Supercritical CO_2
Power Cycles
Symposium

Heat Exchangers for Supercritical CO_2 Power Cycle Applications

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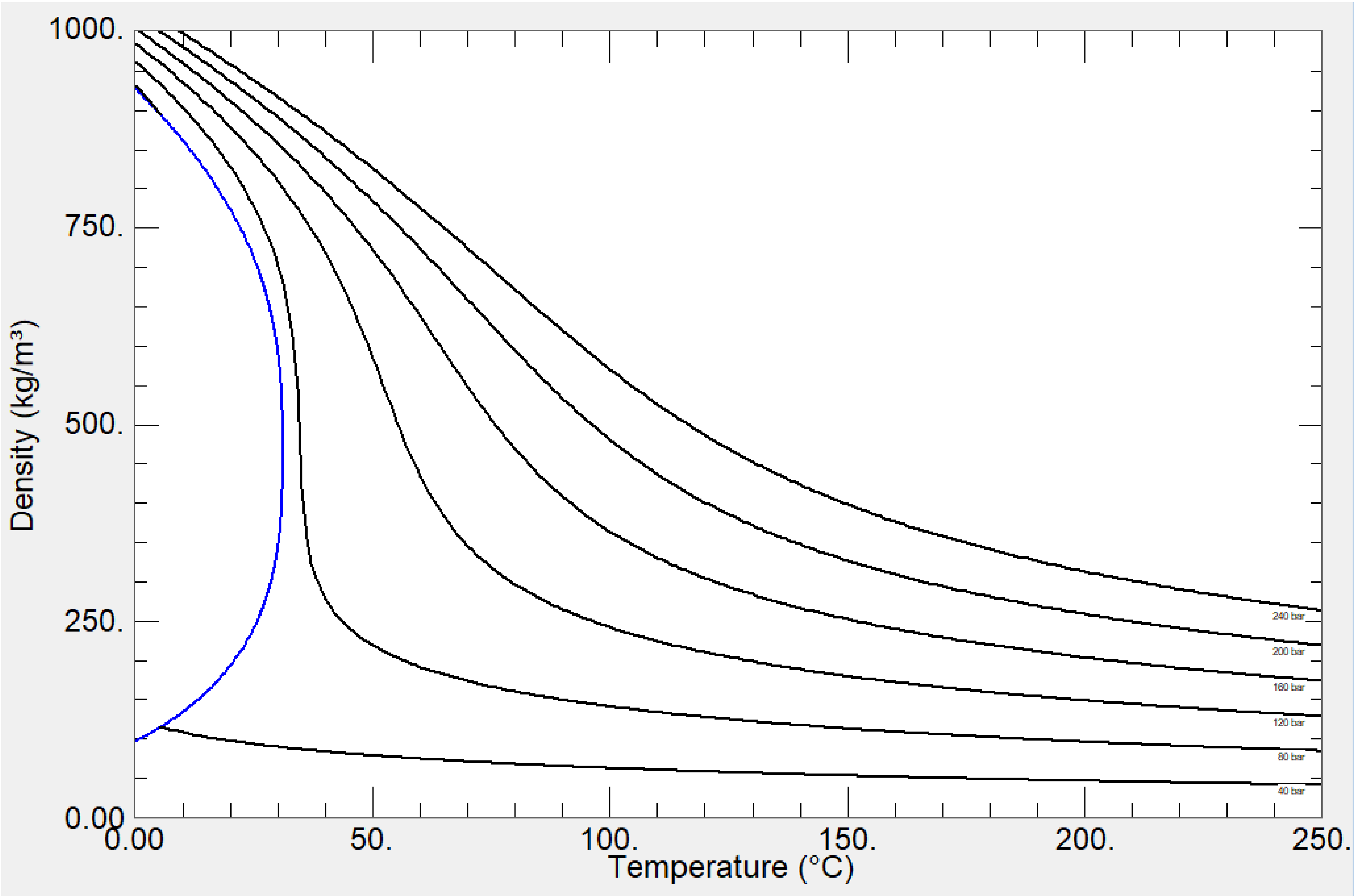
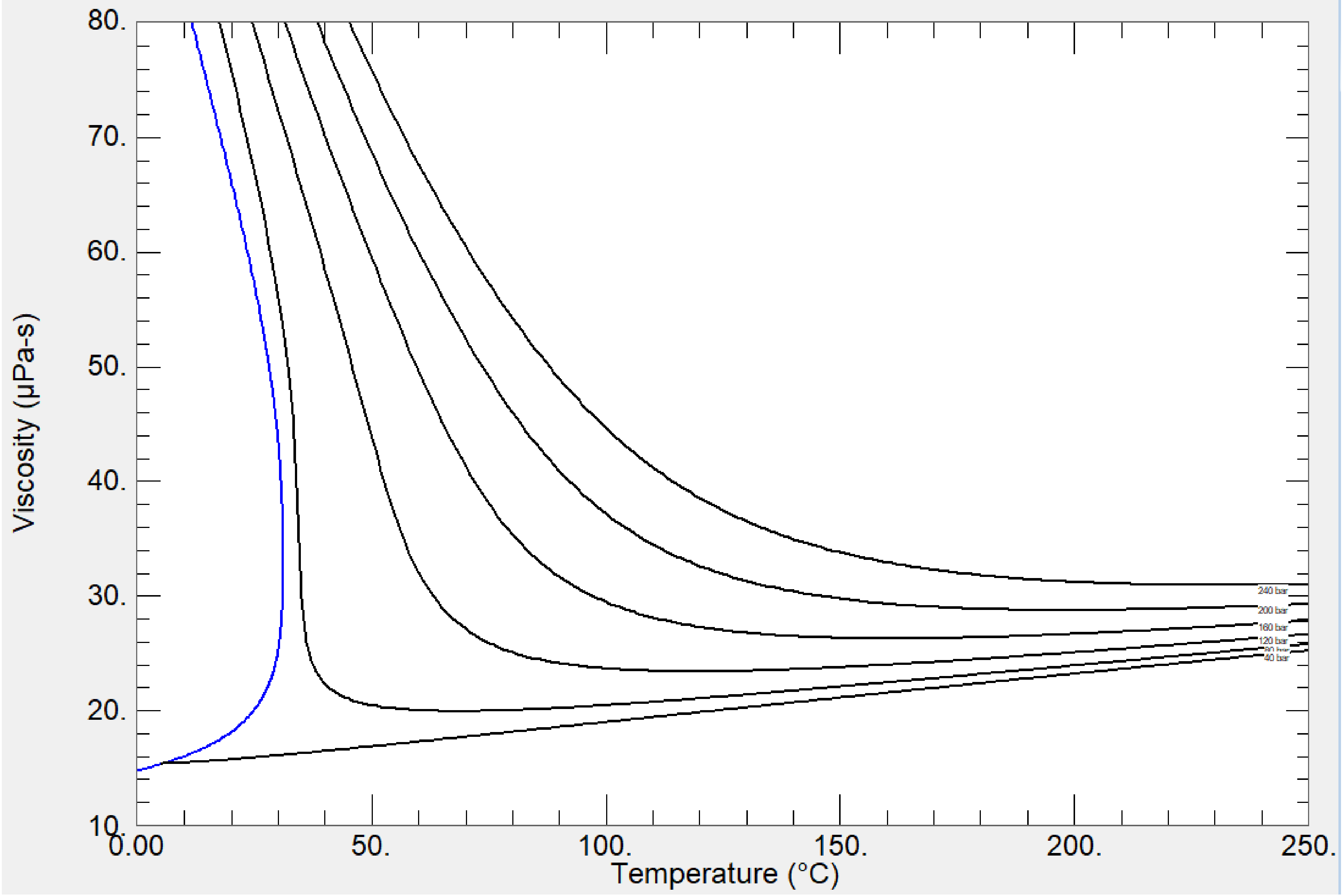
Supercritical CO_2 allows for effective heat transfer in a compact package

- High density in supercritical phase allows for low volume flow through heat exchangers.
- Low viscosity allows for increased heat transfer coefficients, reduced dP.

$$RE = \frac{\boldsymbol{\rho} V D_h}{\boldsymbol{\mu}}$$



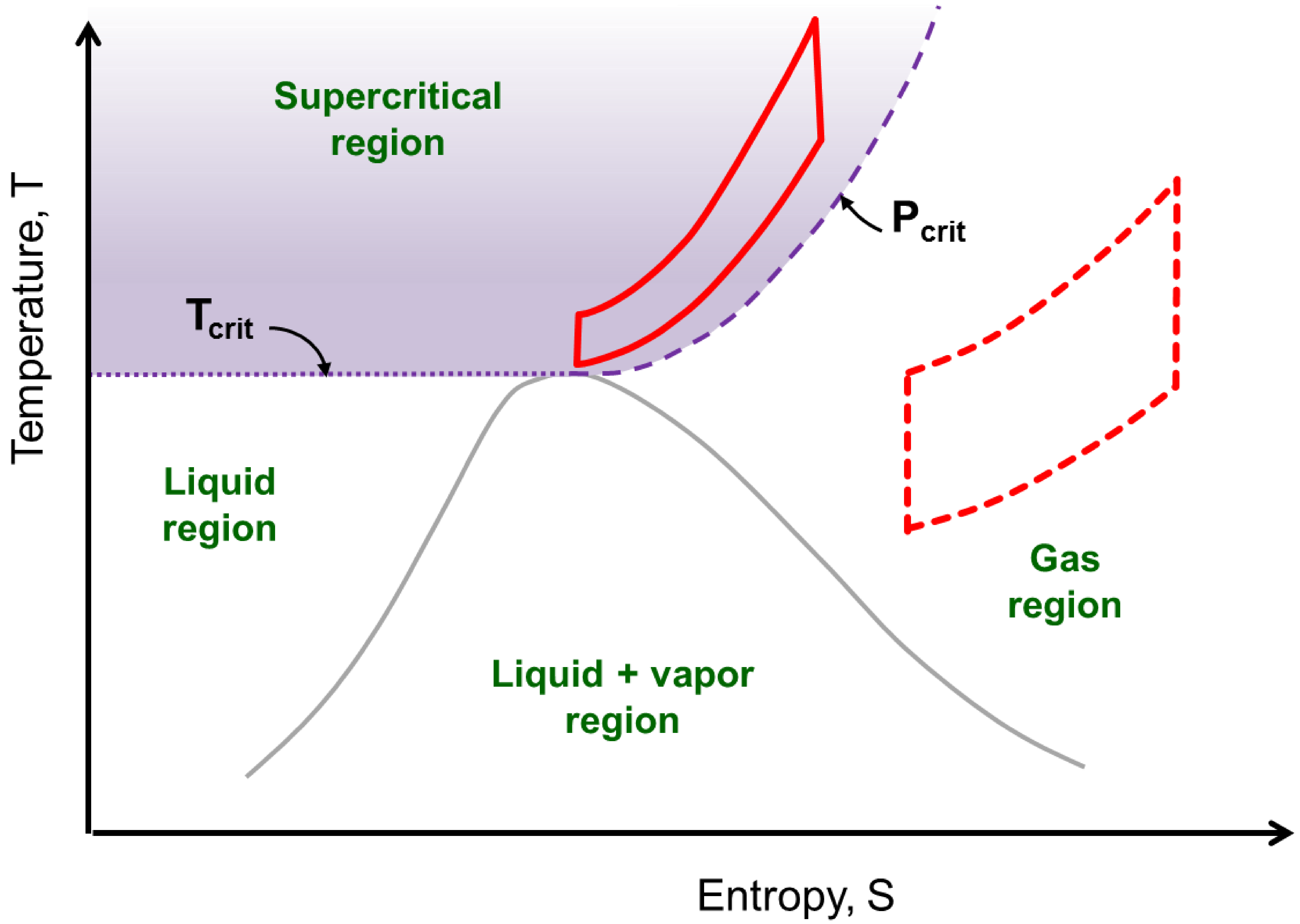
Isobars (bara):
240
200
160
120
80
40



Isobars (bara):
240
200
160
120
80
40

Source: NIST REFPROP, v9.1

Supercritical power cycles are unique in their operating region, and have flexible heat addition and rejection sources



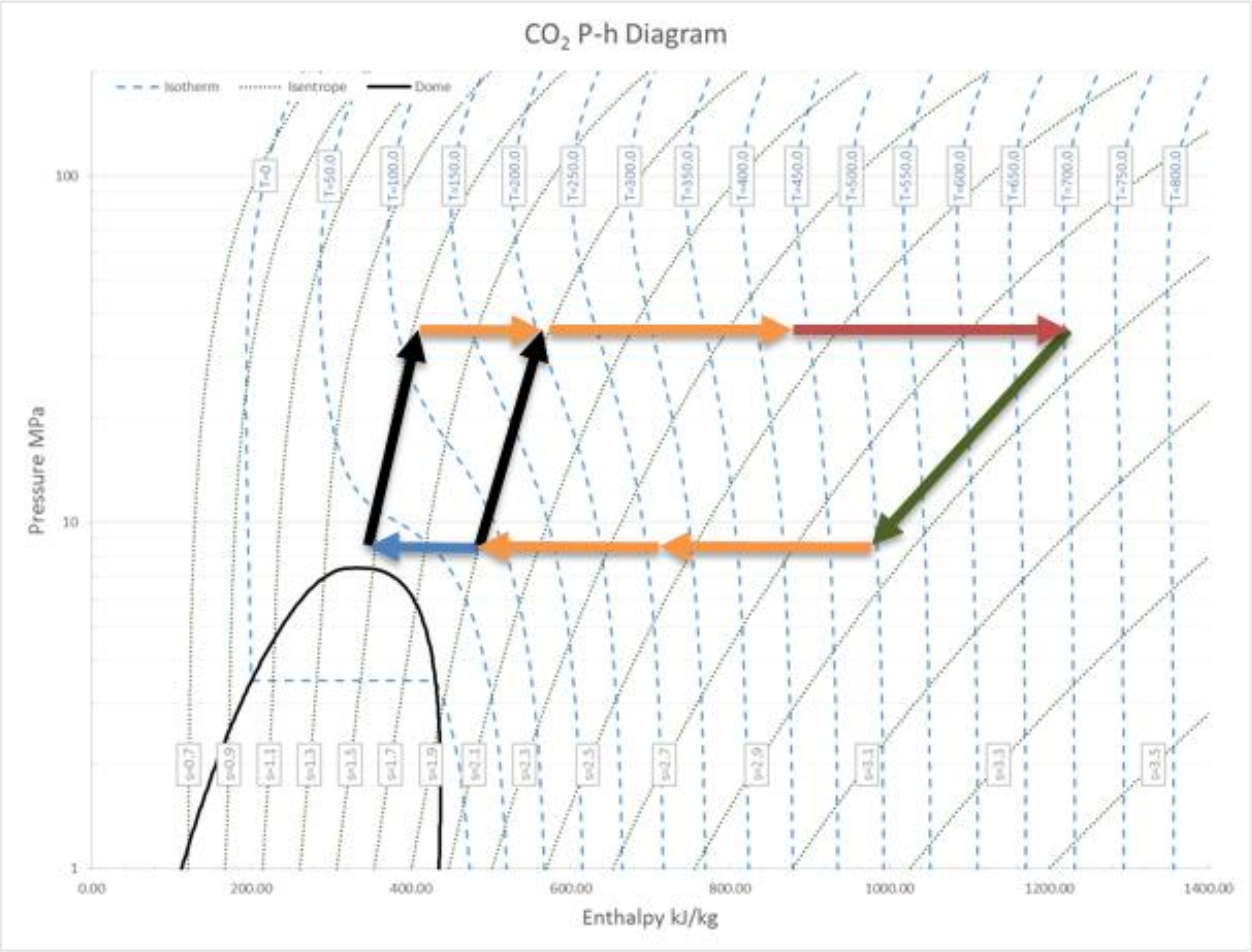
Heat Input:

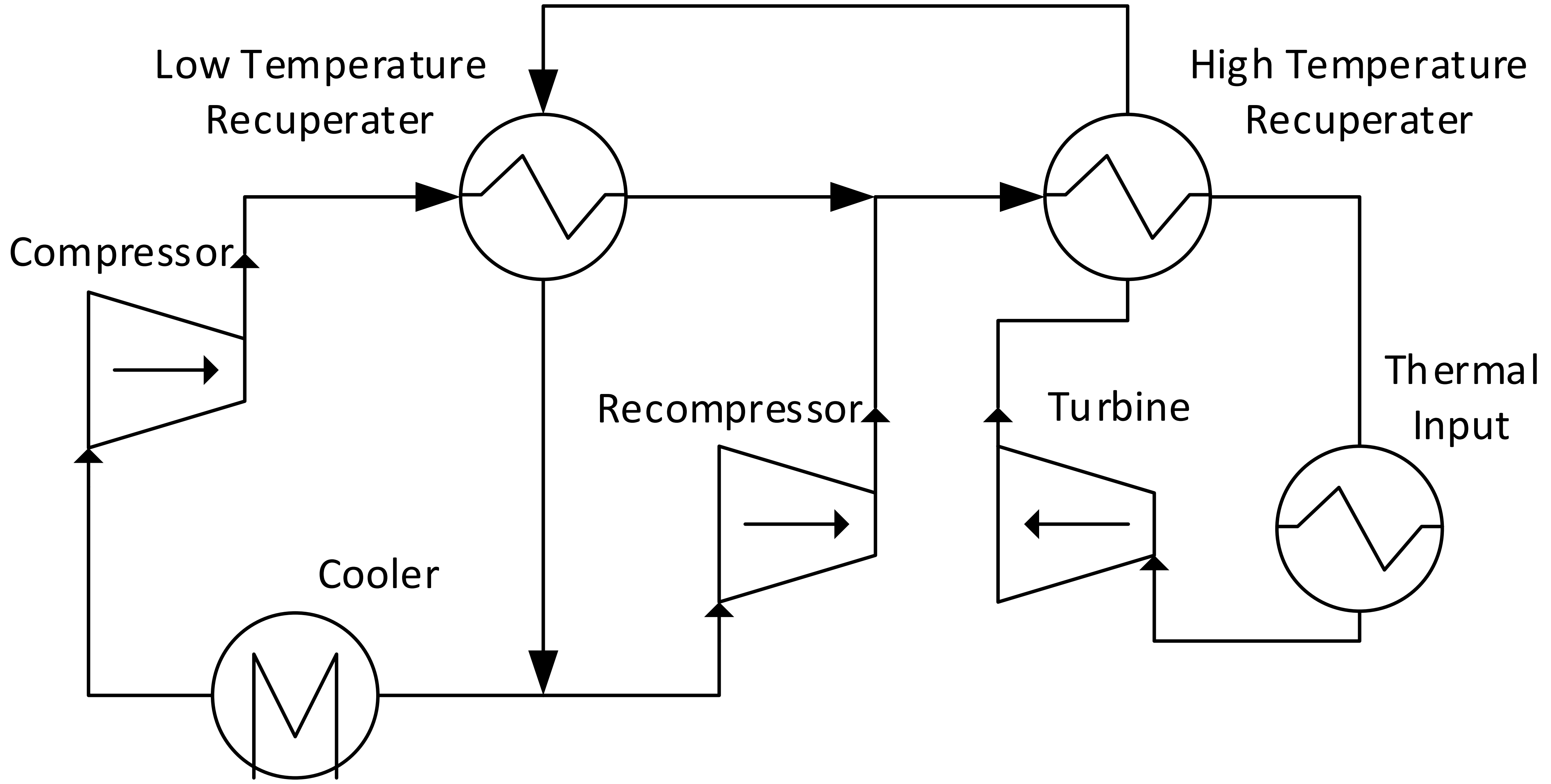
- Direct-fired (oxy-combustion)
- Indirect-fired (main heat exchanger, secondary fluid from variety of sources)

Heat Rejection:

- Non-condensing: Dry (air) or water cooling.
- Condensing: Typically water cooling.

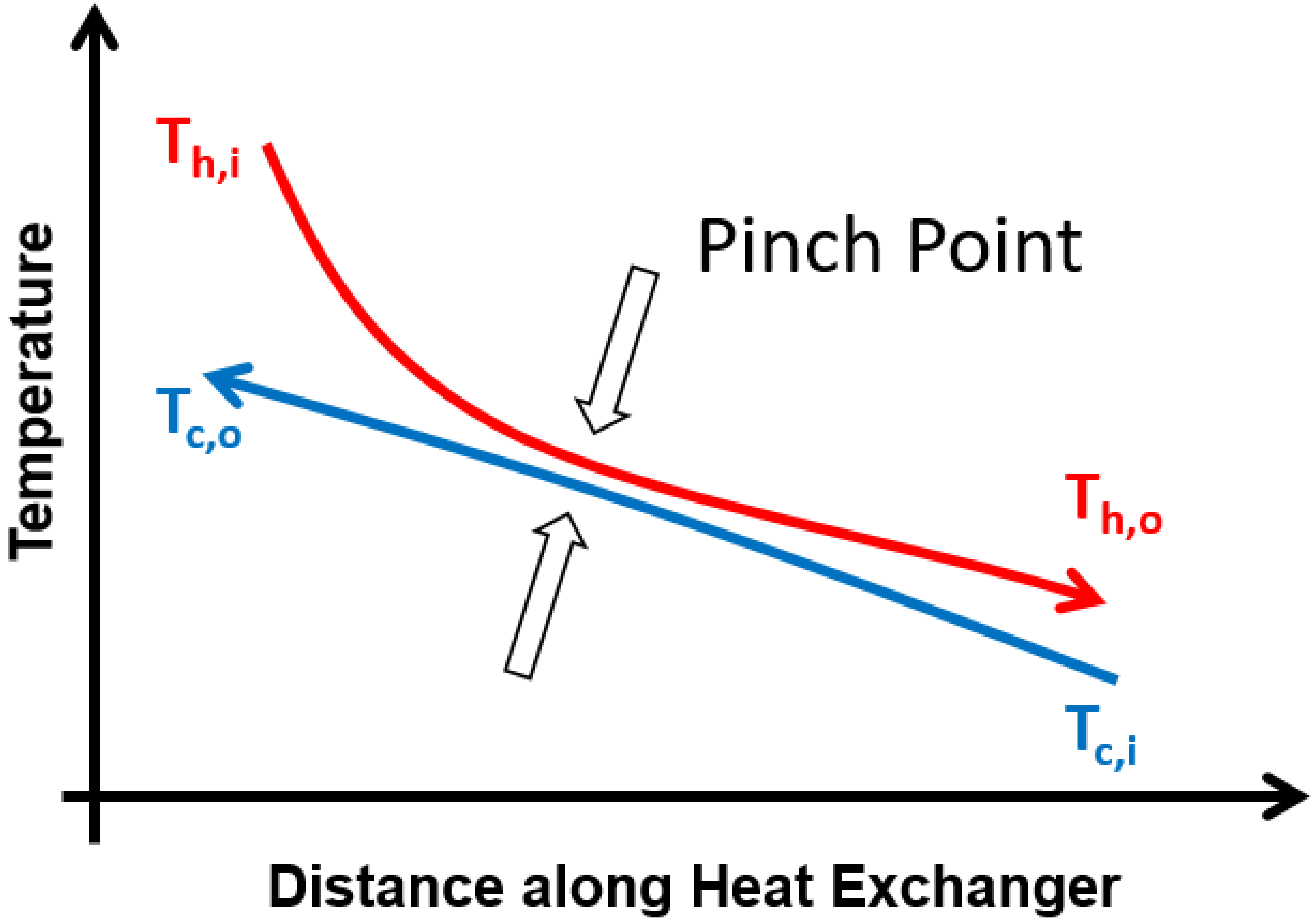
Recompression cycle is benchmark for indirect fired cycles

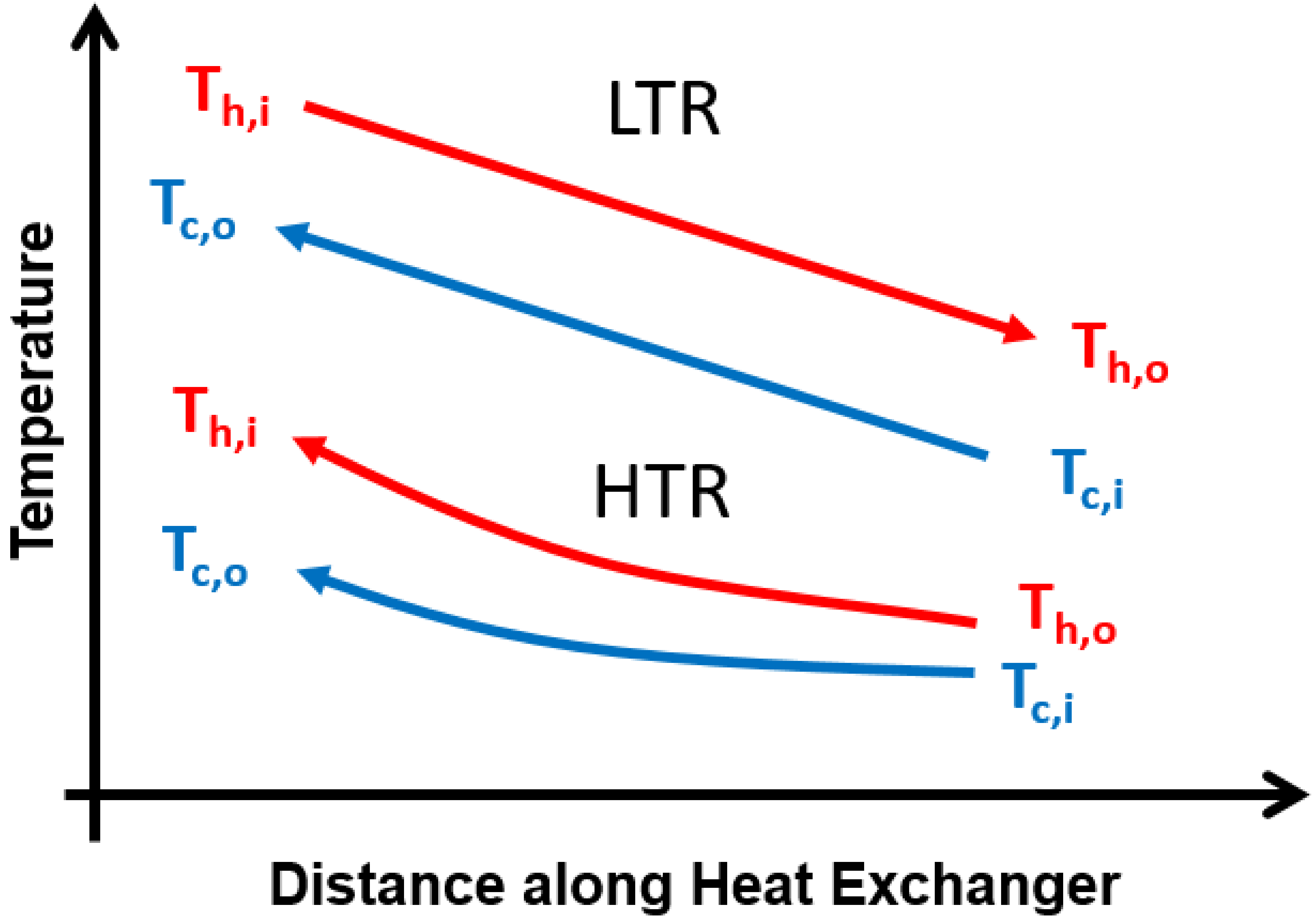




Main HX (Thermal Input) and Cooler can take on several forms, highly recuperated nature of cycle helps to drive up thermal efficiency.

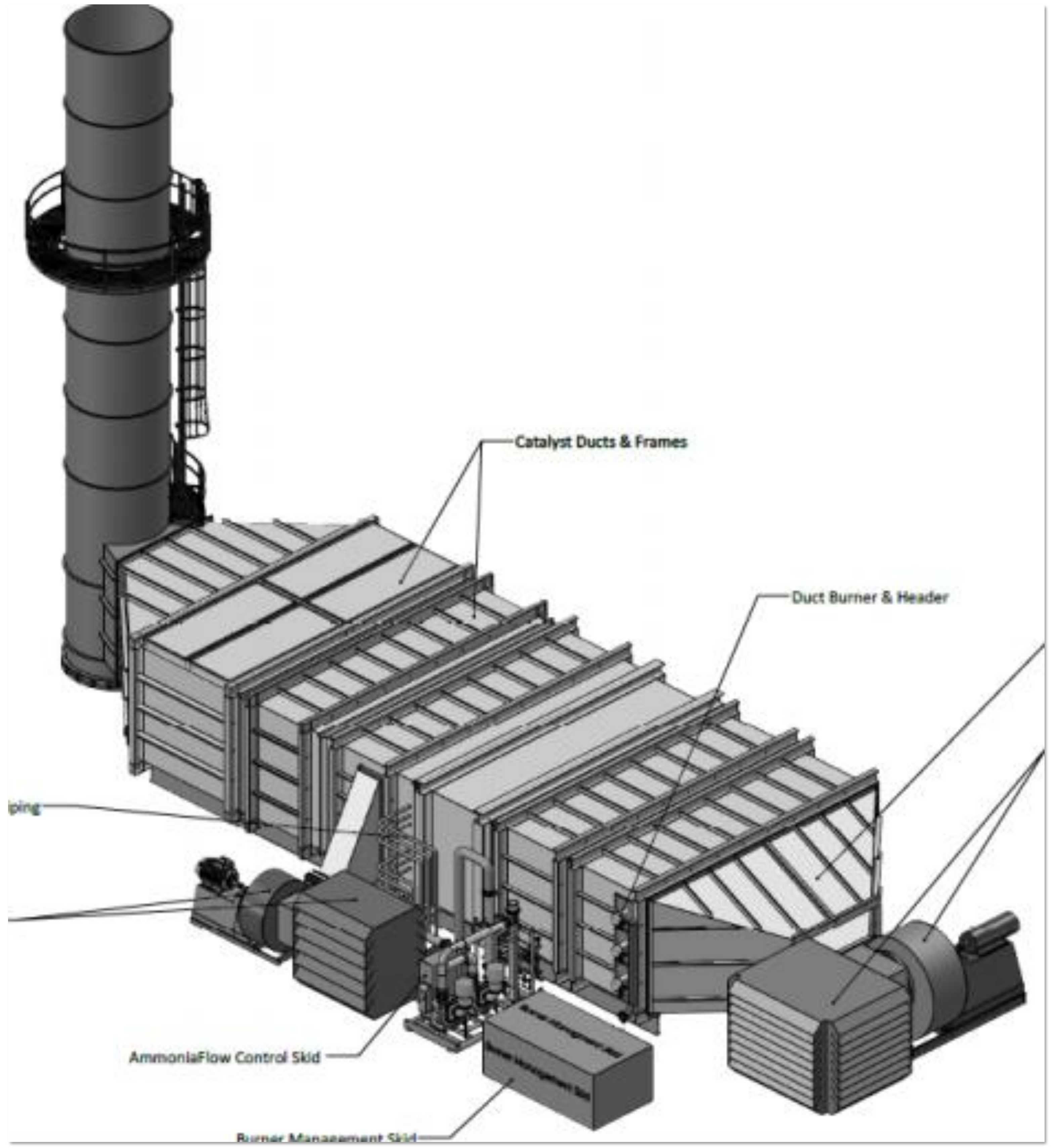
Real gas properties or phase change can create ‘pinch’ points in the temperature profile



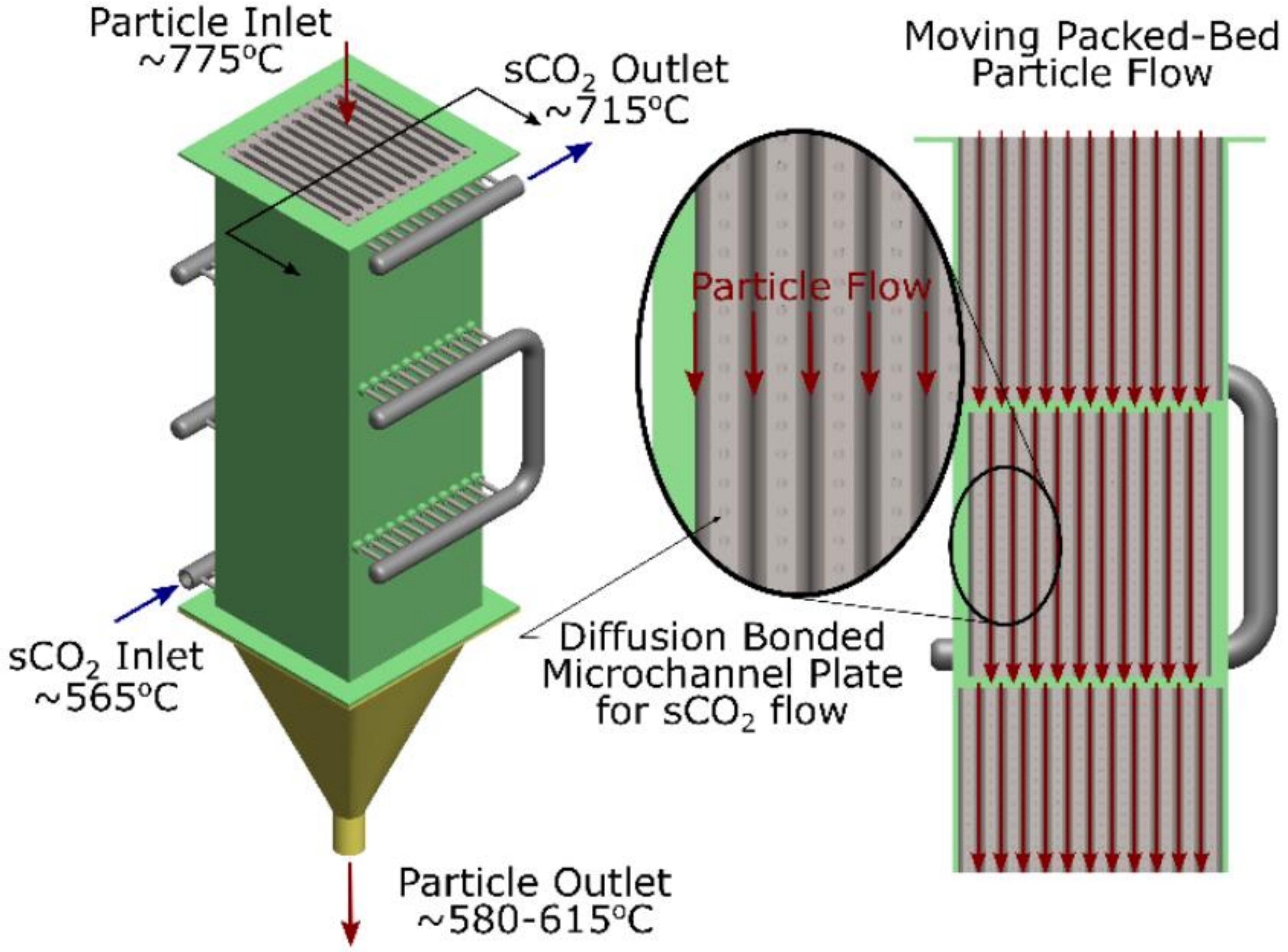


Splitting recuperator into Low Temperature (LTR) and High Temperature (HTR) units and employing cycle flow splits can get around pinch point issue.

Cycle Heat Exchangers – Main Heater



- Main heater design is dependent on heat source.
- Flue gas heat exchanger designs commonly take on the form of nickel superalloy tube bundle, similar in design to HRSG.
- Other applications including CSP may use particle-to-sCO_2 heat exchanger design; nuclear applications could use conventional shell-and-tube heat exchangers.



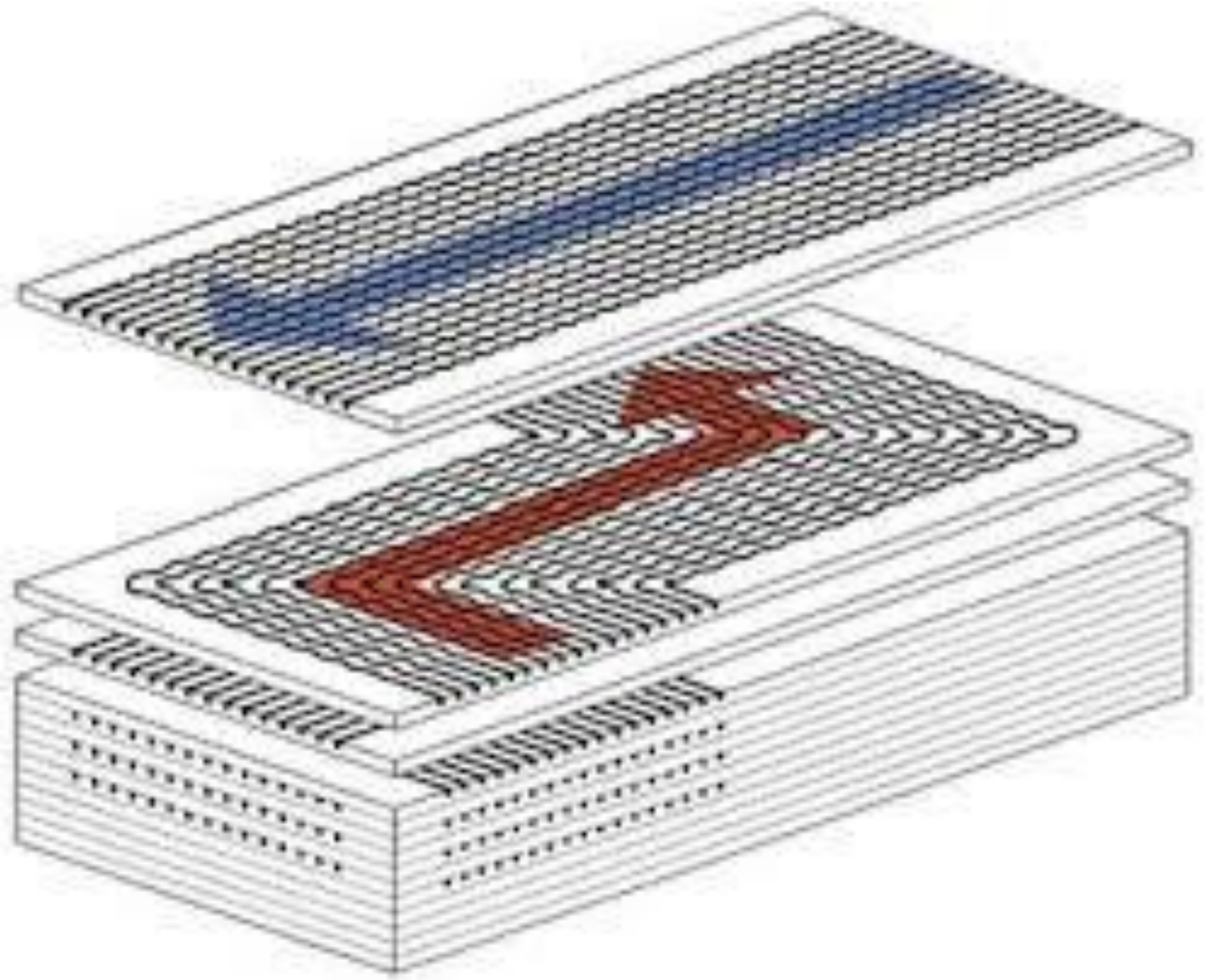
CSP particle-to-sCO_2 HX (Albrecht, Ho, 2019)

(Figure: Southwest Thermal Technology, Inc.)

STEP 10 MWe Facility Natural Gas Fired Heater

Cycle Heat Exchangers – Recuperators

- Recuperator design seeks to maximize heat transfer surface area density for HP and LP streams.
- Printed Circuit Heat Exchangers (PCHE) use etched plates that are diffusion bonded in counterflow heat transfer.
- Proven technology for design pressures exceeding 250 bar and temperatures above 500°C.

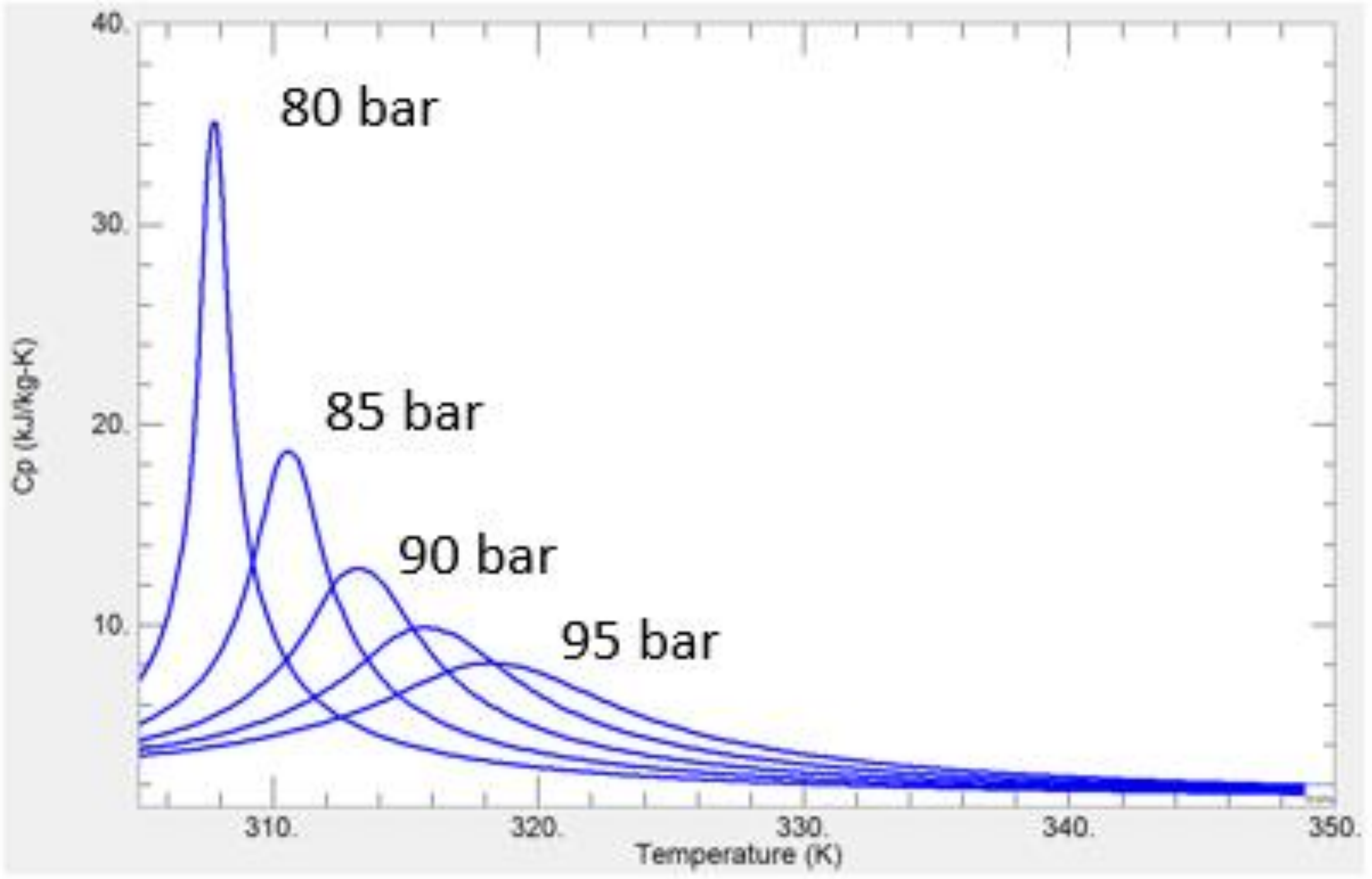


PCHE flow schematic
(Figure: Heatric)

PCHE Recuperator for DOE SunShot program (VPE)

Cycle Heat Exchangers – Coolers

- With a critical temperature around 88°F, sCO2 power cycles are conducive to the use of air coolers.
- Near the critical point, variation in thermal conductivity and specific heat are significant.
- Air coolers use forced convection from fans, and multiple bays can be implemented based off of duty requirements.
- Water coolers could take on a semi-welded plate heat exchanger configuration, PCHE, or shell & tube.



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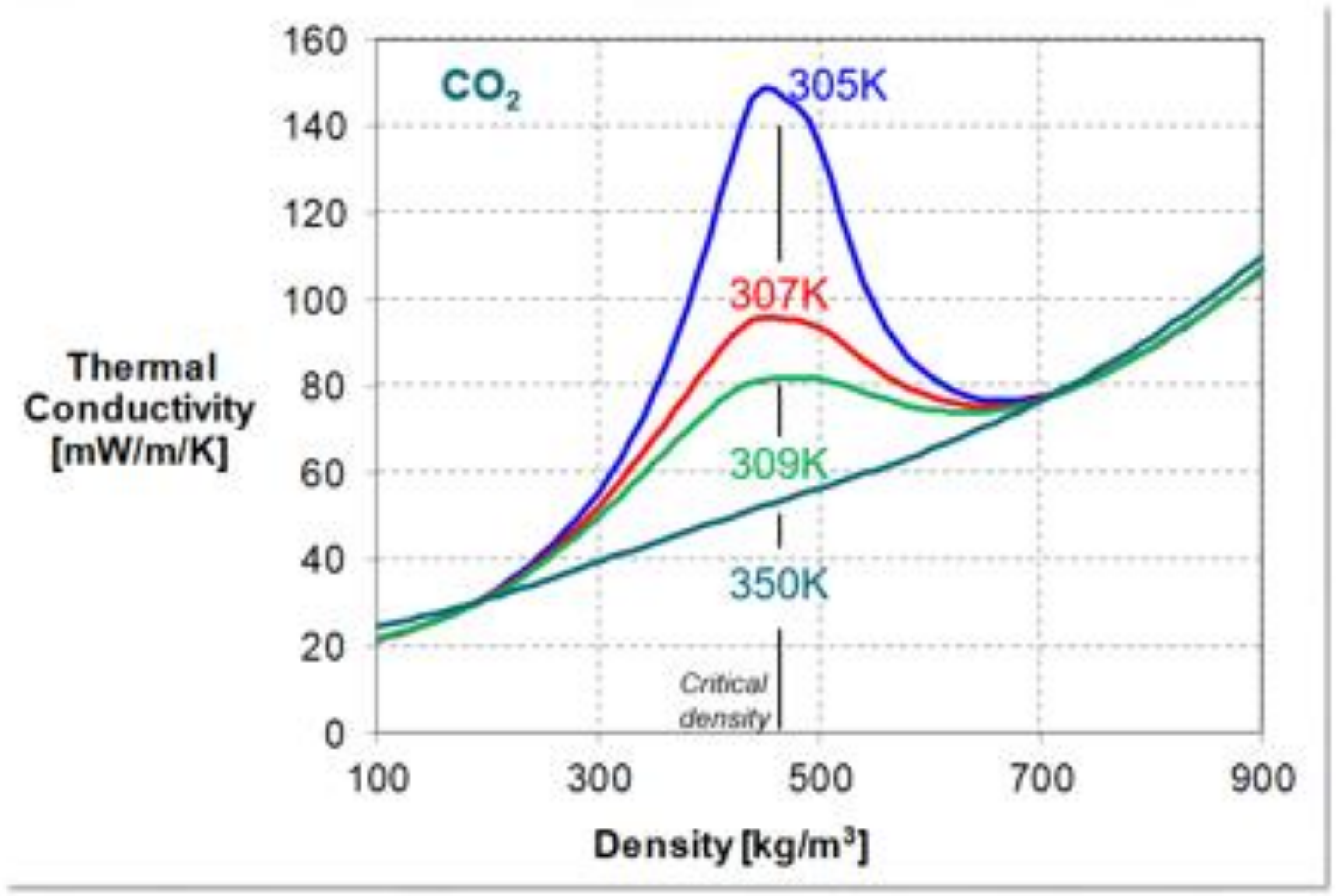

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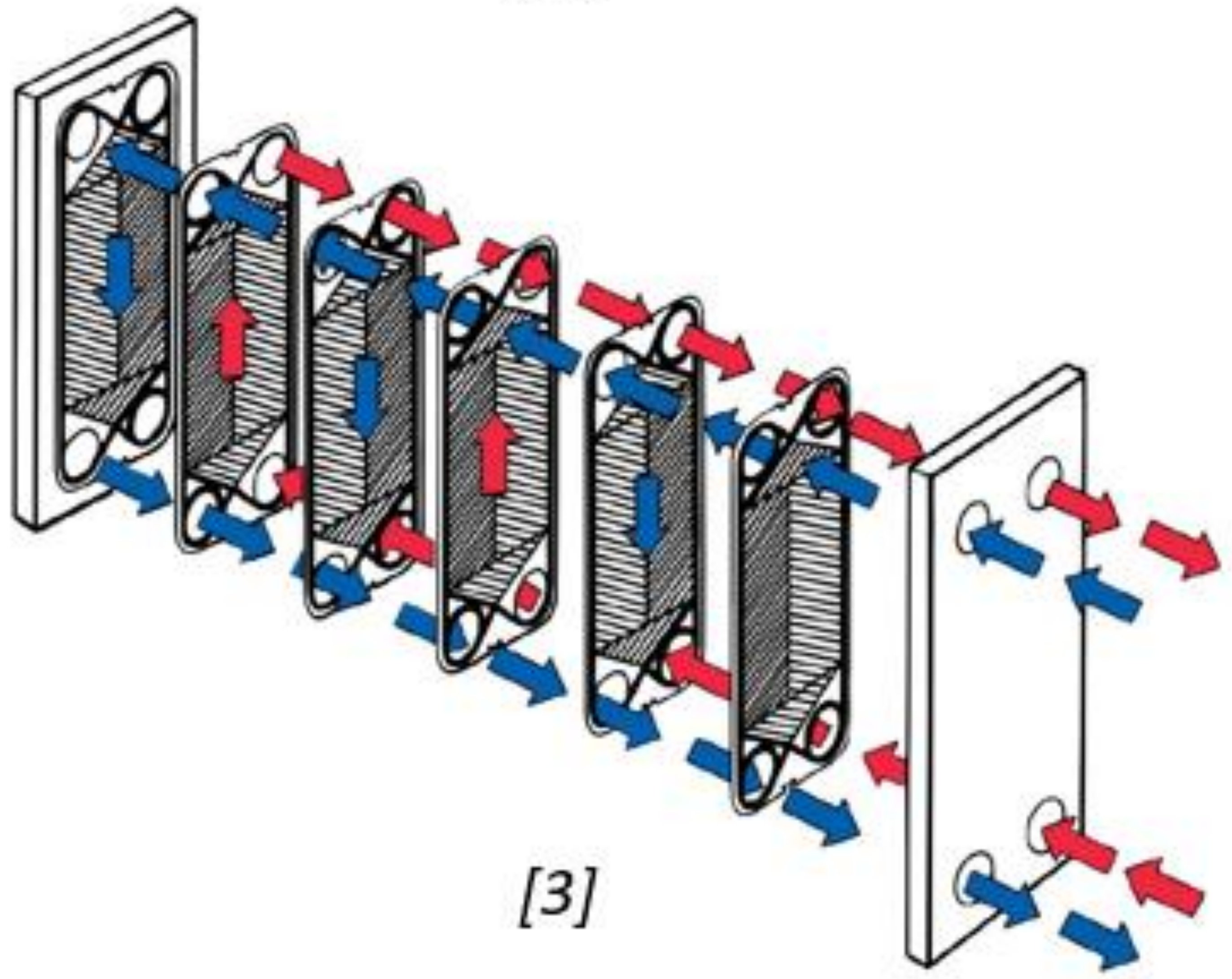


[3]

[4]

[1] NIST REFPROP, v9.1 *[2]* NIST REFPROP, v9.1
[3] Bell & Gossett ; *[4] Goodway Technologies*

Cycle Heat Exchangers – Additive Manufacturing

- Additive manufacturing is a prospective option for sCO_2 recuperators and coolers (water). Typically have limited build volume (kW vs. MW commercial scale).
- Two leading processes are directed energy deposition (DED) and powder bed fusion (PBF).
- DED can achieve faster build rates and specializes in building off of existing material. PBF specializes in intricate channel geometry and steep overhang angle capability.

Figure: Velo3D

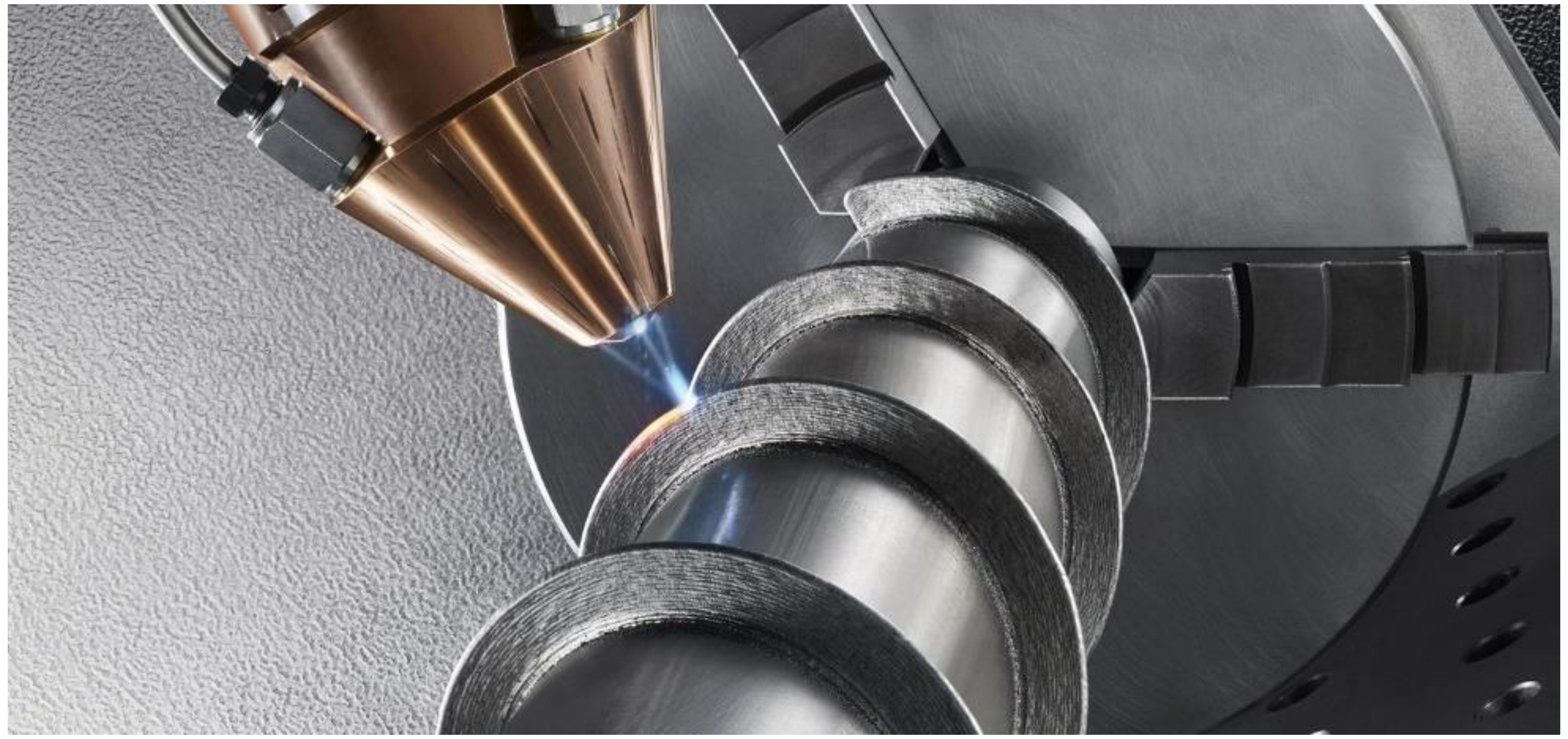
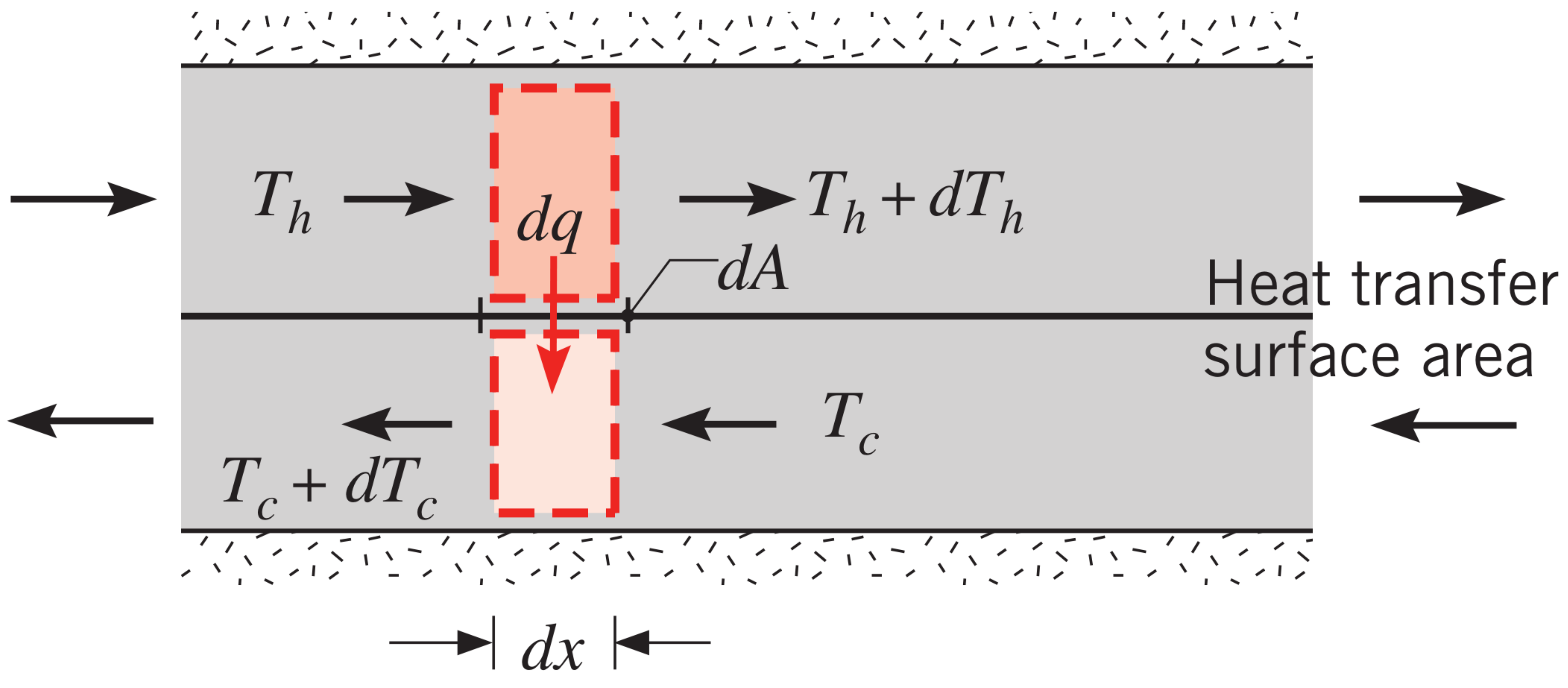


Figure: Trumpf

Heat Exchanger Thermal Design Overview



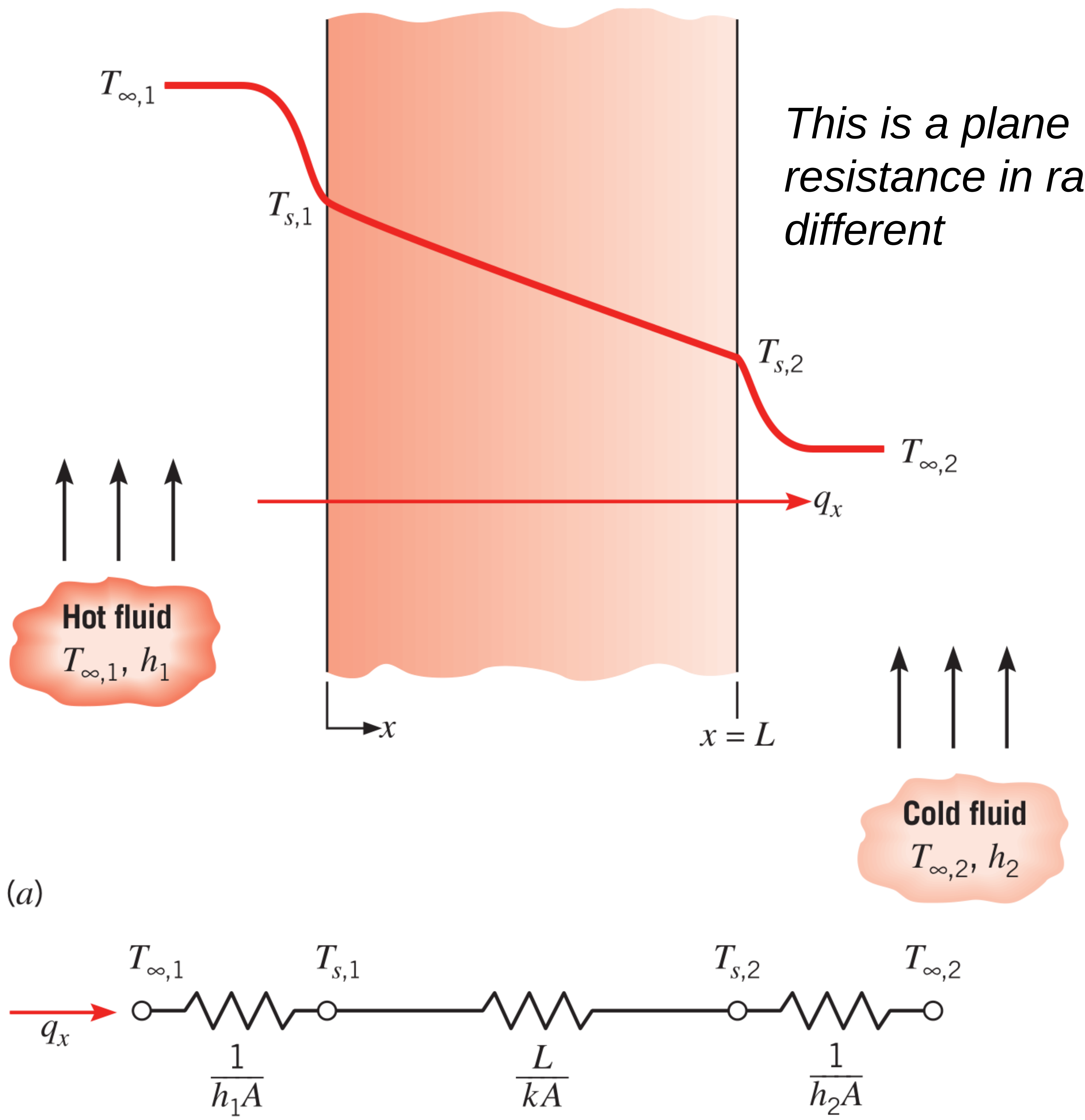
Once the cycle has established heat exchanger design conditions, detailed design can begin.

The overall approach is to determine the heat exchanger Unit Cell and correlations for HTC, DP and conduction resistance.

These data are then used in a discretized model to find the resulting heat exchanger performance using energy conservation.

Discretization is required for non-linear fluid properties. This means that overall approaches like LMTD and $\epsilon - NTU$ are not appropriate.

Overall Heat Transfer



This is a plane wall, wall resistance in radial systems is different

$$\frac{1}{UA} = \frac{1}{(hA)_h} + R_w + \frac{1}{(hA)_c}$$

Heat Transfer

Heat transferred from or to each fluid can be expressed as:

$$Q = UA * \Delta T$$

In this equation ΔT is the driving temperature difference between the hot and cold sides of the exchanger.

UA comes from a 1D heat resistance network connecting the hot and cold sides.

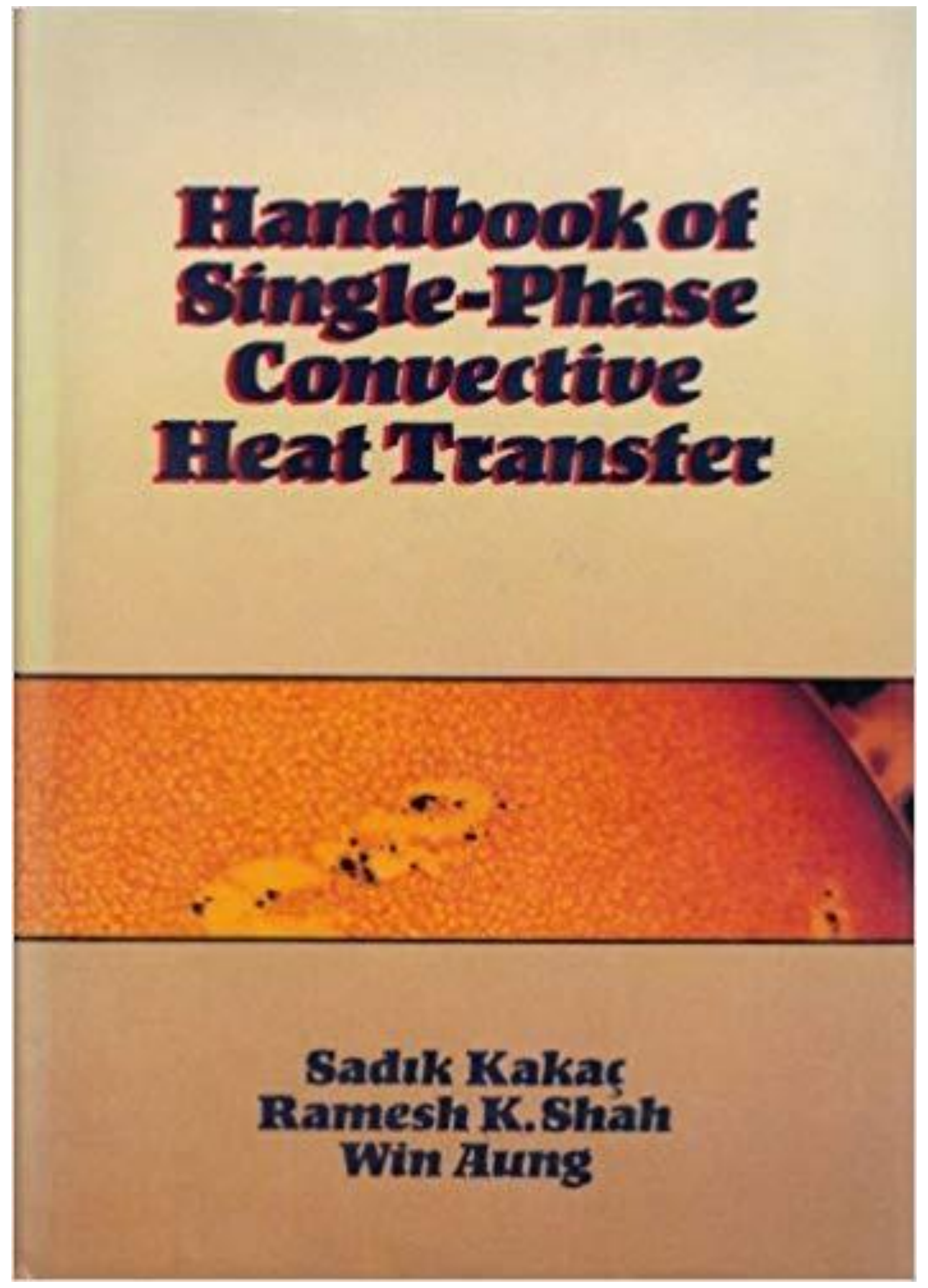
Figure: Incropera, Dewitt, *Fundamentals of Heat and Mass Transfer.*

Fluid Heat Transfer

$$\frac{1}{UA} = \underset{\uparrow}{\frac{1}{(hA)_h}} + R_w + \underset{\uparrow}{\frac{1}{(hA)_c}}$$

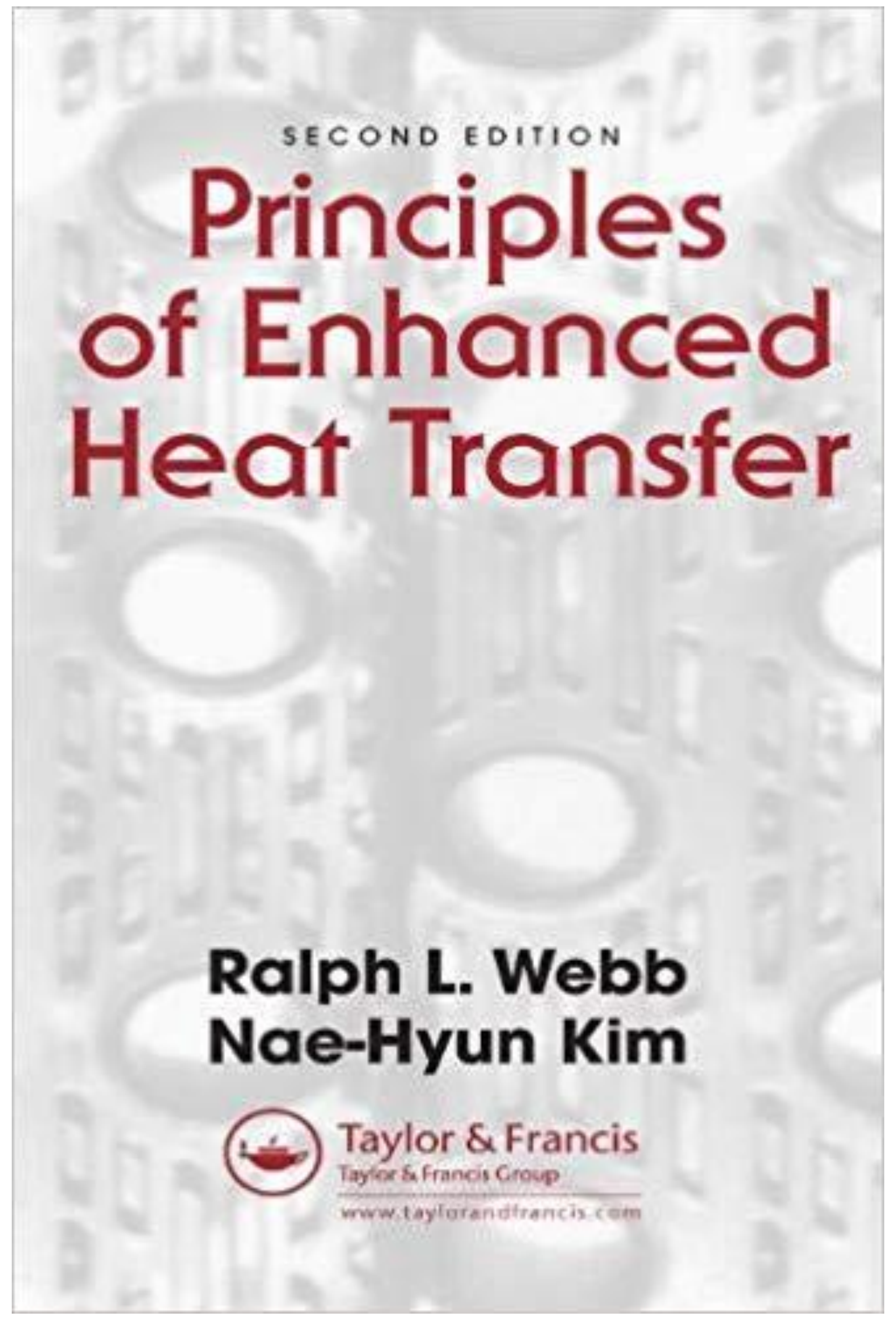
$$Nu_D = \frac{(f/8)(Re_D - 1000)\,Pr}{1 + 12.7(f/8)^{1/2}\,(Pr^{2/3} - 1)}$$

Gnielinski correlation for smooth wall, fully developed turbulent flow in a pipe (0.5<Pr<2000 and 3000<RE<5e6)



Handbook of Single-Phase Convective Heat Transfer

Sadık Kakaç
Ramesh K. Shah
Win Aung



SECOND EDITION

Principles of Enhanced Heat Transfer

Ralph L. Webb
Nae-Hyun Kim

Taylor & Francis
Taylor & Francis Group
www.taylorandfrancis.com

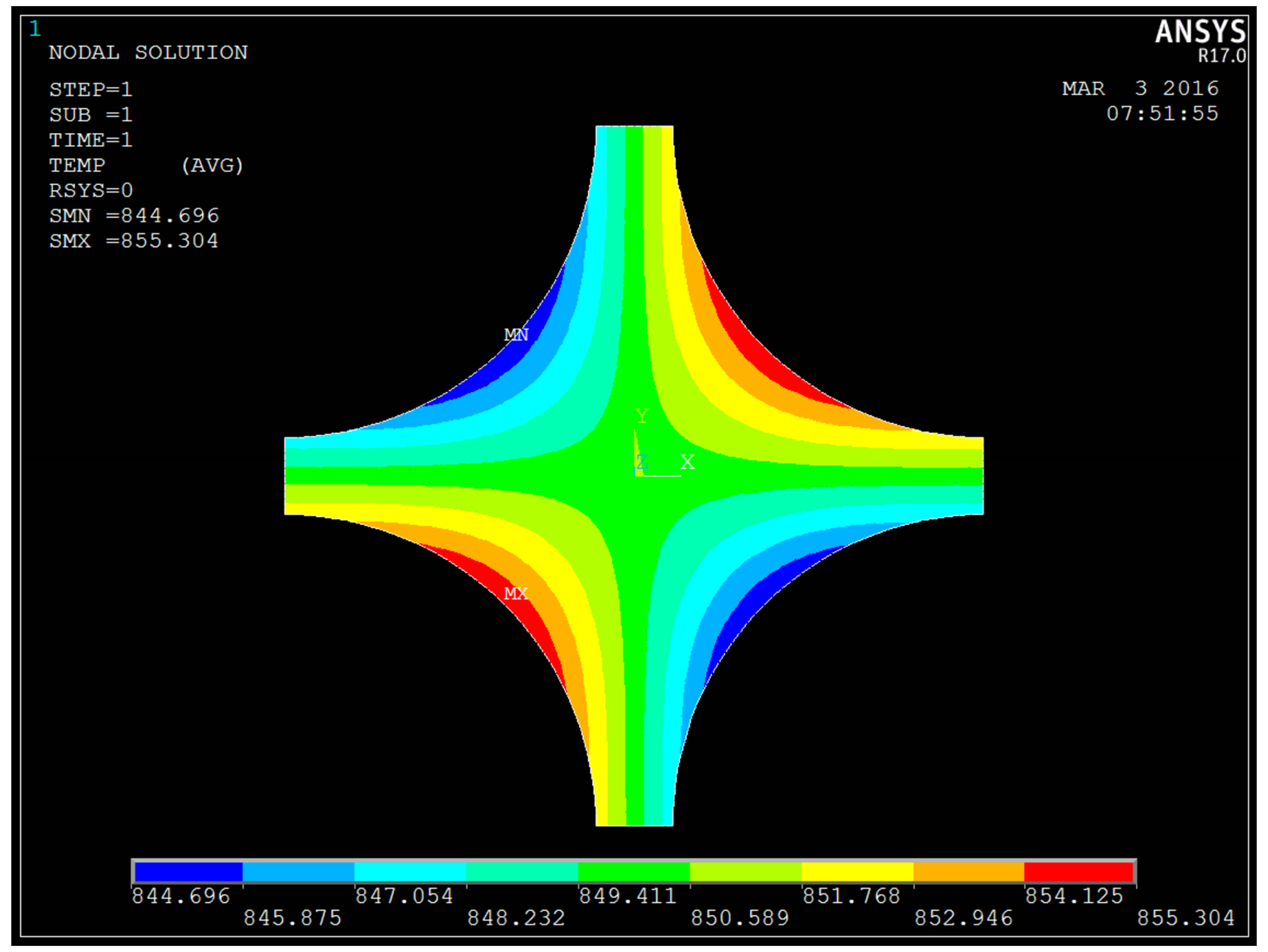
To calculate the required UA term we need the hot and cold side heat transfer coefficients. These can be derived from experiments, CFD, or from correlations.

Experiments or experimentally derived correlations are most accurate but are geometry dependent.

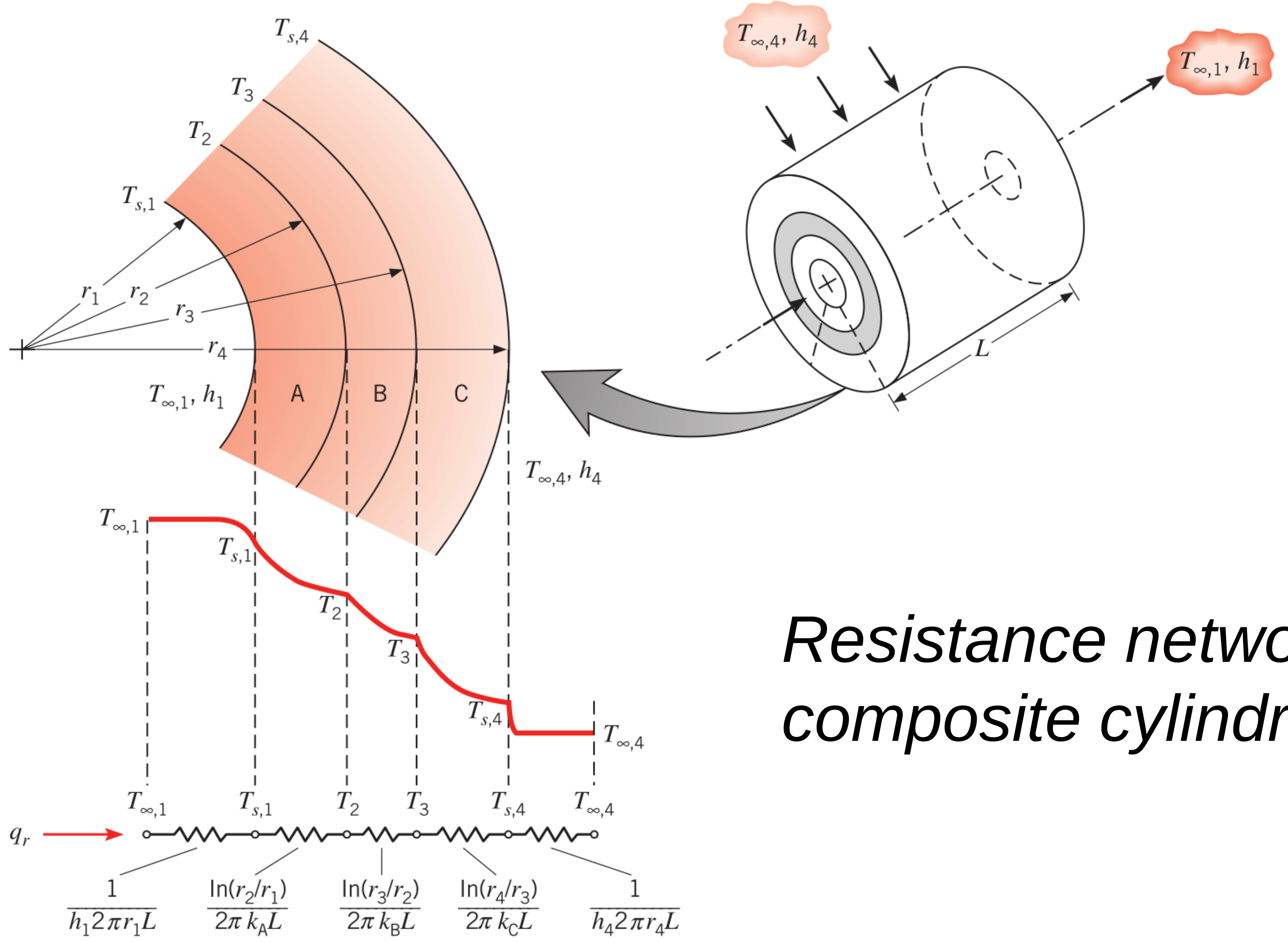
- Channel shape?
- Channel surface roughness?
- Entry lengths?
- Phase?
- Fin area?
- Close enough?
- Hydraulic diameter?

Wall Resistance

$$\frac{1}{UA} = \frac{1}{(hA)_h} + R_w + \frac{1}{(hA)_c}$$



FEA used to calculate equivalent wall resistance for checkerboard circular channels



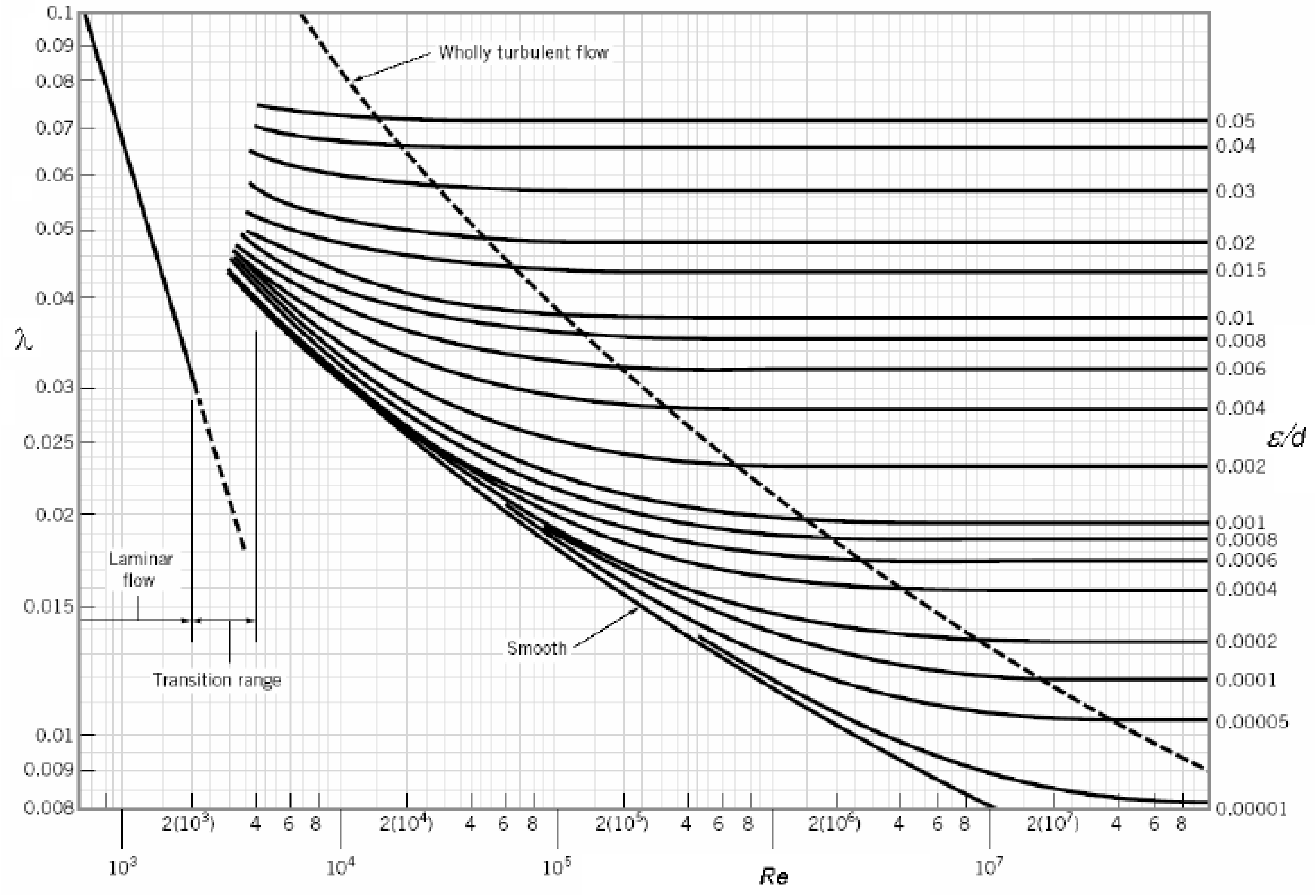
Resistance network for composite cylindrical wall

Wall resistance inhibits heat flow between the fluids. The value of R_w can be obtained from FEA, analytically, or from experiment.

Experiments or experimentally derived correlations are most accurate but are geometry dependent.

Configuration	**UA per m**	**Percent**
No wall resistance	26.632	100.0
Equivalent Plane Wall	25.381	95.30
Checkerboard	24.57	92.25
Staggered	21.90	82.23

Pressure drop



Moody Chart

Source: Munson, et. al. *Fundamentals of Fluid Mechanics.*

Pressure drop changes fluid properties and also affects cycle. Relationships for pressure drop can be derived experimentally or from correlations.

For flow through a tube:

$$DP = f\left(\frac{l}{D}\right)\left(\frac{\rho V^2}{2}\right)$$

f is a function of surface roughness, diameter, and RE through the Moody chart (Colebrook equation)

Energy Conservation

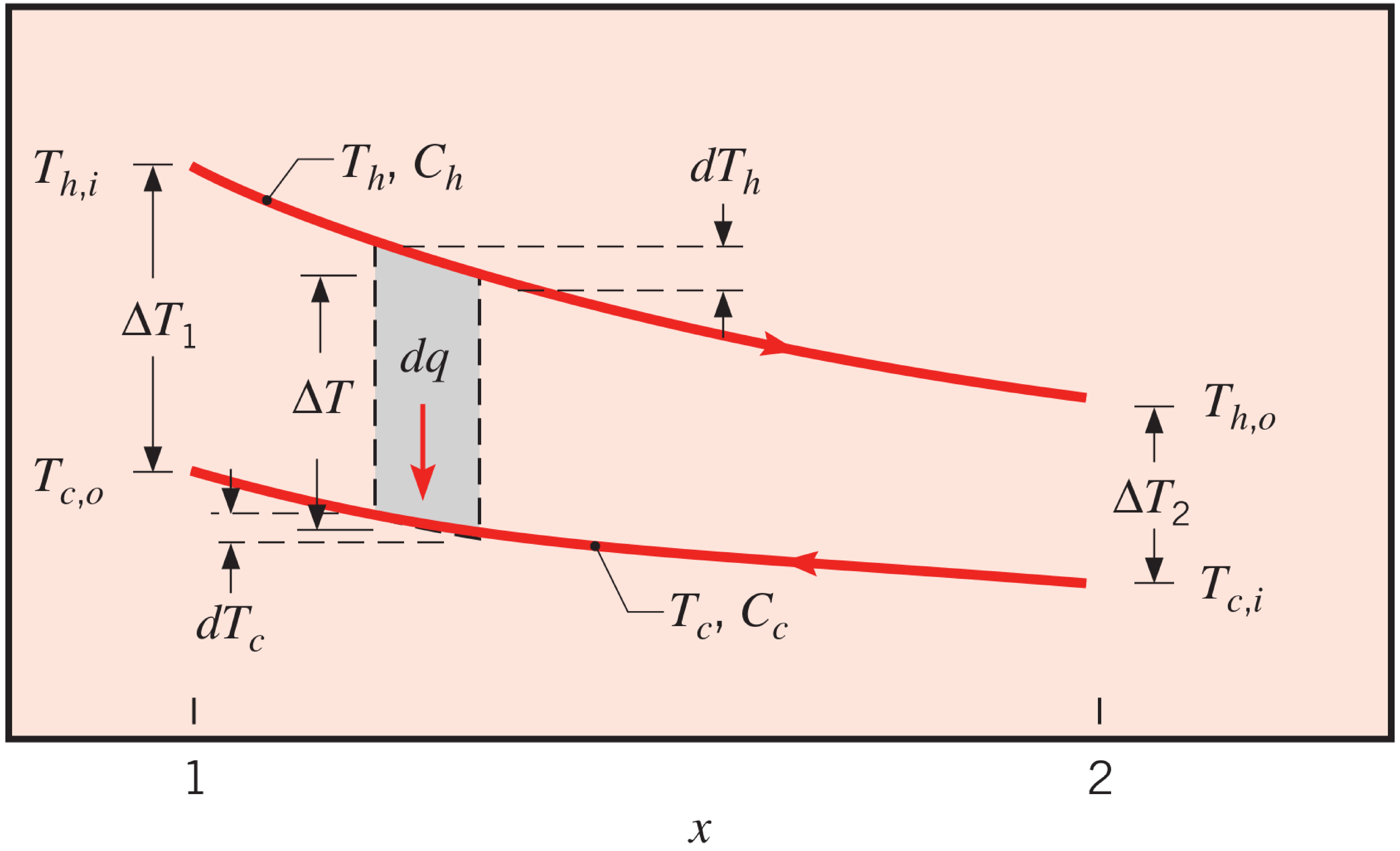


Figure: Incropera, Dewitt, *Fundamentals of Heat and Mass Transfer.*

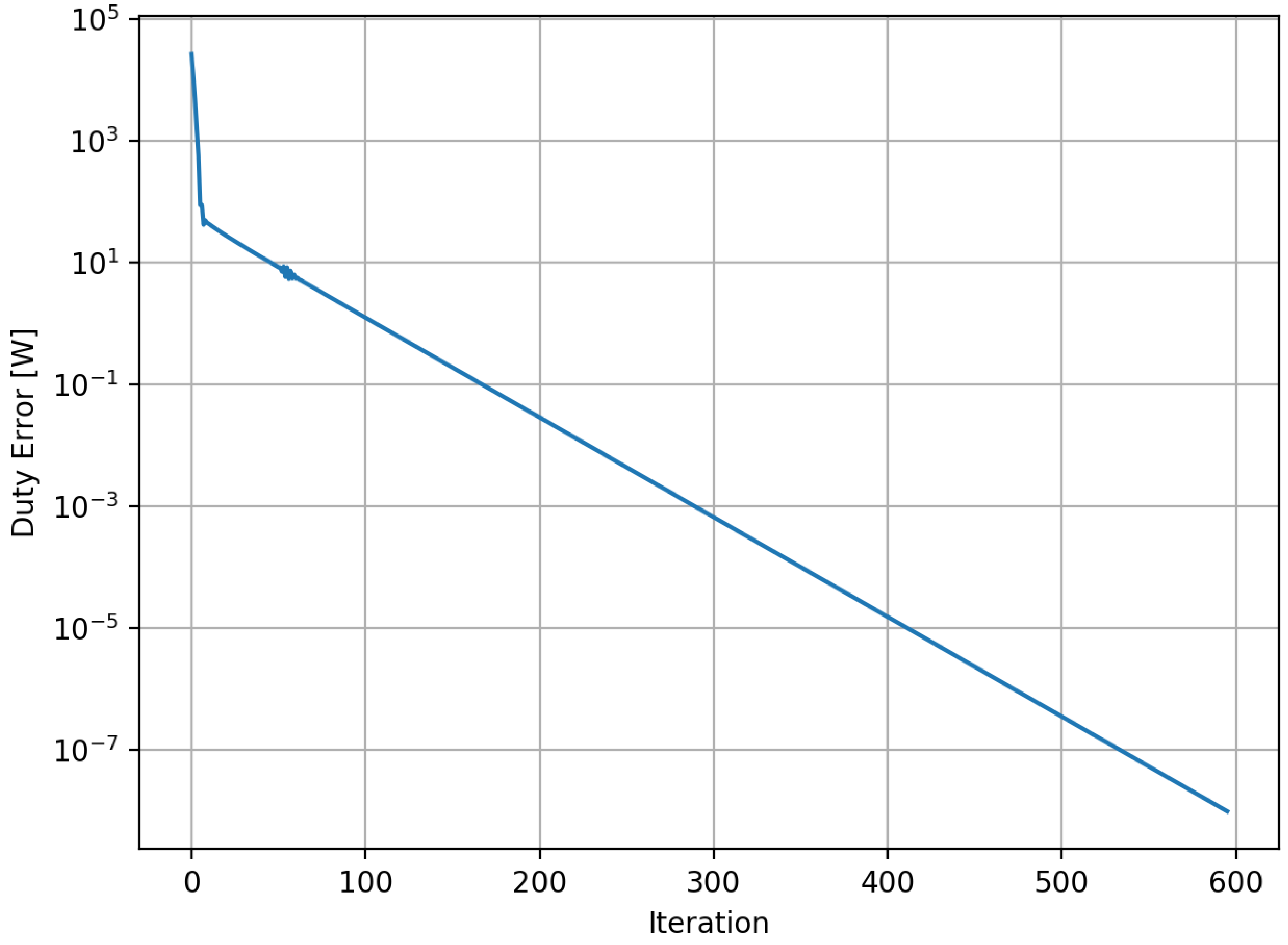
Energy conservation

Heat transferred from or to each fluid is equal to the enthalpy change of the respective fluid.

$$Q = UA * \Delta T = \dot{m} * \Delta h$$

Using a robust fluid property package means you don't need to rely on linearizing assumptions (Specific heat).

Solver



Duty Error as a function of iteration count

Divisions	Direct EOS	Tabulated EOS
5	0.251s	0.022s
15	0.933s	0.081s
50	10.3s	0.871s
250	256s	22.2s

Combine all equations and solve. The problem?

Heat transfer changes fluid properties which changes heat transfer which changes fluid properties and pressure drop. *Solution is iterative.*

Strategy:

-Divide heat exchanger into divisions
-Guess initial temperature distribution

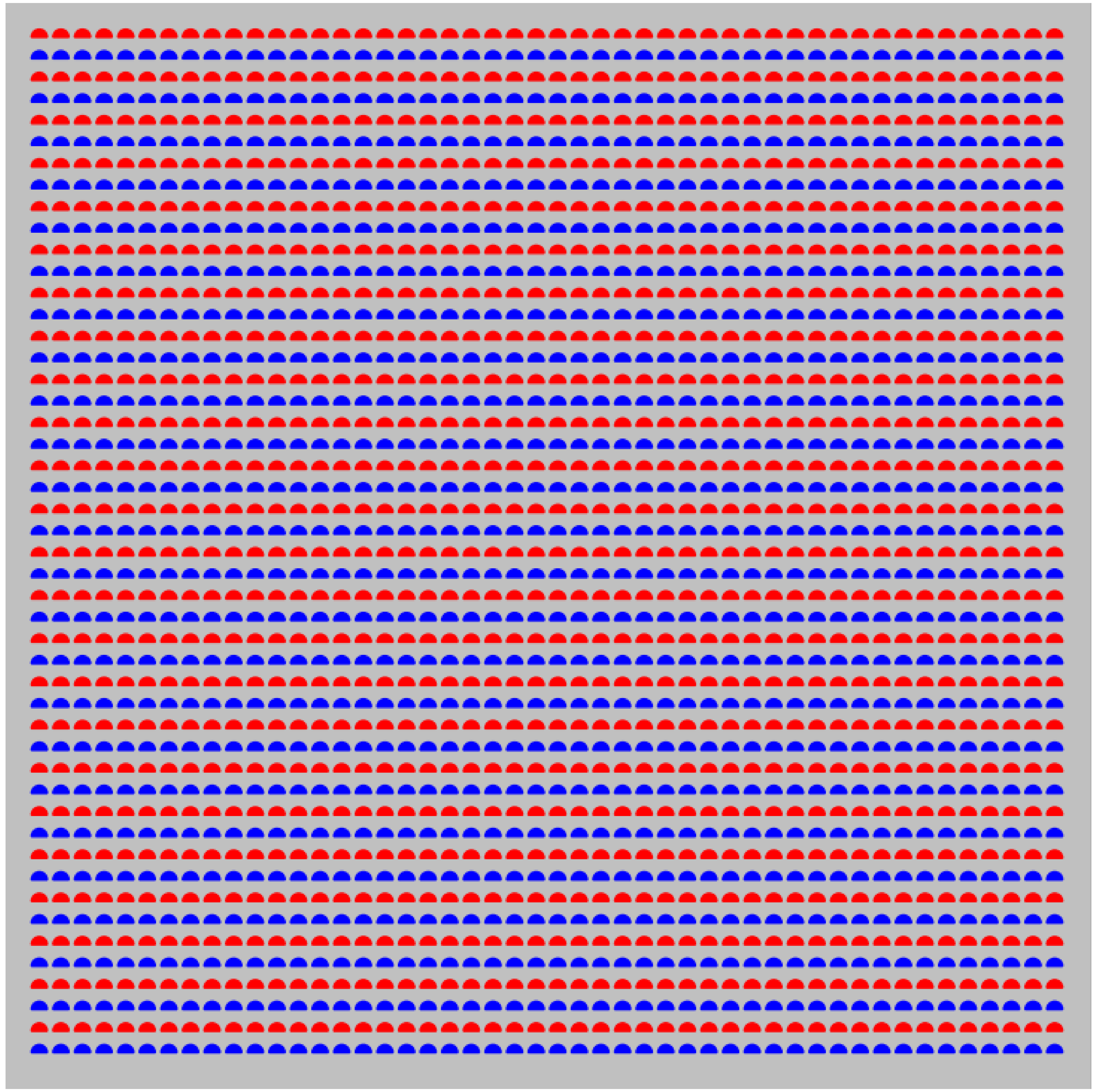
In each division

-Calculate heat transfer and pressure drop on both hot and cold sides
-Calculate overall UA
-Calculate exit enthalpy (enforce conservation)
-Update fluid properties
-Go through each division and repeat until converged.

Most of computational effort is spent calculating fluid properties and solving Colebrook equation. Tabulation and approximations can help.

Parallelflow, Counterflow, Crossflow? Change which fluid element talks to which fluid element.

Optimization Example



HP – Blue, LP - Red

Set Boundary Conditions

- Low Pressure CO_2 Stream: 500 [C], 80 [bar]
- High Pressure CO_2 Stream: 150 [C], 250 [bar]
- Flowrate: 20 kg/s

Establish Basic Geometry and Material

- Circular passages in counterflow arrangement, SS316

Set Independent Variables

- Length of HX core
- Number of passages
- Diameter of HP passages
- Diameter of LP passages

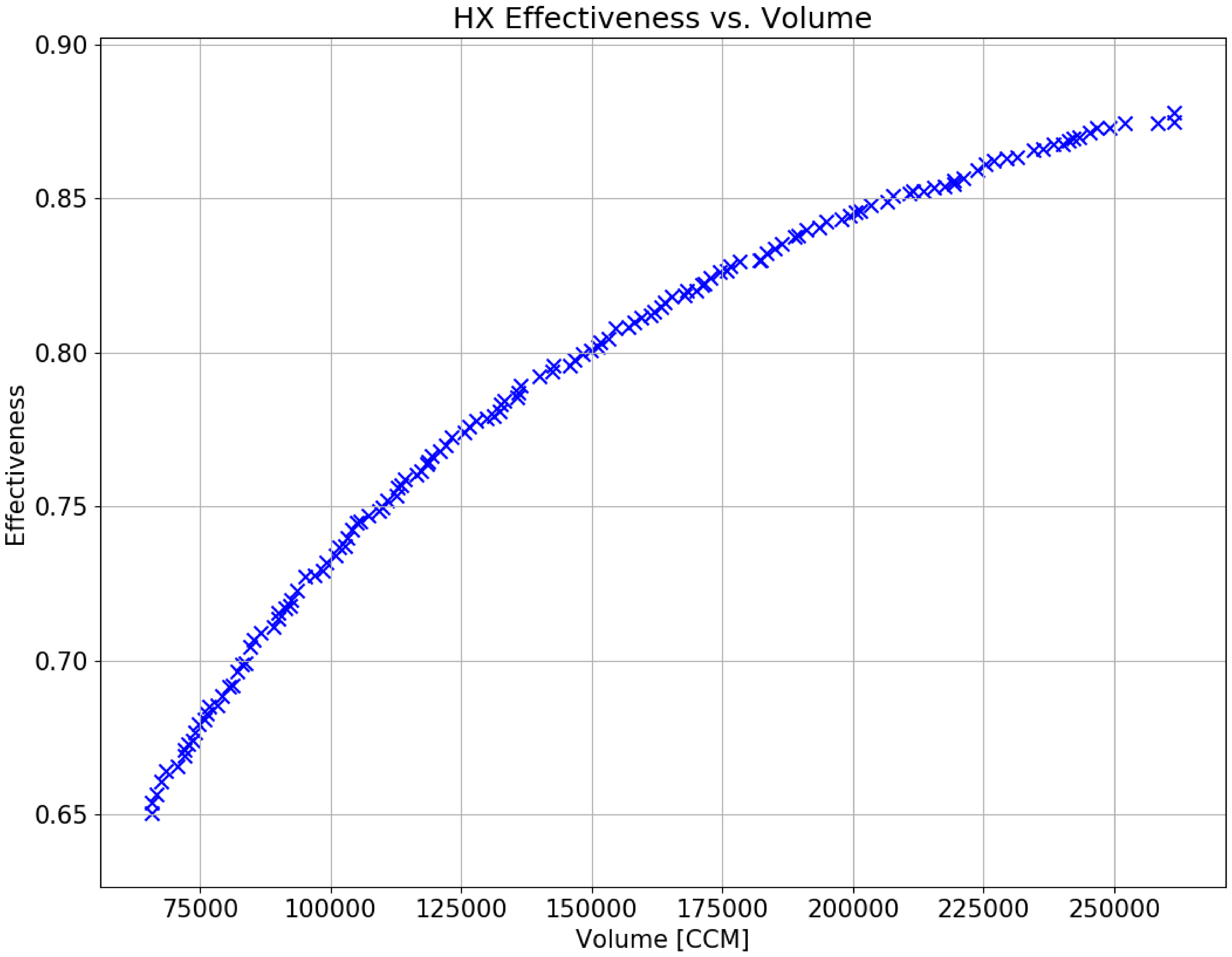
Set Objectives

- Maximize effectiveness
- Minimize volume

Set Constraints

- HP pressure loss < 2%
- LP pressure loss < 2%

Optimization Results



Optimization algorithm

- Select type of algorithm
- Set generation count, population size

Optimization evaluator

- Select fluid property package
- Set equations for solid and fluid thermal resistance
- Set equations for pressure drop
- Use 1-D code for energy conservation

Results

- Tradeoffs between performance and size/cost of heat exchanger becomes evident.
- Numerous factors complicate the design of HX’s, optimization of core geometry is only one component of a worthy design.

HX TEST DATA

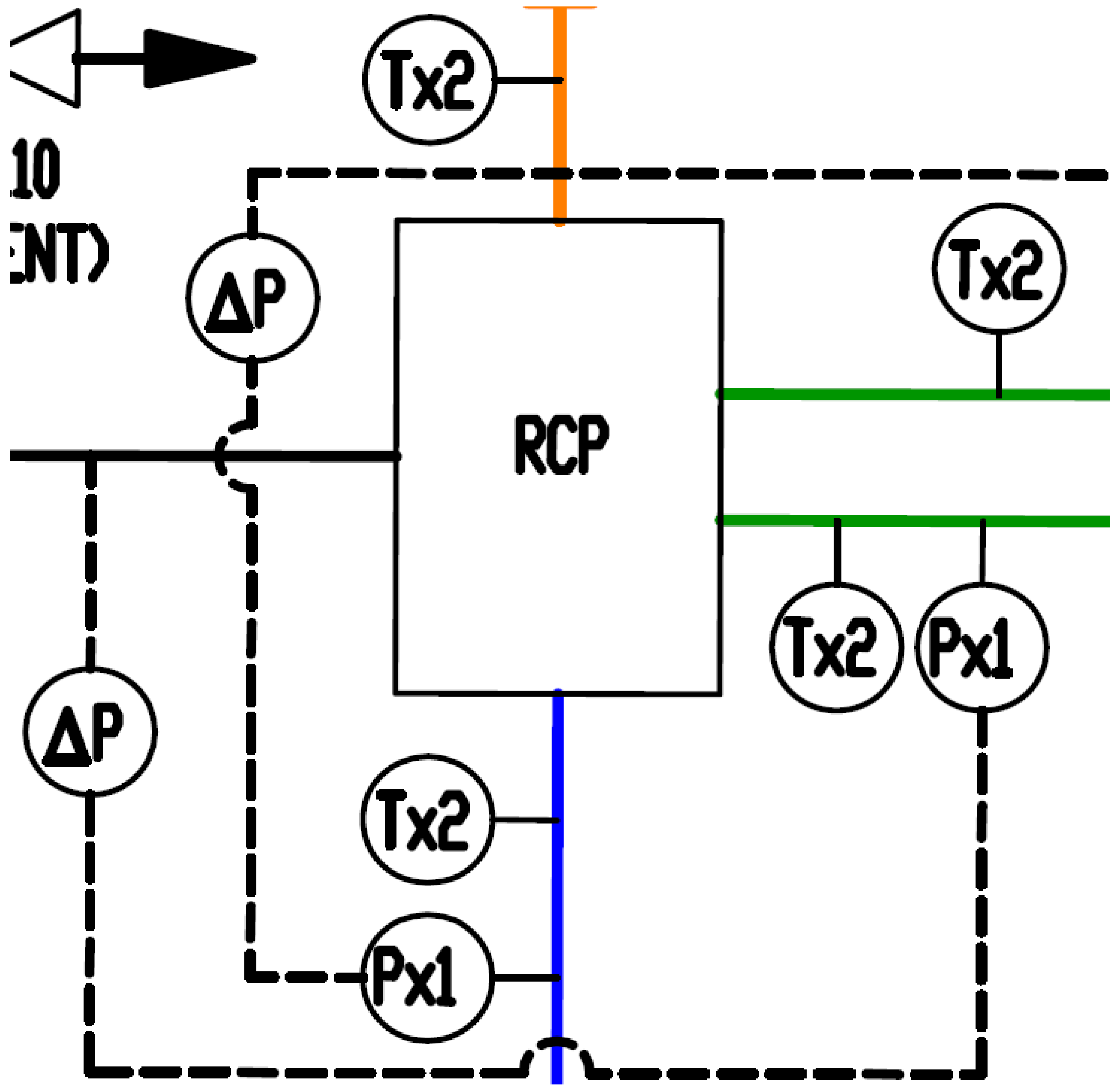
Turbo-expander testing at SwRI

- A MW-scale sCO_2 test loop was constructed by SwRI to test a turbo-expander to a TIT of 715 °C and pressures exceeding 240 bar.
- Loop implemented MW-scale PCHE recuperators and primary heater.
- In addition to initial 37.5 hours of testing for SunShot program, heat exchangers have continued for multiple DOE programs.

3 MWth recuperator (VPE)

1 MWth Primary HX (Thar/SwRI)

Recuperator Operating Data



- HP flow originates from pump outlet in loop.
- LP flow originates from turbine exhaust.
- Recuperator includes dP measurement and multiple temperature readings on each connection.

HP flow (kg/s)	HP flow (kg/s)	HP Pressure (bar)	HP Temp (C)	LP Pressure (bar)	LP Temp (C)	Duty (MW)	Effect. (%)	HP % dP	LP % dP
4.97	4.79	200	30.0	85.1	447	2.76	79.2	0.513	1.38
5.78	5.54	239	40.5	83.0	533	3.21	90.3	0.565	2.78

Primary Heat Exchanger Data

- Heat exchanger made up of 740 H tube bundle with multiple passes, allowing for thermal growth.
- At a higher cost, finned tubing can increase performance by reducing air-side thermal resistance.

CO_2 Flow (kg/s)	CO_2 Pressure (bar)	CO2 Inlet T (°C)	CO2 Outlet T (°C)	Air Inlet T (°C)	Air Flow (m^3/s)	Duty (MWth)
5.05	220	398	577	804	3.45	1.12
5.56	238	406	597	896	4.31	1.32

8th International Supercritical CO_2 Power Cycles Symposium
San Antonio, TX U.S.A.
February 26 - 29, 2024

Heat Exchangers for Supercritical CO_2 Power Application

Compact Heat Exchangers Design & Additive Manufacturing

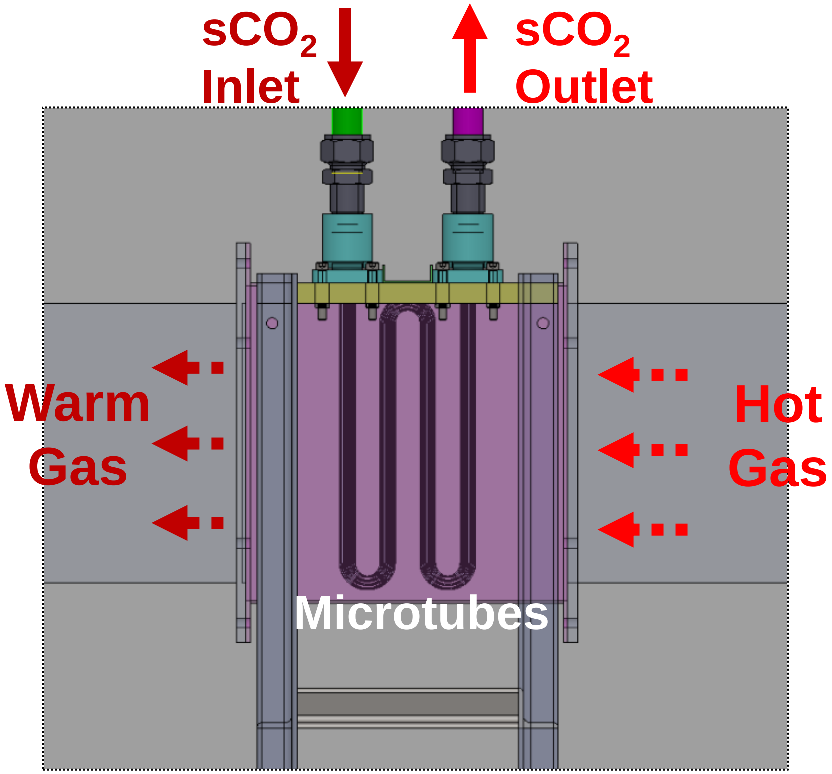
Addendum: Operations & Testing

Lalit Chordia, PhD, Vahid Vahdat, PhD, **Marc Portnoff**

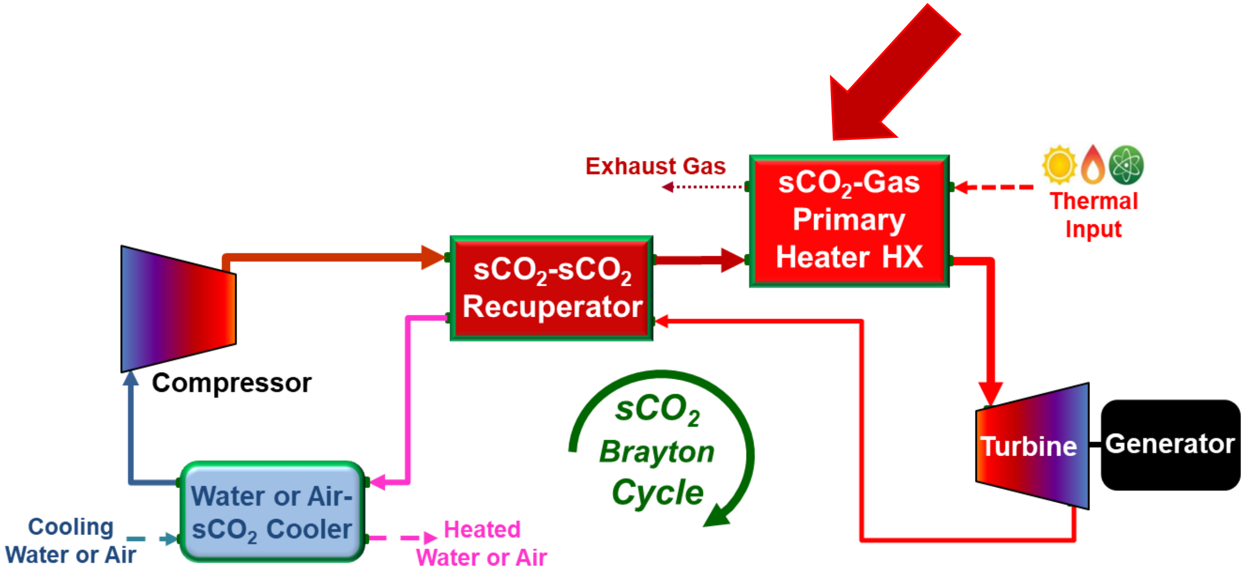
TharEnergy

Primary Heater Heat Exchanger

Hot gas to sCO_2



Cross Flow, Counter-current Microtube Heater

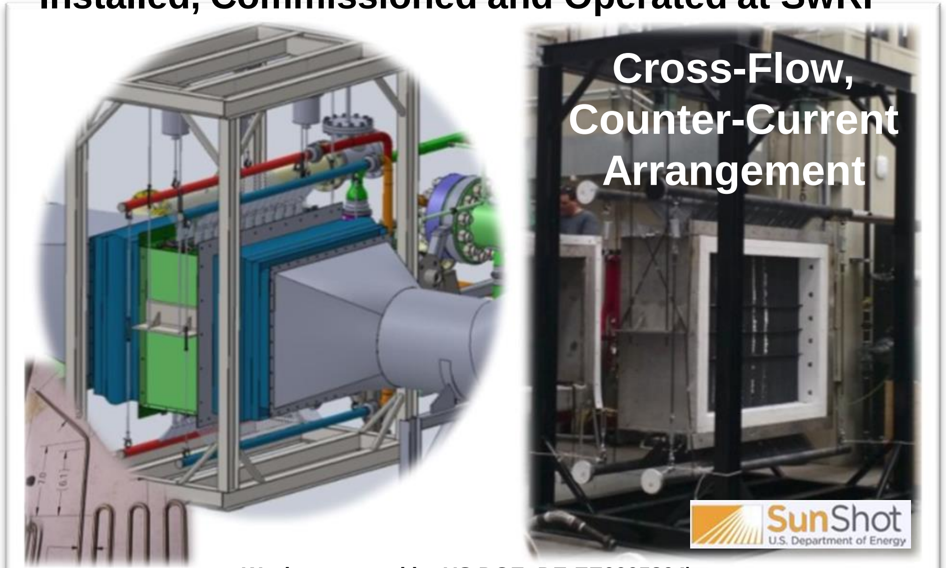


- Heats up the pressurized sCO_2 to high temperature prior to entering the turbine

Work supported by US DOE NETL: DE-FE0024012

Primary Heater– Design Considerations

Thar Energy's sCO₂ Primary Heater
Installed, Commissioned and Operated at SwRI

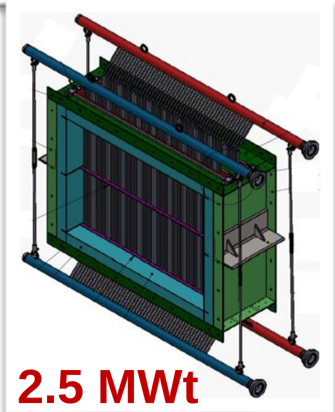


Work supported by US DOE: DE-EE0005804\

Design Conditions:

Gas Fired Burner/Blower Outlet
Combustion Gas Temp: 870°C

sCO_2 HX Outlet:
Max Temperature: 715°C @ 255 bar
Design Pressure: 280 bar



2.5 MWt Thermal Capacity

1 Material Selection

- High strength at high temperature (Inconel 740H)
- ASME, Section 8, Div. I approved, 800°C / 300 bar
- Design to creep rupture strength rather than allowable stress

2 Corrosion

- Select materials that are stable in sCO_2 and combustion gas corrosion

3 Thermal Expansion

- Design the structure to allow free thermal expansion under high temperature

4 Sizing

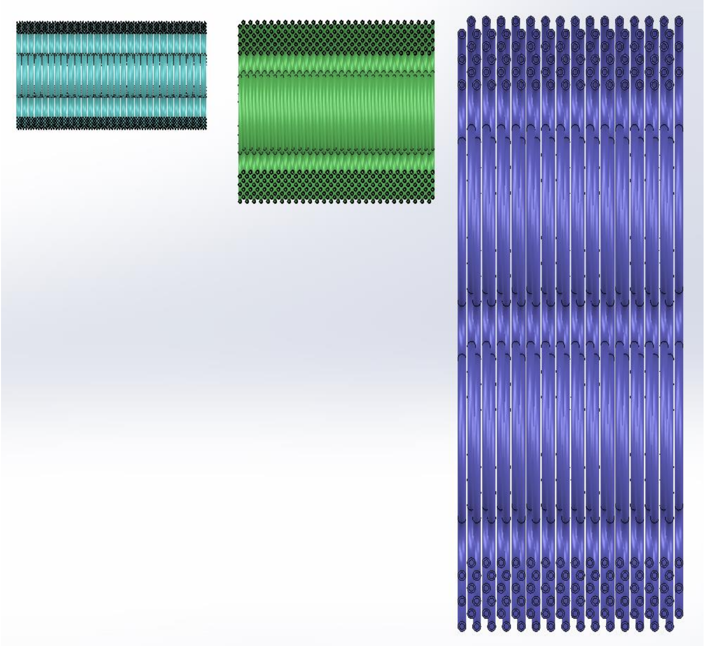
- Air side pressure drop sized to be under limit to ensure overall efficiency
- Particle contaminants are a concern – size for periodic cleaning

Primary Heater

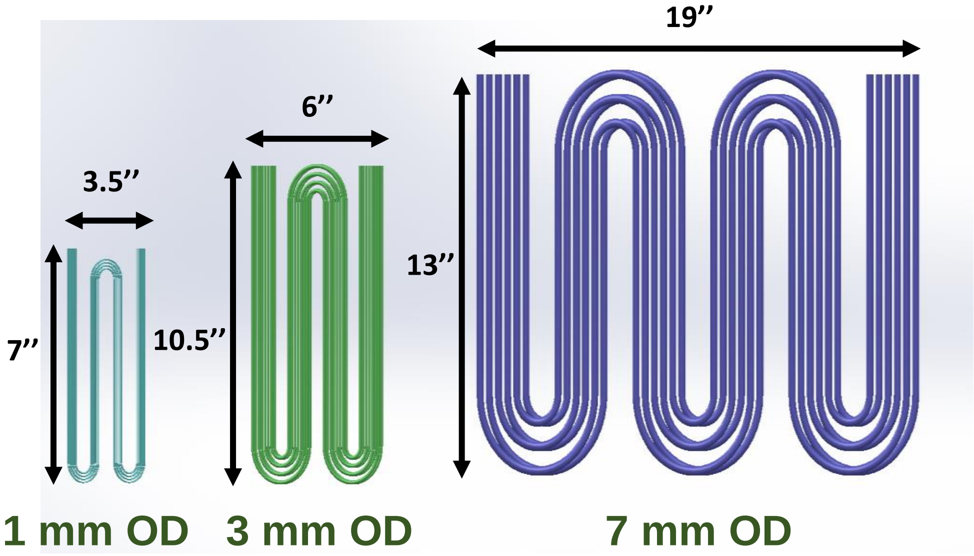
Cross flow, Counter-current Microtube Heat Exchanger

Overall Size Comparison

- Microtube vs. conventional tube, air to CO_2 cross flow, counter-current heat exchangers
- Different tube sizes with the same thermal capacity, effectiveness and air side pressure drop



1 mm OD 3 mm OD 7 mm OD



Tube OD	1 mm	3 mm	7 mm
Total Tube Length	16,800''	9,240''	7,020''
Tube Number	600	220	90
Bundle Weight	4.5 lb	20 lb	90 lb
Surface Density	46 in^2/in^3	17 in^2/in^3	7 in^2/in^3

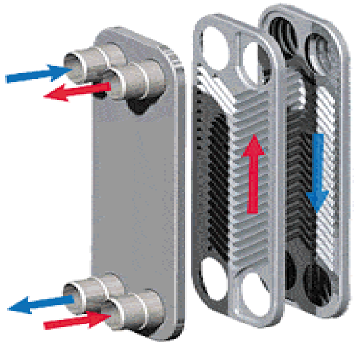
Air Cooler: Air to sCO_2
Water Cooler: Water to sCO_2

Air Cooled

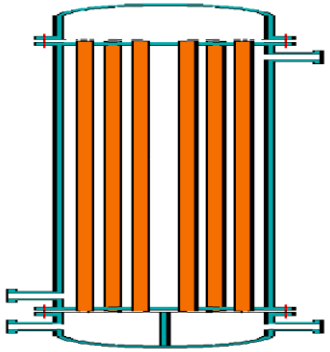
Finned-Tubes

Micro-channel

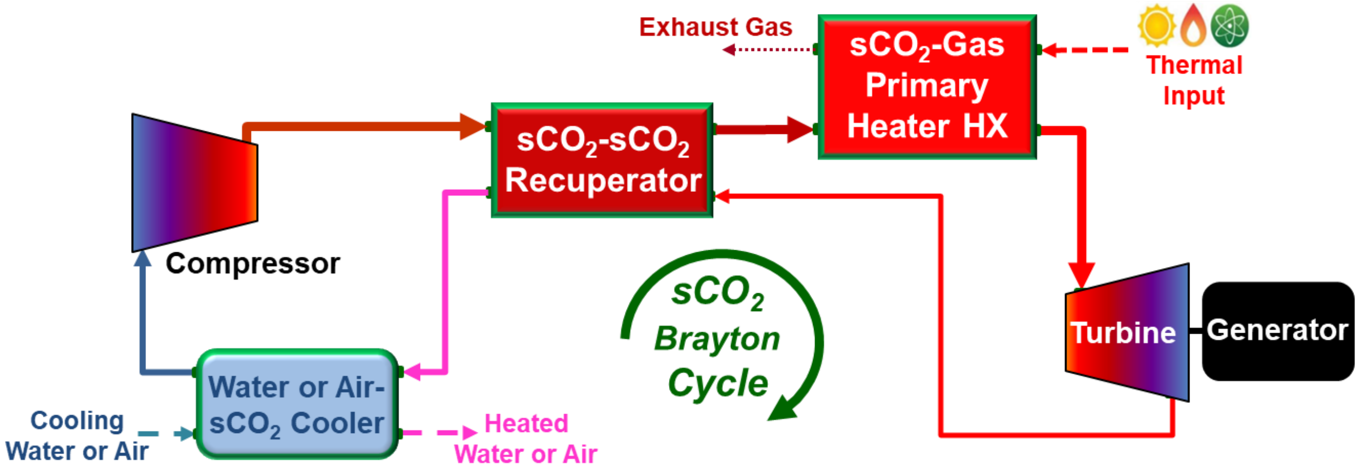
Water Cooled



Brazed-Plate



Tube/ Microtube



- Cool sCO_2 to increase density and reduce compressor energy

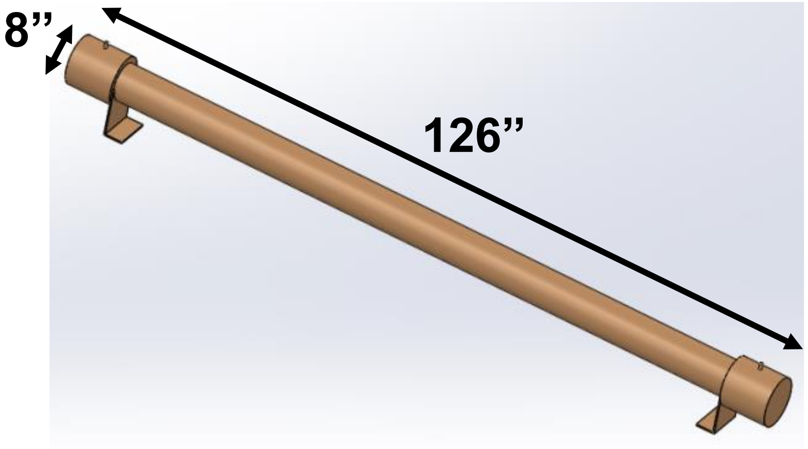
Trade off between water vs. air cooling

- Water – more compact, counter-flow, pumping water uses less energy, water treatment
- Air – Cross-flow, sized to minimize fan energy and to accommodate contaminant removal

sCO$_2$ Water Cooler – Design Considerations

Design Conditions:

- Max Temperature: up to 100°C
- Pressure: 100 bar



Counter-Flow
Shell & Tube Water Cooler

Material: Stainless Steel 304

1 **Material Selection**

- More flexible due to low temperature
- Tradeoffs in cost vs. reliability depends on the water quality

2 **Corrosion and Erosion**

- Apart from corrosion issue, erosion should also be taken into account

3 **Maintenance**

- Water-cooled heat exchanger requires occasional maintenance

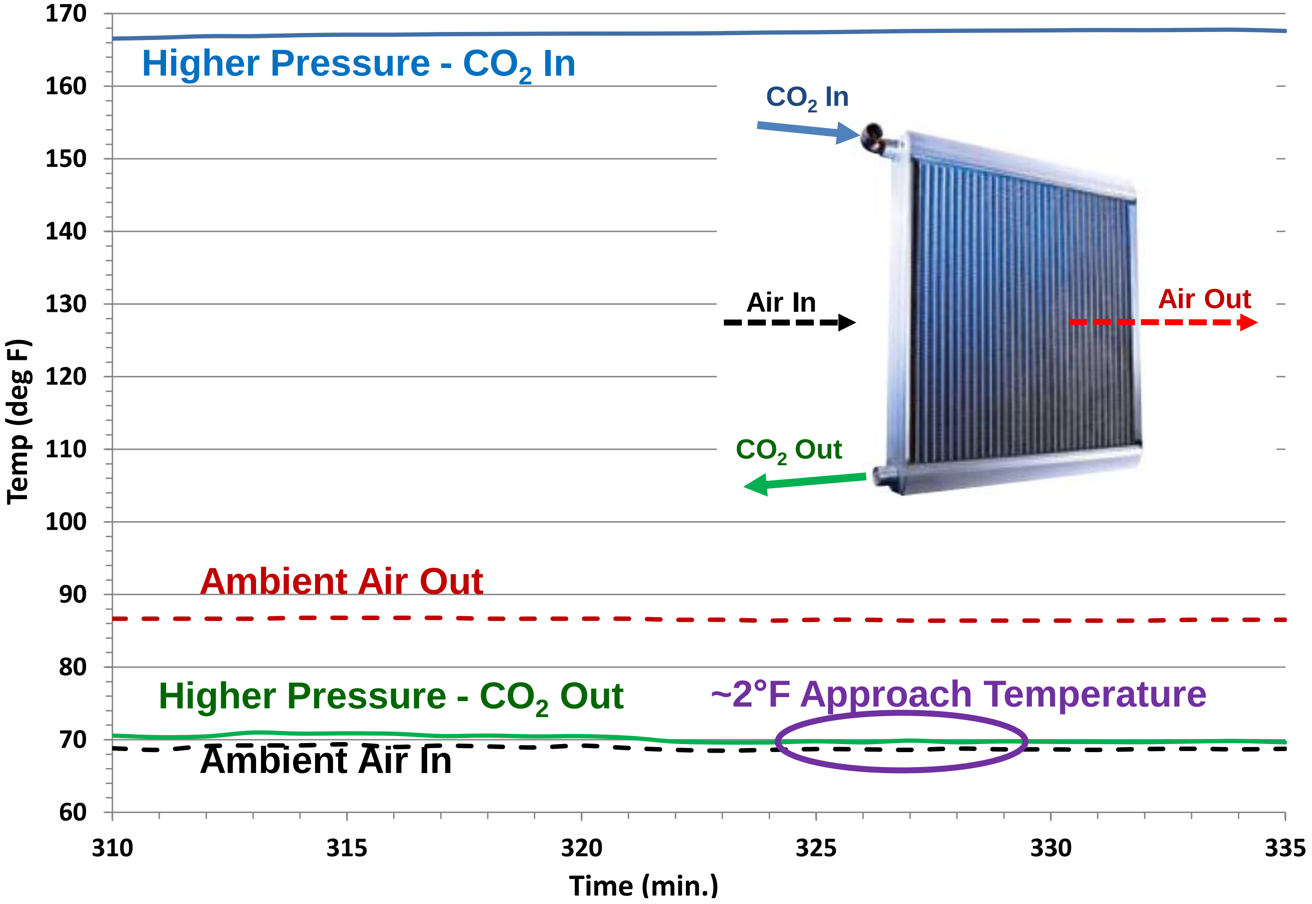
sCO$_2$ Air Cooler – Micro-Channel Coils

- **Micro-channel coils are**
  - **40% more efficient**
  - **40% smaller**
  - **50% less refrigerant**
  - **Lower air side ΔP**

  than standard tube & fin coils

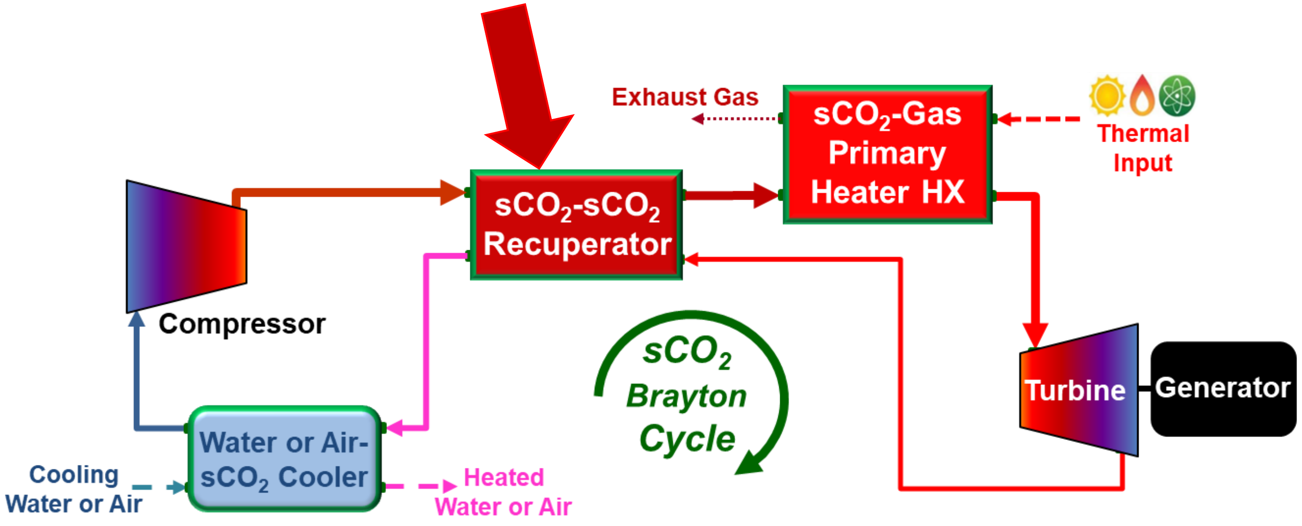
- At Thar's test facility, air and CO$_2$ approaching temperature as low as 2°F was achieved using micro-channel coil.

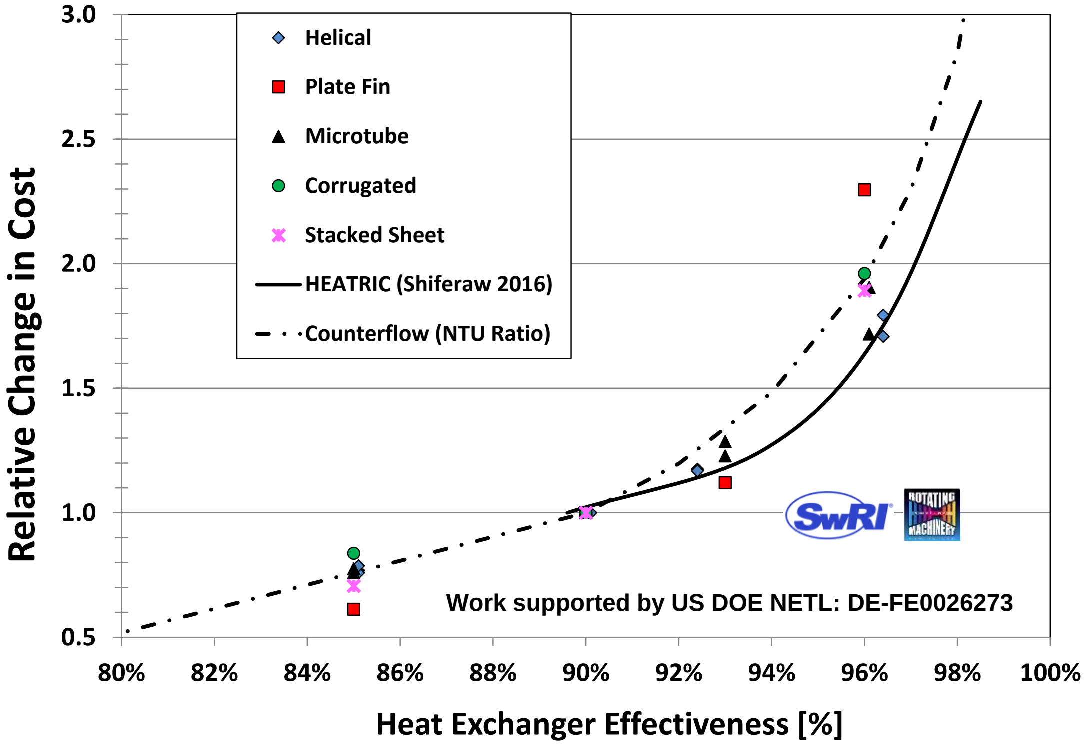
Commercial availability is improving with use of CO$_2$ (R744) as a refrigerant



Recuperator - sCO_2 to sCO_2

Counter-current





Work supported by US DOE NETL: DE-FE0026273

- **Increases the system efficiency by reusing turbine exhaust sCO_2 energy**

Recuperator specifications influencing the cost:

- **Approach Temperature / Effectiveness**
- **Pressure Drop**

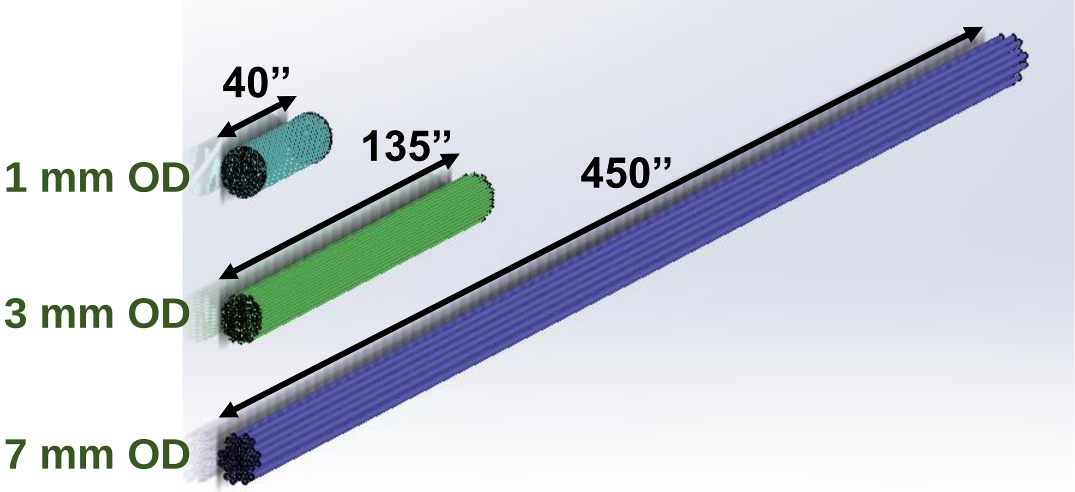
Relatively independent of the heat exchanger concepts evaluated

Microtube Recuperator

Counter- current

Overall Size Comparison

- Microtube vs. conventional tube, counter-current heat exchangers
- Different tube sizes with the same thermal capacity, effectiveness and pressure drop



1 mm OD 3 mm OD 7 mm OD

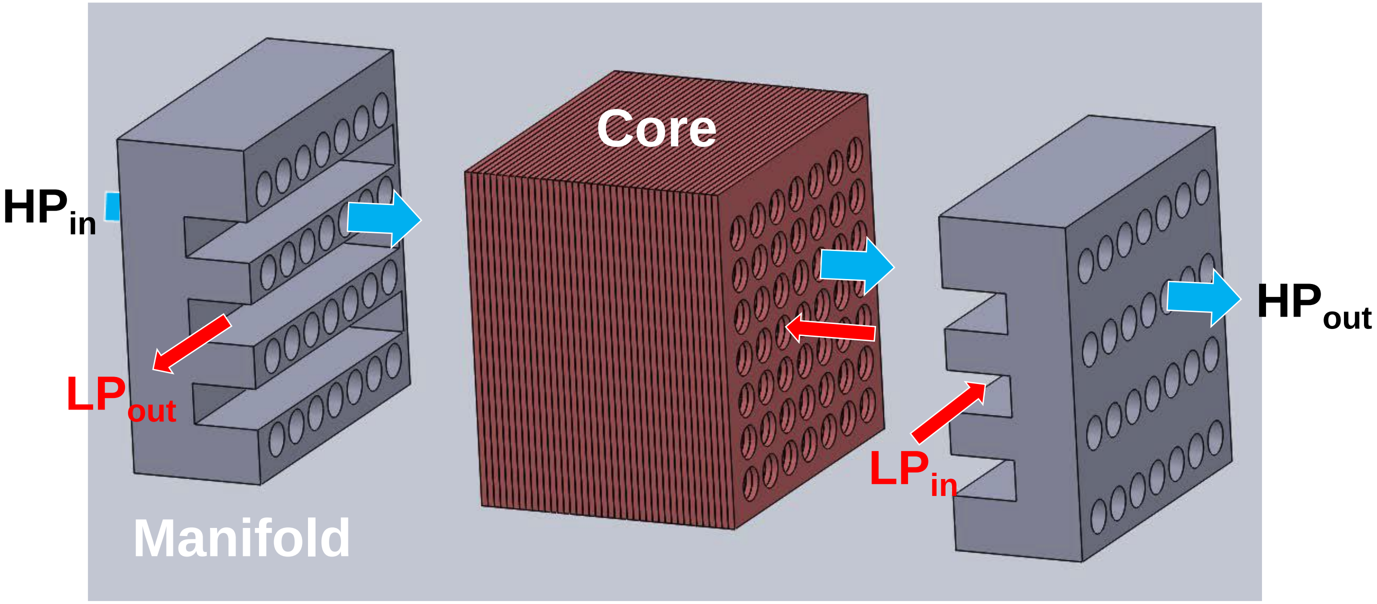
Tube OD	1 mm	3 mm	7 mm
Tube Length	40''	135''	450''
Tube Number	1500	175	30
Bundle Weight	17 lb	59 lb	244 lb
Surface Density	76 in^2/in^3	30 in^2/in^3	12 in^2/in^3

Thar Energy and SwRI conducted a multi-year study focused on building cost effective recuperators, at the MWt scale.

- Identified a recuperator concept – Stacked-Sheet Heat Exchanger (SSHX)
  - High thermal and hydraulic performance (counter-current)
  - Improve structural integrity and thermal compliance
  - Compact and light weight
  - Optimized material usage

- Successfully designed, fabricated, and tested prototype SSHX recuperators using several advanced manufacturing processes, such as:
  - Additive manufacturing (3D printing)
  - High power laser cutting
  - Diffusion brazing
  - Advanced CMM QA/QC methods

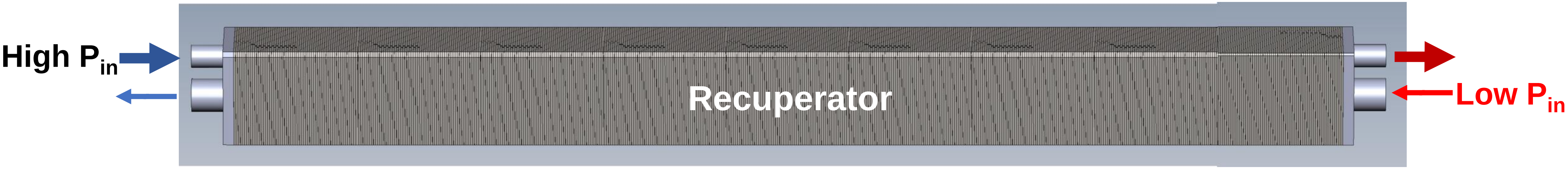
Stacked-sheet Recuperator Concept (SSHX)



- **Patterns cut, punched or etched into individual sheets**
- **Sheets are aligned, stacked, and joined (brazed, diffusion bonded)**
- **Manifolds/headers are added to separate flow streams and ensure uniform flow distribution**

The bond between the sheets is parallel to the mechanical stresses & perpendicular to the thermal stresses (temperature across the bond is almost constant)

Improves structural integrity and thermal compliance



Work supported by US DOE NETL: DE-FE0026273

Prototype SSHX Recuperators

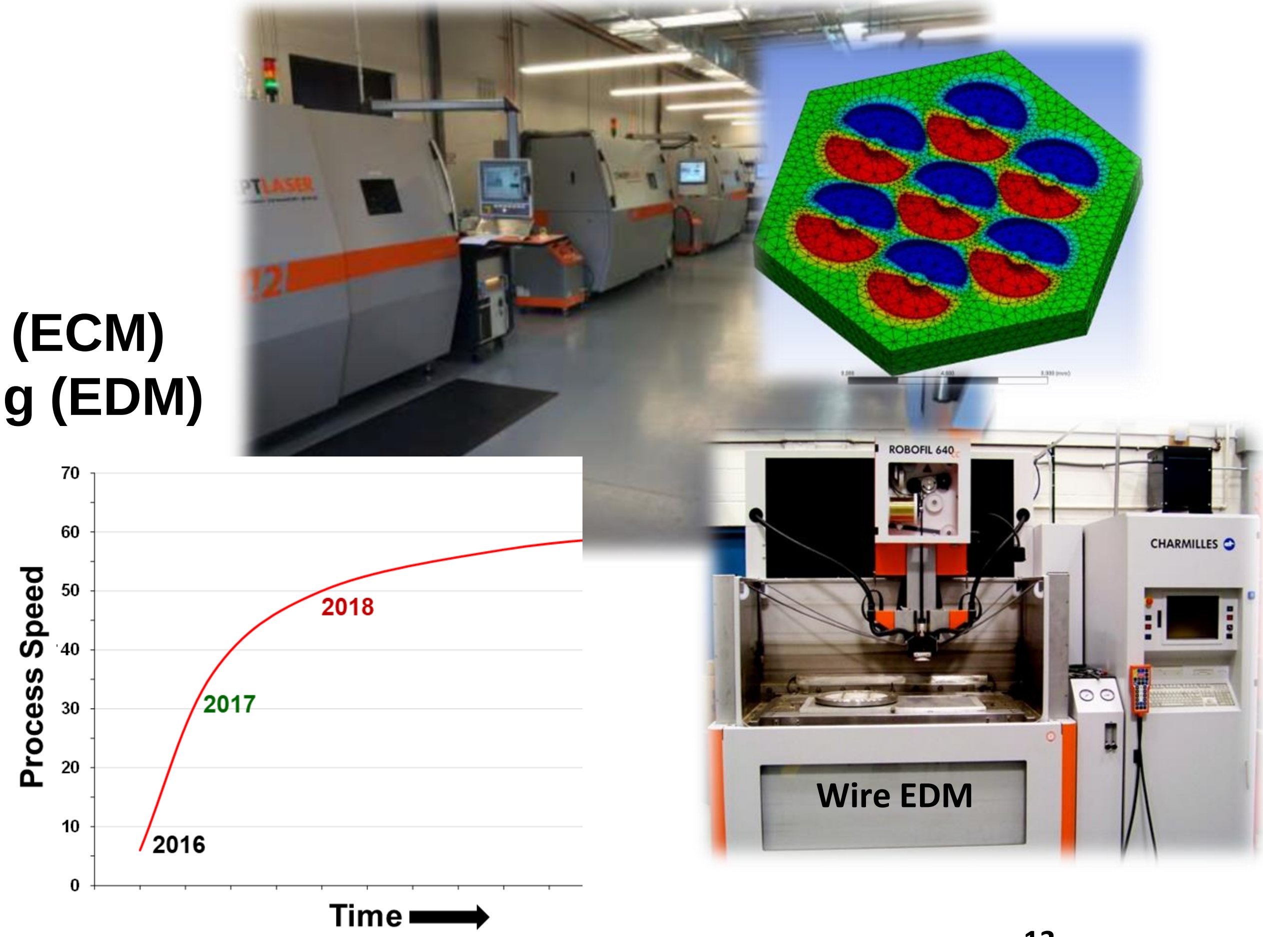
Criteria	3D-SSHX Prototype	Laser-SSHX Prototype
Manufacturing Method	3D Printed	Laser Cut Sheets
Materials	Inconel 625	Stainless 347H
Channel Pattern	Circle-Star	Circle-Circle
Manifold Design	3D Printed	Laser Cut Sheets
Joining Method	Diffusion Braze	Diffusion Braze
Opacity	~46%	~73%

Work supported by US DOE NETL: DE-FE0026273

Manufacturing technologies are advancing as a rapid pace

Subtractive Manufacturing
Additive Manufacturing
QA/QC Methods

- **Laser cutting**
- **Laser welding**
- **Water jet cutting**
- **3D metals printing**
- **Electrochemical etching**
- **Electrochemical machining (ECM)**
- **Electro discharge machining (EDM)**
- **EDM wire cutting**
- **Sheet bending/forming**
- **Metal plating**
- **Stamping**
- **Brazing**
- **Welding**
- **Diffusion bonding**



Additive Manufacturing

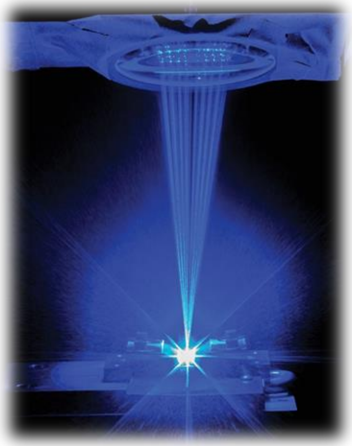
1. **Need to balance resolution with tolerance repeatability**

2. **Balance resolution and design with powder removal**

3. **Prototyping vs. Production**

4. **Need real time QA/QC to minimize production losses**

5. **Watch for new innovations like the blue LED lasers**
    - **Improved energy absorption**
    - **Qualitative and quantitative advantages**



https://www.photonics.com/Article.aspx?AID=63941&refer=IPL&utm_source=IPL_2018_11_27&utm_medium=email&utm_campaign=IPL&PID=20

Rapid quality inspection is key to advancing metal additive manufacturing.

Industry requires metal parts to be fabricated according to stringent metallic material properties and specifications.

Load feedstock, prepare machine	Build Parts	Cycle Machine	Depowder	Stress Relieve	Plate Removal	Thermal Processes	Testing
4 hours	1 - 30 days	4 hours	8 hours	3 - 5 days	3 - 5 days	5 - 15 days	10 - 20 days

1.5 BUILDS per machine each day × 12 PIECES per build × 17 MACHINES = 306 PARTS per day

POTENTIAL PROBLEM

306 parts/day X 60 days ➡ 18,360 scrapped parts

18,360 scrapped parts X $200/part ➡ $3,672,000 scrapped parts

Costs increase the longer it takes to identify a problem

Donovan. M., Metal Additive Manufacturing, Jabil, https://www.machinedesign.com/3d-printing-cad/article/21175581/put-the-metal-to-the-pedal?o_eid=5808C0148145G8Z&oly_enc_id=5808C0148145G8Z&rdx.ident[pull]=omeda|5808C0148145G8Z&utm_campaign=CPS240131167&utm_medium=email&utm_source=MN+MD+Today

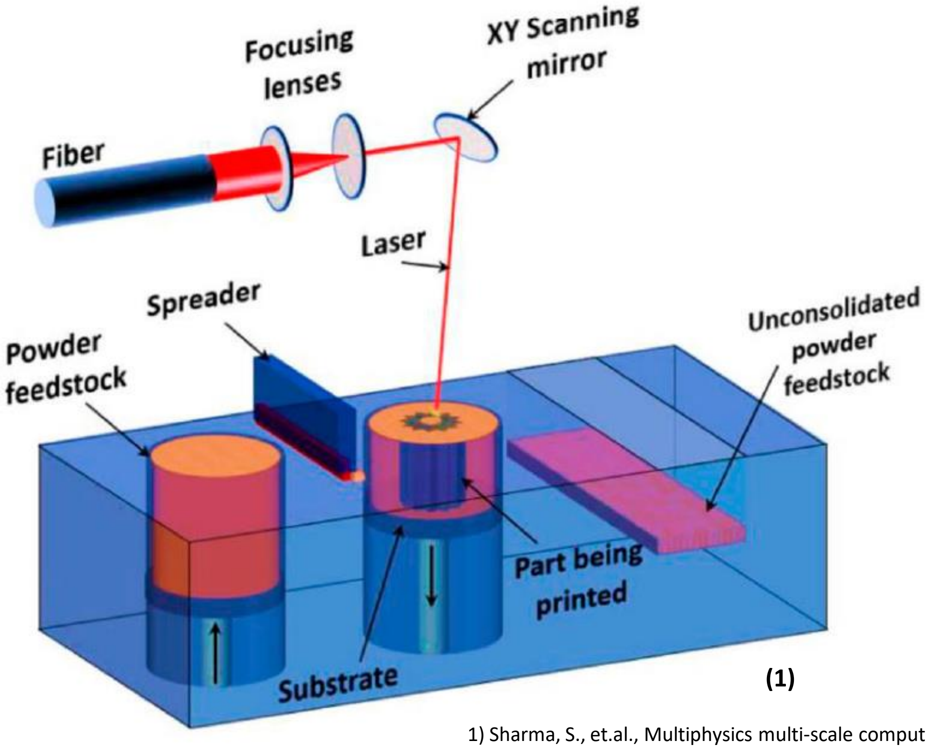
Additive Manufacturing Overview

- Direct Metal Laser Sintering (DMLS)
    - Best resolution and part density
    - Highest cost
        - Oxide free metal powders are expensive and complicated to work with
    - Now with real time QA/QC


DLMS
IN718
2013

Tested
at KAPL

sCO_2-sCO_2
Recuperator



(1)


2016
IN625 3D Printed Recuperator

DLMS – H282 3D-SSHX Recuperator


2022

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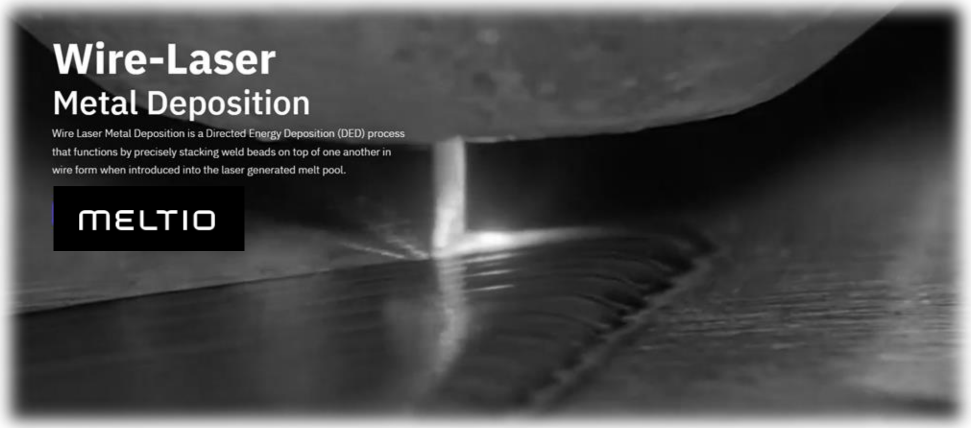
1) Sharma, S., et.al., Multiphysics multi-scale computational framework for linking process–structure–property relationships in metal additive manufacturing: a critical review, International Materials Reviews, https://doi.org/10.1080/09506608.2023.2169501

Additive Manufacturing Overview

- Wire melting (arc discharge or laser)
    - No special facility requirements
    - Lower resolution but with high part density
    - Simpler operation
    - Faster build rate
    - More cost effective than DMLS
    - Larger part builds
    - More alloy compositions available in wire form

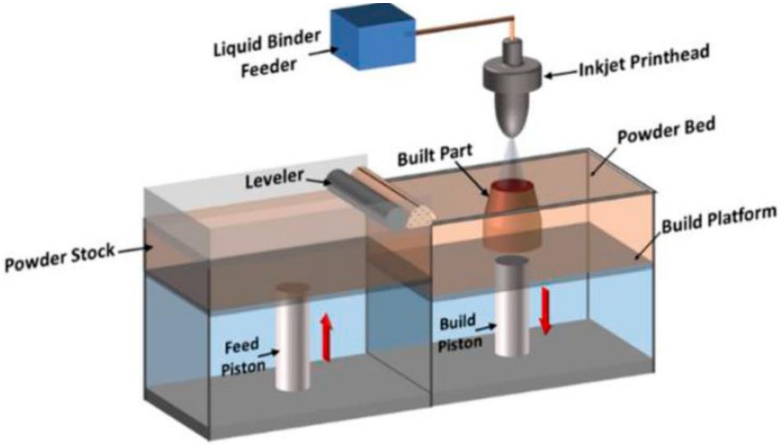


Wire-Laser
Metal Deposition

Wire Laser Metal Deposition is a Directed Energy Deposition (DED) process that functions by precisely stacking weld beads on top of one another in wire form when introduced into the laser generated melt pool.

MELTIO

- Metal Binder Jet
    - Lower resolution and part density
    - Lowest cost material – metal injection molding powders
    - Needs to accommodate part shrinkage when firing oxide metal powders
        - ❖ Sinter software now simulates part shrinkage



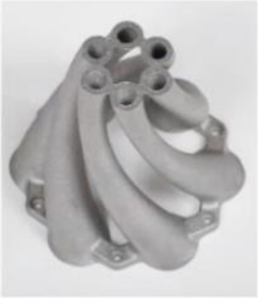
1) Sharma, S., et.al., Multiphysics multi-scale computational framework for linking process–structure–property relationships in metal additive manufacturing: a critical review, International Materials Reviews, https://doi.org/10.1080/09506608.2023.2169501

Additive Manufacturing Overview

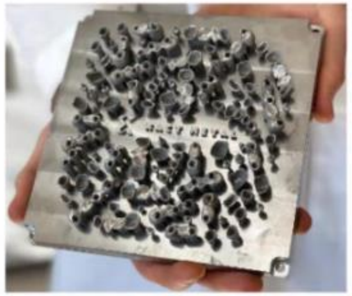
Xact Metal – DLMS / Metal Powder-Bed Fusion

https://xactmetal.com/

Chip Removal Tool



Curved Manifold



Dental Crowns

Injection Mold Insert

Impeller

Copper Parts

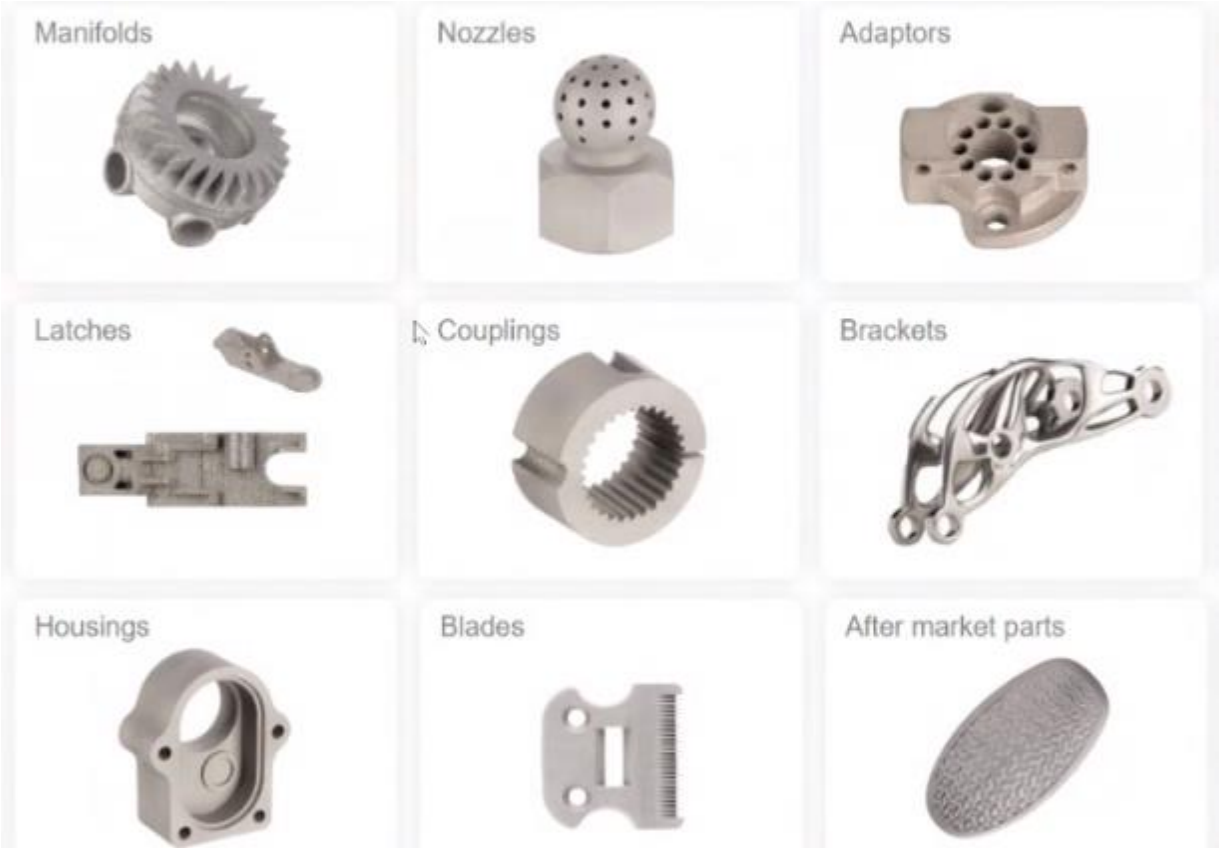
Meltio – Laser Metal Deposition

https://meltio3d.com/

Additive Manufacturing Overview

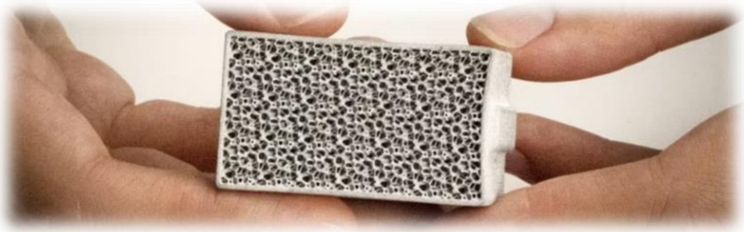
Desktop Metals – Binder jet

https://www.desktopmetal.com/



HP Metal Jet – Binder jet

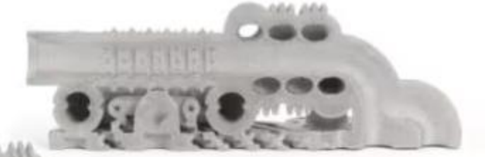
https://www.hp.com/us-en/printers/3d-printers/products/metal-jet.html



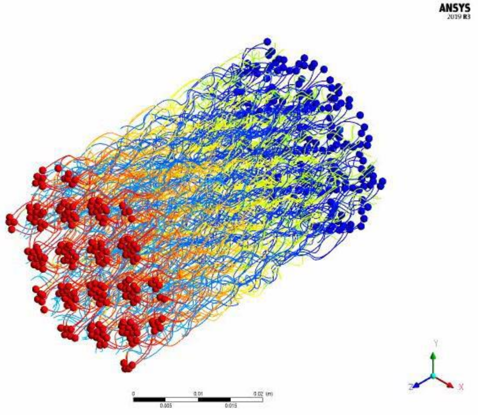
Air Filter - 690V
Circuit breaker
SS 316L

Engine Component
SS 17-4PH

Fluidic Manifold
SS 316L



GE DMLS Additive - ex. AM303 Heat Exchanger



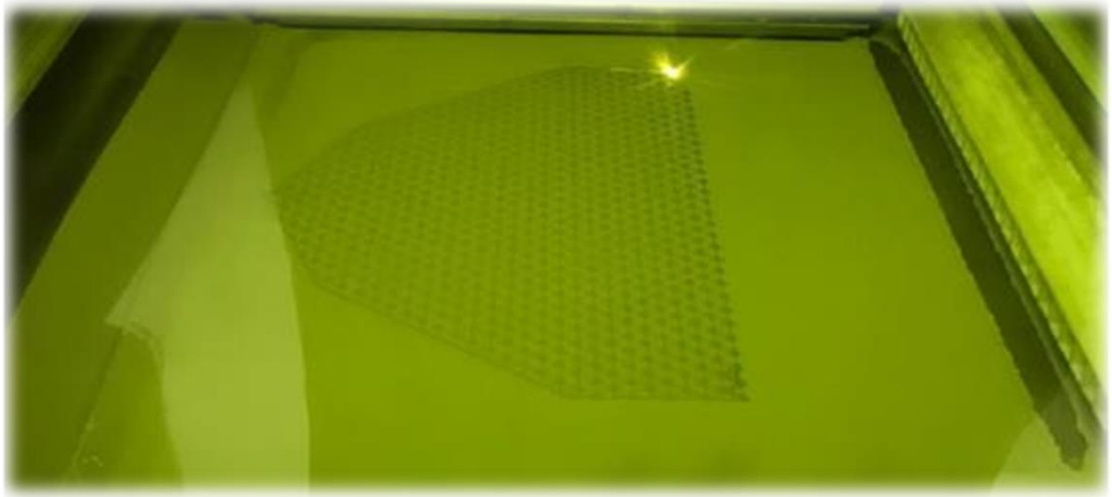
HX Design Basis:

Trifurcating unit cell enables up to 7X mass-based power density at ΔP/Pin of 2%

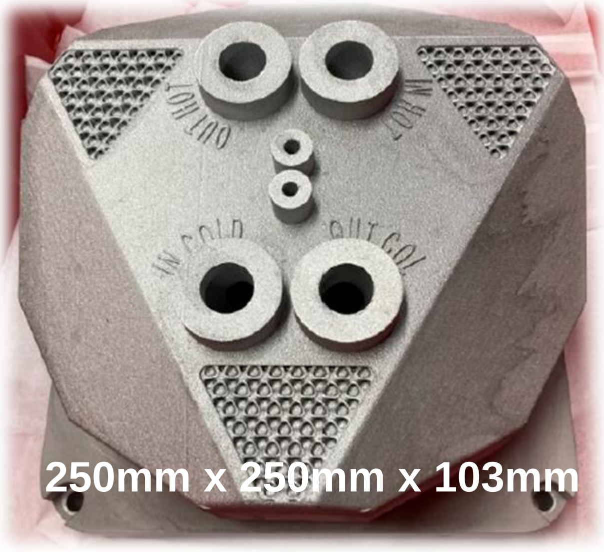
New Alloy:

GE's AM303 Ni-based superalloy enables 900°C / 250 bar operation

DMLS - GE Research



Full Scale Prototype



250mm x 250mm x 103mm

Wall Thickness: 0.75 mm

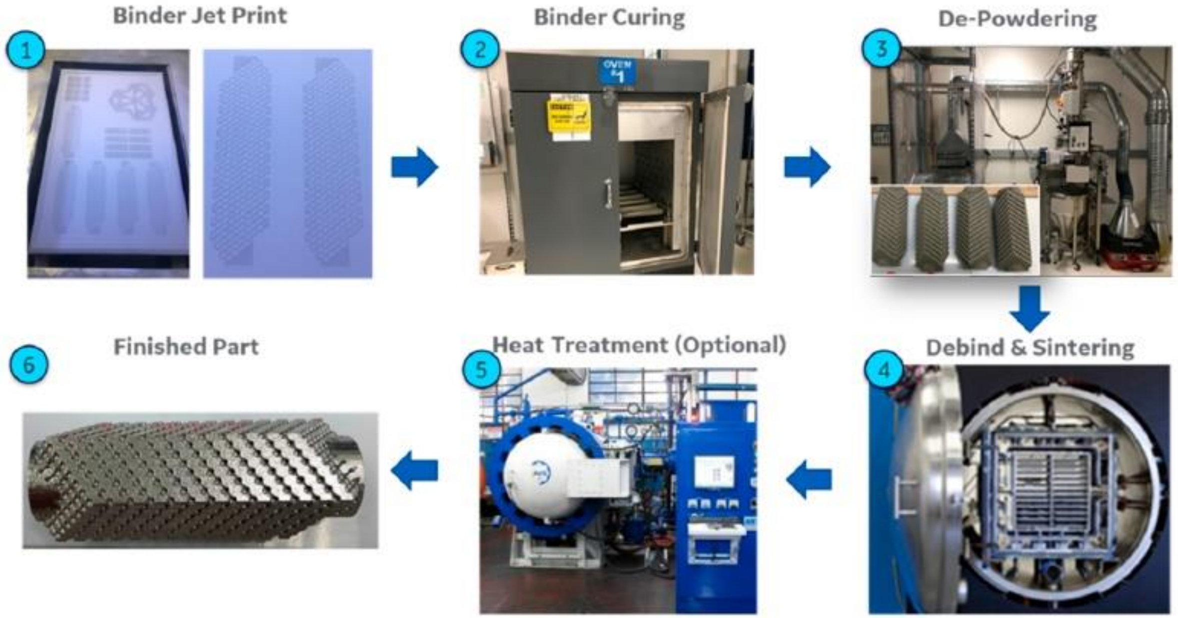
Hole Diameter: 2 mm

Osusky, L., Ultra Performance Heat Exchanger enabled by Additive Manufacturing, GE Research, ARPAe - High Intensity Thermal Exchange through Materials and Manufacturing Processes (HITEMMP) Annual Program Review Meeting, February15, 2023, Atlanta, GA

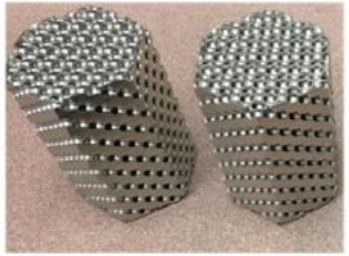
Binder Jet Additive - ex. SS316L Heat Exchanger

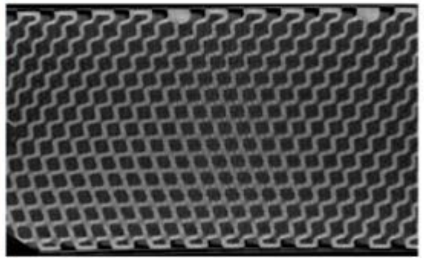
Trifurcating Flow Path Design

Process Steps



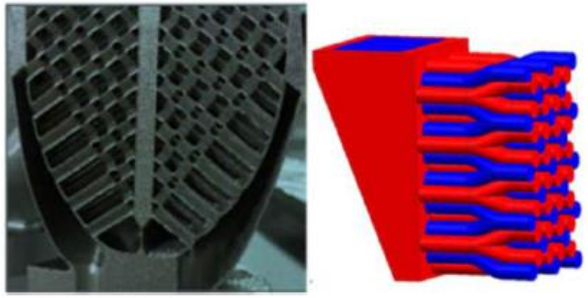
Printed heat exchanger core





Cross-section of a printed heat exchanger core

Planar Trifurcating HX core geometry



Trifurcating flow channels

Boundary layer resets at every 1-3 D_h

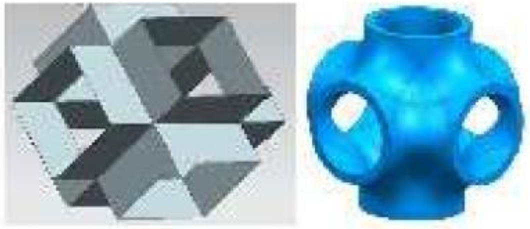
3x HTC laminar flow

1.2-1.3x HTC turbulent flow

Developed process to remove powder from multiple small internal passages

Curved Unit Cell Design reduced stress >50%

Planar **Curved**

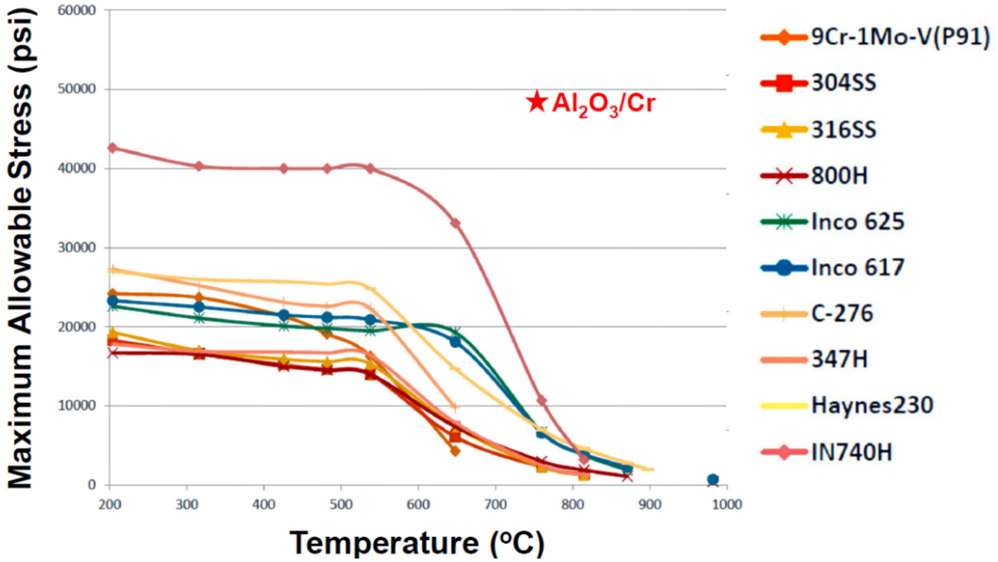


Thiagarajan, N., Et. Al., Novel Binderjet Additive HXs, A Pathway to 5¢/kWh CSP, General Electric Research – Niskayuna NY, September 20, 2021

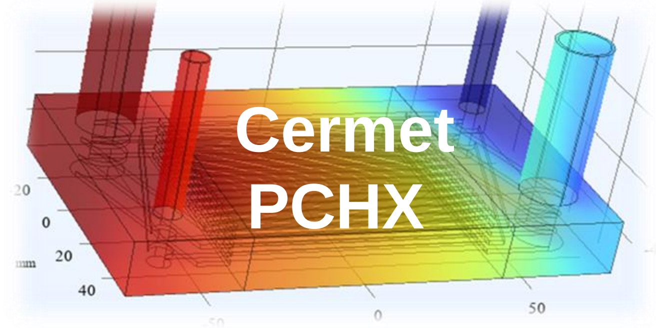
Ceramic Heat Exchanger ex. Al_2O_3/Cr Composite

Superalloy Performance at Stainless Steel prices

- **Improved thermal stability**
  - High melting: Al_2O_3 = 2054°C and Cr = 1863°C vs. Haynes 230 (Ni-Cr-W alloy) = 1290°C
- **Improved creep resistance**
  - Predicted Al_2O_3 /Cr creep rupture life at 750°C >30 years at 447,000 psi vs. H230 creep life <1.2 years at 13,200 psi
- **Stiffer and higher strength**
  - Al_2O_3 /Cr strength (no yield, in flexure) at 750°C = 50,000 psi vs. Haynes 230 strength (tensile yield) at 750°C = 41,000 psi
- **Excellent oxidation resistance**
  - Projected Cr recession <0.0003 inches over 1 year at 750°C in CO_2 and in air
- **Similar thermal conductivity**
  - Al_2O_3 /Cr = 14.7-24.7 W/m-K from 150°C-800°C vs. 11.4-24.4 W/m-K from 150°C-800°C for Haynes 230



2010 ASME Boiler Pressure Vessel Code, Sec. II, from Tables 1A and 1B, July 1, 2010, New York, NY (compiled by Mark Anderson)



Sandhage, K., et.al., Oxidation Resistant, Robust, Reaction Formed Al_2O_3 /Cr Composites for High Temperature Heat Exchangers for Concentrated Solar Power, SolarPACES 2022, Purdue University W Lafayette, IN, USA. US DOE - Energy Efficiency and Renewable Energy - Solar Energy Technology Office, DE-EE-0008998.

COMPACT Heat Exchangers

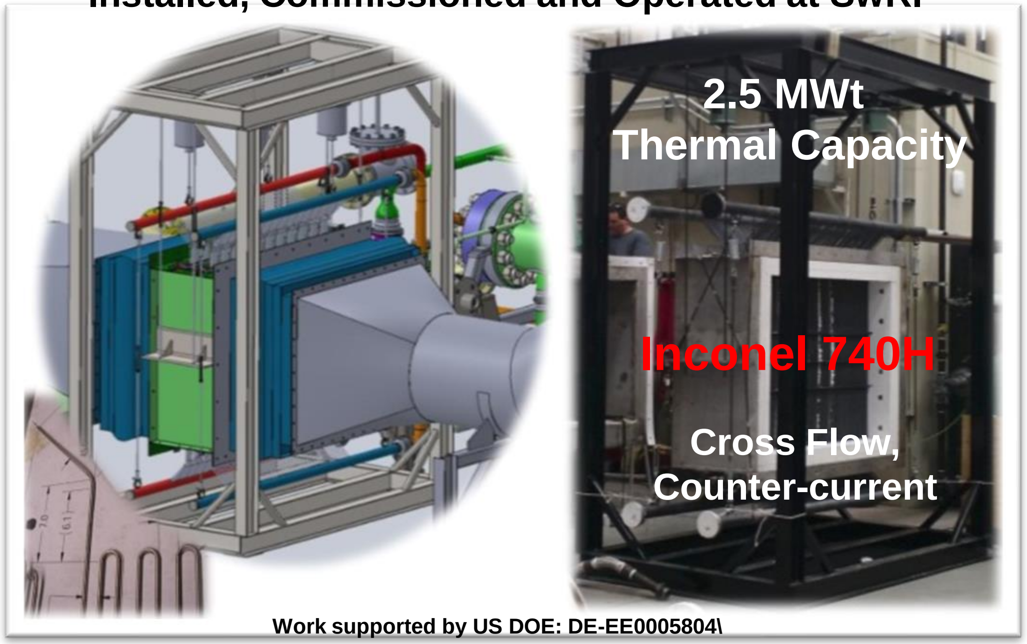
Higher Performance *Smaller Footprint* *Lighter Weight*

Recuperators Primary Heater Gas/Air Coolers Water Coolers

- Advanced Manufacturing Methods
- Optimized material use
  - *Aluminum*
  - *Stainless Steels*
  - *Nickel Super Alloys*
- Modular Design & Factory Fabricated
- *Demonstrated at extreme T & P*
- *Thermal capacity from kWt to MWt*

sCO_2 Primary Heater

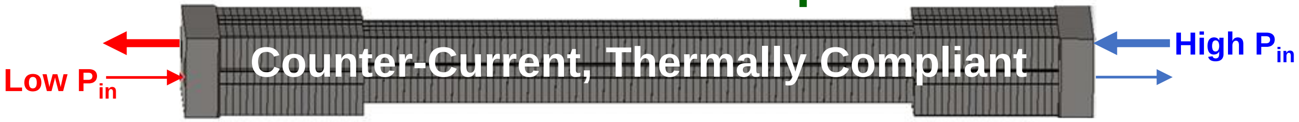
Installed, Commissioned and Operated at SwRI



Work supported by US DOE: DE-EE0005804\

Gas Cooler

Stacked Sheet Recuperator



Thank you for your kind attention!

Contact: **Marc Portnoff**

Manager, New Technology
150 Gamma Drive, Pittsburgh, PA 15238
412-251-4615
mportnoff@tharenergy.com
tharenergy.com

Delivering clean energy solutions - rooted in natures' design

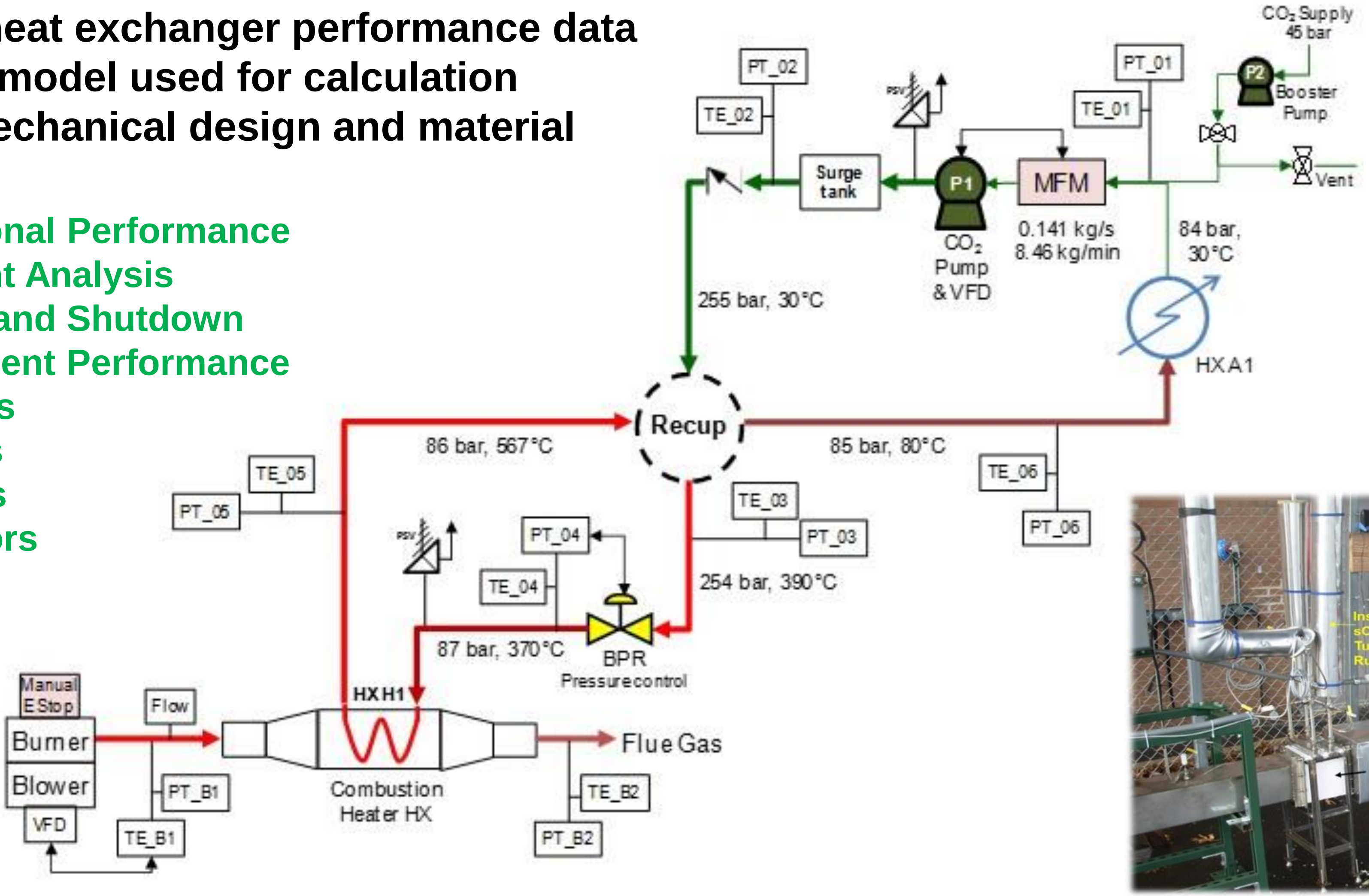
Addendum

Prototype SSHX Recuperators Operations and Testing

Thar sCO$_2$ HX Test Loop

Purpose of Test Loop

1. Collect heat exchanger performance data
2. Validate model used for calculation
3. Verify mechanical design and material strength
   - Operational Performance
   - Transient Analysis
   - Startup and Shutdown
   - Component Performance
     - ❖Pumps
     - ❖Filters
     - ❖Valves
     - ❖Sensors



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Thar sCO_2 HX Test Loop vs. a standard sCO_2 Brayton Cycle Loop

Different from Standard Loop

- Reciprocal piston pump used in place of a compressor
- Turbine is replaced by back pressure regulator (BPR)

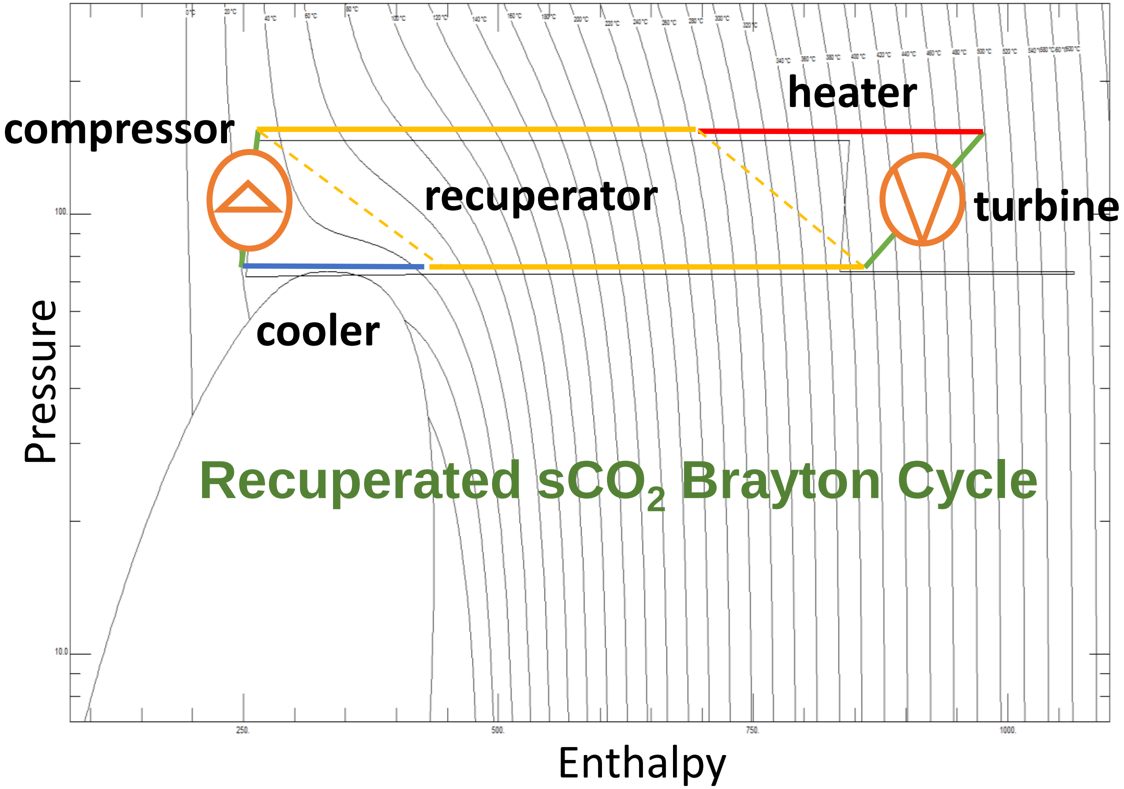
Test Condition

Supercritical Carbon Dioxide

- Operating Pressure: 255bar / 87bar
- Operating Temperature: 570°C

Combustion Gas

- Maximum Temperature: 750°C
- Maximum Flow: 250 scfm @ 750°C



Recuperated sCO_2 Brayton Cycle

Thar Loop Compared to Standard Brayton Cycle

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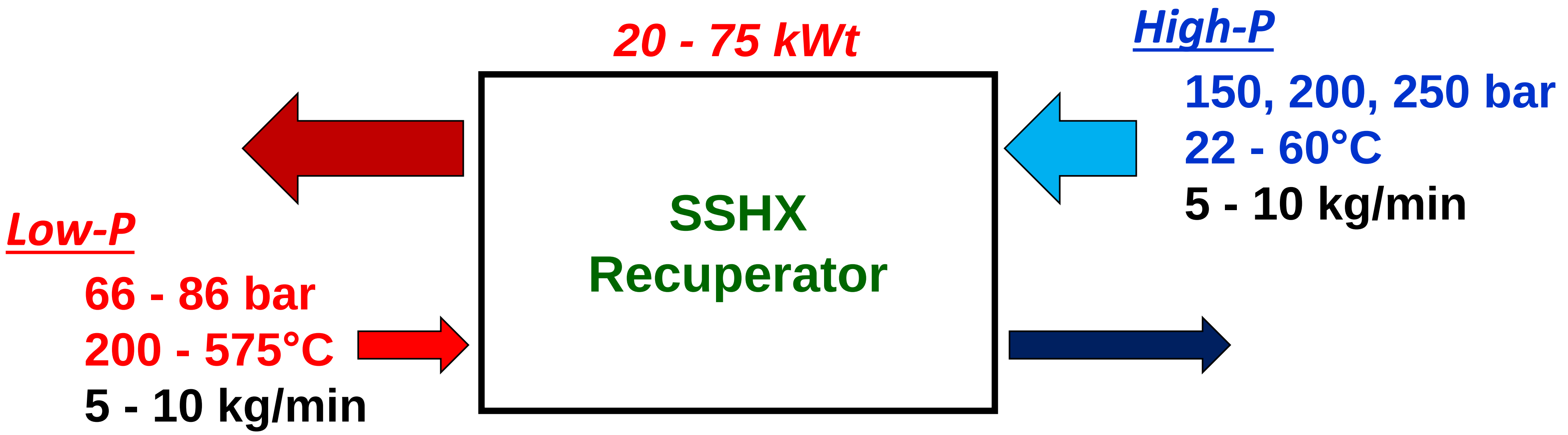
Test Conditions - SSHX Recuperator Prototypes



20 - 75 kWt

SSHX Recuperator

High-P

150, 200, 250 bar
22 - 60°C
5 - 10 kg/min

Low-P

66 - 86 bar
200 - 575°C
5 - 10 kg/min

- Test thermal/hydraulic performance over a range of operating conditions
- Compare actual to predicted performance

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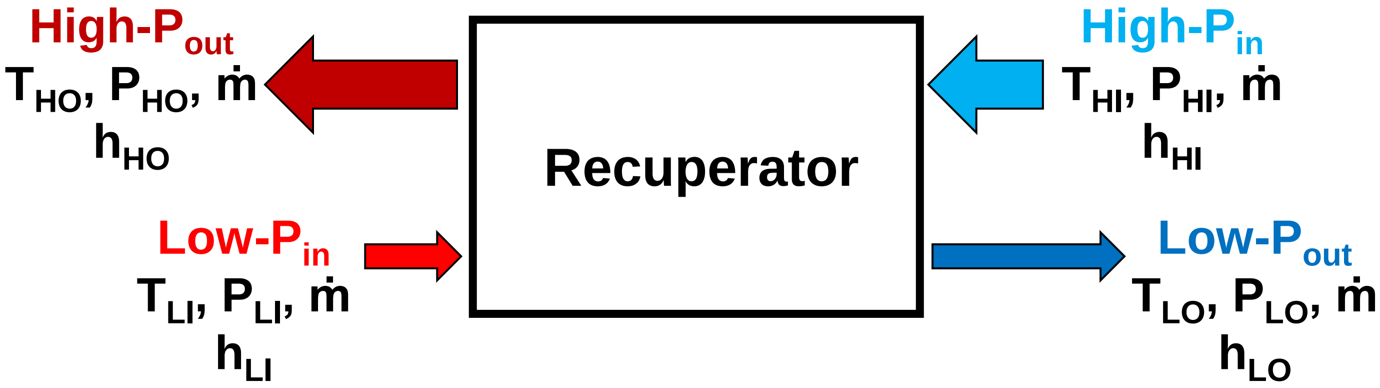
HX Performance Heat Transfer Equations



Effectiveness: $\epsilon = {Q_{act}}/{Q_{max}}$

$Q_{act} = \min(Q_{HI\text{-}HO}, Q_{LI\text{-}LO})$

$Q_{HI\text{-}HO} = \dot{\mathbf{m}} \times (h_{HO} - h_{HI})$

$Q_{LI\text{-}LO} = \dot{\mathbf{m}} \times (h_{LI} - h_{LO})$

$Q_{max} = \min(Q_{h\,max}, Q_{c\,max})$

$Q_{h\,max} = \dot{\mathbf{m}} \times (h_{LI} - h(T_{HI}, P_{LO}))$

$Q_{c\,max} = \dot{\mathbf{m}} \times (h(T_{LI}, P_{HO}) - h_{HI})$

Overall Thermal Conductance: $UA = {Q_{act}}/{\Delta T_{Ln}}$

$$\Delta T_{Ln} = \frac{\Delta T_i - \Delta T_{ii}}{\ln(\Delta T_i / \Delta T_{ii})}$$

$\Delta T_i = T_{LI} - T_{HO}$

$\Delta T_{ii} = T_{LO} - T_{HI}$

Approach Temperature: $\Delta T_{app} = T_{LO} - T_{HI}$

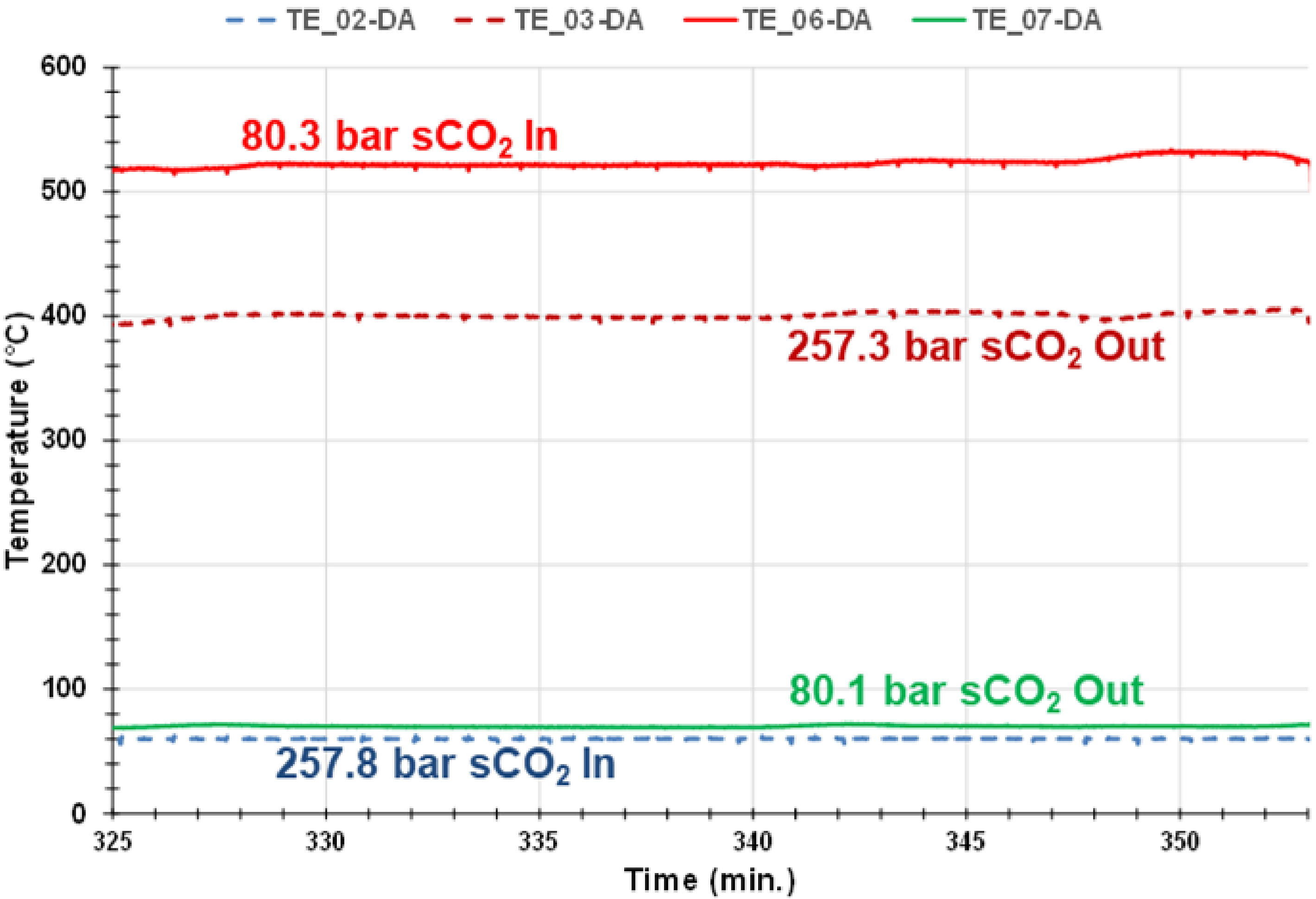
% Pressure Drop: $\%\Delta P = {(P_{in} - P_{out})}/{P_{in}}$

R. K. Shah and D. P. Sekulic, Fundamentals of Heat Exchanger Design, John Wiley & Sons, Inc., 2003

Steady State Temperature Plot

Prototype SSHX Recuperators

3D-SSHX – Steady State Plot



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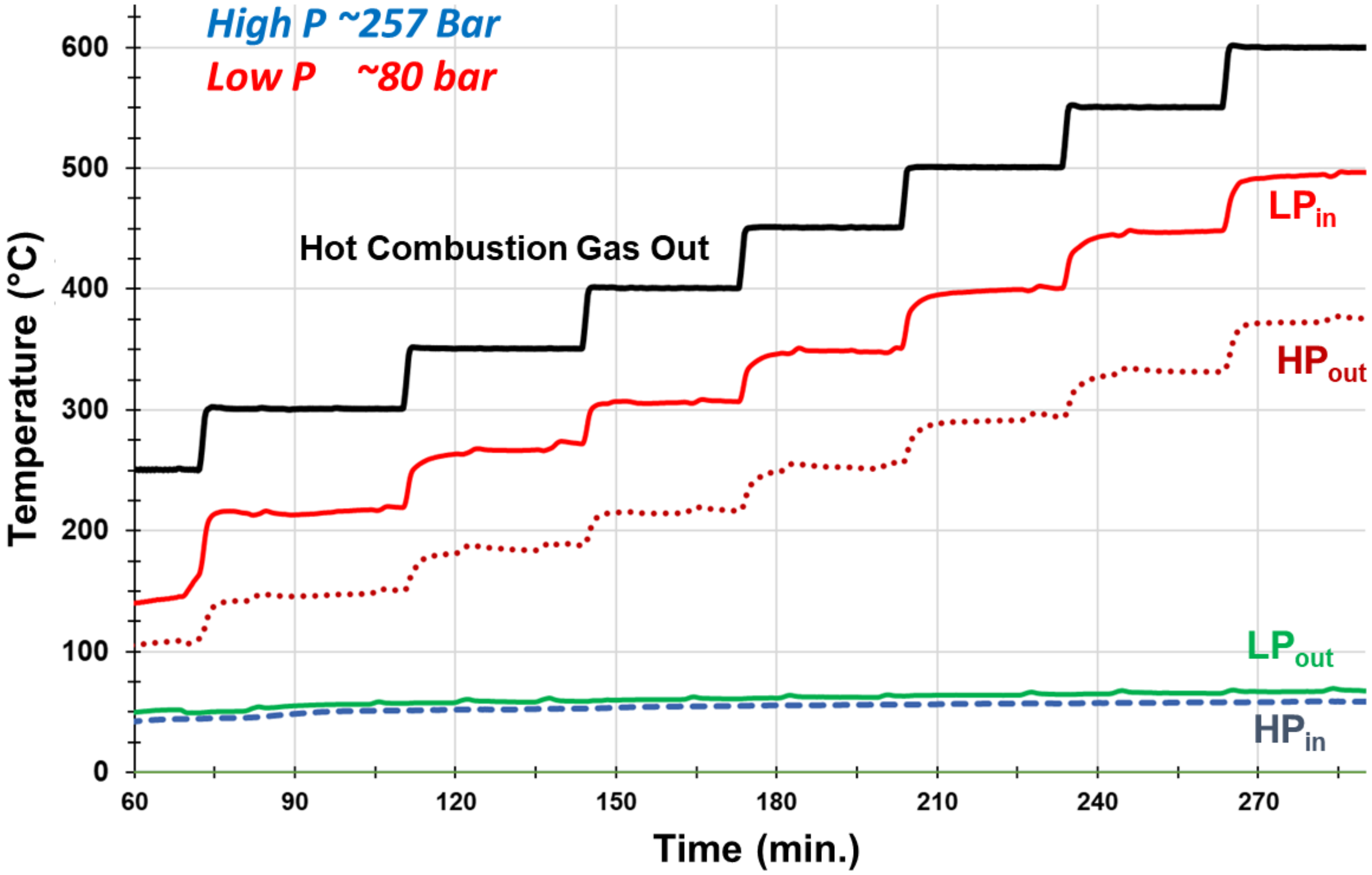
Temperature Plot

Good Energy Balance, < 2% error



Approach T < 10°C

Work supported by US DOE NETL: DE-FE0024012, DE-FE0025348 , DE-FE0026273

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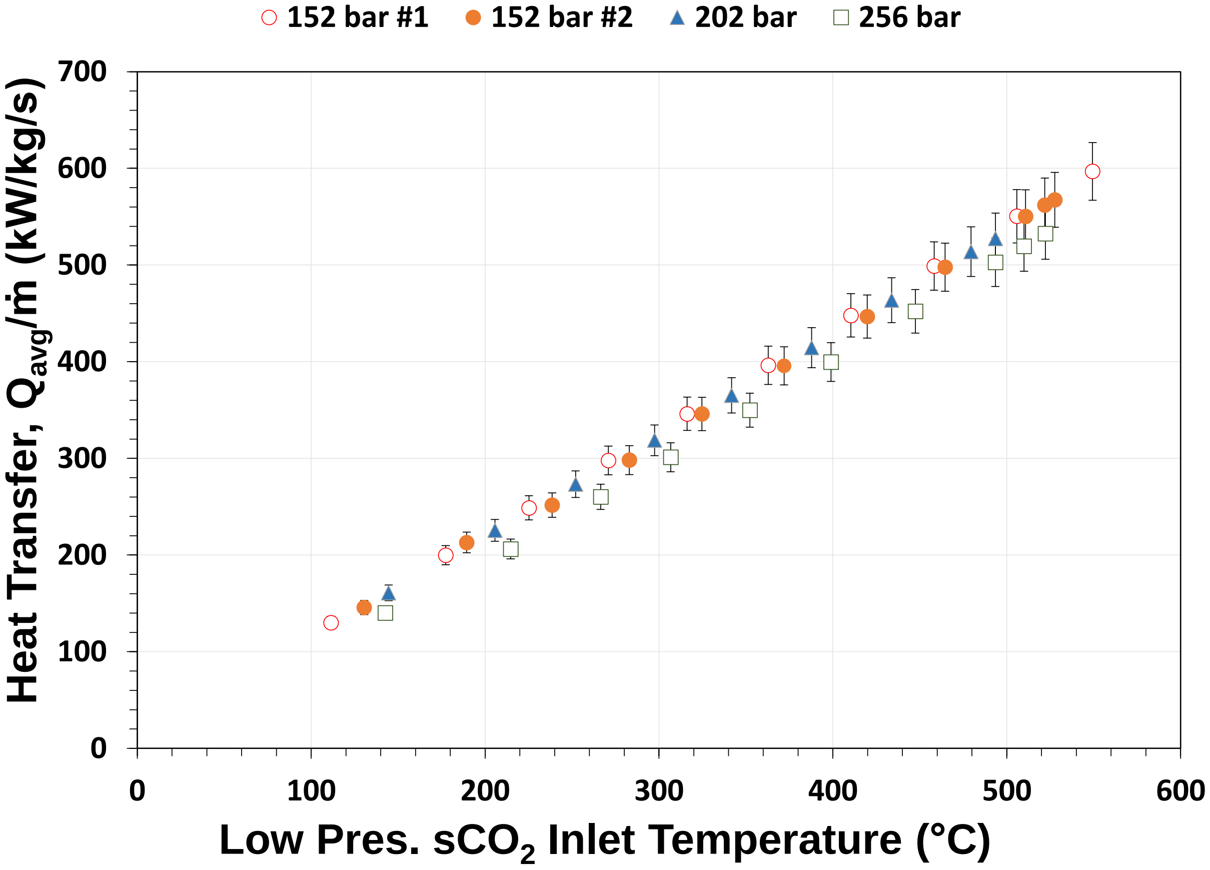
Energy Transfer Plots

SSHX Recuperator Prototypes

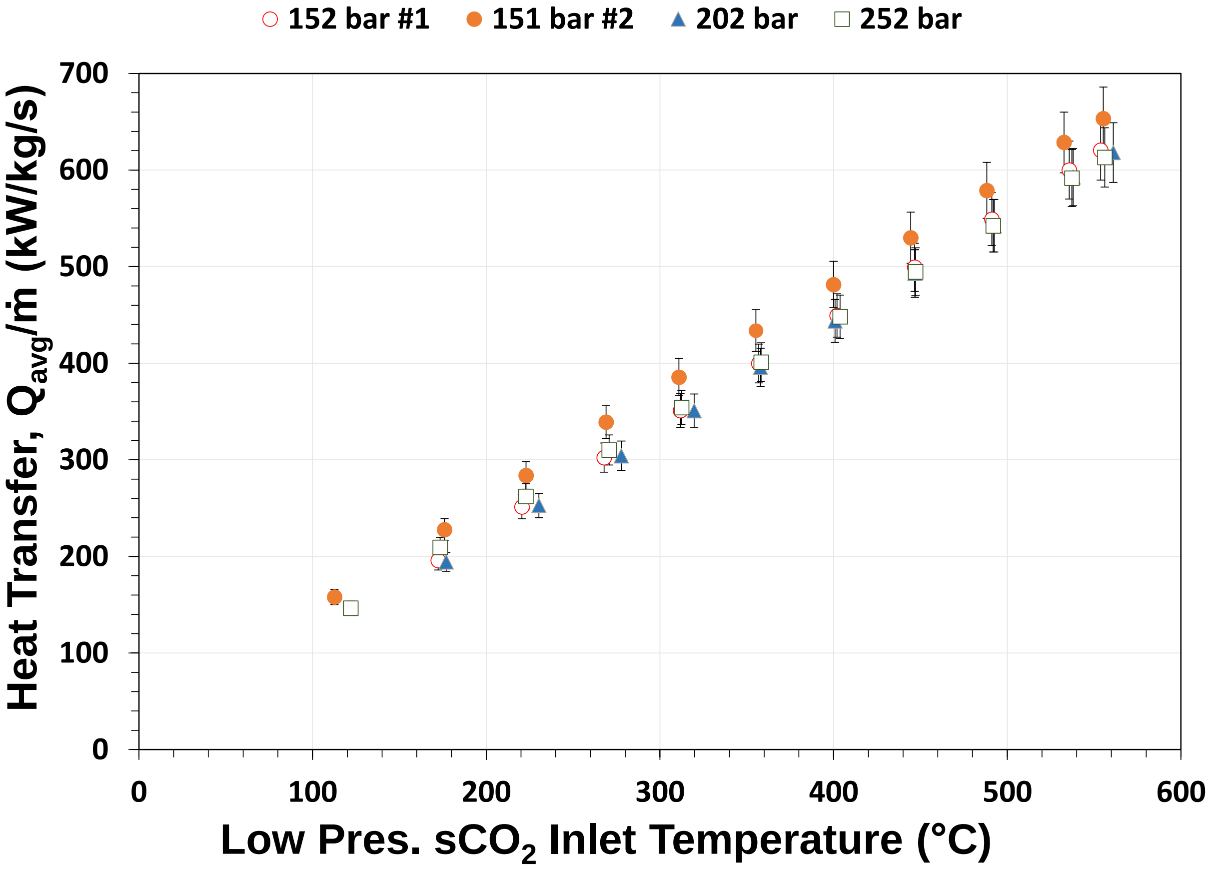
3D-SSHX

Inconel 625



Laser-SSHX

347H Stainless Steel



Linear Response

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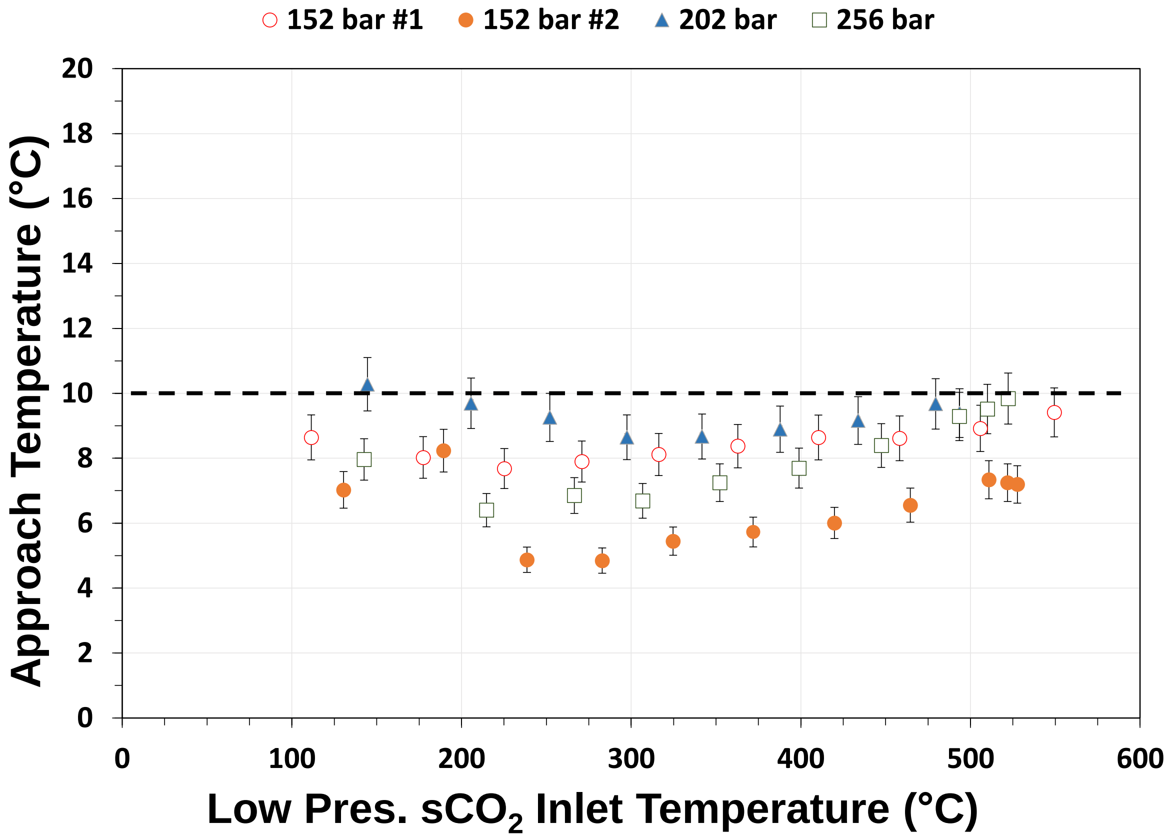
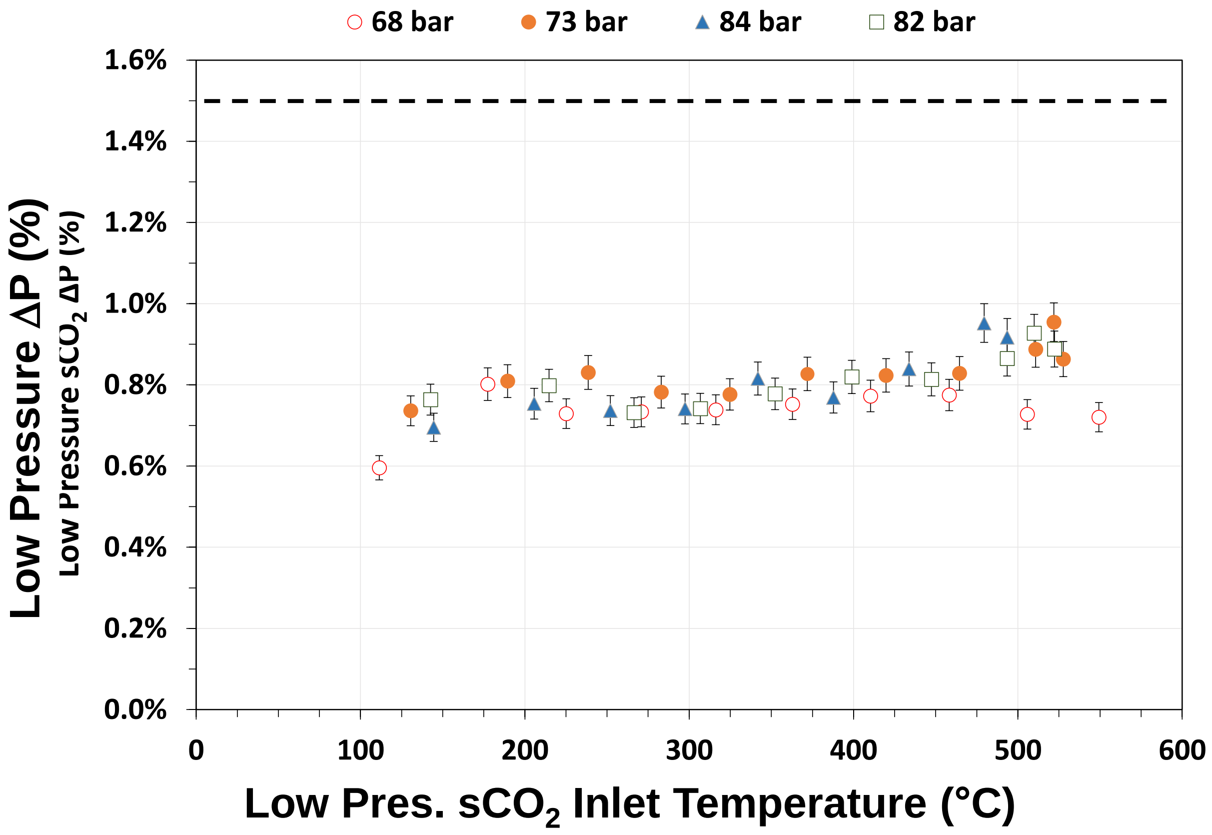
3D-SSHX Prototype Recuperator

Approach Temperature Plot



Approach T < 10°C

Pressure Drop Plot



$\Delta P_h < 1.5\%$

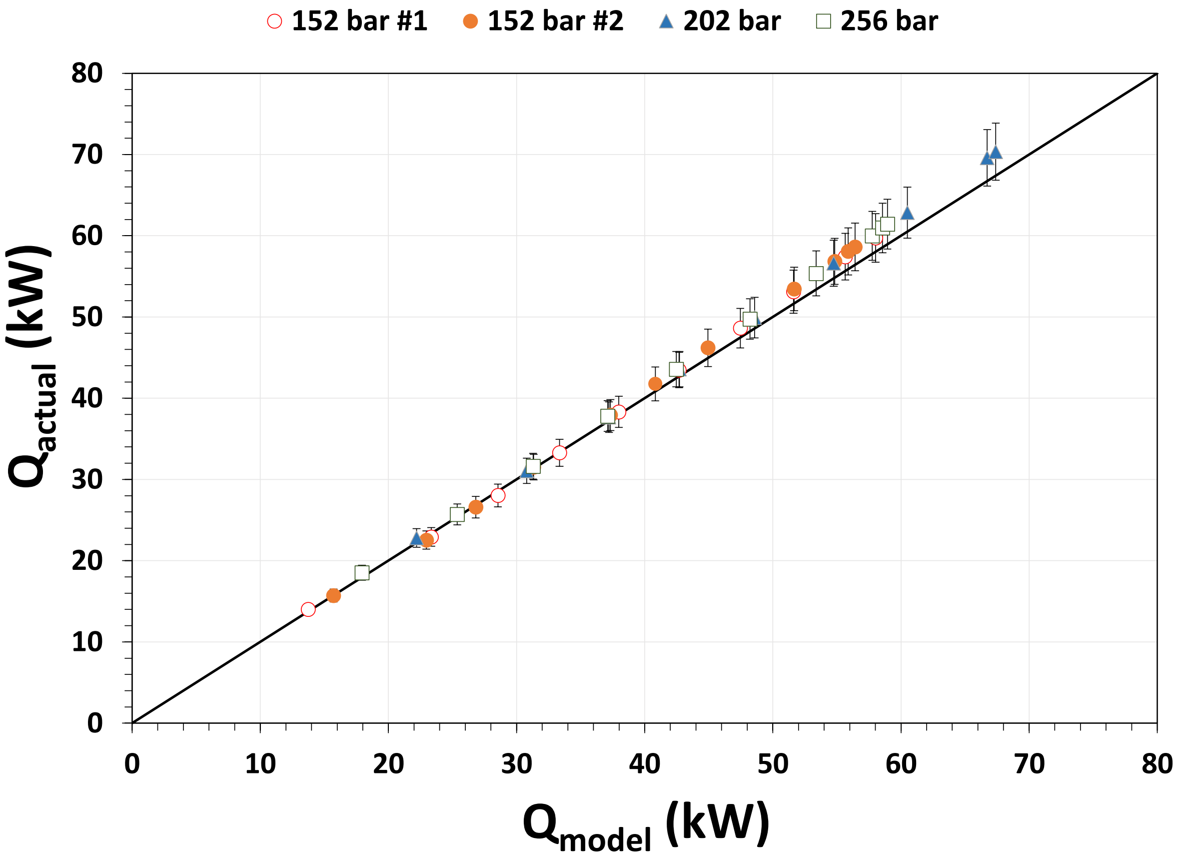
Meets design specifications

Work supported by US DOE NETL: DE-FE0026273

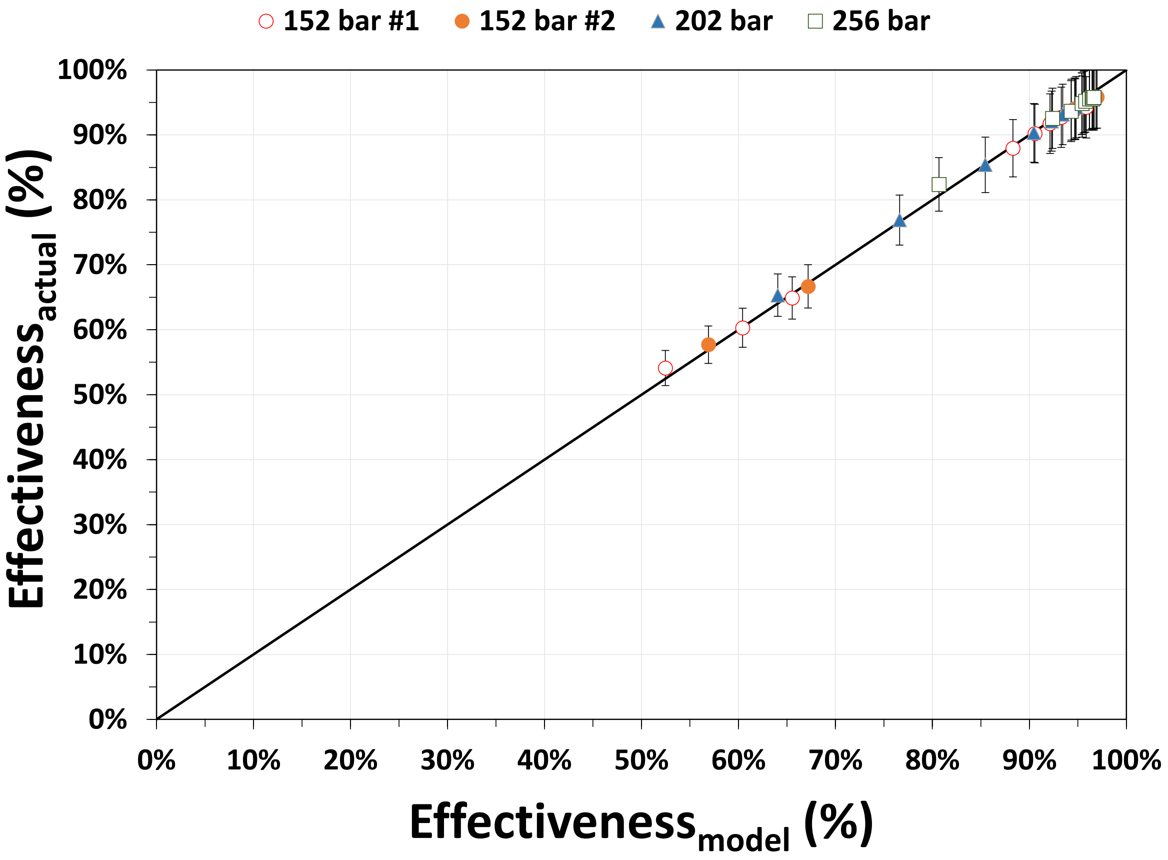
3D-SSHX Prototype Recuperator

Good correlation between Design & Actual HX performance data

Heat Transfer, Q



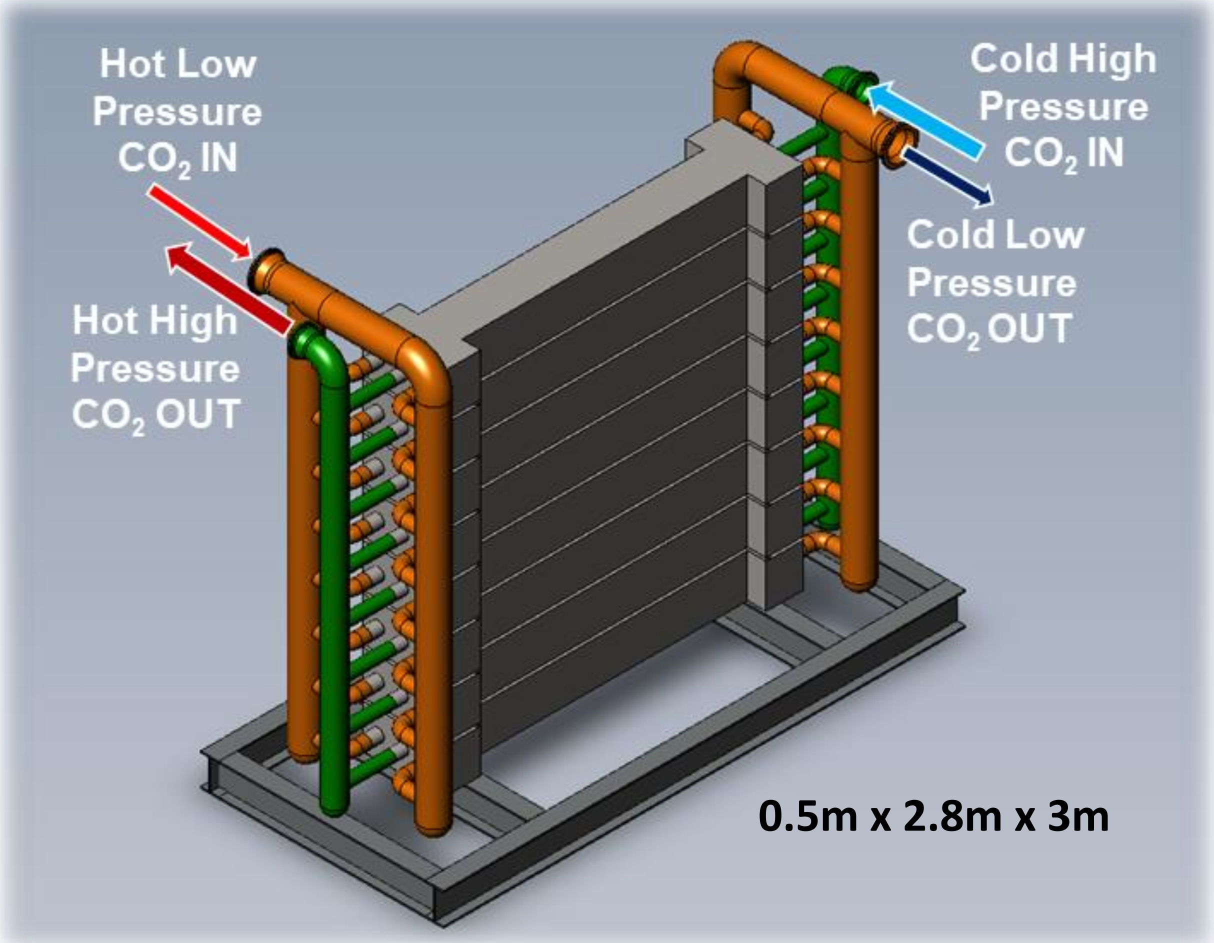
Effectiveness, ϵ



Work supported by US DOE NETL: DE-FE0026273

46 MWt Laser-SSHX Recuperator

Parallel Modular Design, Factory Fabricated



Example: Eight stacked Laser-SSHX sub-modules

3D-SSHX
57% volume decrease

Work supported by US DOE NETL: DE-FE0026273

Data confirms SSHX Recuperator Performance

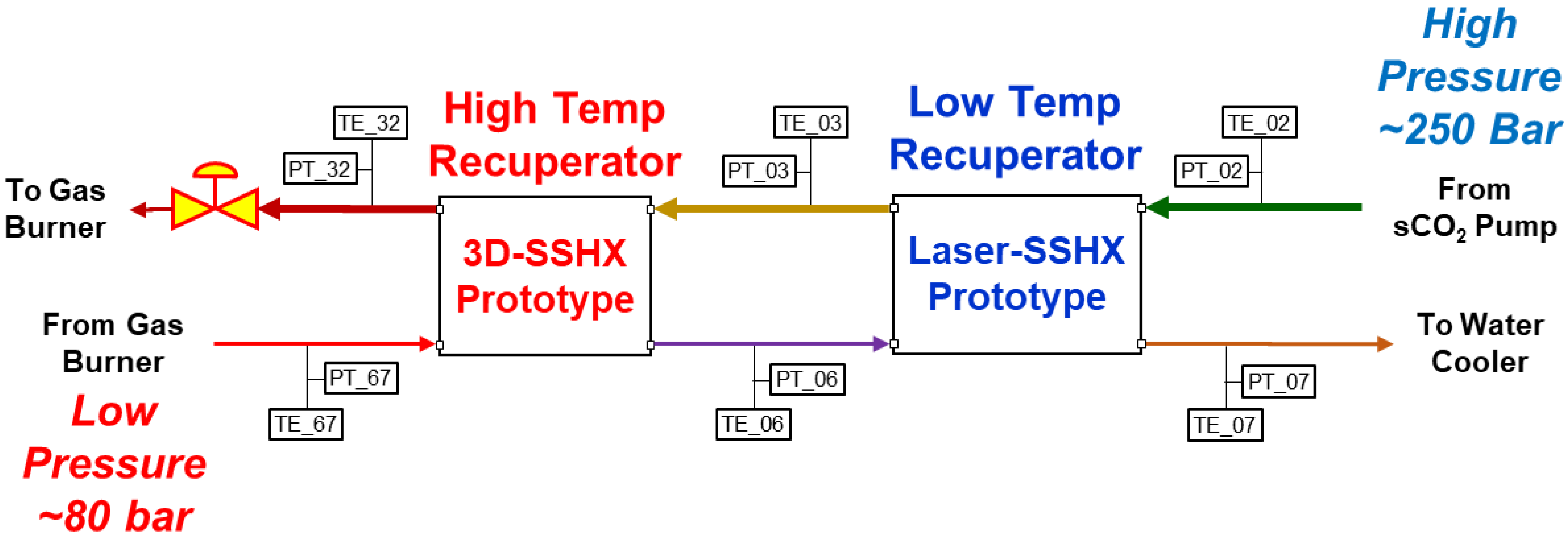
SSHX Recuperator meets or exceeds program requirements

Criteria	S.T.E.P. Target (Aug 2016)	SSHX Prototype
Thermal Capacity	**45.9 MWt**	✓
Thermal Effectiveness	**97%**	✓
Pressure Loss	$\Delta P_h < 1.5\%$ (1.3 bar)	✓
	$\Delta P_c < 0.6\%$ (1.3 bar)	✓
Temperature Limit	**577°C**	✓
Differential Pressure	152 bar	✓
Life	30,000 hr	TBD
Cost	< $100 / kWt	✓
Package Dimensions	8.8 x 3.6 x 2.6 m	✓

Work supported by US DOE NETL: DE-FE0026273

Transient Tests

COMBO-SSHX:
Laser-SSHX & 3D-SSHX piped in series



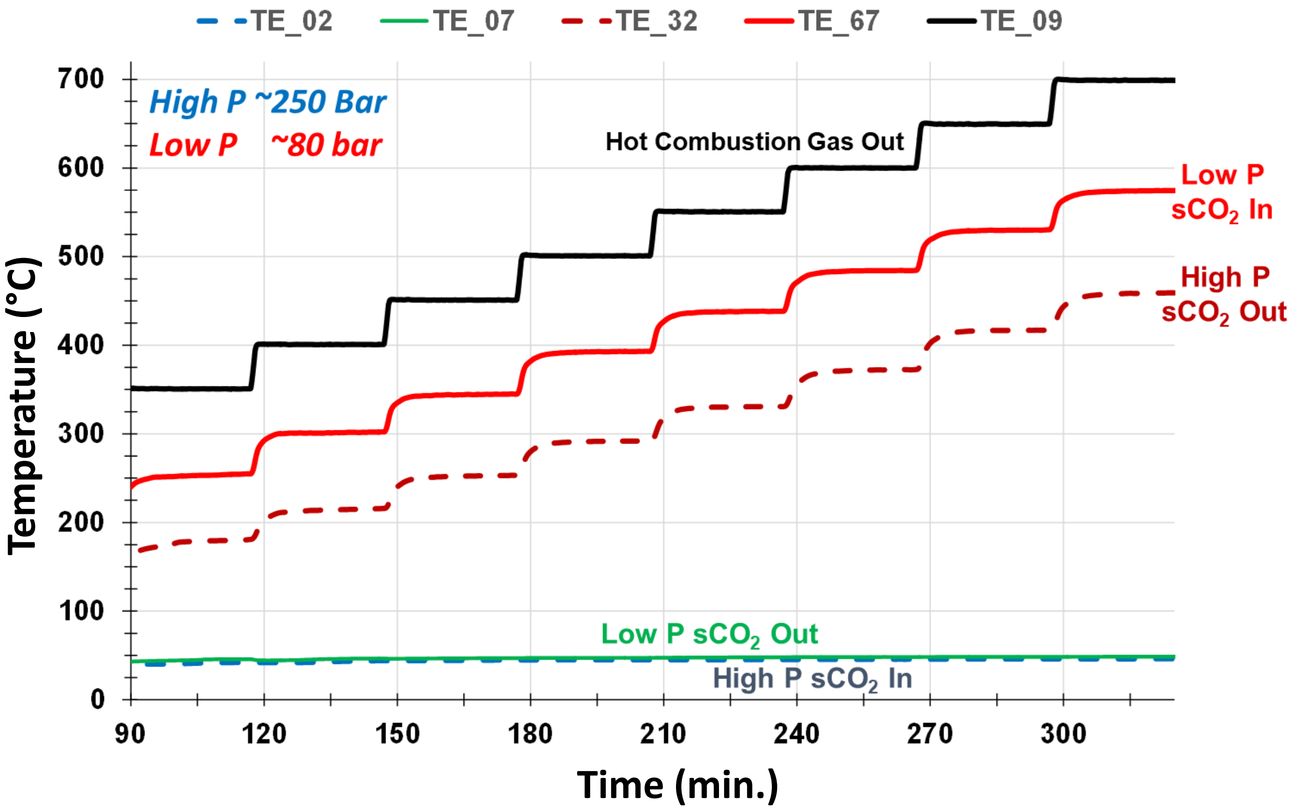
Work supported by US DOE NETL: DE-FE0026273

Test & Energy Balance Plots

COMBO-SSHX Recuperator

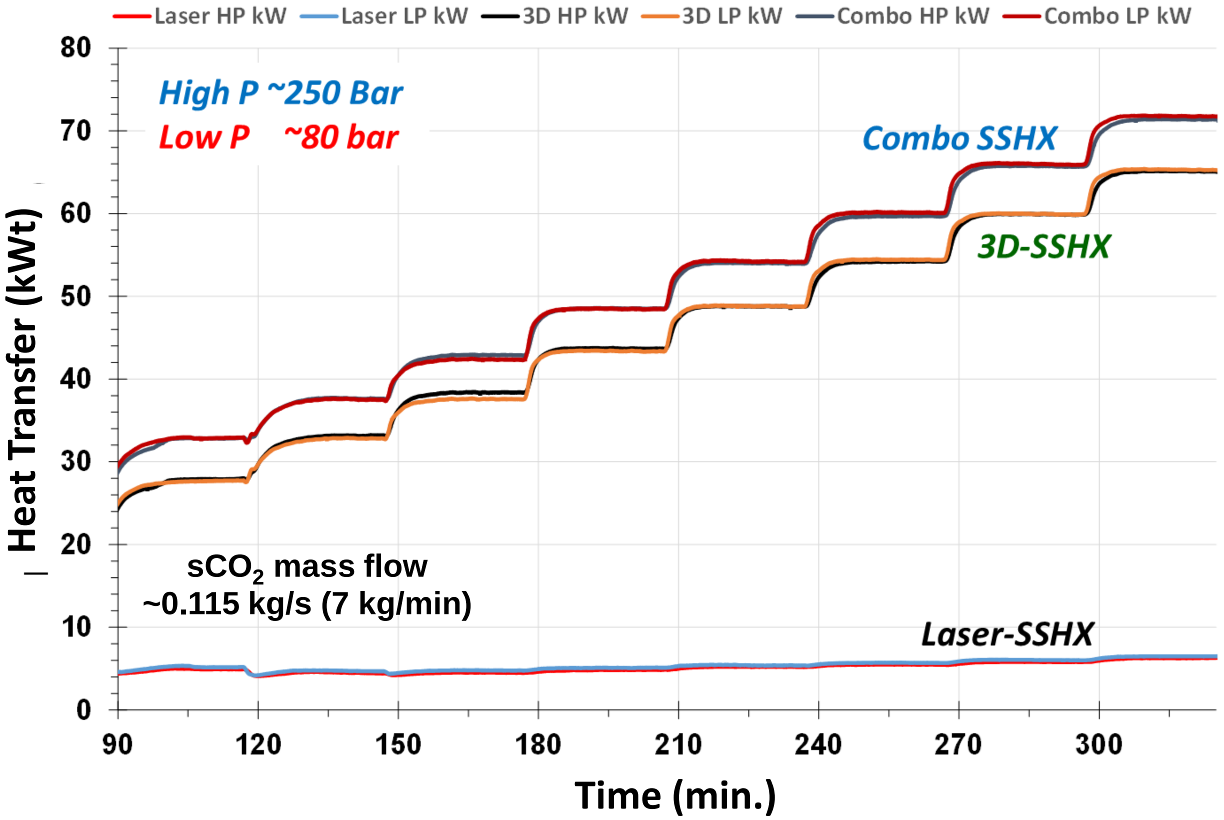
(Laser-SSHX & 3D-SSHX connected in series)

Temperature Plot



Approach T: < 5°C
Effectiveness: > 98%

Energy Balance Plot



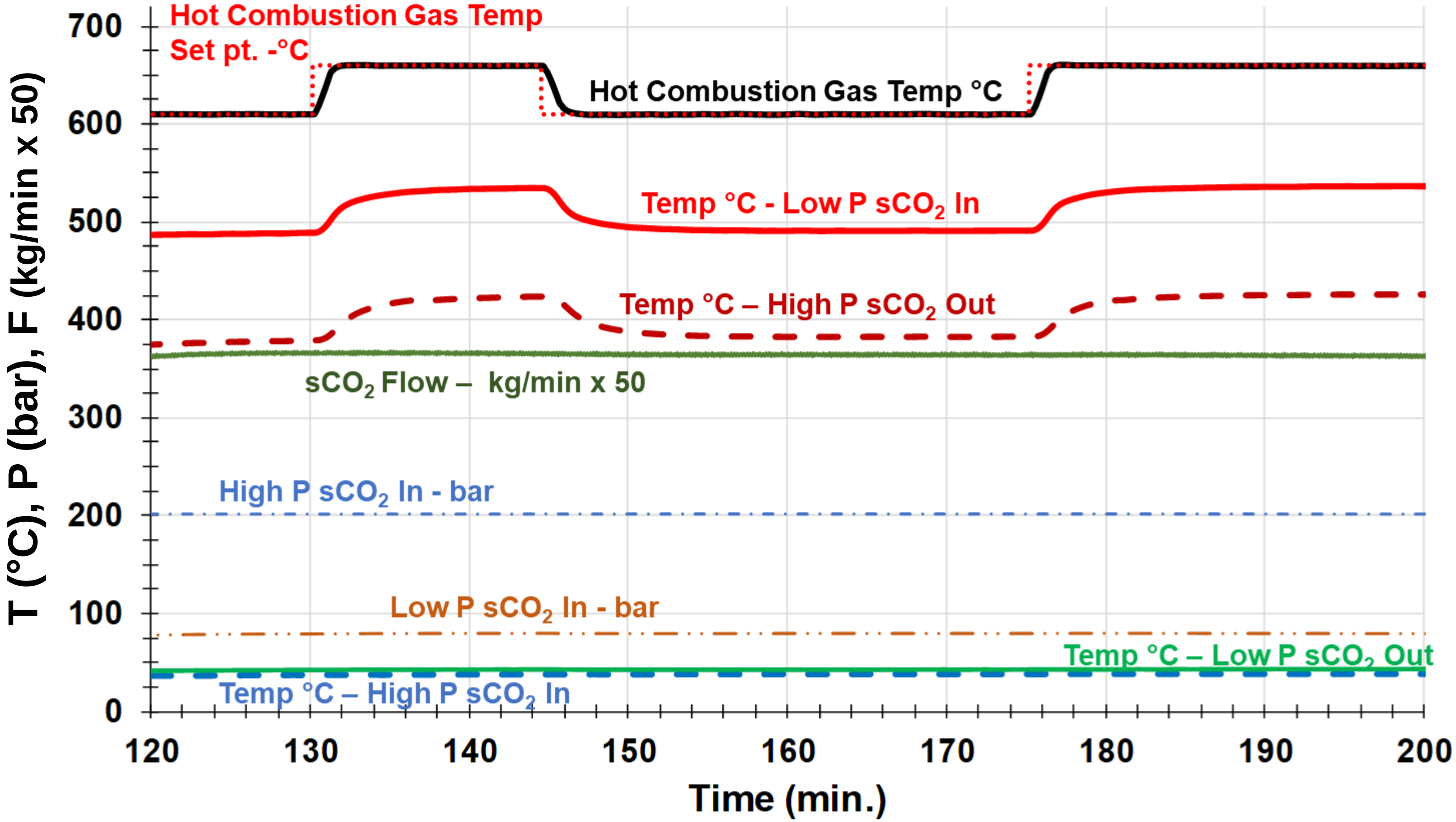
Good Energy Balance, < 2% error

Work supported by US DOE NETL: DE-FE0026273

Corporate Headquarters
150 Gamma Drive
Pittsburgh, PA 15238

COMBO-SSHX

Temperature Transient Plot

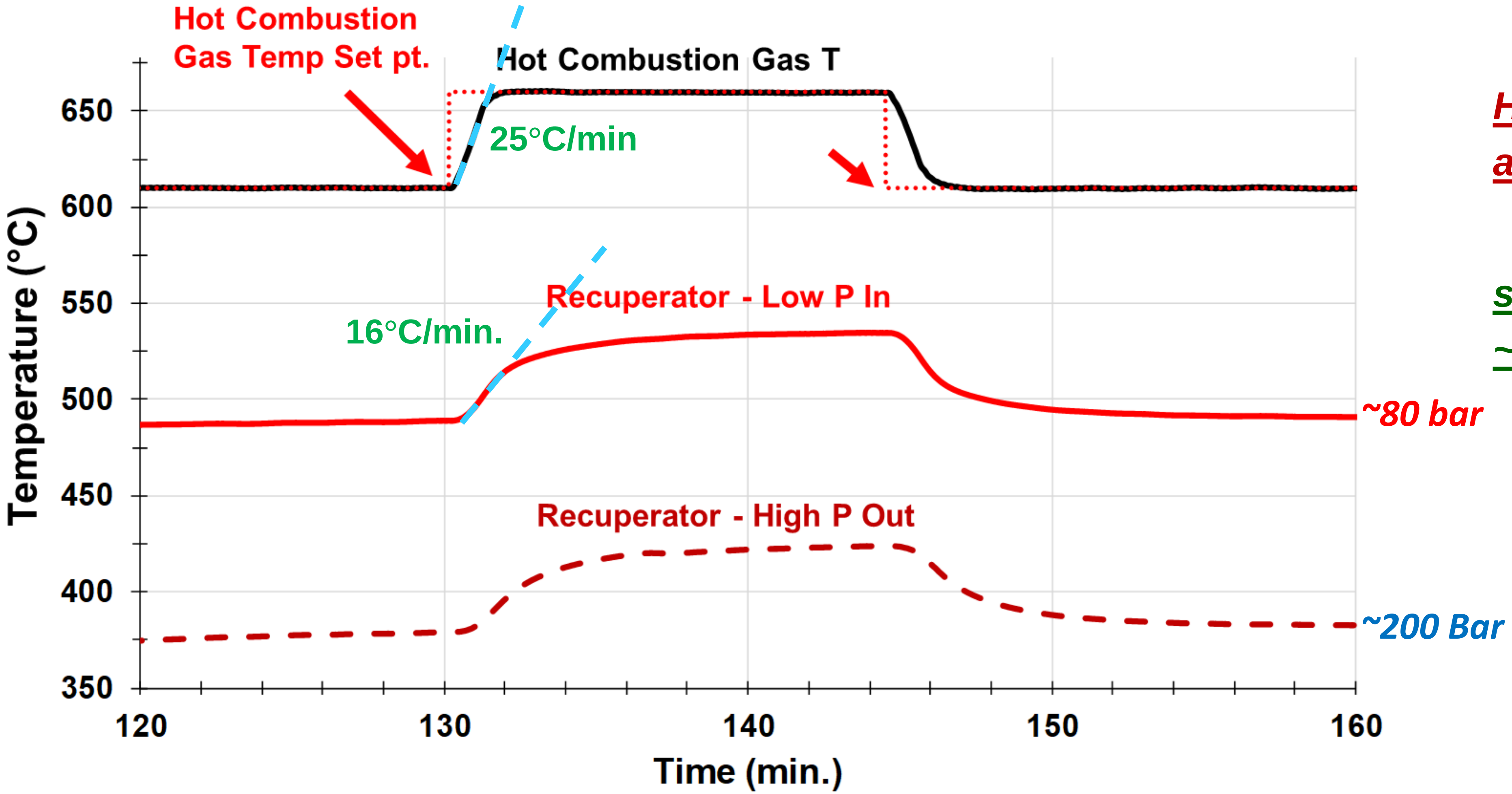


Pressure and flow remain stable

Work supported by US DOE NETL: DE-FE0026273

COMBO-SSHX

Temperature Transient Plot - expanded

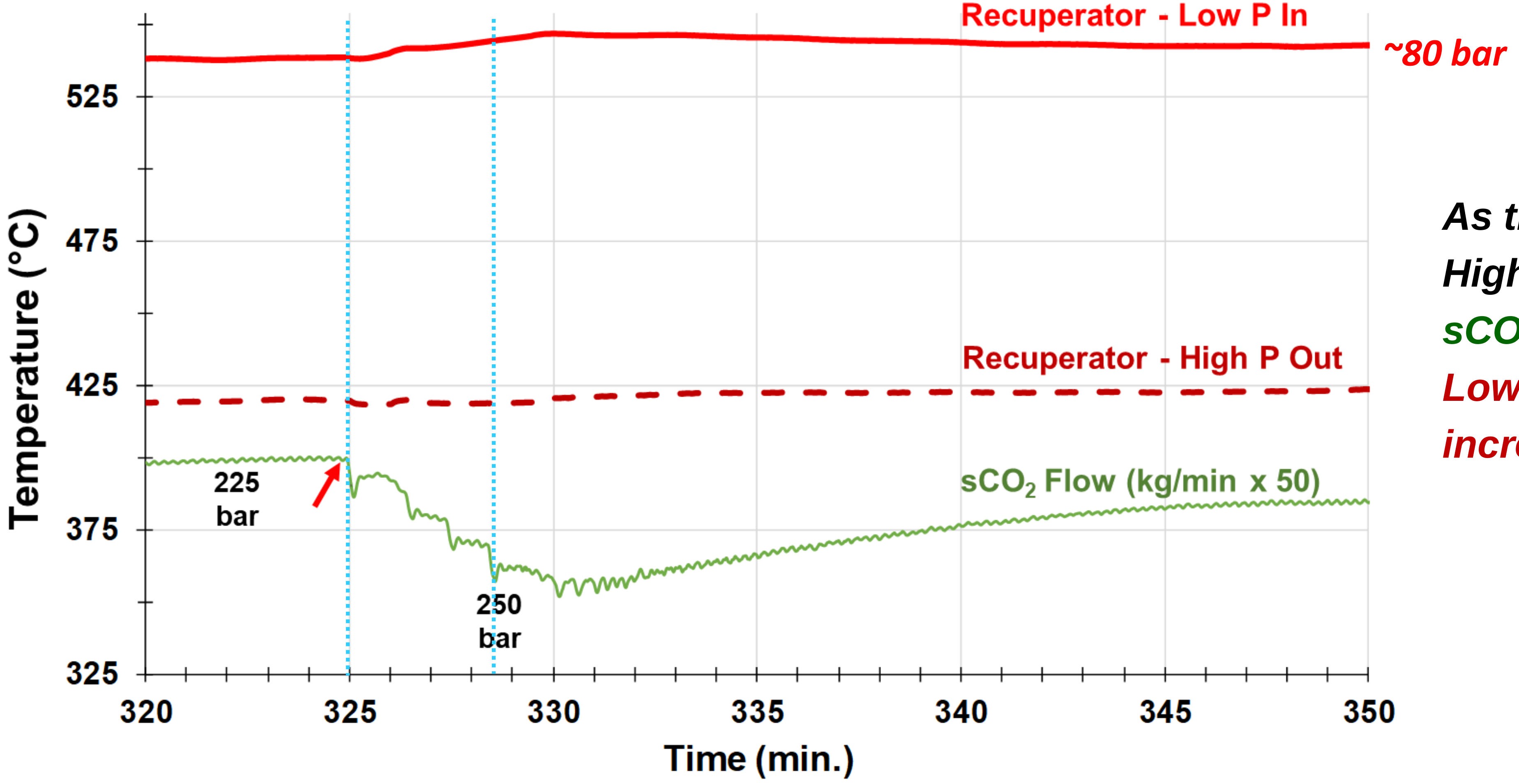


Hot combustion gas adjusts in ~2 min

sCO$_2$ streams take ~10-15 min.

COMBO-SSHX

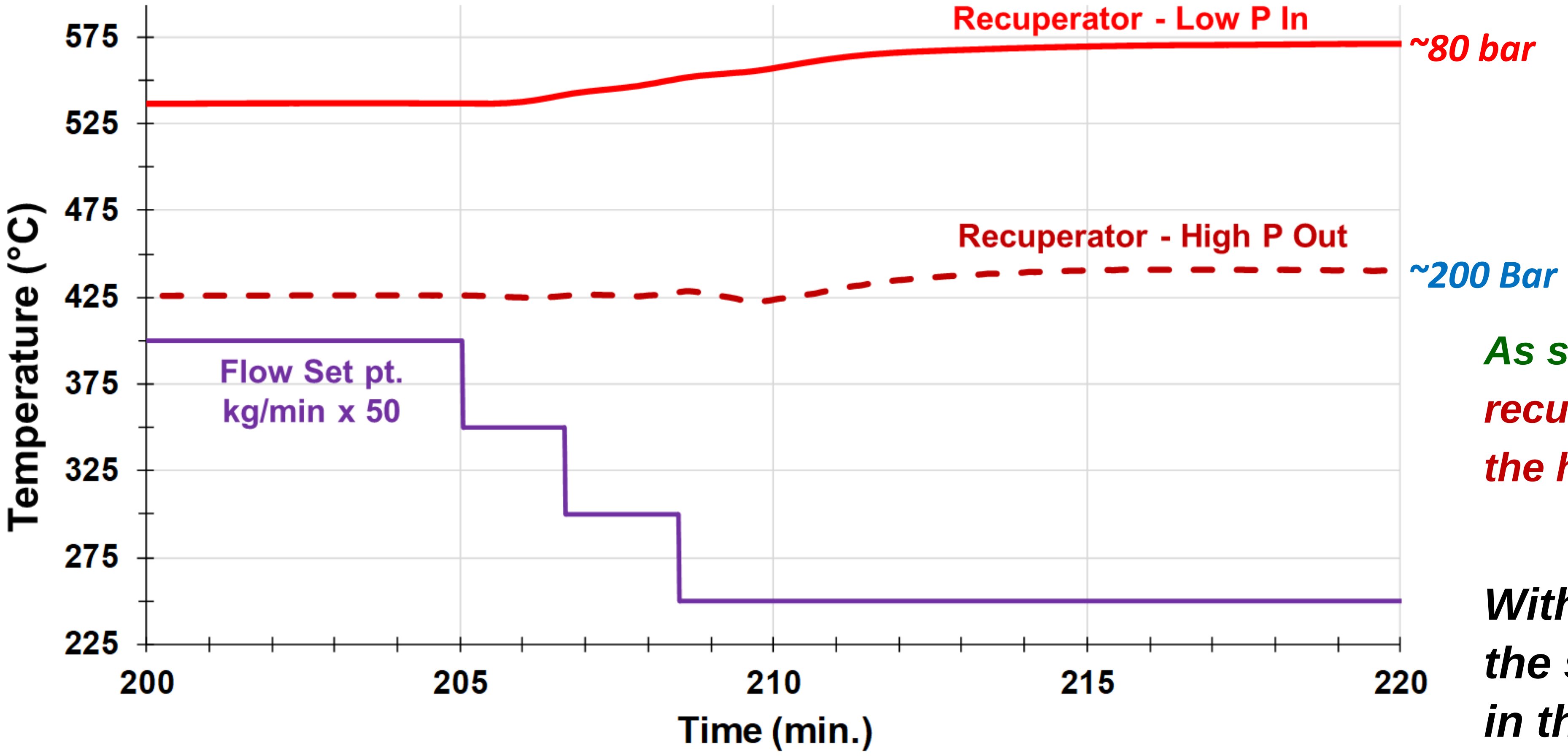
Change of Pressure



As the pressure on the High-P side is increased, sCO_2 flow decreases, & Low-P side temperature increases.

COMBO-SSHX

Change of Flow Rate



As sCO_2 flow rate decreased, recuperator temperature on the heater side increases.

With the lower flow rate, the sCO_2 residence time in the heater increases.

INTRODUCTION
TO
HEATRIC PCHEs*

- (Printed Circuit Heat Exchangers)

Presented by:
Renaud Le Pierres – Business Development Engineer

February 2024

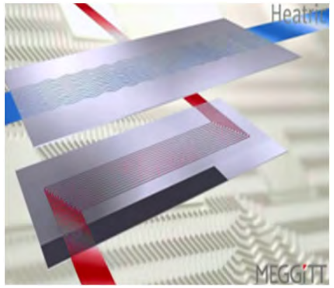
1| Why Heatric PCHEs?

Experts in Heat Transfer

Experience	• Over **3500** heat exchangers units supplied worldwide, most still in operation • Nearly **40** years dedicated heat transfer experience and engineering excellence
Manufacturing Capabilities	• Heatric have the **largest** PCHE dedicated chemical-etching facility in the world, by volume of material removed • All of our manufacturing takes place in the **UK**, to ensure the highest level of product quality • **Largest** radiographic cells in the south UK with 50 tonne capacity
Lifecycle Support	• Heatric Services offer **full lifecycle support** for your project; from engineering support and process development, to product maintenance by means of cleaning to extend the life of existing units
Customer Driven	• As a Parker Hannifin company, our aim is to provide exceptional-quality heat transfer solutions through the application of our values; teamwork, integrity, and excellence • Heatric work with customers to develop best heart transfer solutions and maximise up-time

2| PCHEs design and construction

Construction process

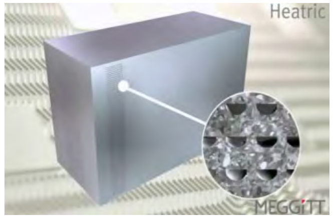


- Design:

PCHE is designed in-house by specialised engineering team to customer requirements

- Etching:

PCHEs are constructed of stainless steel plates, which are chemically etched to create the channels. Chemical etching the channels does not create stress-points which can cause channel failure.

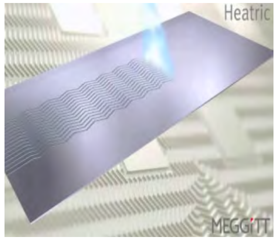


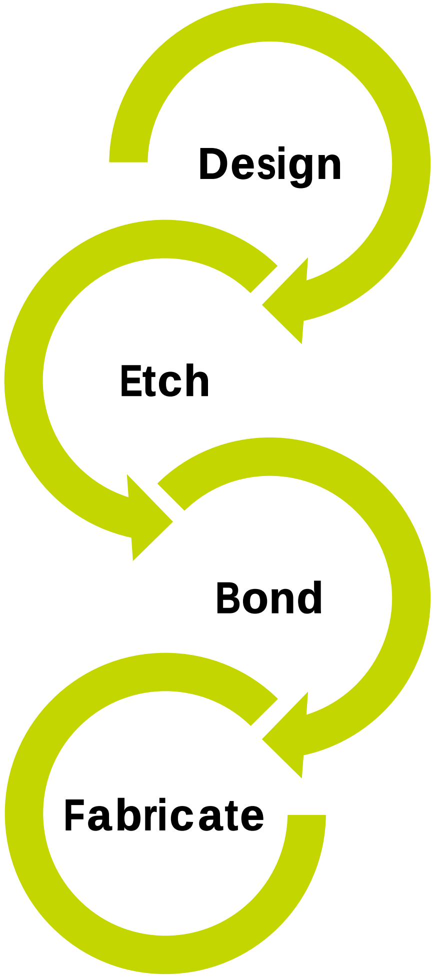
- Bonding:

Etched plates are stacked and diffusion-bonded together; to produce a core with the same integrity as a block of steel

- Fabrication:

The cores are then welded together, with headers and flanges attached as required to produce the completed exchanger





Design

Etch

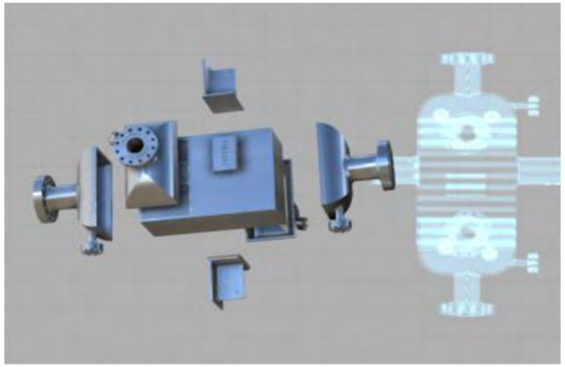
Bond

Fabricate

3|Benefits of PCHEs

Printed Circuit Heat Exchangers

Superior Performance

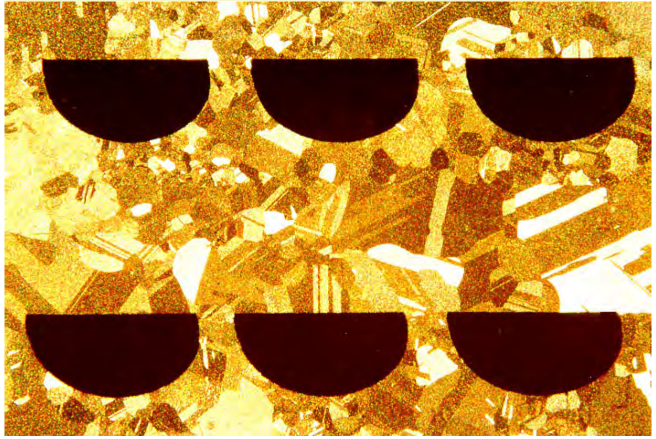


OPEX saving across wide range of processes

PCHEs are bespoke diffusion bonded compact heat exchangers providing:

- close temperature approaches (>2°C)
- very high thermal performance (i.e. 13.6MWth/m^3 sCO2 recuperator)
- high pressure capability (>1,000 Bar)
- widest range of temperatures (-196°C to 900°C)

Inherently Safe



Reduced operational risks

Using diffusion bonding with a fully welded construction, PCHEs:

- can operate at full differential pressure between streams
- are immune to flow induced vibrations and pressure fluctuations
- do not suffer from catastrophic failure mode
- have 30 years track record of safe operation

Compact

Overall Project CAPEX saving

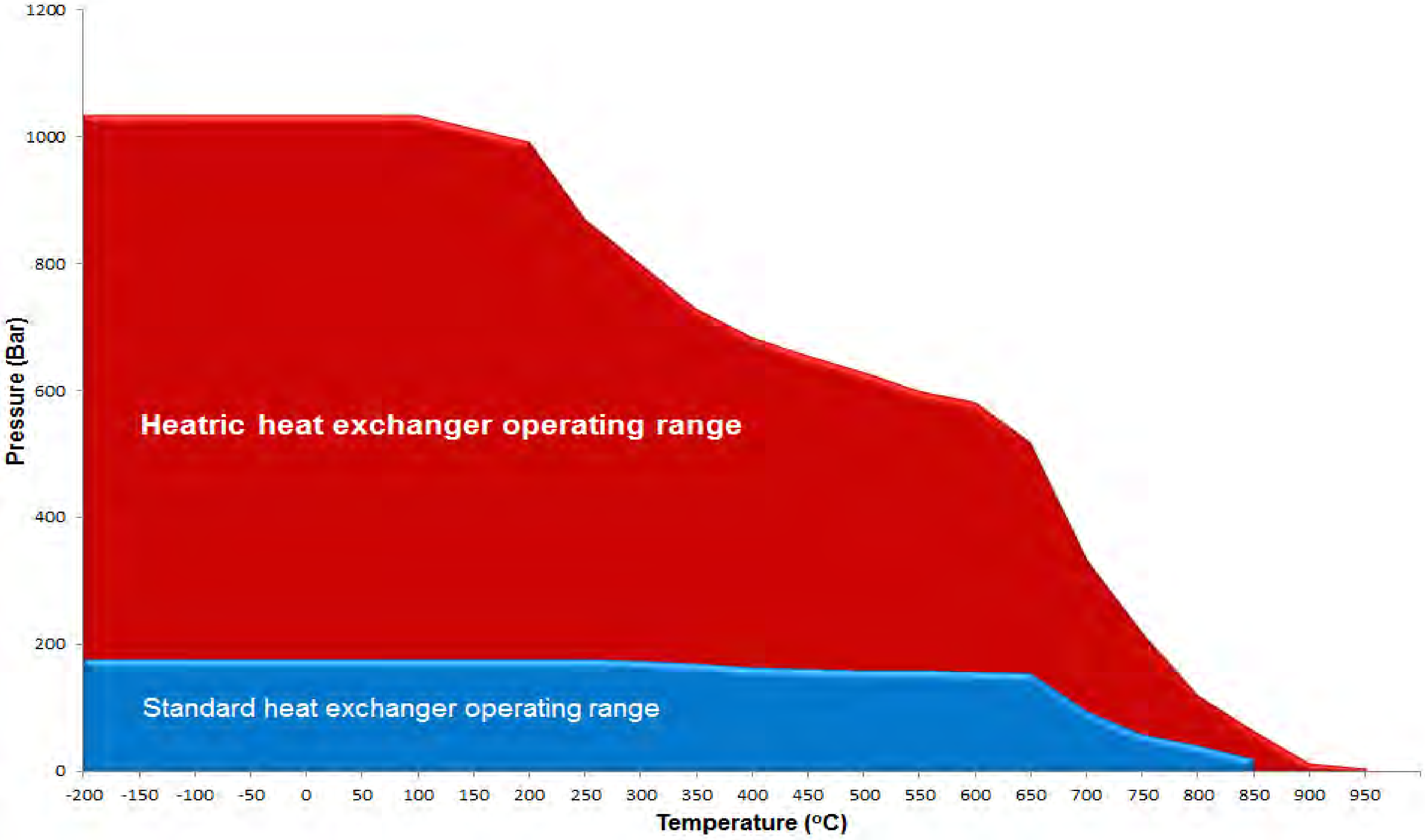
PCHEs are up to 85% smaller than Shell and Tube exchangers, offering:

- modularisation for ease of transport, on-site installation
- reduced foundation structure
- reduced pipework and safety valves
- retrofit capability in-lieu of S&T
- PCHE is made from 100% fire resistant materials

Heatric

3| Benefits of PCHEs

Mechanical capability



4| Heatric sCO2 Key Delivered Project Timeline

Since 1994

1994

First PCHE using sCO2 – Offshore re-injection

2003

Heatric supply to their first PCHE Recuperator for Tokyo Institute of Technology sCO2 loop

2009

Heatric's supply three PCHEs to Sandia National Laboratories sCO2 Brayton test loop

2011

Heatric supply to Echogen EPS 100, the world's first commercial sCO2 WHR unit

2016

Heatric supply to NETPower Pilot Plant in Texas

2019

Heatric supply to GTI / SWRI for the STEP facility

2021

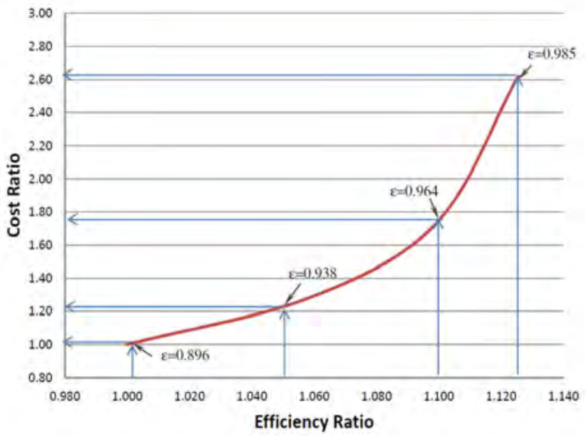
Heatric supply to MAN Energy Solutions for the ETES Esbjerg District Heating plant (electro thermal energy storage)

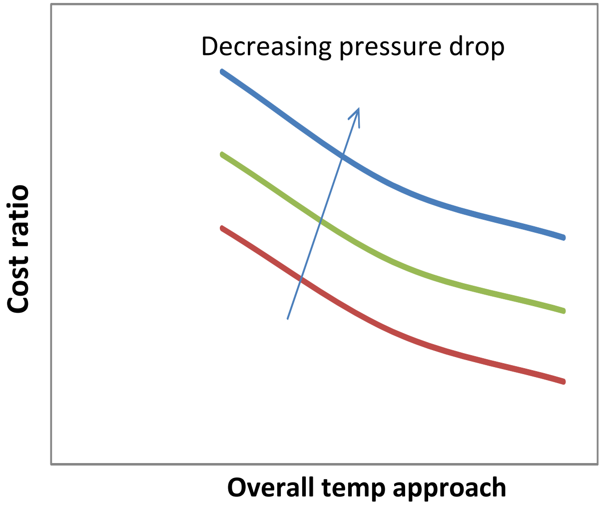
	USA	Australia	U.K.	Germany	Canada	China	Denmark	Japan	Korea
N° Project	10	1	3	1	1	1	1	1	1
N° Units	24	3	3	2	2	2	2	1	1

* 42 sCO2 exchangers delivered, 27 sCO2 projects quoted, >1000 exchangers bespoke designs

5| Economic feasibility of PCHEs for sCO2 power cycles

- Increasing design temperature:
  Change conventional material to high grade alloys (10x – 20x more expensive and potentially limited supply)
- Increasing design Pressure:
  Thicker walls with non standard product forms for some components (i.e. hubs, special forgings, pipes)
- Temperature approaches:
  Diminish efficiency returns versus exchanger potentially doubling in size for minimum gains (Q=U.A.LMTD)
- Allowable pressure drop:
  Very high free flow area required (increase size of HE) potentially beyond compressor / pump cost savings
  - Hence sCO2 process design must be balanced between equipment cost and efficiency gain



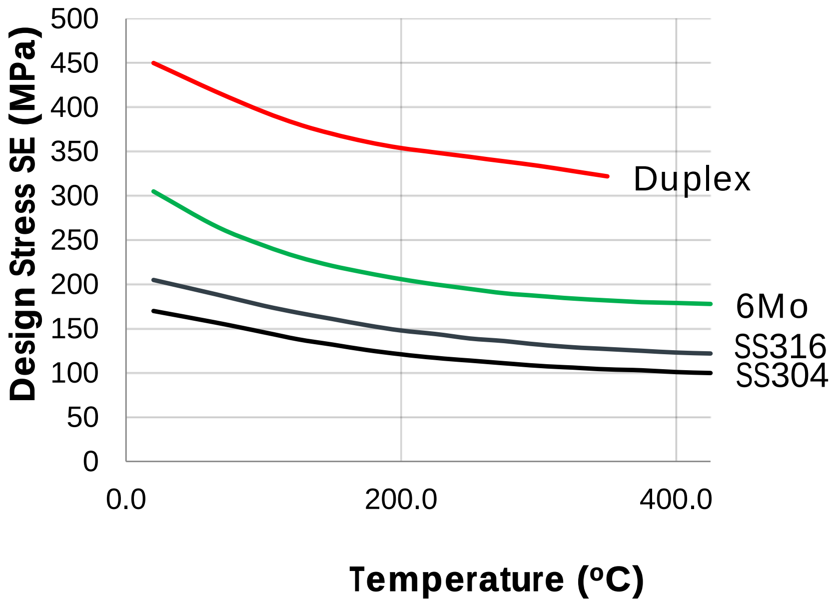


6| PCHEs design and construction

Material process

Qualified:

- Austenitic Stainless steels 304/304L (S30400, S30403)
- Austenitic Stainless steels 316/316L (S31600, S31603)
- Duplex 2205 (S31803)
- Superduplex (S32750)
- Titanium Grade 2 (R50400)
- 6 Moly (N08367)
- Alloy 617 (N06617)



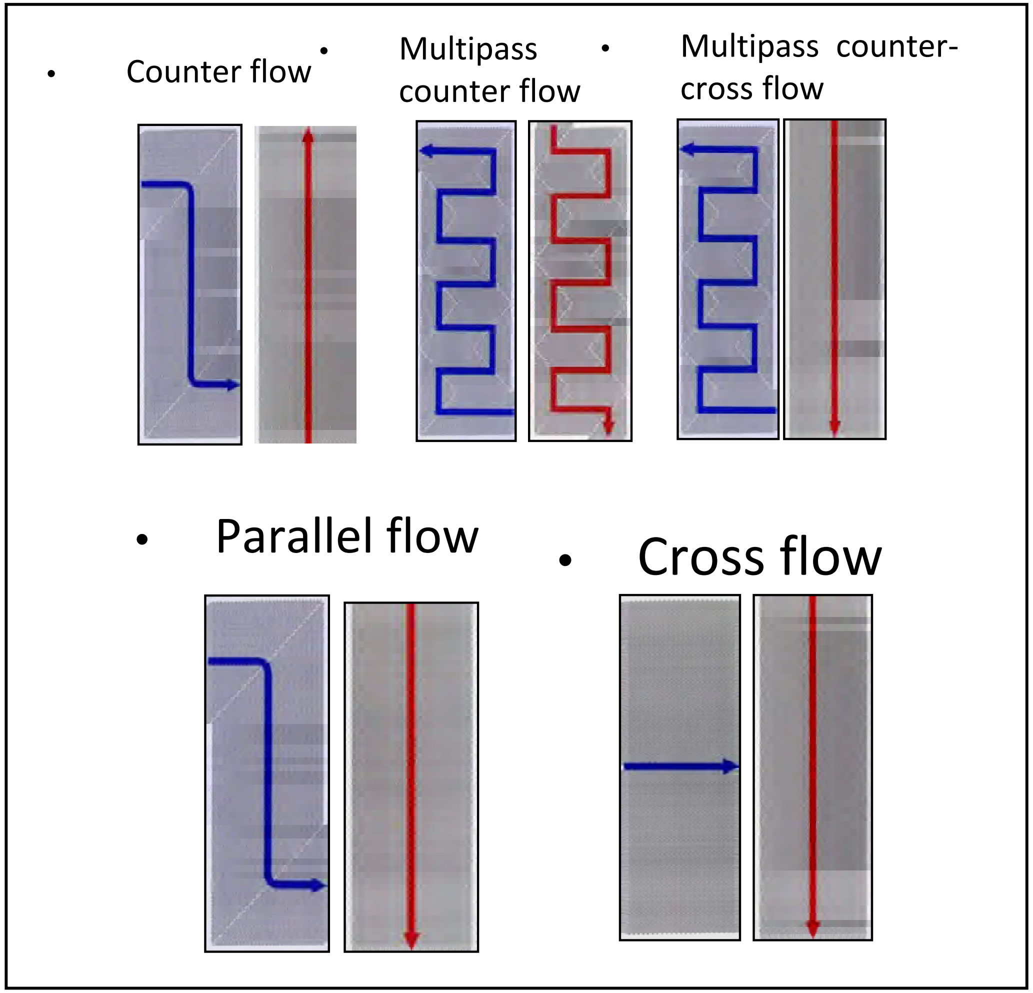
Material Allowable Stress:

- SS304 @ 425°C = 100MPa ASME II Part D
- Duplex @ 150°C = 370MPa ASME II Part D
- 6Moly @ 275°C= 190MPa ASME II Part D

6| PCHEs design and construction

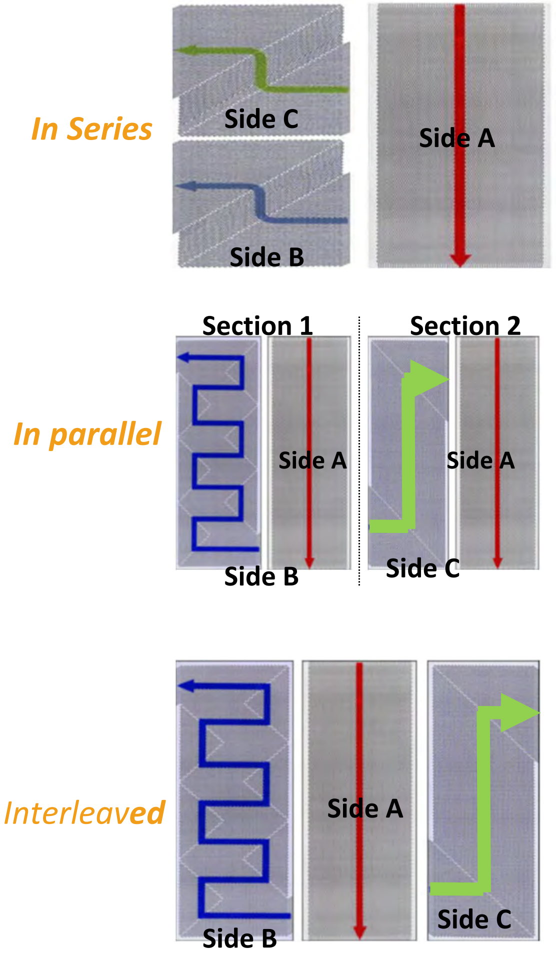
Thermal design considerations

Thermal contact arrangement (2 streamers)



- Counter flow
- Multipass counter flow
- Multipass counter-cross flow
- Parallel flow
- Cross flow

Thermal Contact (multi-streamers)



6| PCHE design and construction

Hydraulic design consideration

- ΔP distribution through PCHEs
  - **Active Core** → min. 50% of the total calculated ΔP_{TOTAL}.
  - **Header** - **Nozzles** → dynamic head losses enforced, check for maldistribution

- Due to friction:
  - Pressure drop through the core
  - Treated similarly to loses in pipes
  - PCHE experimental studies on fanning friction factor (f) and Re.

$$\boxed{\Delta P = \frac{\rho V^2 fL}{2D}}$$

- Due to fittings:
  - Pressure drop through standard core attachments
  - Also for additional fittings (elbows, manifolds, etc)
  - Apply the resistance coefficient (K) method
  - Most commonly used → expansion and contraction

$$\boxed{\Delta P = KV_{head}}$$

6| PCHE design and construction

Mechanical design Code & Certifications

- Direct Stress (primary, secondary or both)

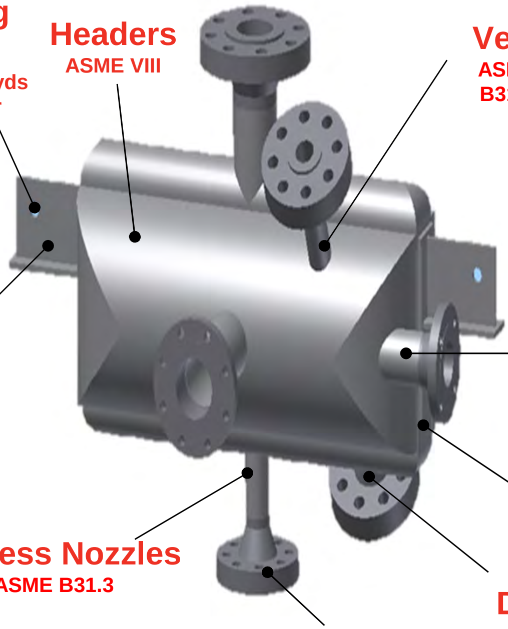
$$\text{Direct Stress } (\sigma_d) = \frac{Force\ (F)}{Area\ (A)}$$

- Bending Stress (secondary stress)

$$\text{Bending Stress } (\sigma_b) = \frac{Moment\ (M) x\ Distance\ to\ neutral\ plane\ (y)}{Second\ Moment\ of\ Area\ (I)}$$

- Hoop Stress (primary stress)

$$\text{Hoop Stress } (\sigma_h) = \frac{Pressure\ (P) x\ radius\ (r)}{thickness\ (t)}$$



Lifting Lugs
DNV & Lloyds Register

Headers
ASME VIII

Vent
ASME B31.3

Supports
ASME II Part D Structural Design Rules

Maintenance nozzles
ASME B31.3

Core
ASME VIII

Process Nozzles
ASME B31.3

Drain
ASME B31.3

Flanges
ASME B16.5
ASME VIII Appendix II
SPO
Teklok

7| Operation challenges in heat exchangers

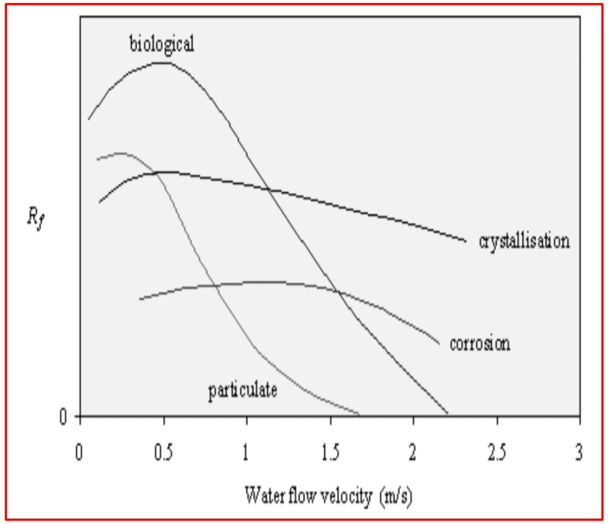
Structural, Performance and Metallurgical challenges of HEs

Structural Challenges	Performance Challenges	Metallurgical Challenges
• Failures caused by flow induced vibration • Leakage from bolted	• The excessive tube fouling • Thermal stresses in the internal of the heat exchanger	• Stress corrosion • Galvanic corrosion • Erosion corrosion • Pitting corrosion

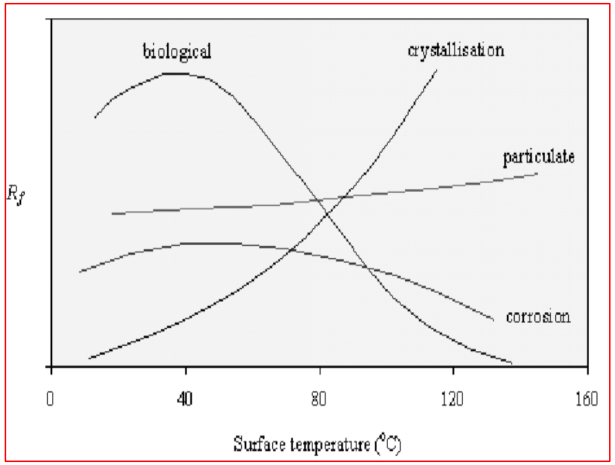
7| Operation problem in heat exchangers

PCHEs Fouling Consideration

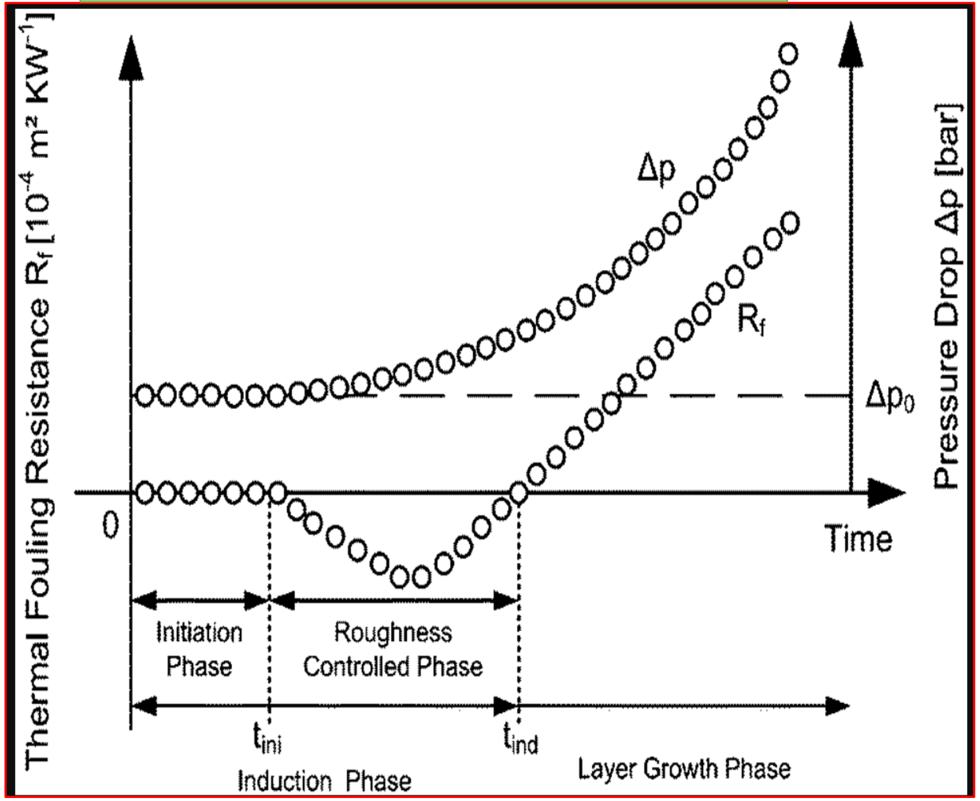
Effect of velocity at constant temperature



Effect of temperature at constant velocity



Graphical definition and schematic development of the thermal fouling resistance and the pressure drop over process time.



7| Operation considerations for heat exchangers

Corrosion

- Corrosion of a PCHE is uncommon due to the materials from which they are constructed. Typically stainless steel 316 / 316L

- However, in some extreme cases corrosion has occurred. The two types of corrosion that need to be considered are:
  - **Pitting Corrosion**
  - **Chloride Stress Corrosion Cracking (CSCC)**

Heatric

8| Preventative Measures & Maintenance

Complete lifecycle support

1. Field Service Support

- Operator Training
- PCHE Inspection
- Commissioning
- Site Survey
- Performance Review

2. Cleaning

- Chemical circulation
- UHP water jetting
- Back puffing
- Sample analysis

3. Service Support

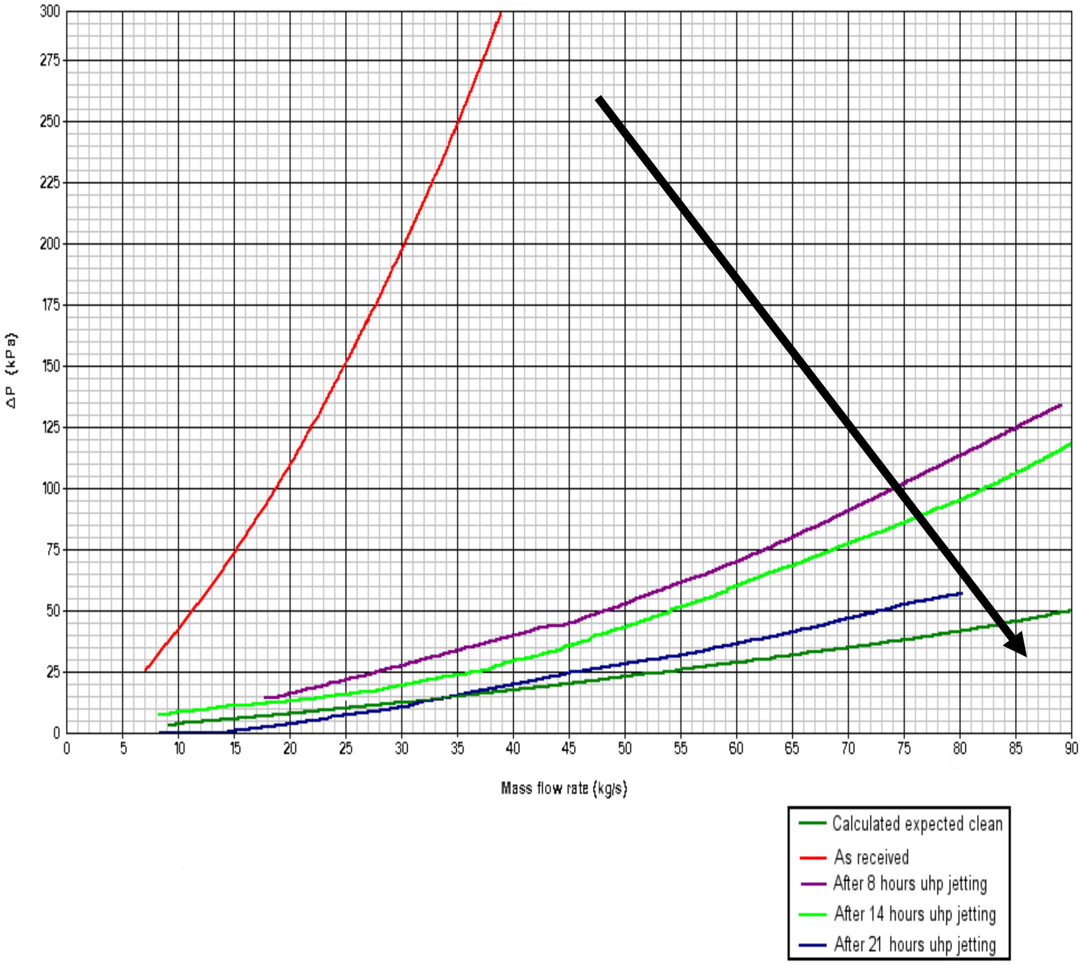
- Weld repair
- Re-core
- Failure investigation
- Maintenance nozzle retrofit

4. Additional Offerings

- Nitrogen preservation
- Helium leak testing
- Hydrostatic testing
- New or replacement strainers

8| Preventative Measures & Maintenance

UHP cleaning example



Before

After

Find out more

heatric.com

htrc-info@meggitt.com

Corporate Brochure

Servicing & Maintenance

Parker MEGGITT