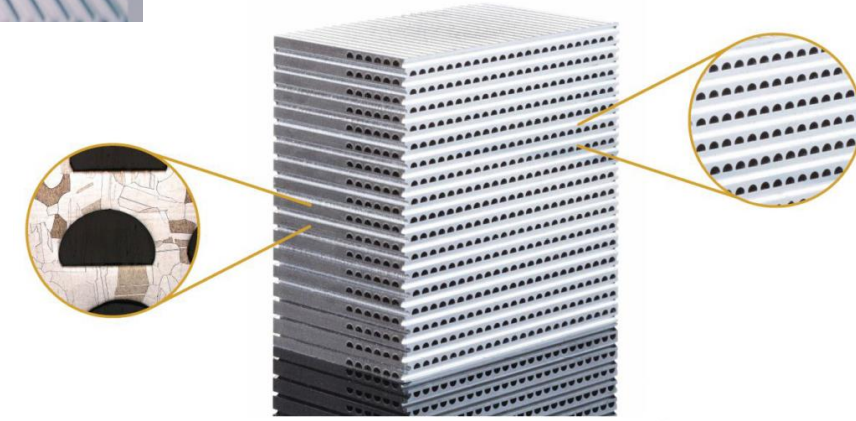
eVinci™ Micro-Reactor, Courtesy of Westinghouse Electric Company LLC

Printed Circuit Heat Exchanger

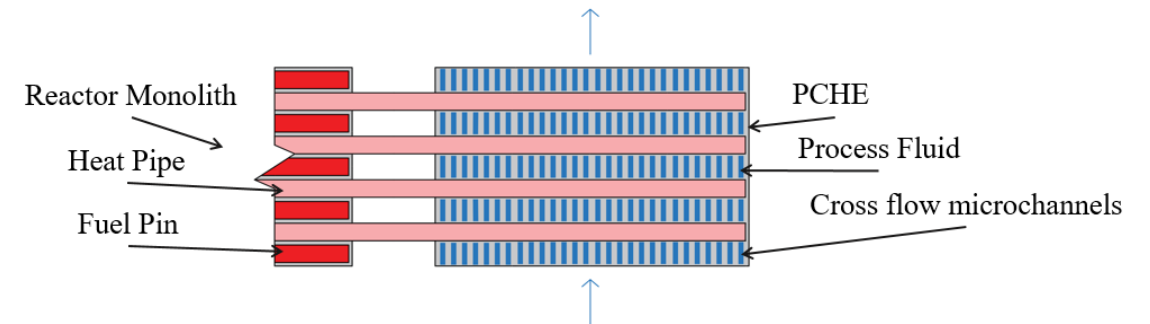
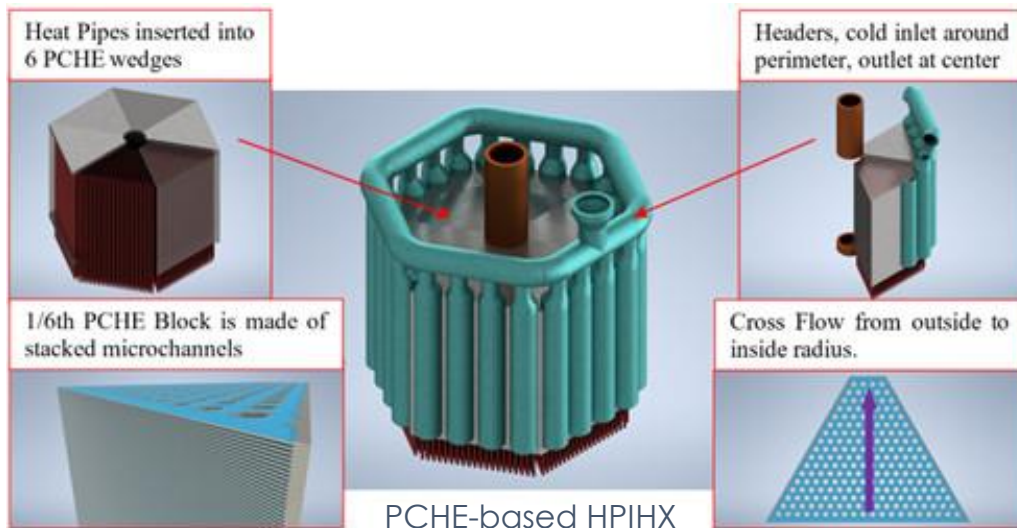
- Printed circuit heat exchanger
 - Thin metal sheets are chemically etched
 - Diffusion bonded together
 - Forms microchannels with high heat transfer area
- HPIHX PCHE
 - **Single fluid**, cross-flow
 - Add heat pipe holes to plates for HPIHX



Chemically etched microchannel [1]



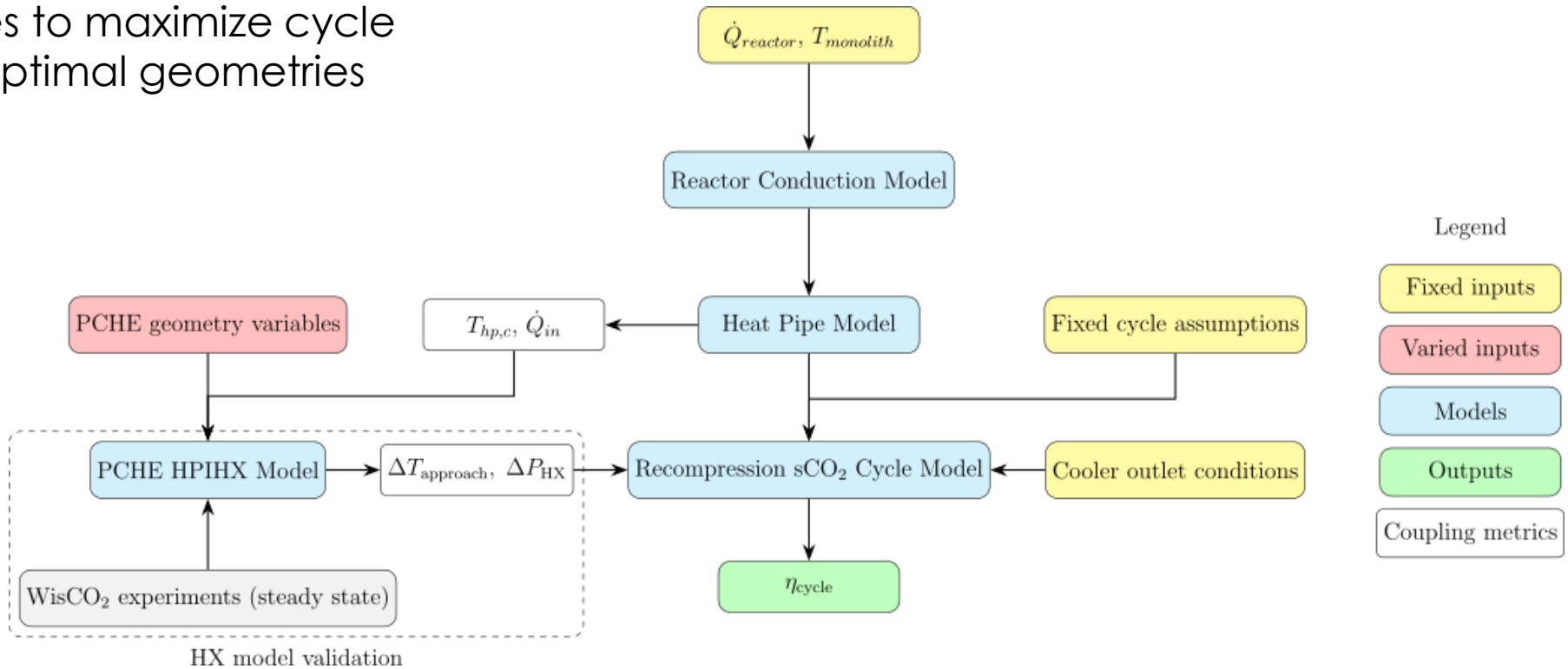
Cutout of diffusion bonded PCHE (VPEI [2])





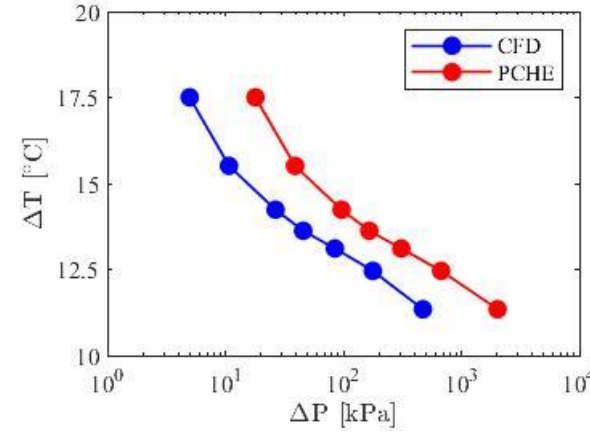
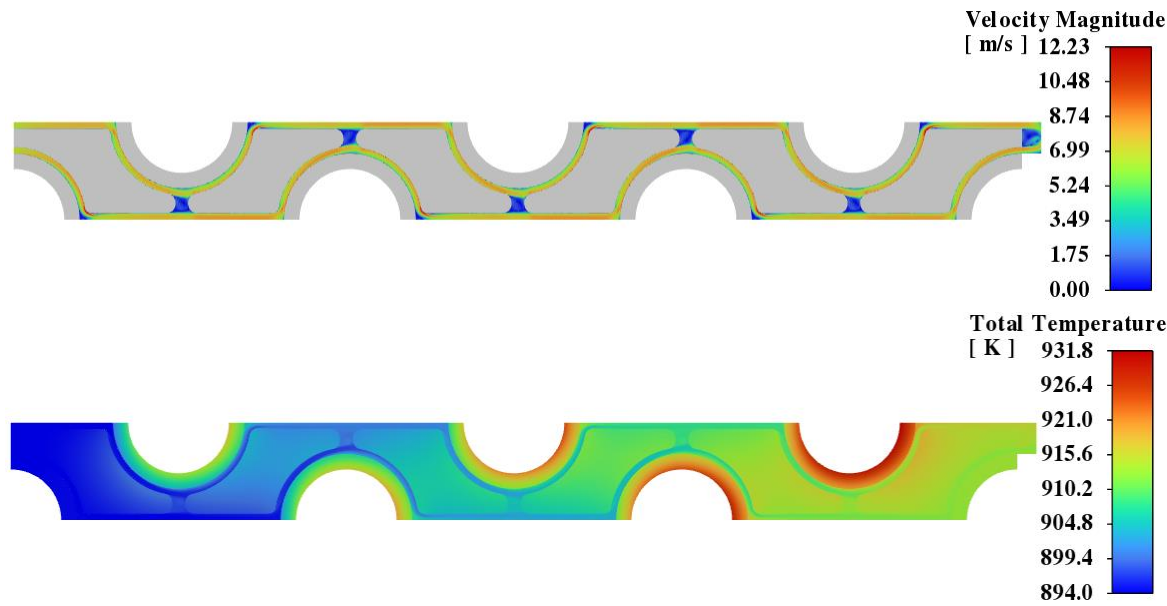
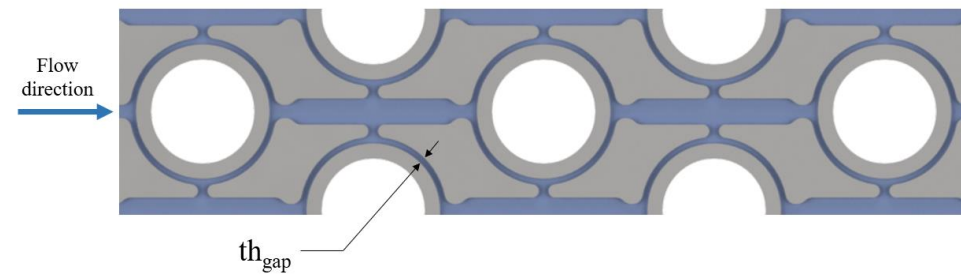
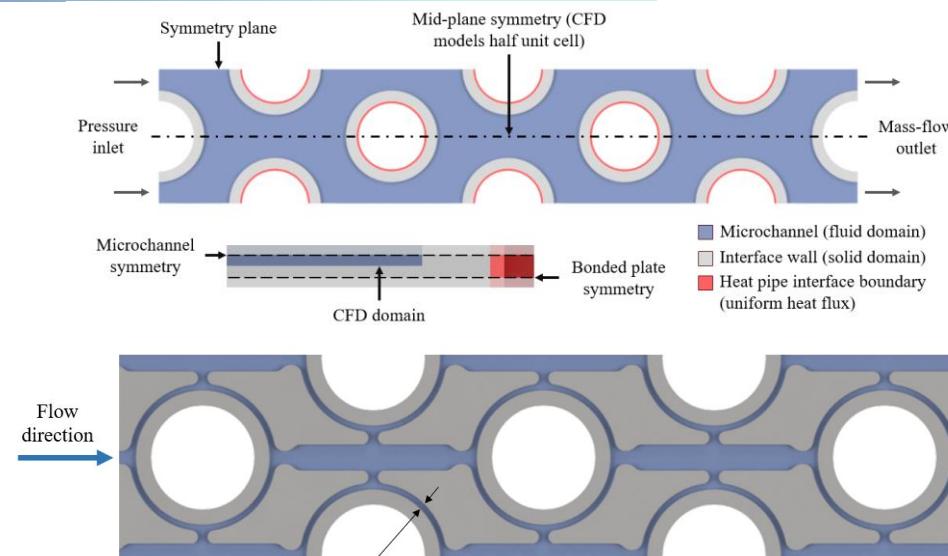
Interface Heat Exchanger Optimization

- Optimized using cycle model
 - Varied HX geometries to maximize cycle efficiency and find optimal geometries
- PCHE HX models
- $\Delta P = P_{in} - P_{out}$
- $\Delta T = T_{hp,max} - T_{fluid,out}$
- sCO₂ Brayton cycle
- CFD PCHE model



CFD Microchannel Optmization

- 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



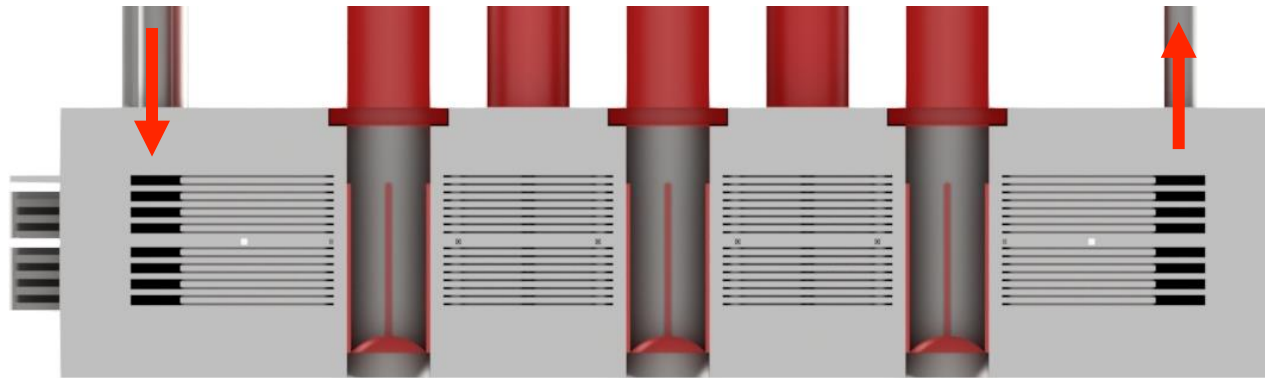
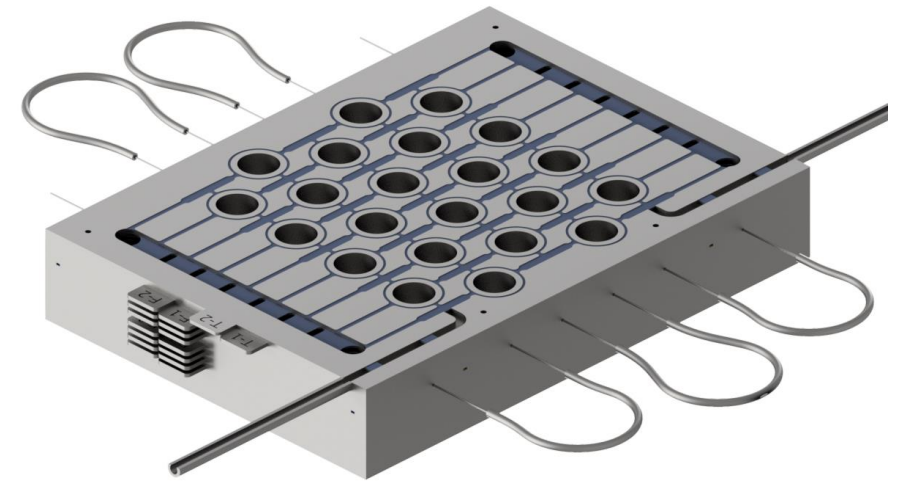
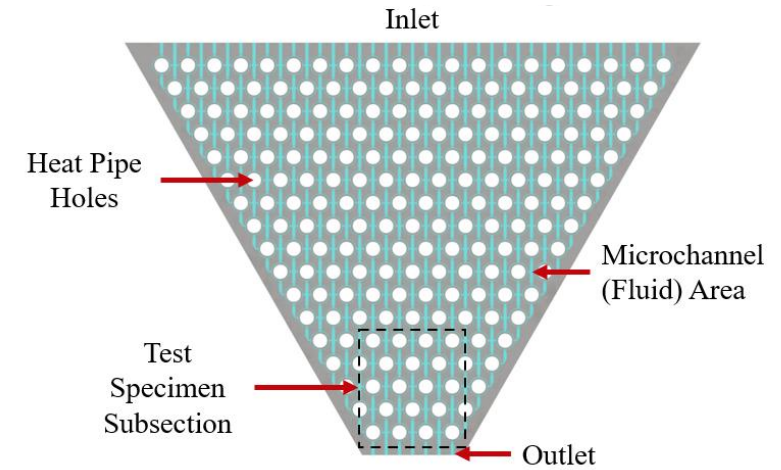
sCO₂ Test Article

Manufacturing and instrumentation

sCO₂ 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"

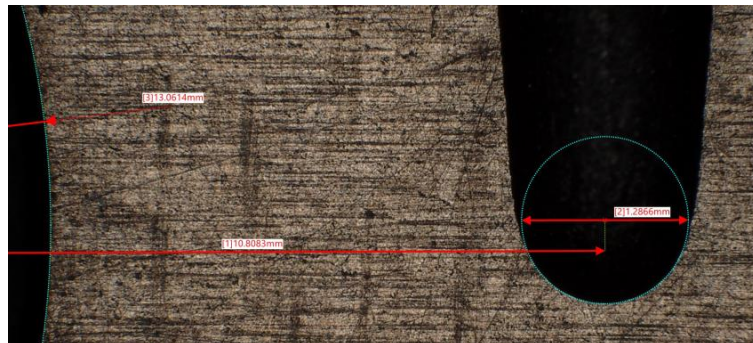
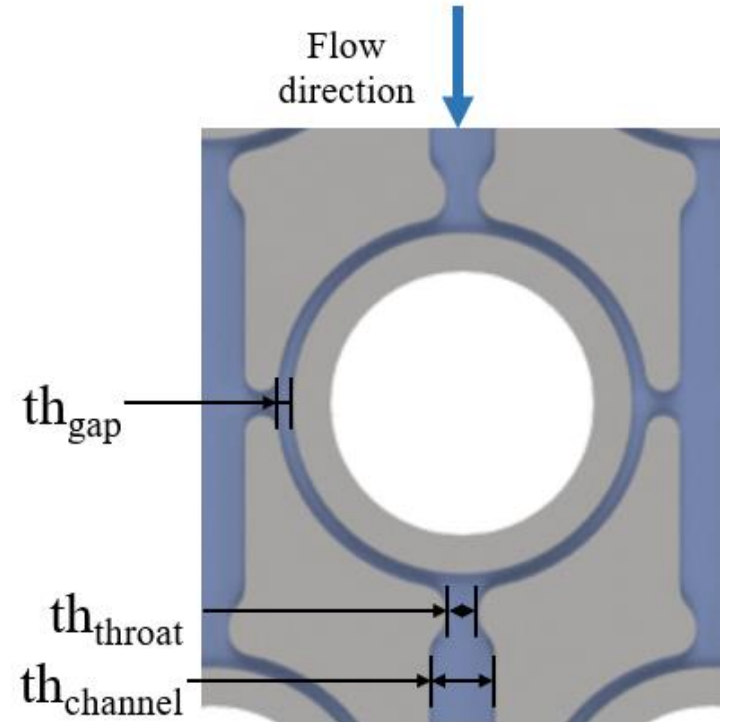


	Test Article	Full Size HX
Power	2.75 kW	5000 kW
Energy density	66 W/in ²	67 W/in ²
Cross section	0.08 in ²	0.08-0.34 in ²
Mass flow rate	0.06-0.16 kg/s	24.5 kg/s

sCO₂ 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



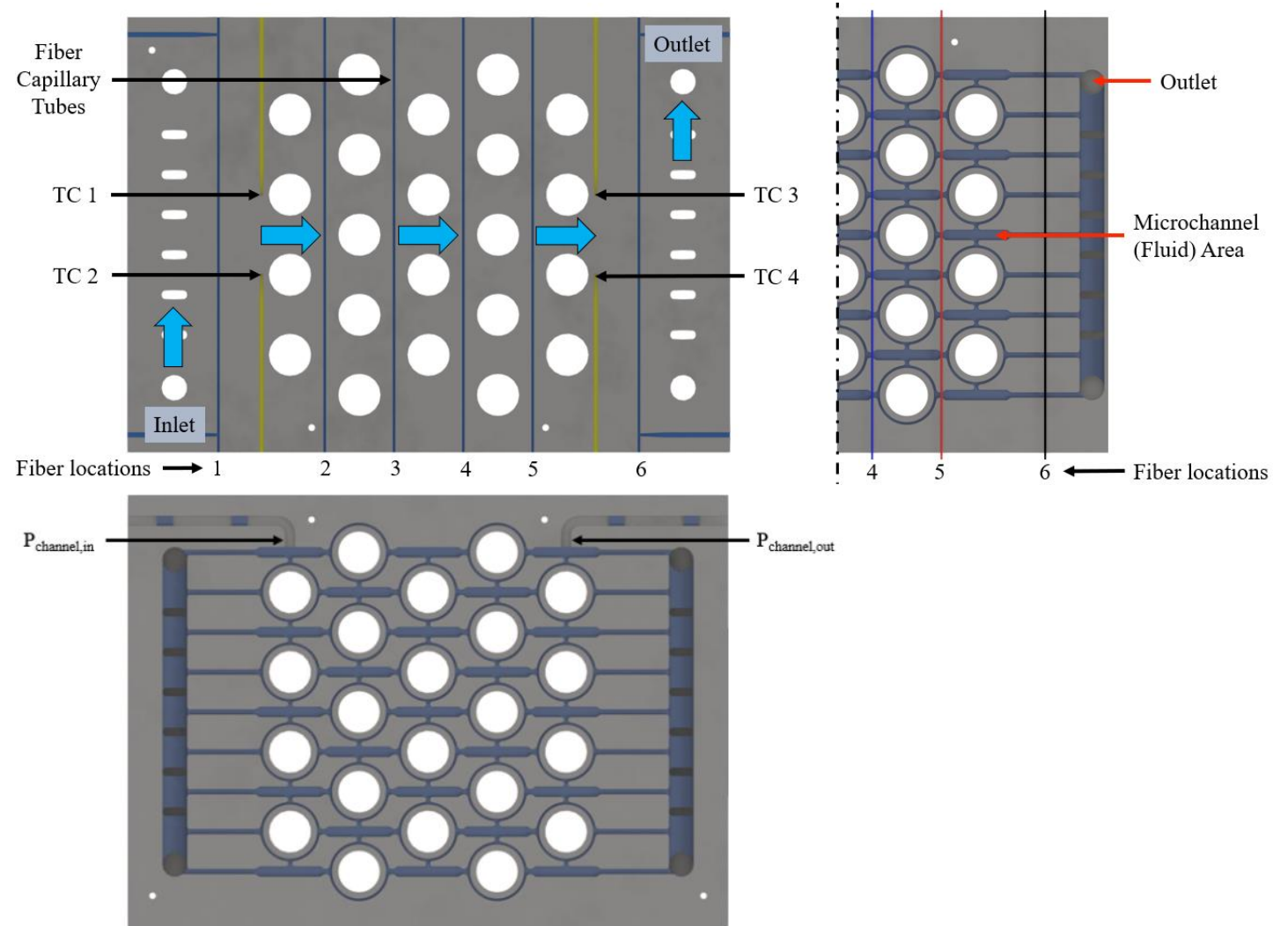
Instrumentation



- 4 – embedded TCs
- 6 – fiber optic temperature sensor passes
- Inlet and outlet fluid TCs
- Inlet and outlet pressure
 - Channel and test specimen

- Key parameters

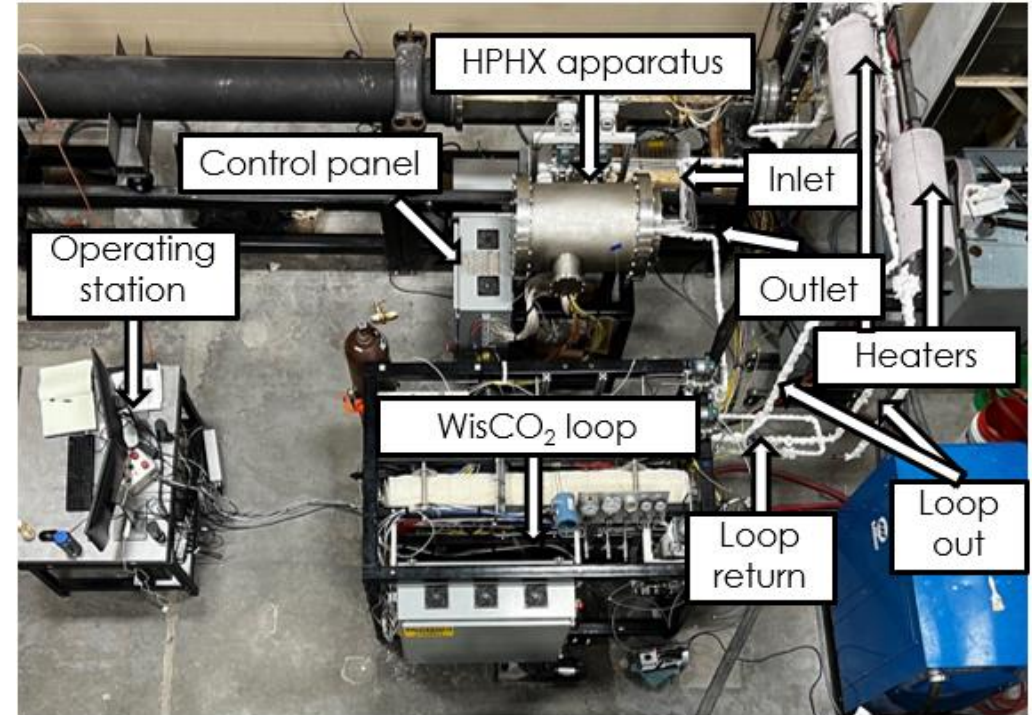
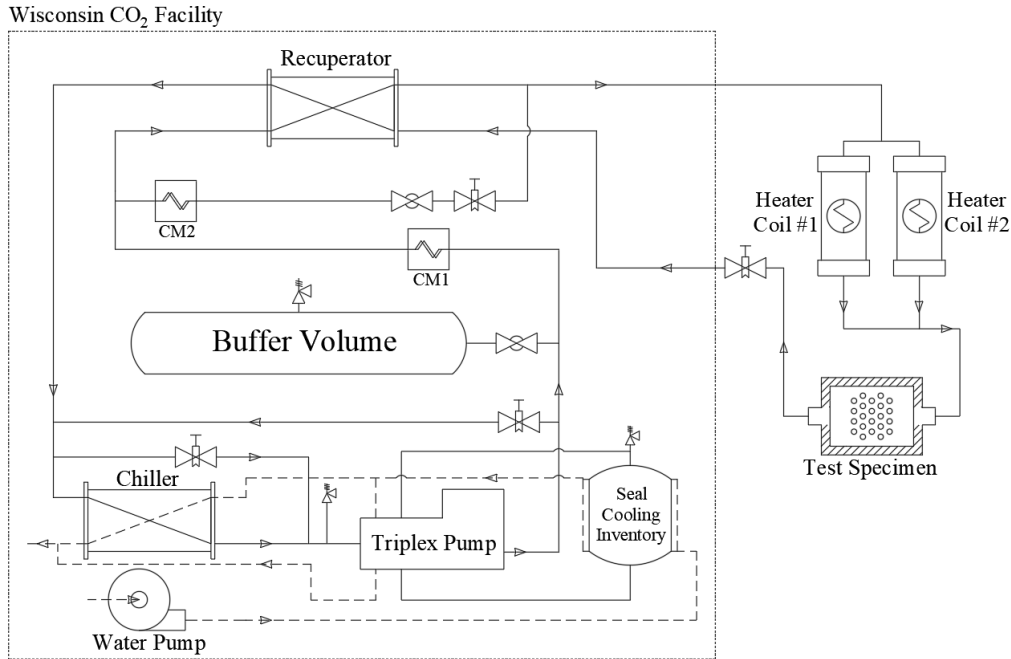
- $\Delta T_{approach} = \frac{TC_3 + TC_4}{2} - TC_{out}$
- $\Delta P_{channel} = P_{channel,in} - P_{channel,out}$





WisCO₂ Facility

Facility and integration



WisCO₂ 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		

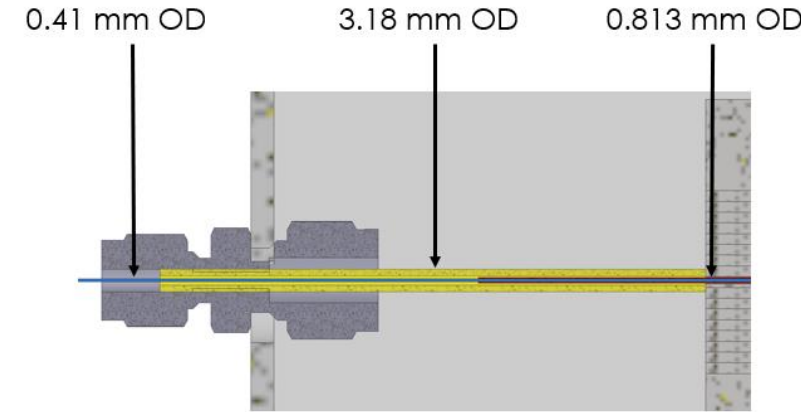
Test Specimen Integration



- Insulation tray
 - Minimize heat losses
 - Feedthroughs support fiber optic sensor
- Test apparatus
 - SS chamber provides biological shield
 - CO₂ detector monitors for leaks
 - Heater control and DAQ panel



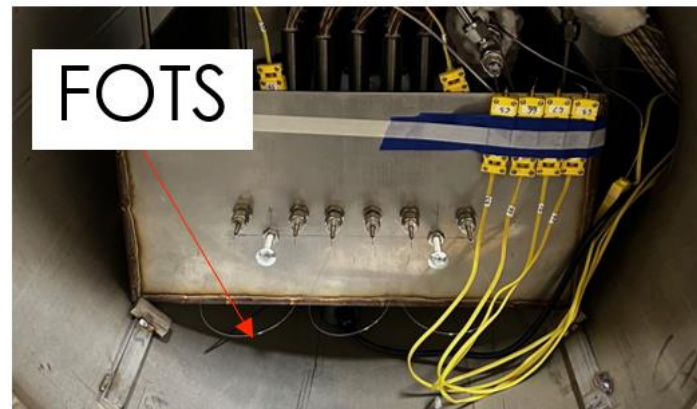
Test specimen insulation tray



FOTS feedthroughs



Instrumented and insulated test specimen



Installed fiber optic temperature sensor



Heat exchanger test apparatus



sCO₂ Testing

Model validation and FOTS



sCO₂ Pressure Test Results

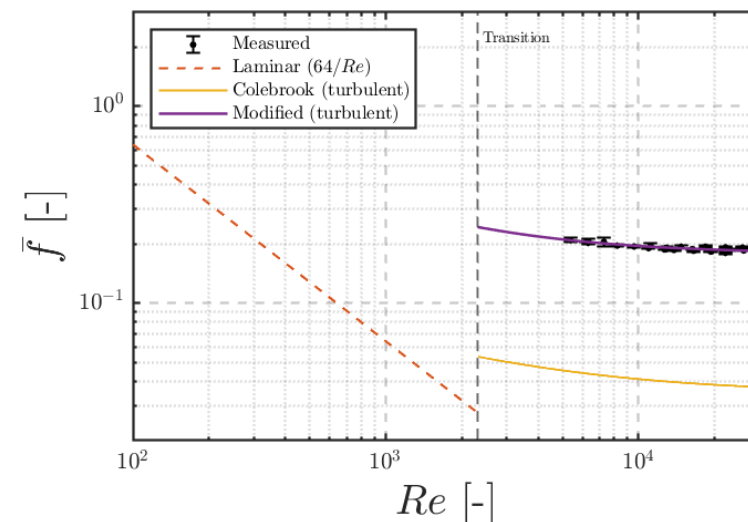
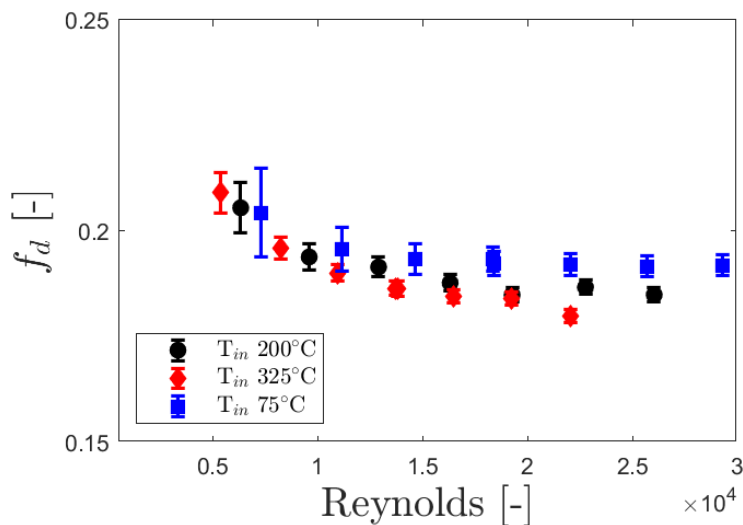
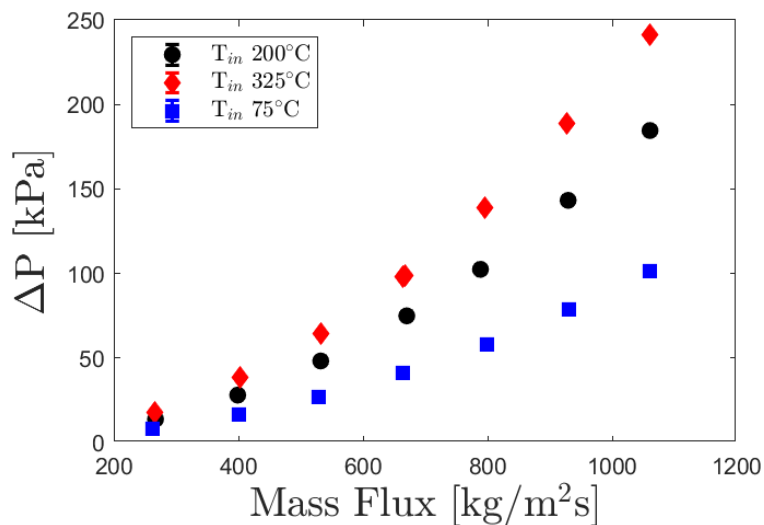
- Pressure drop increases with flow rate and temperature
 - Higher flow rates and lower densities result in increased velocities
- An apparent friction factor begins to collapse with Reynolds
- Increased \bar{f} result from minor-loss contributions (form drag)

$$\bar{f} = \frac{2\Delta P_{channel} D_h}{\rho L v^2}$$

$$\bar{f}(Re) = f_0 + f_{cb}(Re)$$

$$\frac{1}{\sqrt{f_{cb}}} = -A \log_{10} \left(\frac{RR}{B} + \frac{C}{Re \sqrt{f_{cb}}} \right), A = 2, B = 0.1816$$

$$C = 34.10, f_0 = 0.0410, RR = 0.0081$$

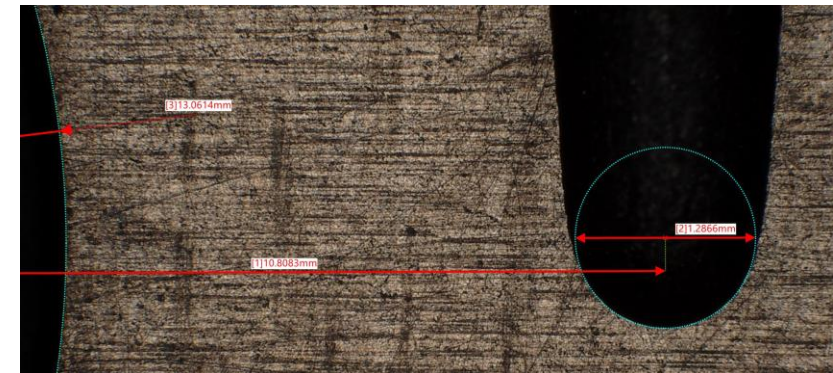
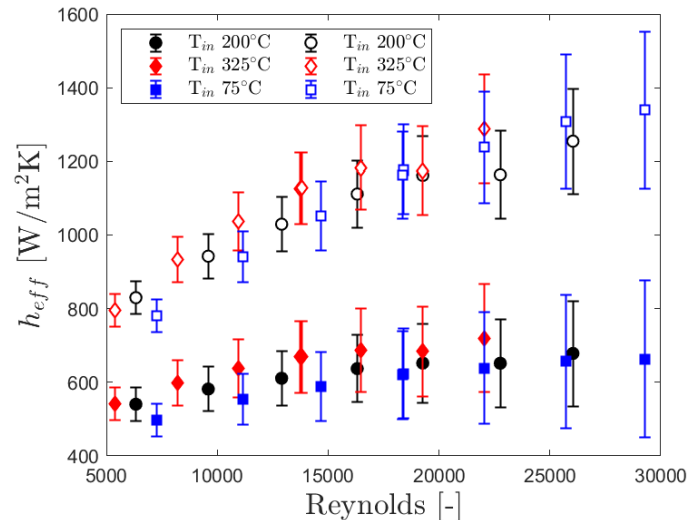
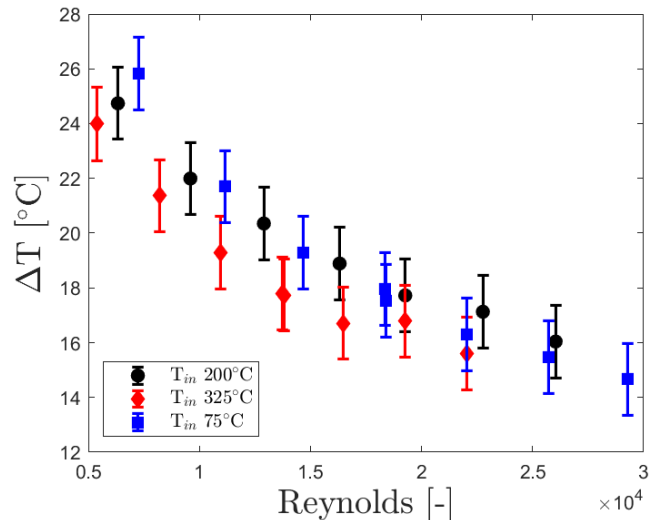


sCO₂ Thermal Test Results



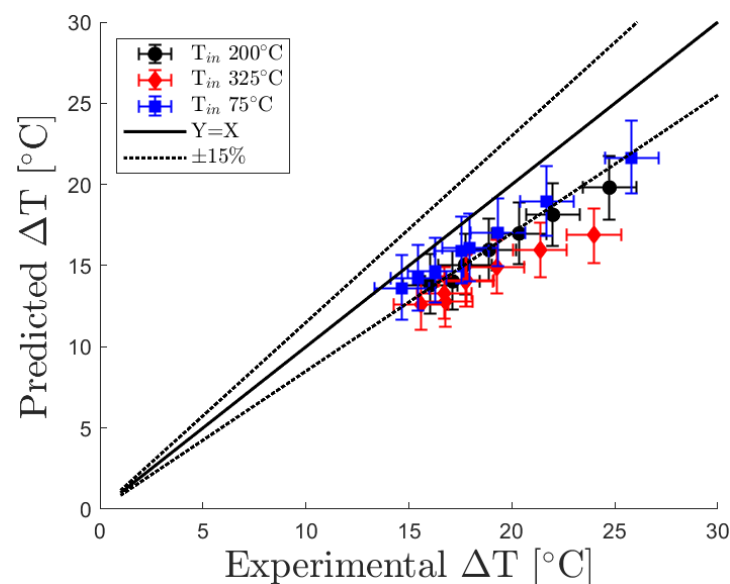
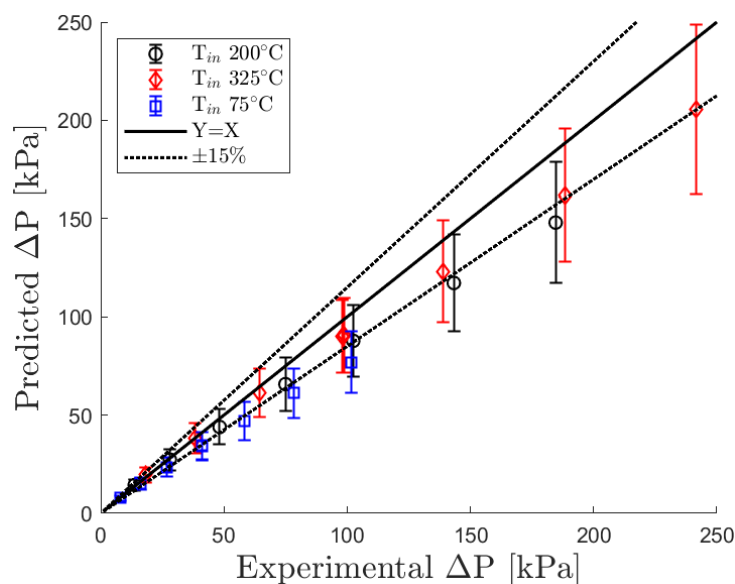
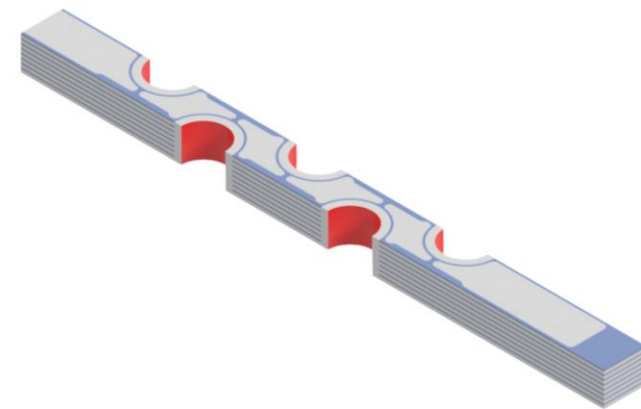
- Approach temperature decreases with Reynolds (HTC increases)
- Temperature increase from 200 to 325°C lowers approach temperature (conductivity increases)
- Non-monotonic from 75 to 200 °C due to property variations near the pseudocritical region below 100°C (Cp is ~2x at 75°C)
- Effective heat transfer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

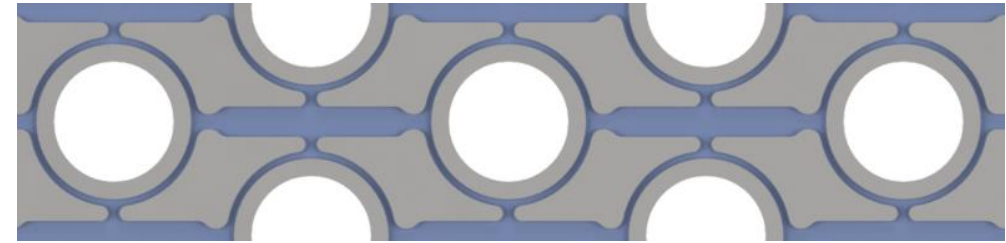
- Model comprised of unit cell with 8 channels and instrument layer
- Uniform heat flux heater boundary condition
- Close agreement with trends and approximately 15% under predicted both pressure drop and approach temperature
- Error bars for predicted values are primarily from etch depth (± 0.02 mm)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



sCO₂ Cycle Analysis Impact

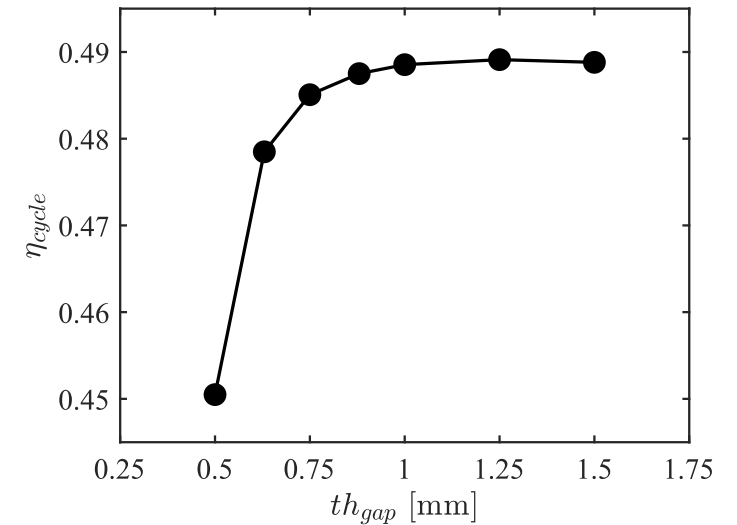


- Correction factors integrated into system-level
 - Pressure drop – 1.15
 - Approach temperature – 1.2
- Cycle efficiency decreased ~0.1%
- Add in in etch uncertainty when selecting optimal channel thickness
- Shift towards 1.3 mm to account for ± 0.3 mm uncertainty



Optimized geometry

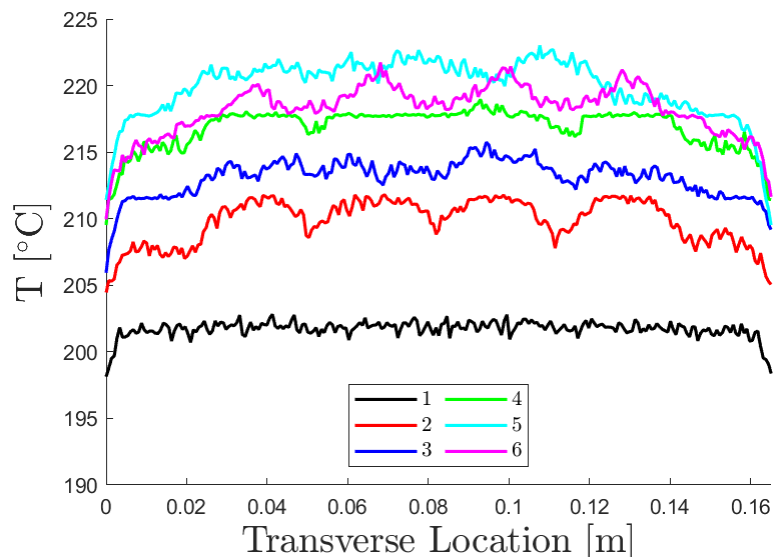
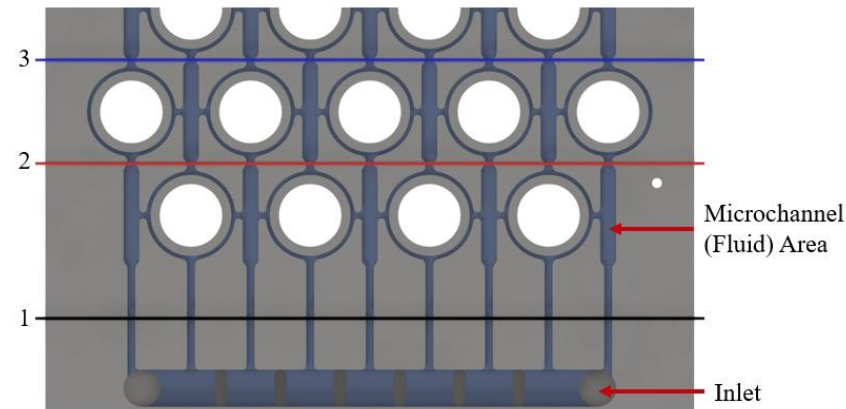
Heat Exchanger	Annular/PCHE Gap	Cycle Efficiency	ΔP [kPa]	ΔT [°C]
AFHX (air)	1.9 mm	34.3 %	32.6	51.1
PCHE (air)	1.0 mm	35.3 %	14.2	43.1
PCHE (sCO ₂)	1.2 mm	48.5 %	39.0	15.5



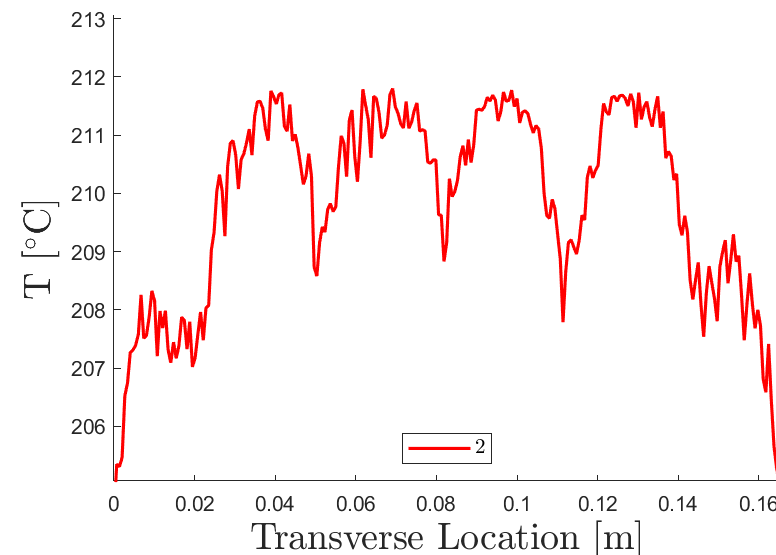
Cycle efficiency vs channel thickness

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



$T_{in} = 200 \text{ C}^\circ$
 $\dot{m} = 0.16 \text{ kg/s}$



Conclusions – HPIHX

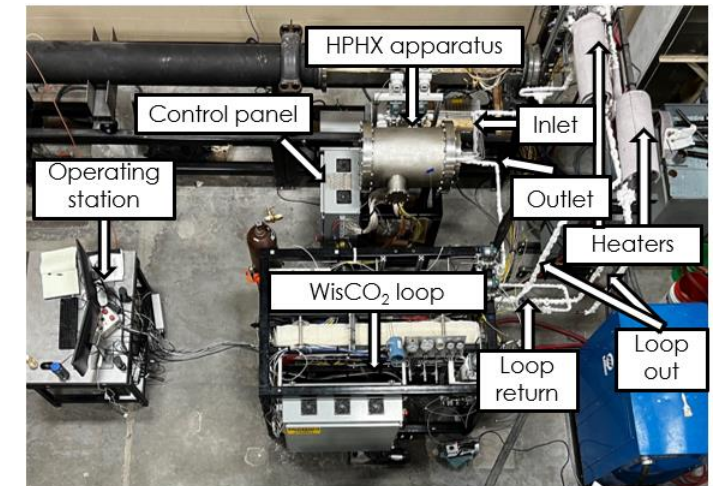


- Conclusions

- PCHE based HPIHX test specimen was manufactured and experimentally demonstrated using supercritical $s\text{CO}_2$
- Experimental data was used to validate $s\text{CO}_2$ model for PCHE
- With the validated model cycle efficiency decreased $\sim 0.1\%$ 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



Questions?



WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON



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