Heat Exchangers for Supercritical CO_2 Power Cycle Applications

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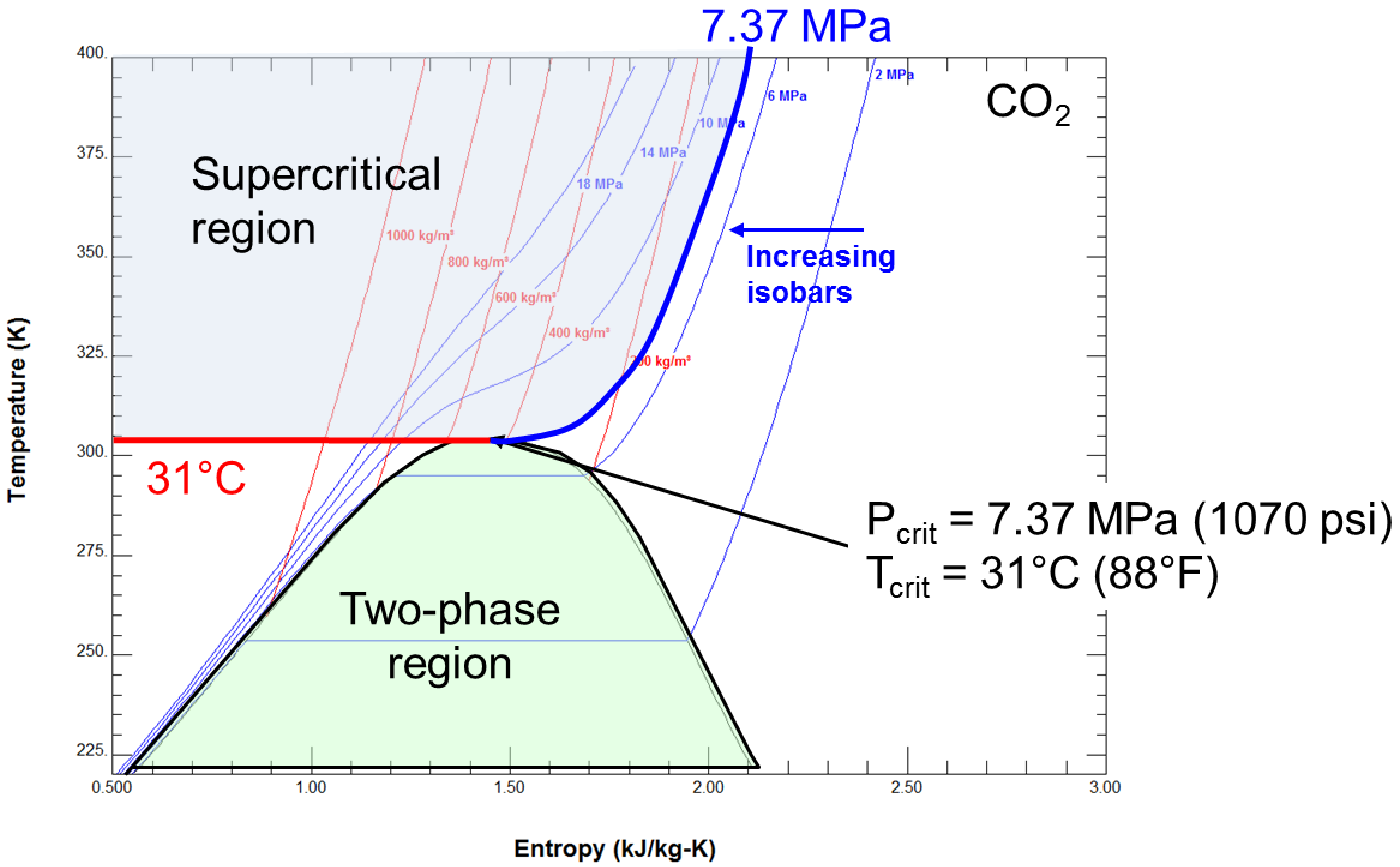
Supercritical CO_2 has pressure and temperature above critical values



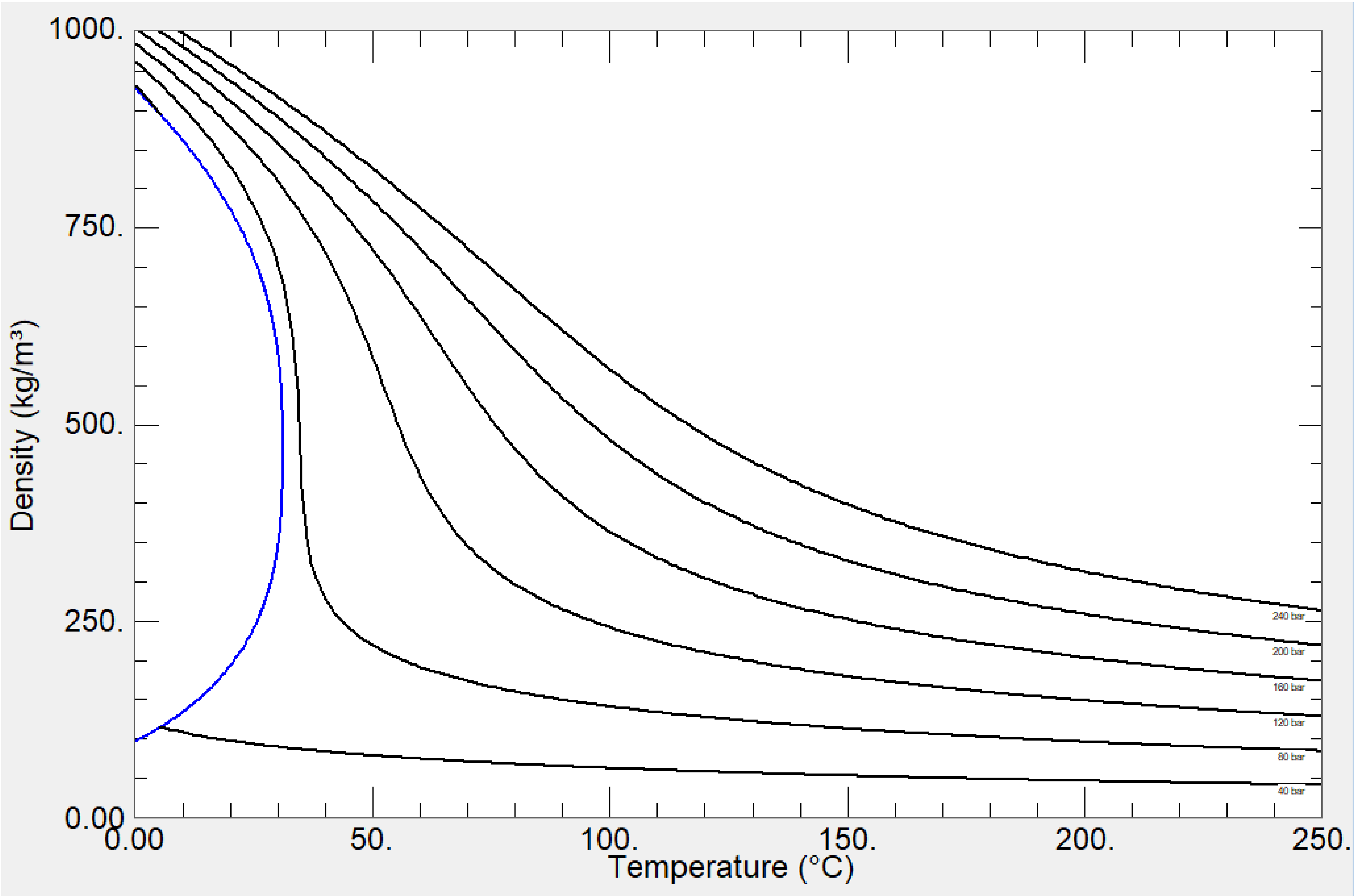
P_{crit} = 7.37 MPa (1070 psi)
T_{crit} = 31°C (88°F)

Source: Musgrove et al. GT2012-70181

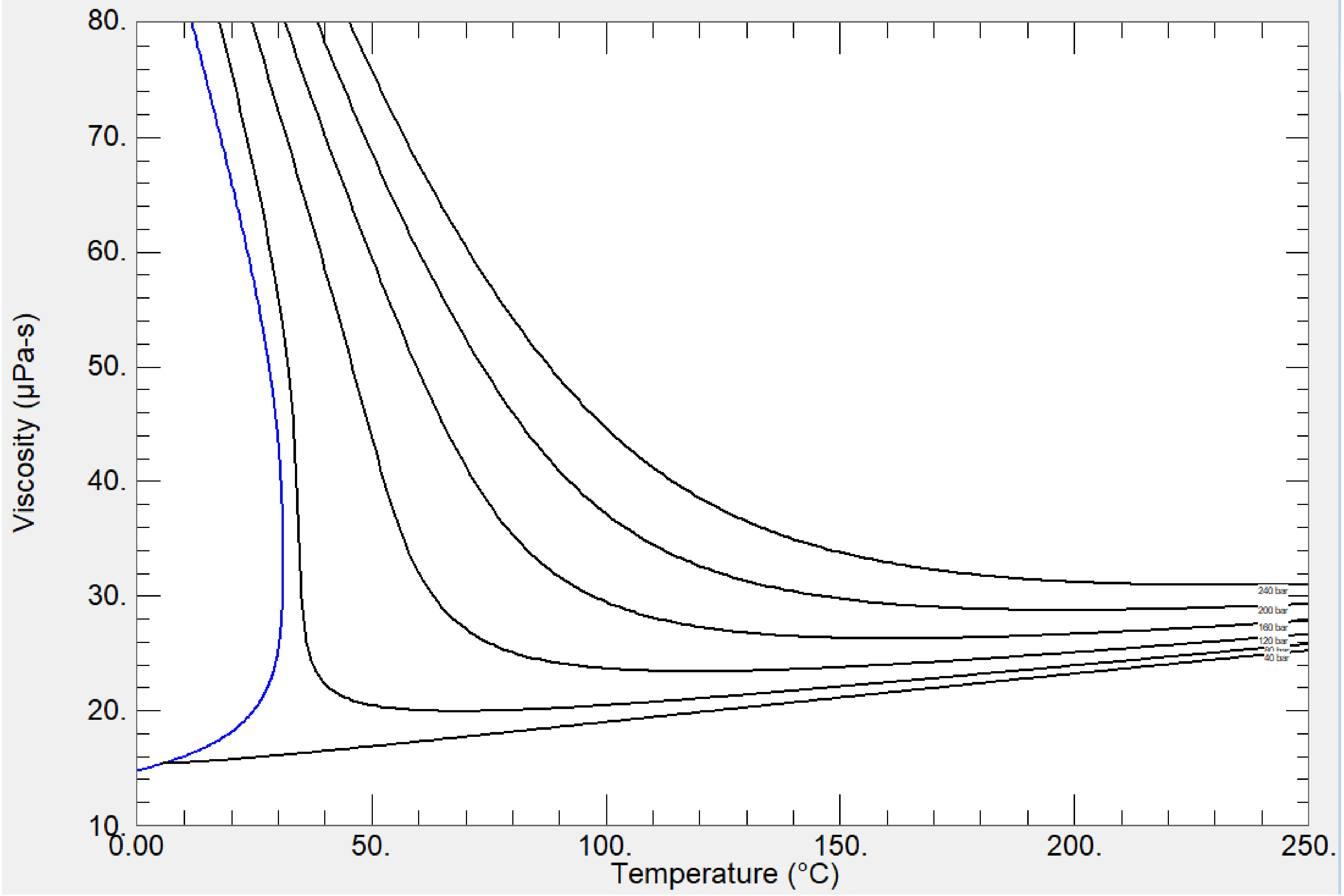
Supercritical CO_2 allows for effective heat transfer in a compact package

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

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



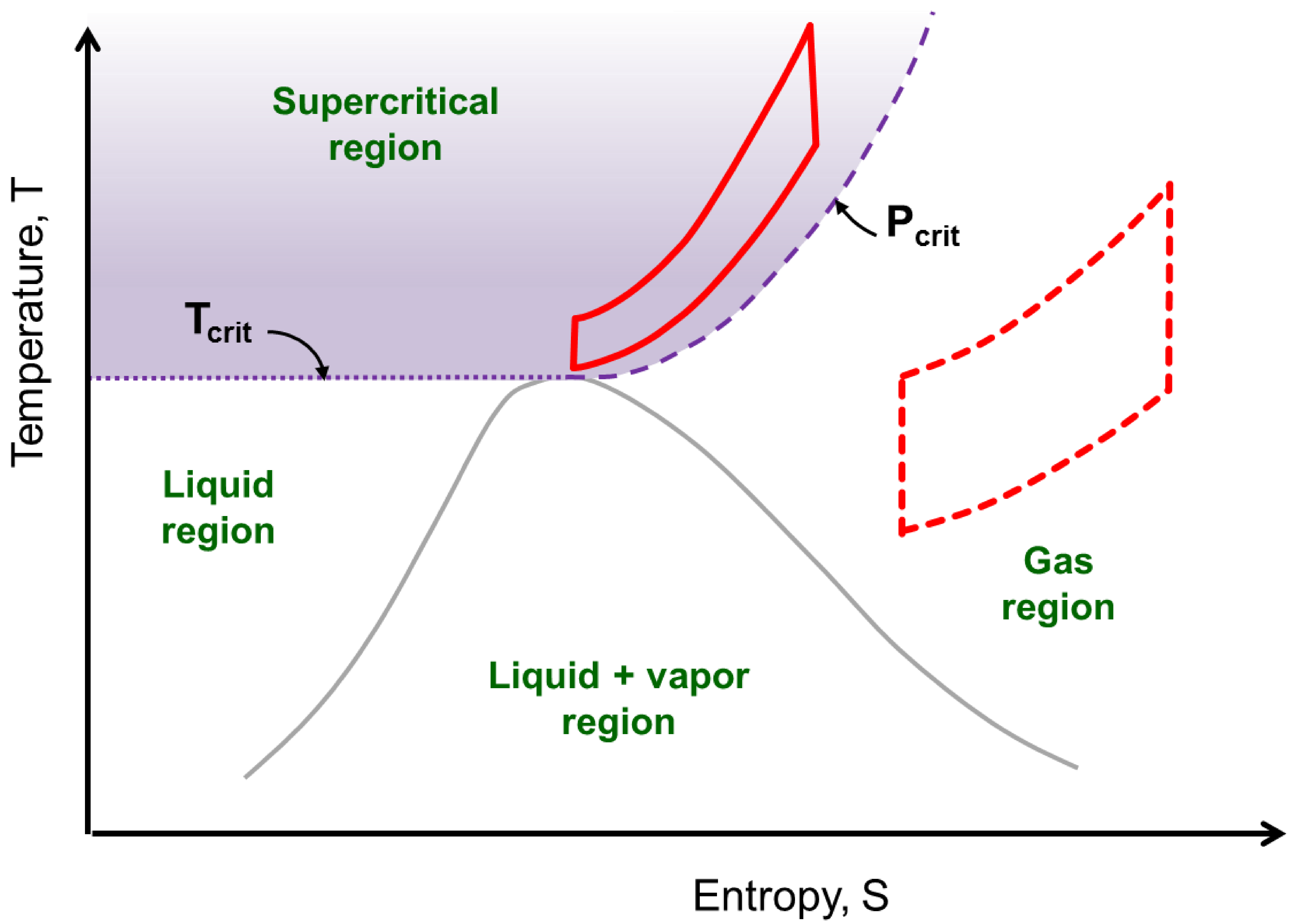
Isobars (bara):
240
200
160
120
80
40



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



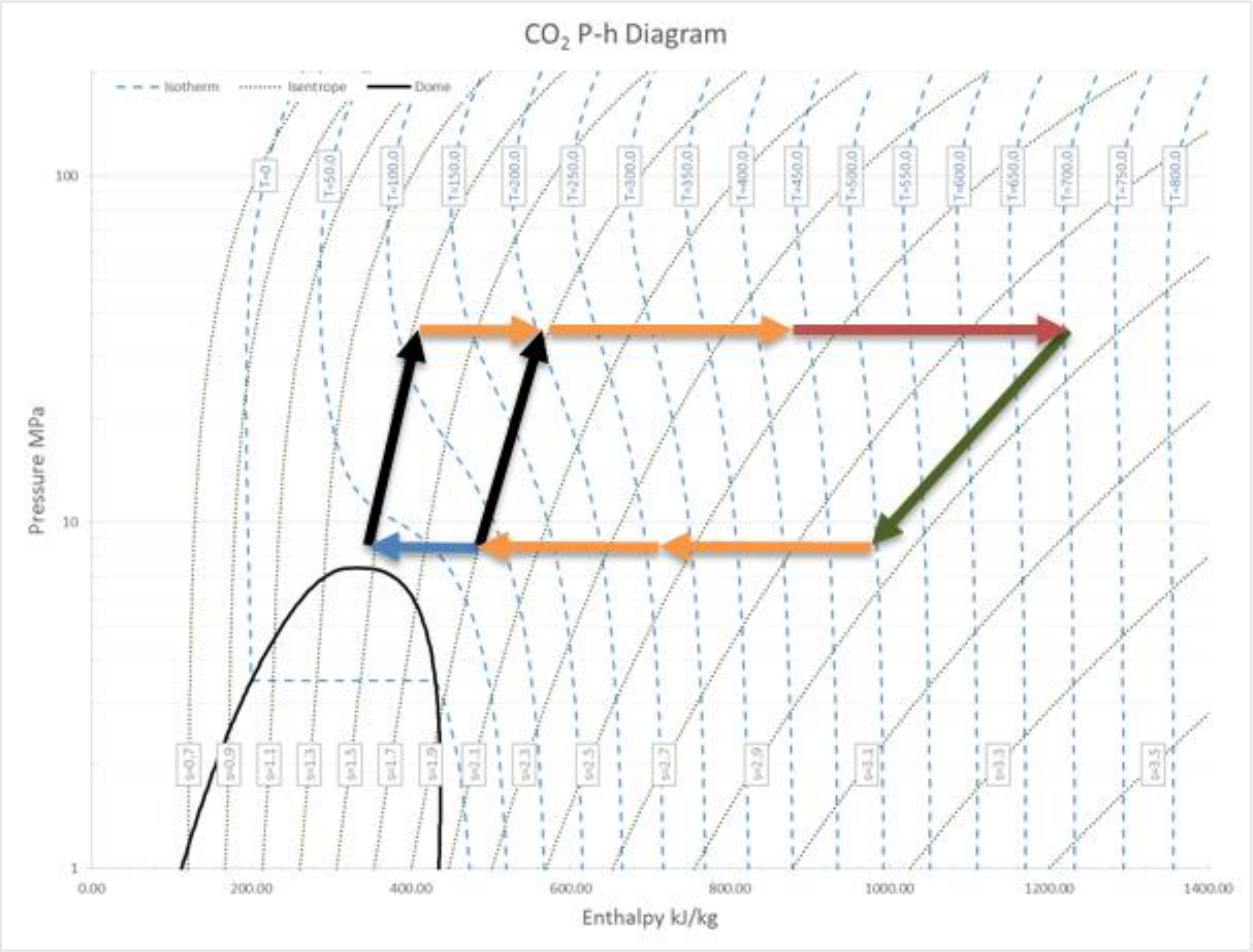
Heat Input:

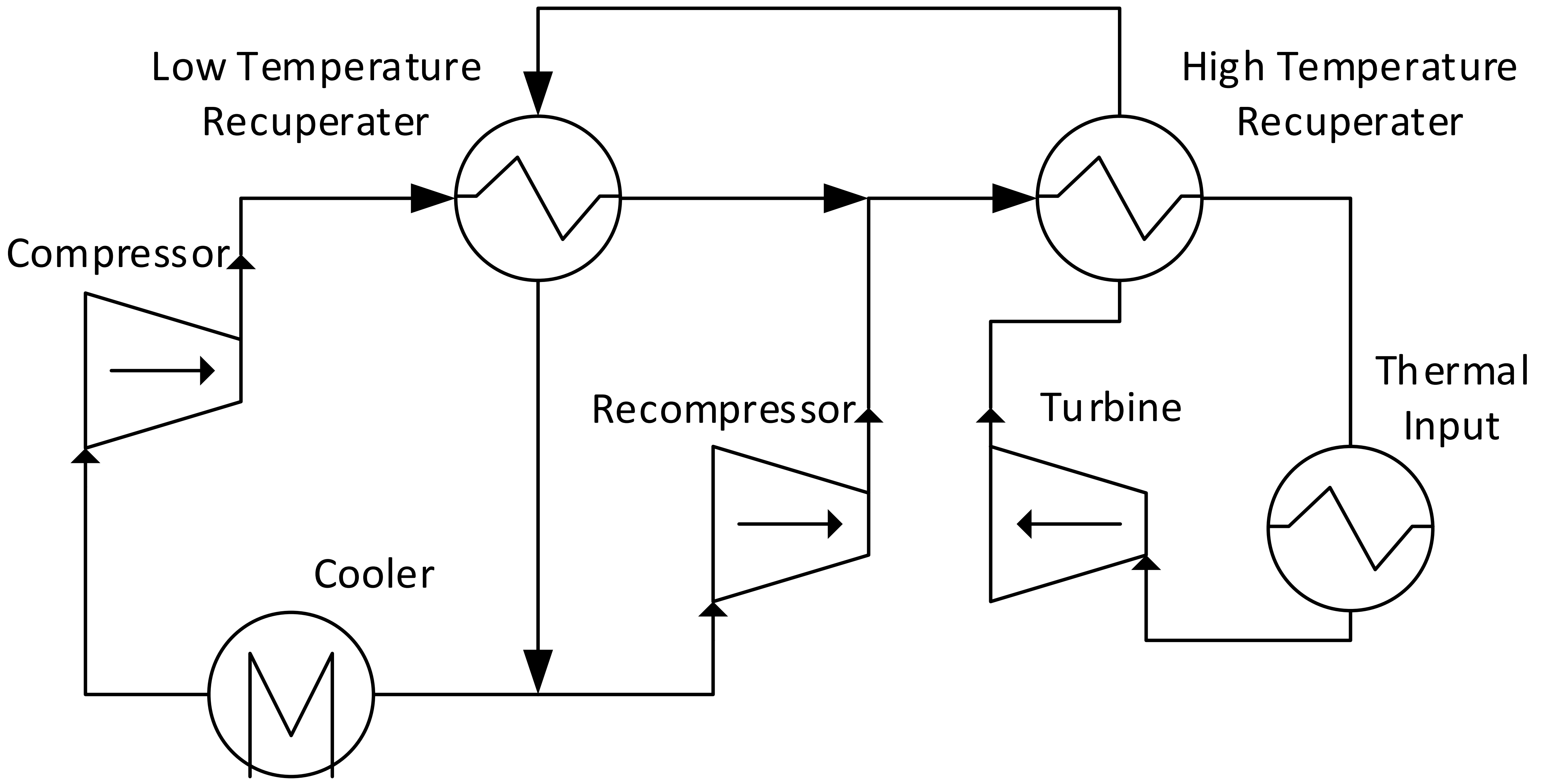
- Direct-fired (oxy-combustion)
- Indirect-fired (main heat exchanger, secondary fluid from variety of sources)

Heat Rejection:

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

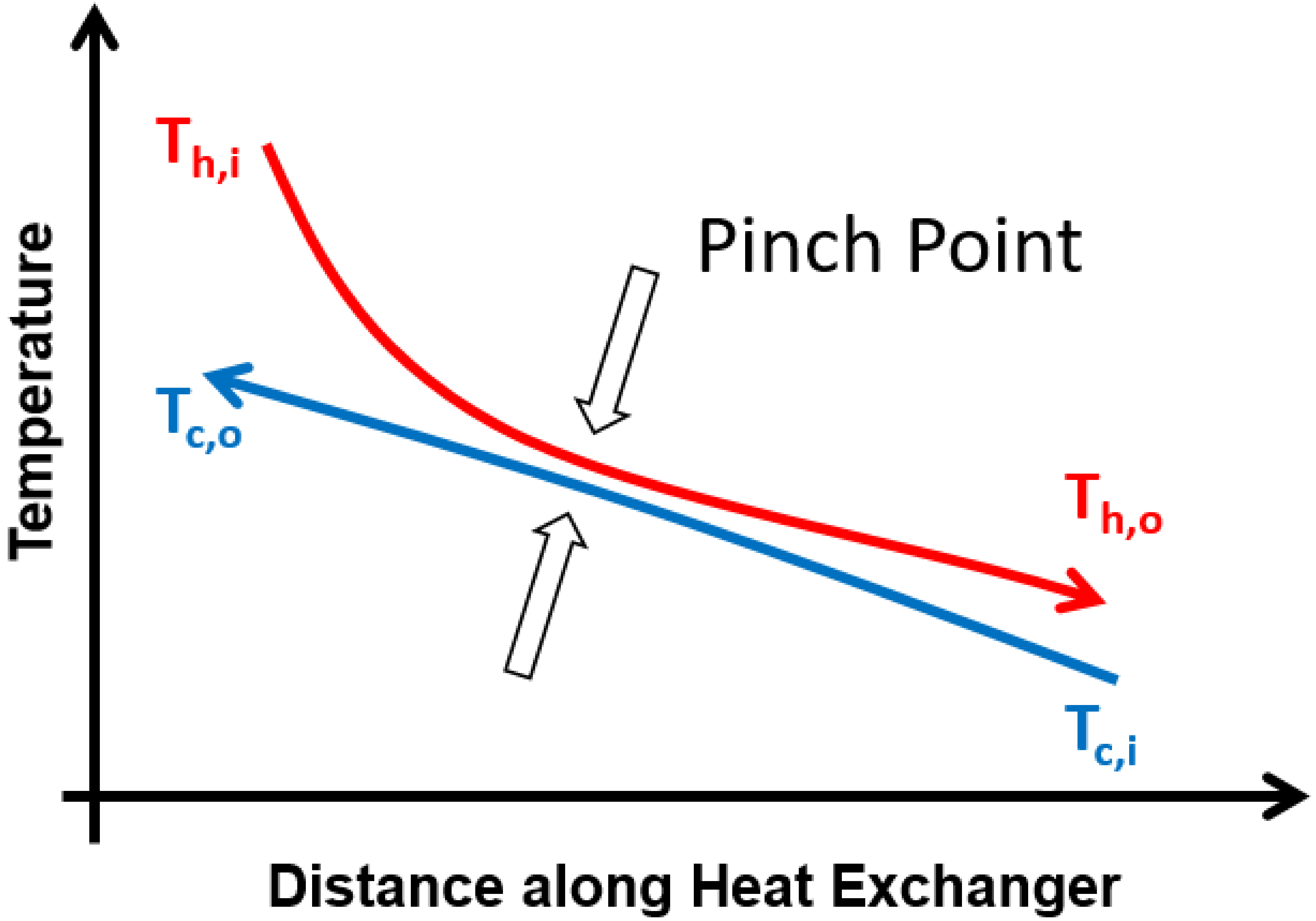
Recompression cycle is benchmark for indirect fired cycles.

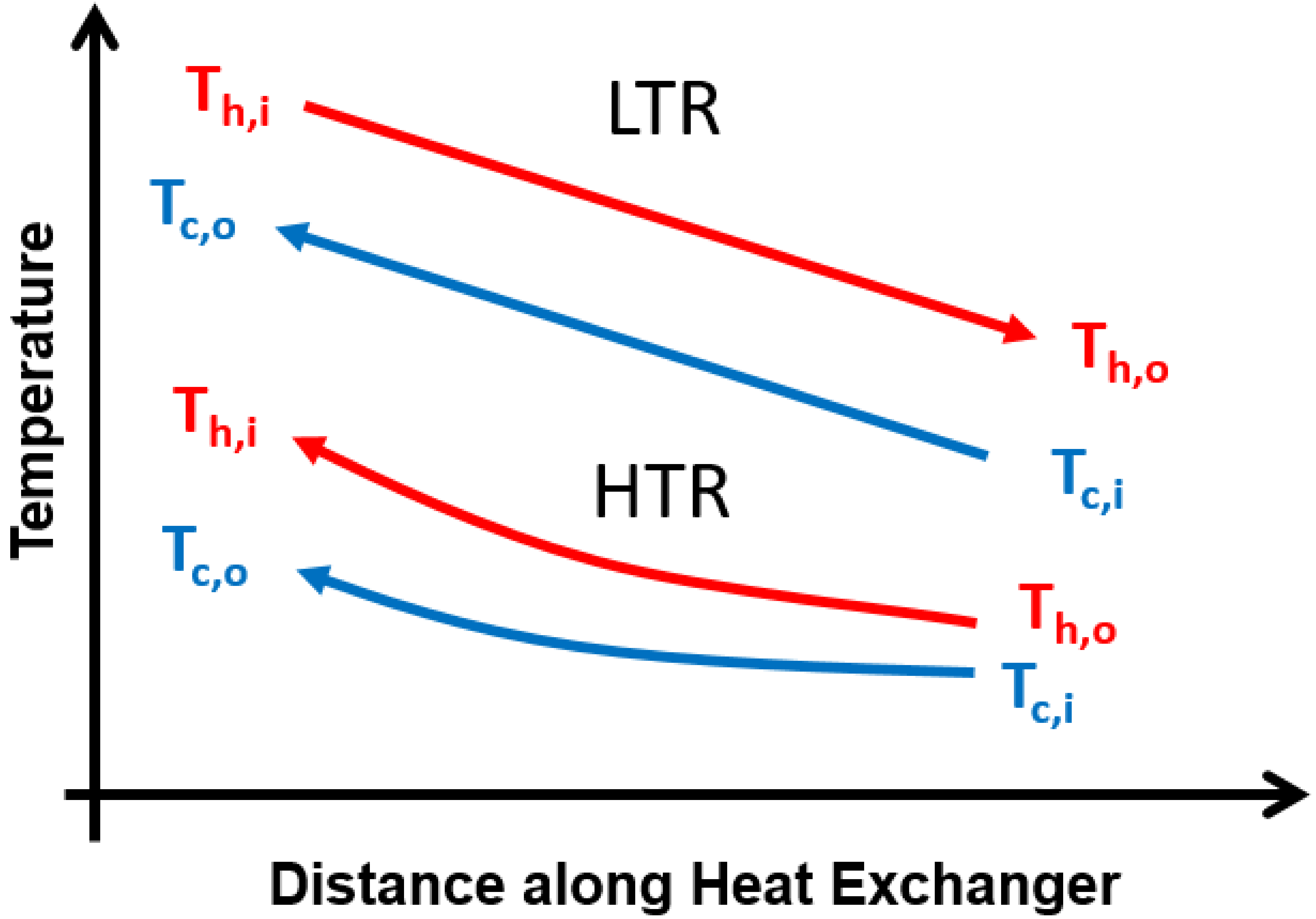




Main HX (Thermal Input) and Cooler can take on several forms, highly recuperated nature of cycle helps to drive up thermal efficiency.

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

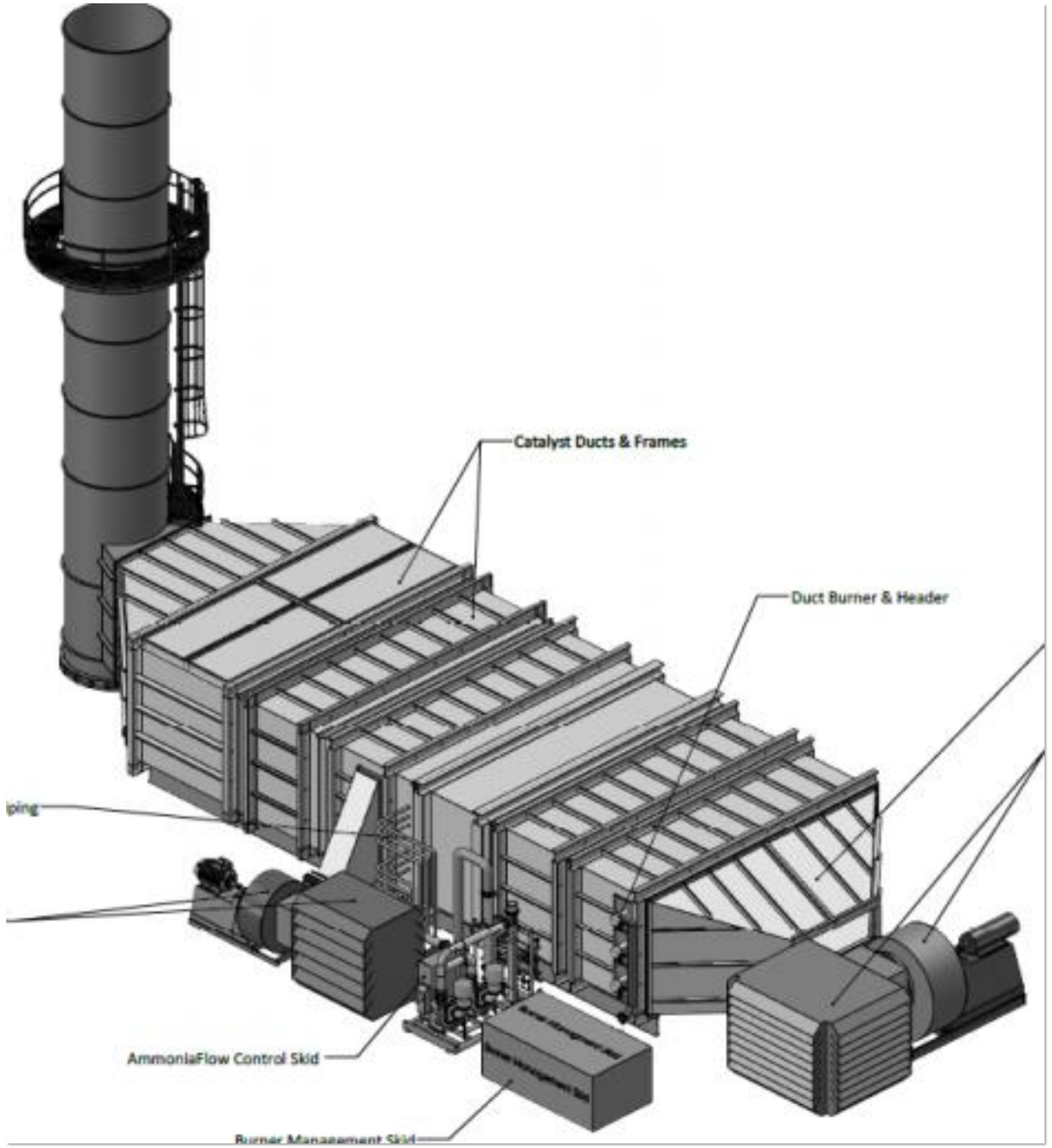




Splitting recuperator into Low Temperature (LTR) and High Temperature (HTR) units and employing cycle flow splits can get around pinch point issue.

Cycle Heat Exchangers – Main Heater

- Main heater design is dependent on heating medium/energy source.
- Waste Heat Recovery applications can use vertical or horizontal exhaust stack similar to HRSG.
- Other applications including CSP or Nuclear could utilize conventional shell-and-tube heat exchangers.



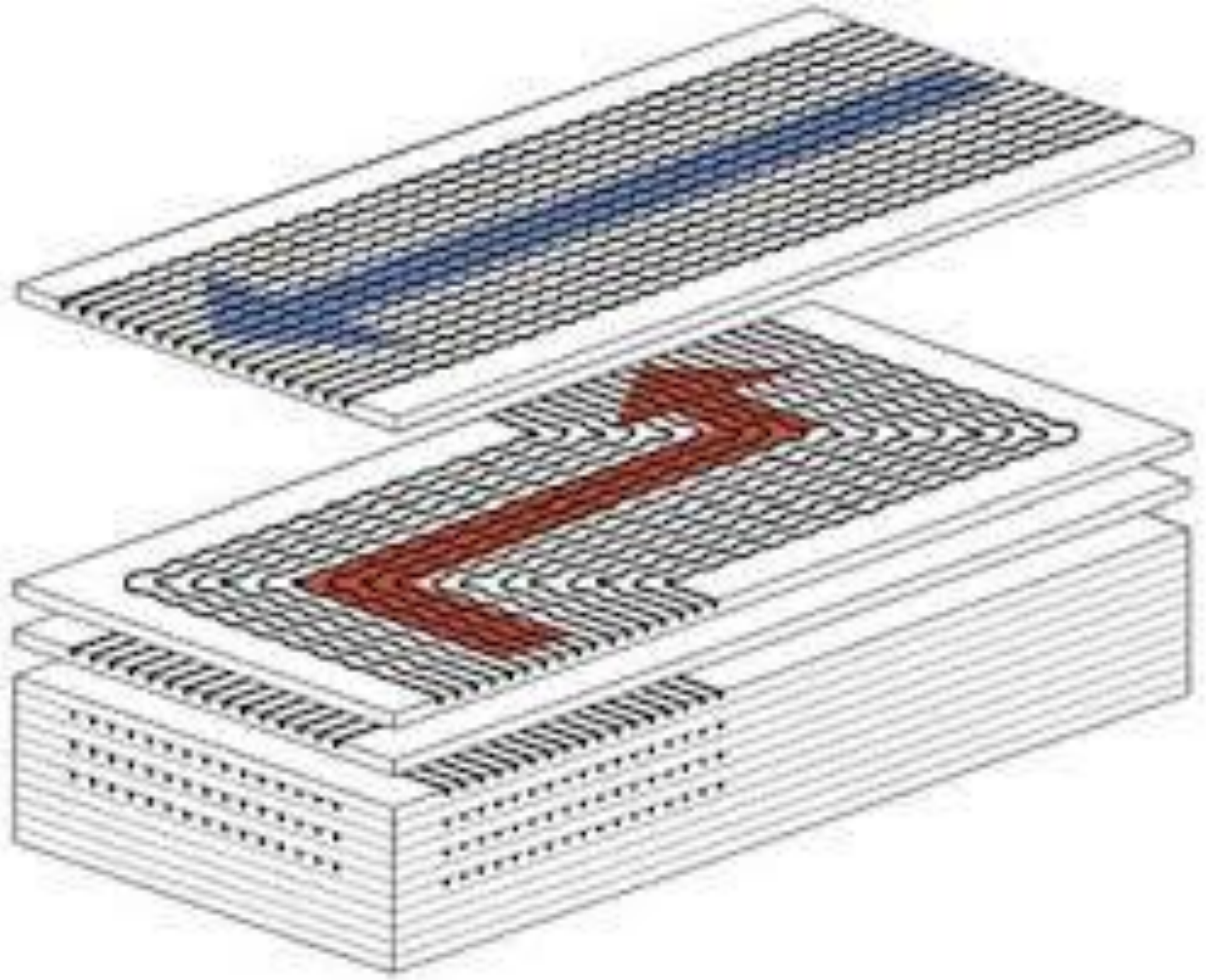
STEP 10 MWe Facility Natural Gas Fired Heater
(Figure: GTI)

(Figure: Southwest Thermal Technology, Inc.)

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.

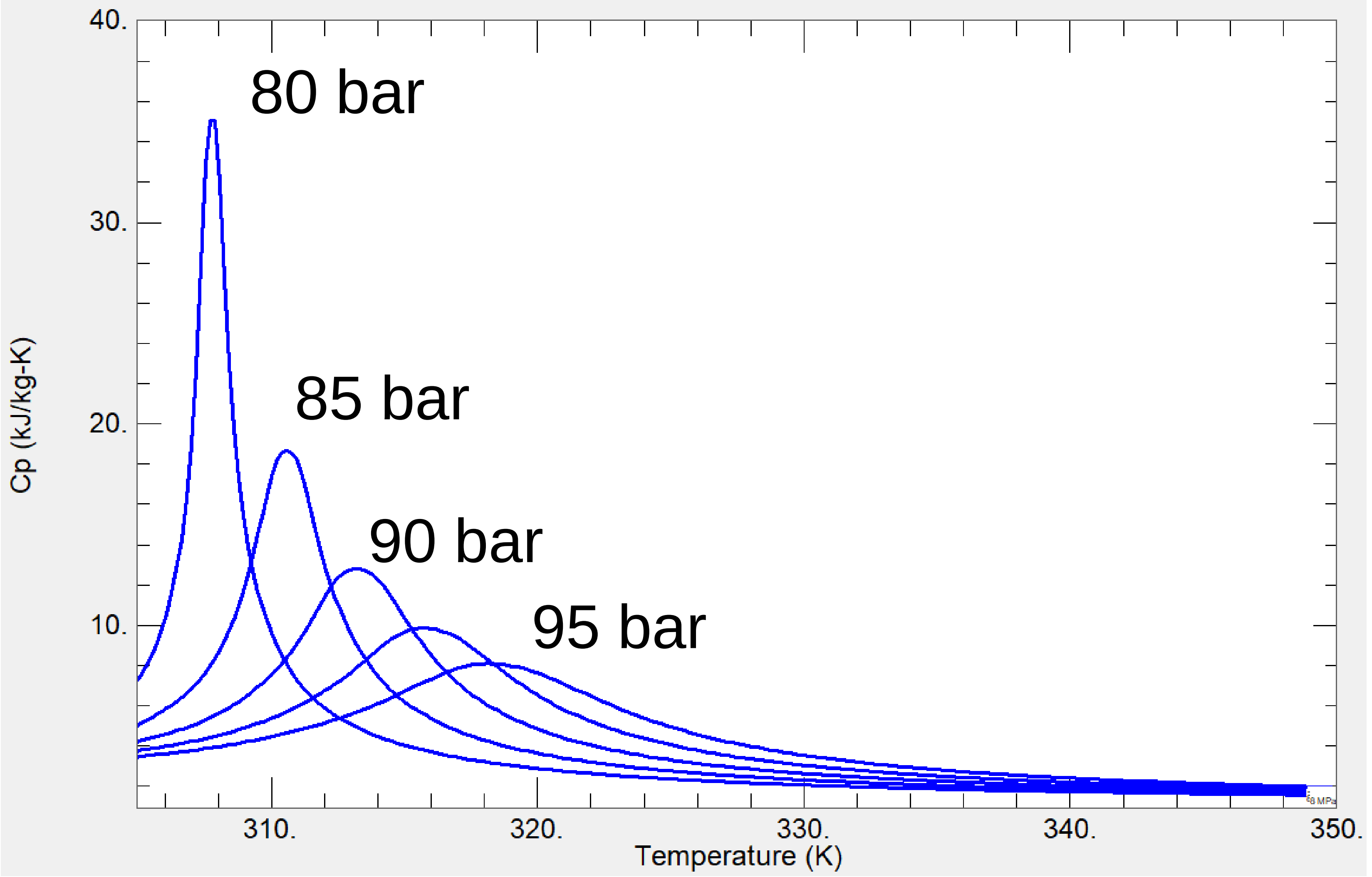
PCHE Recuperator for DOE SunShot program (VPE)



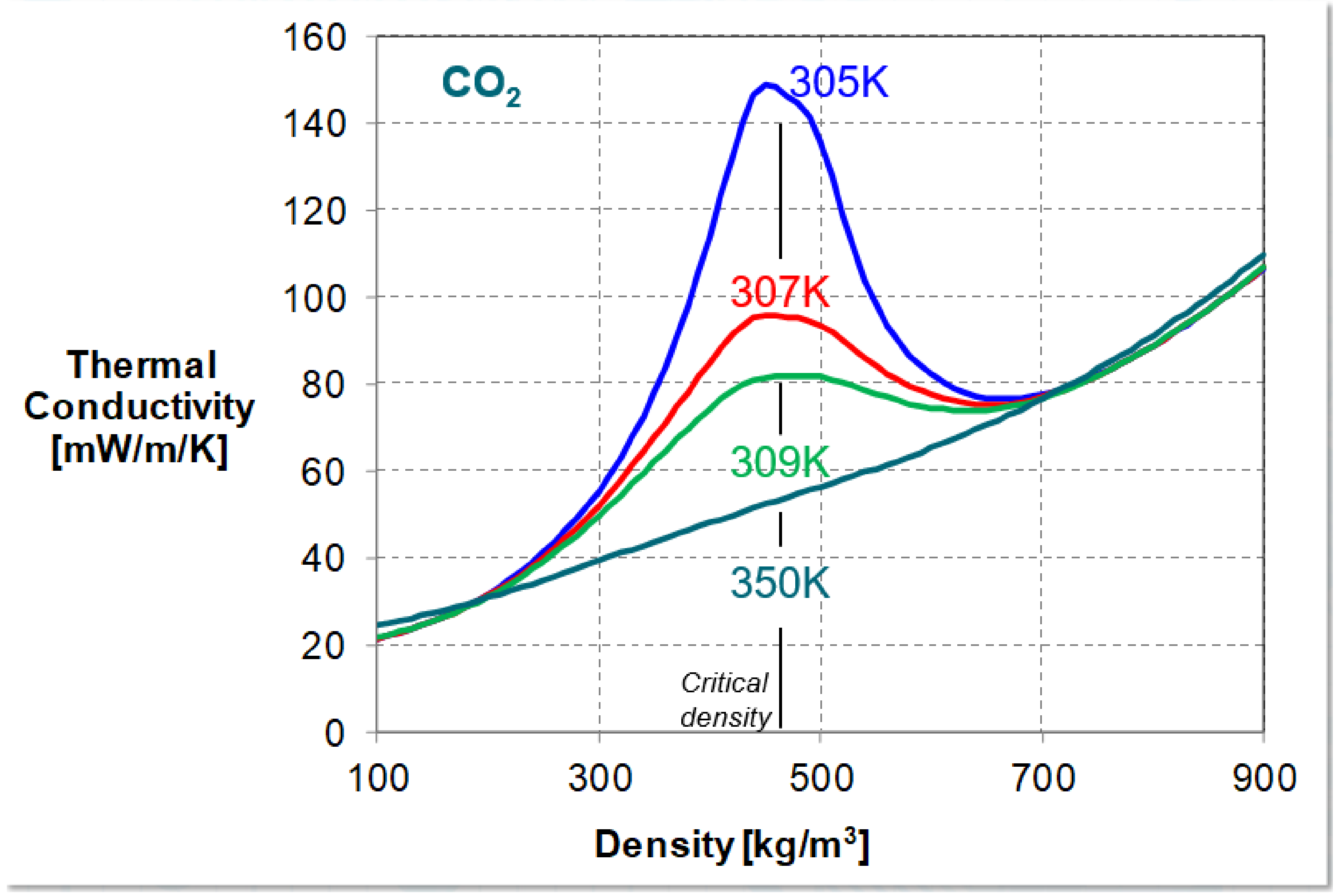
PCHE flow schematic
(Figure: Heatric)

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.



Source: NIST REFPROP



Source: NIST REFPROP

Figure: Goodway Technologies

Cycle Heat Exchangers – Additive Manufacturing

- Additive manufacturing is a prospective option for sCO_2 recuperators and coolers (water).
- 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

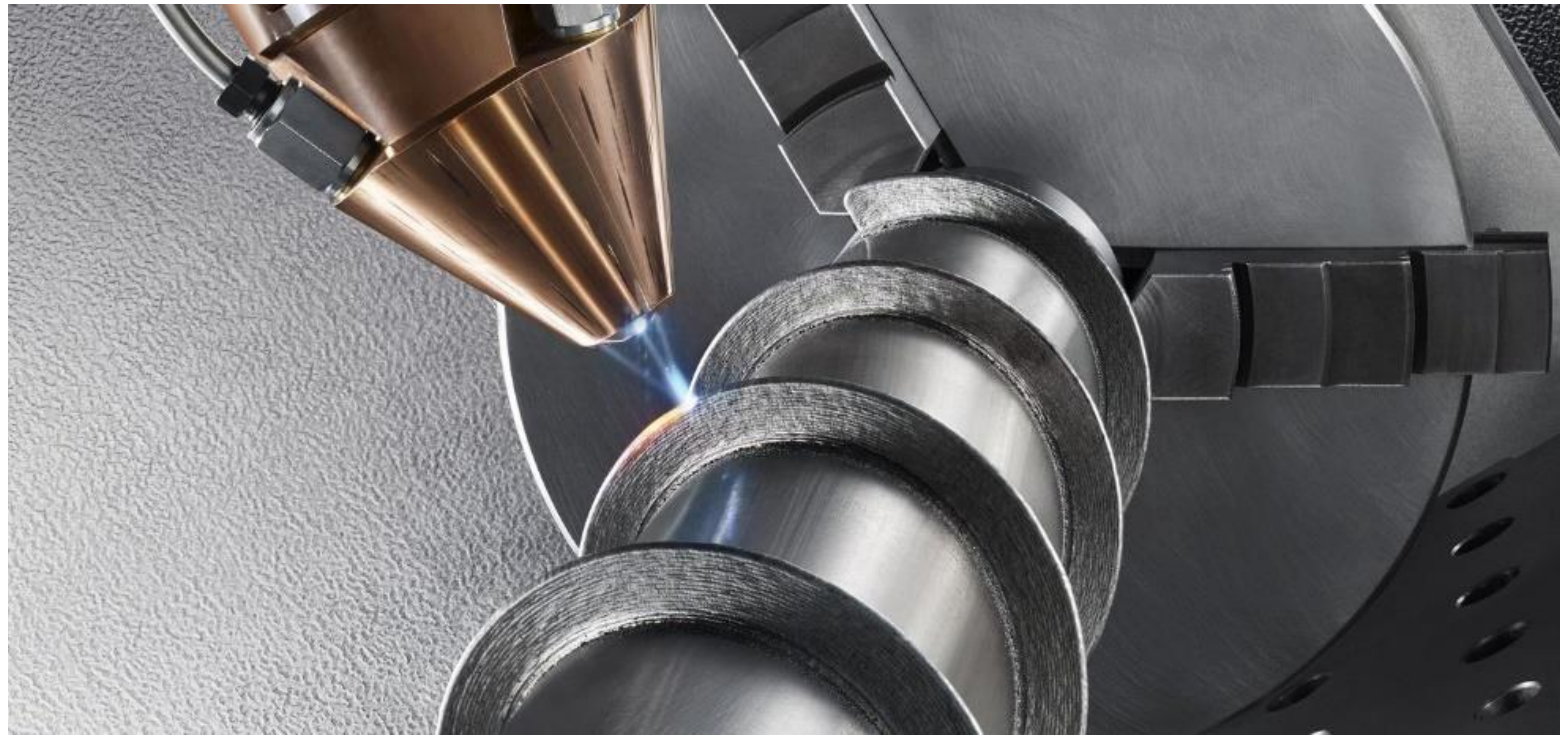


Figure: Trumpf

Cycle Heat Exchangers – Additive Manufacturing

- Additive Manufacturing machines typically have limited build volume (kW vs. MW commercial scale). Core would likely need to be built in parallel.
- For safe operation, verification methods are needed to determine material properties and the presence of imperfections (CT-scan).
- Development programs include ARPA-E HITEMMP, multiple projects looking to test additive heat exchangers in 800 °C environment

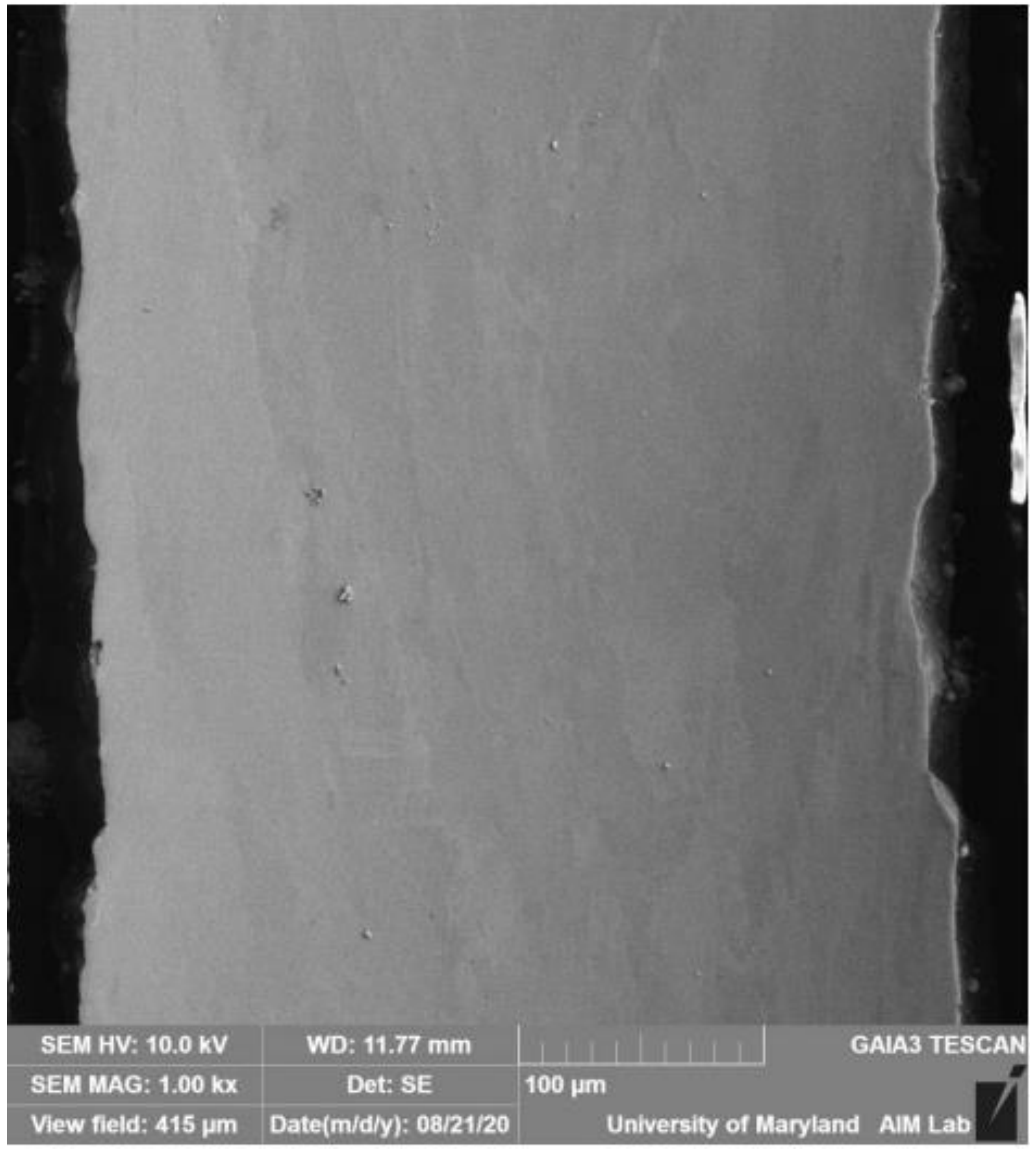
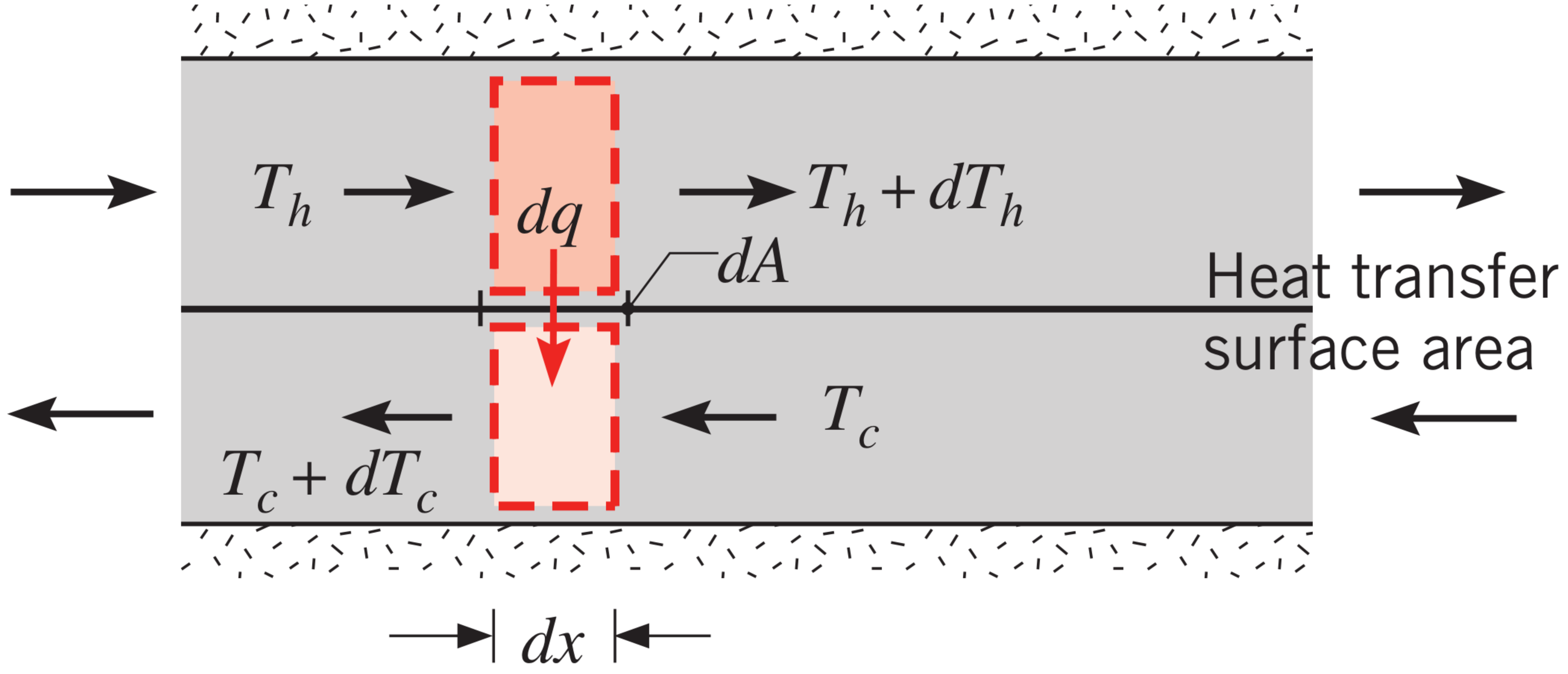


Figure: Zhao, J.C. et. al. , ARPA-E HITEMMP Annual Meeting.

Heat Exchanger Thermal Design Overview



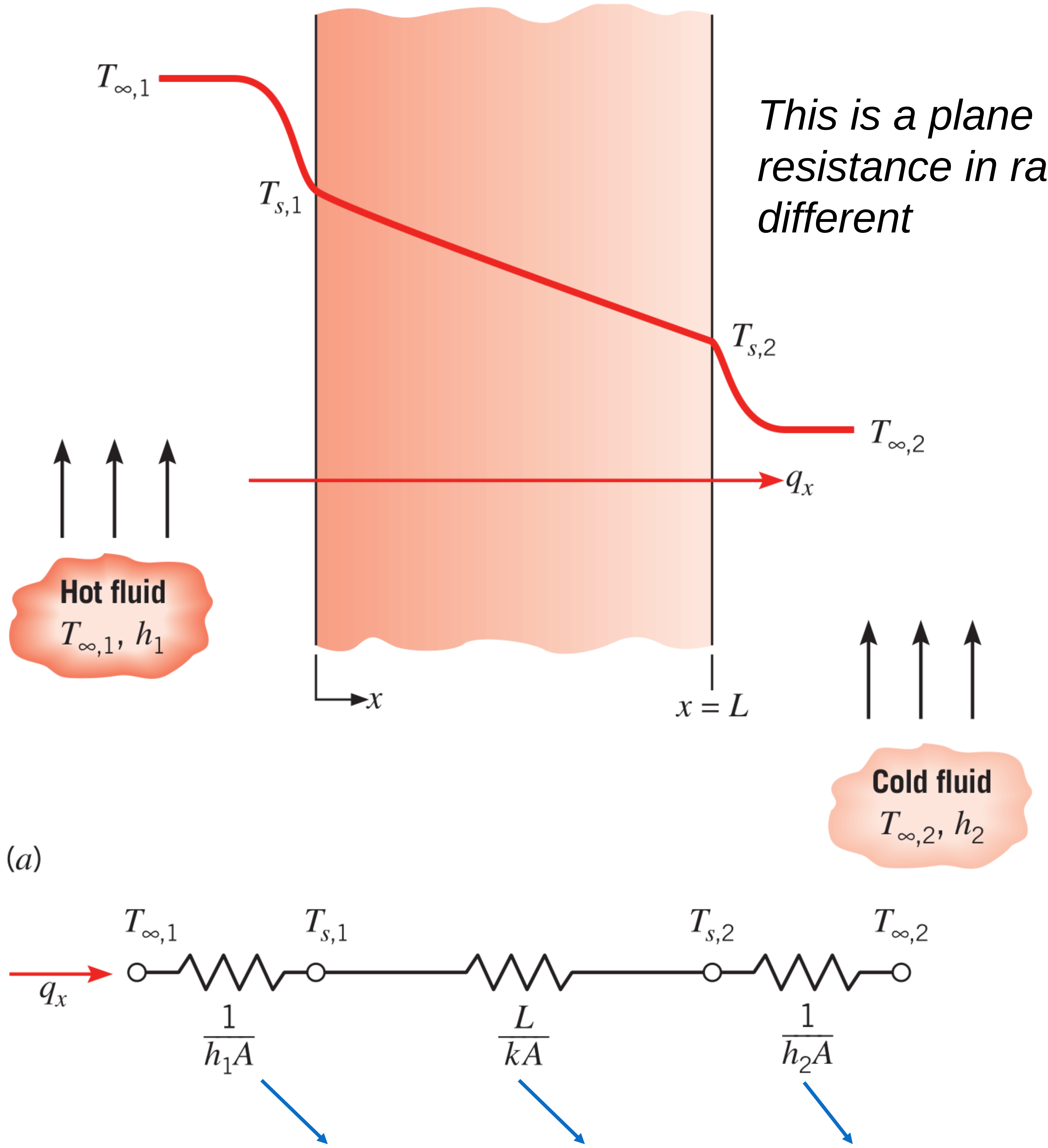
Once the cycle has established heat exchanger design conditions, detailed design can begin.

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.

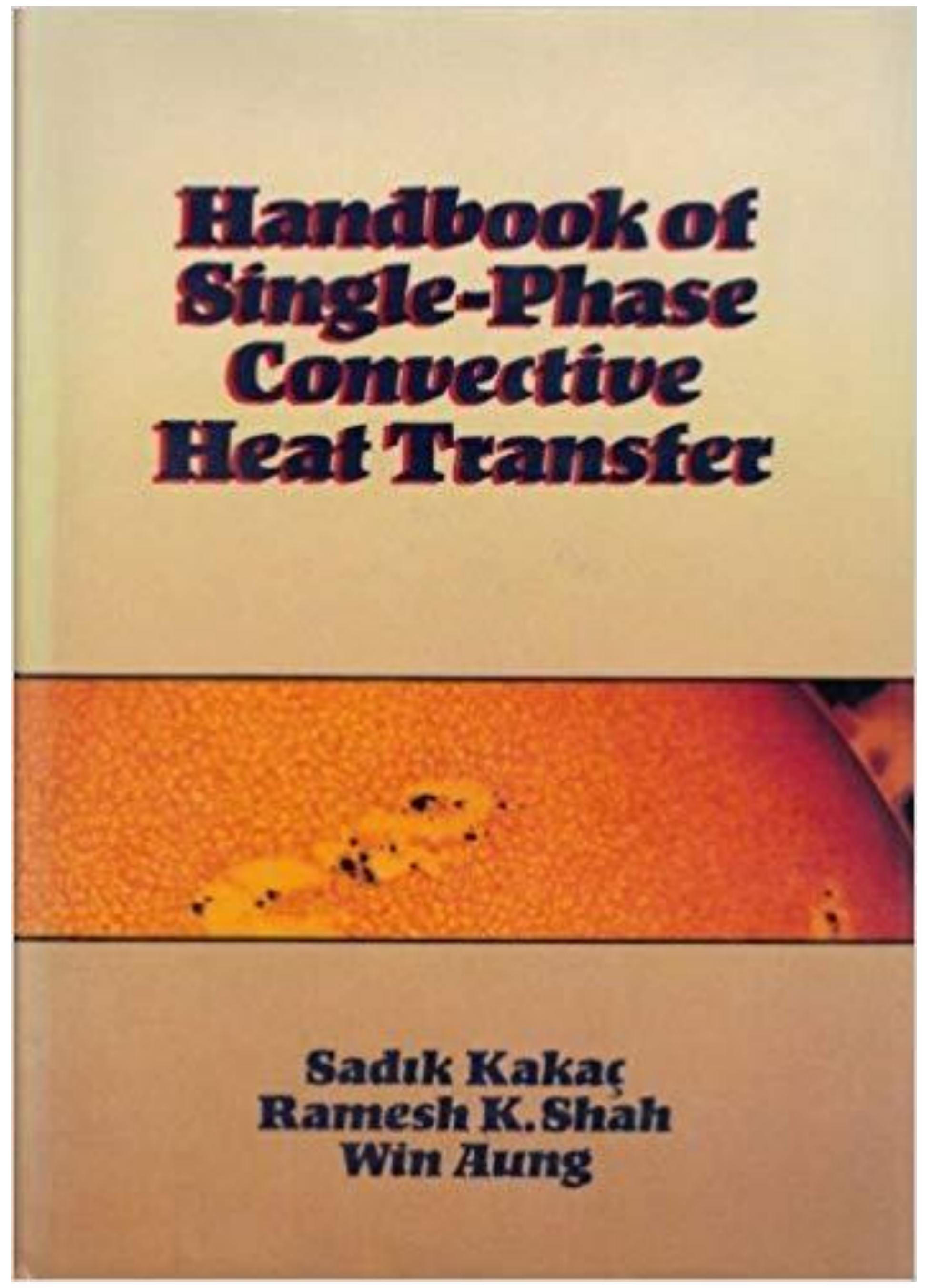
Figure: Incropera, Dewitt, *Fundamentals of Heat and Mass Transfer.*

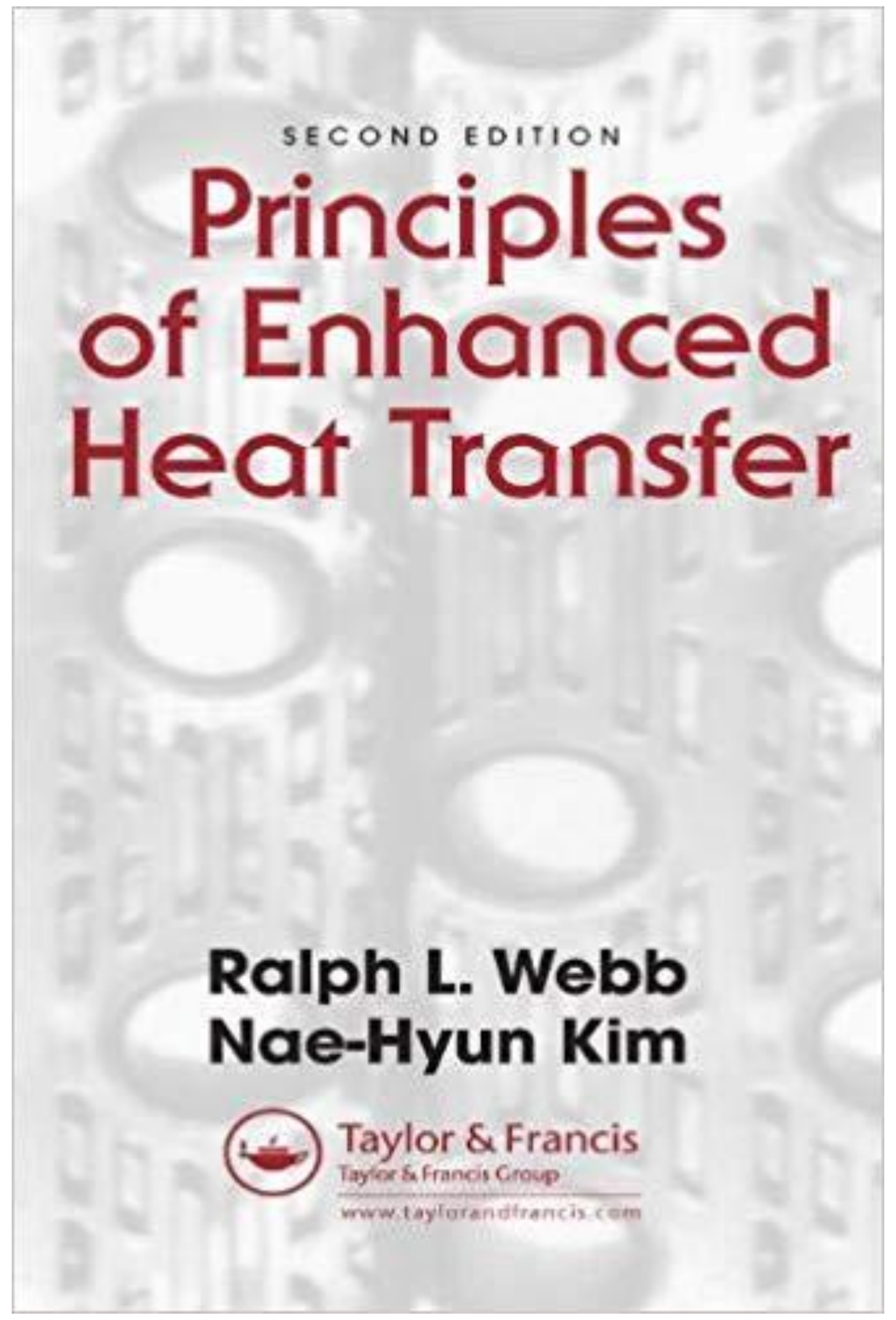
Fluid Heat Transfer

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

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

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



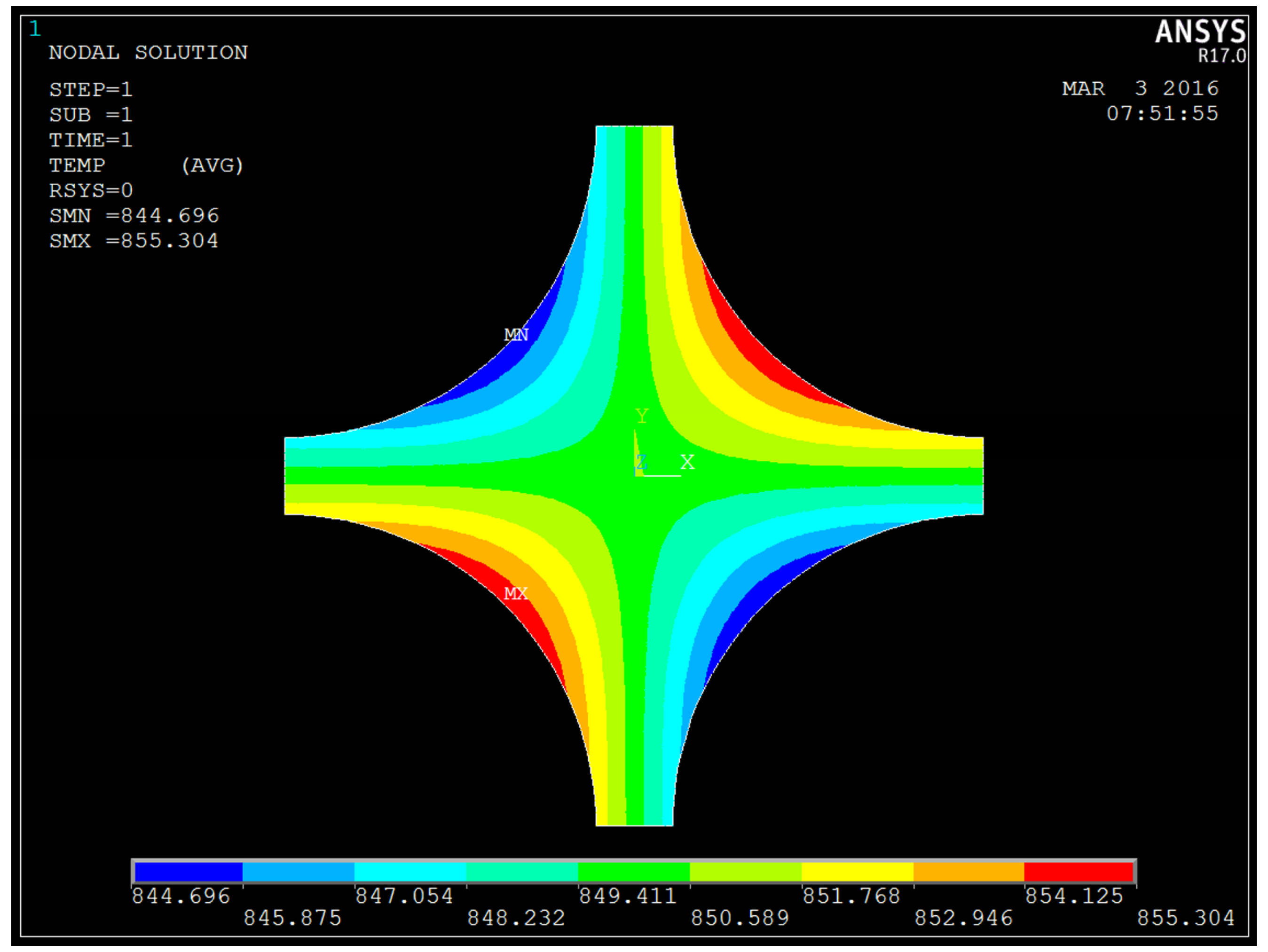


To calculate the required UA term we need the hot and cold side heat transfer coefficients. These can be derived from experiments, CFD, or from correlations.

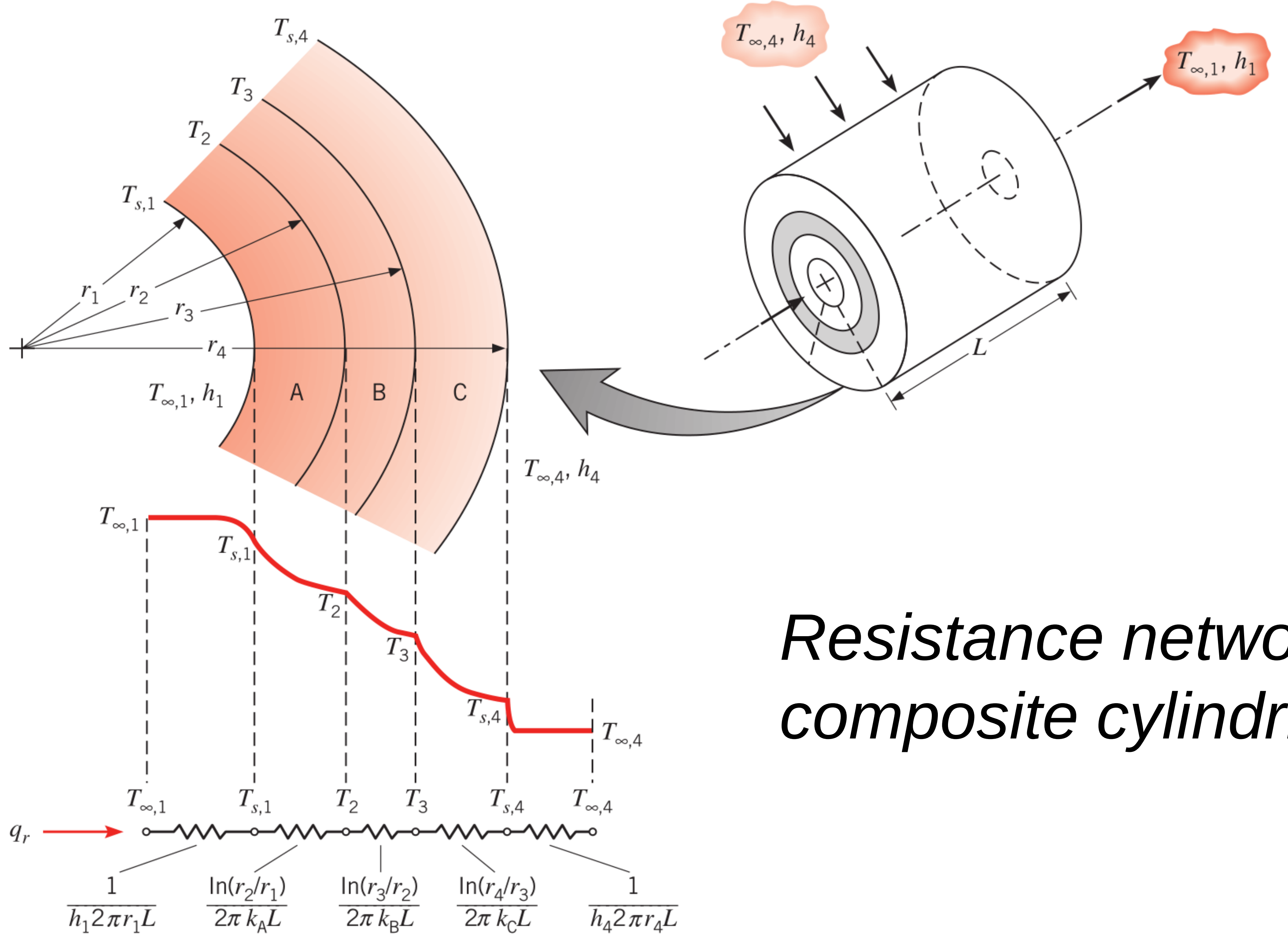
Experiments or experimentally derived correlations are most accurate but are geometry dependent.

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

Wall Resistance



FEA used to calculate equivalent wall resistance for checkerboard circular channels



Resistance network for composite cylindrical wall

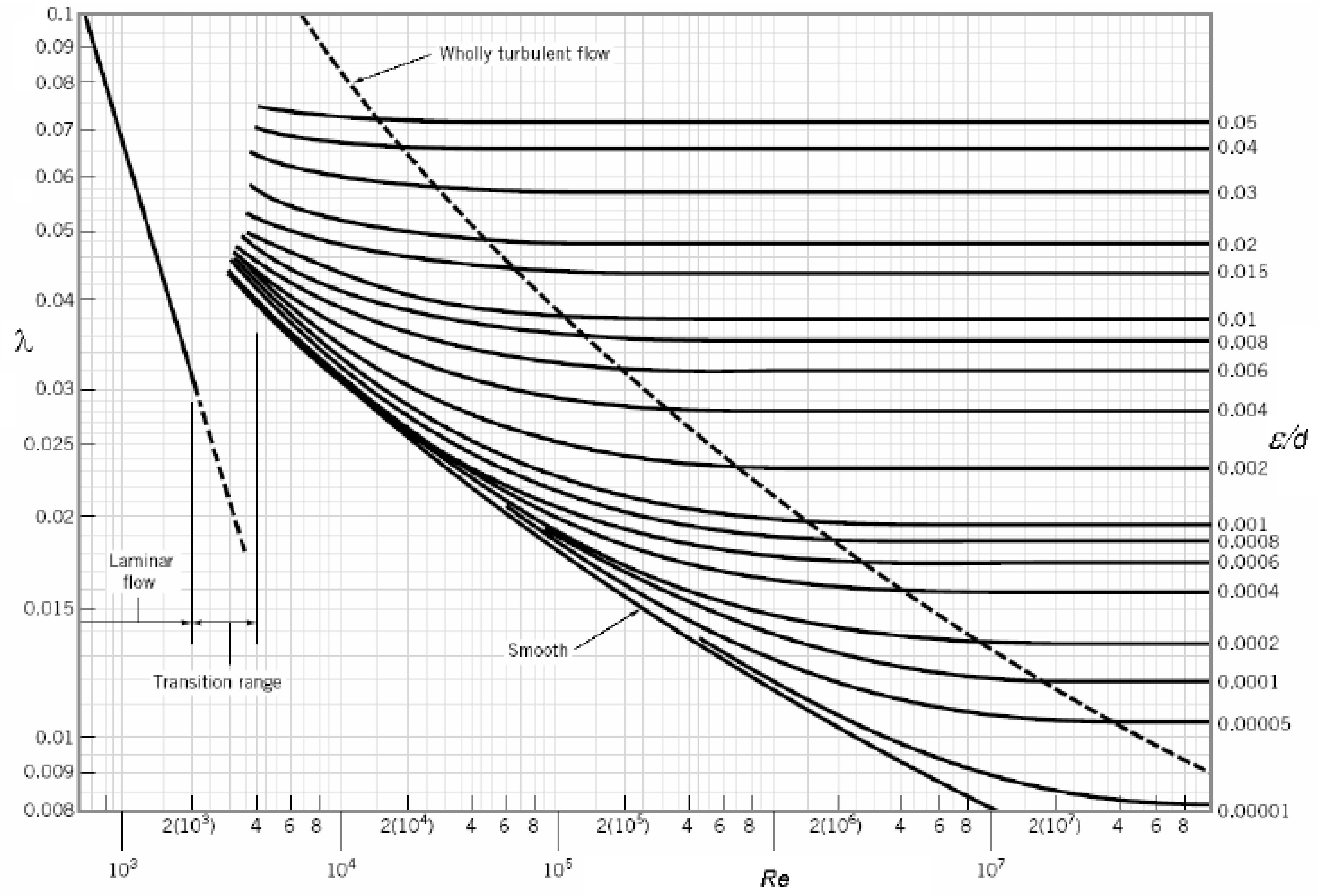
$$\frac{1}{UA} = \frac{1}{(hA)_h} + R_w + \frac{1}{(hA)_c}$$

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

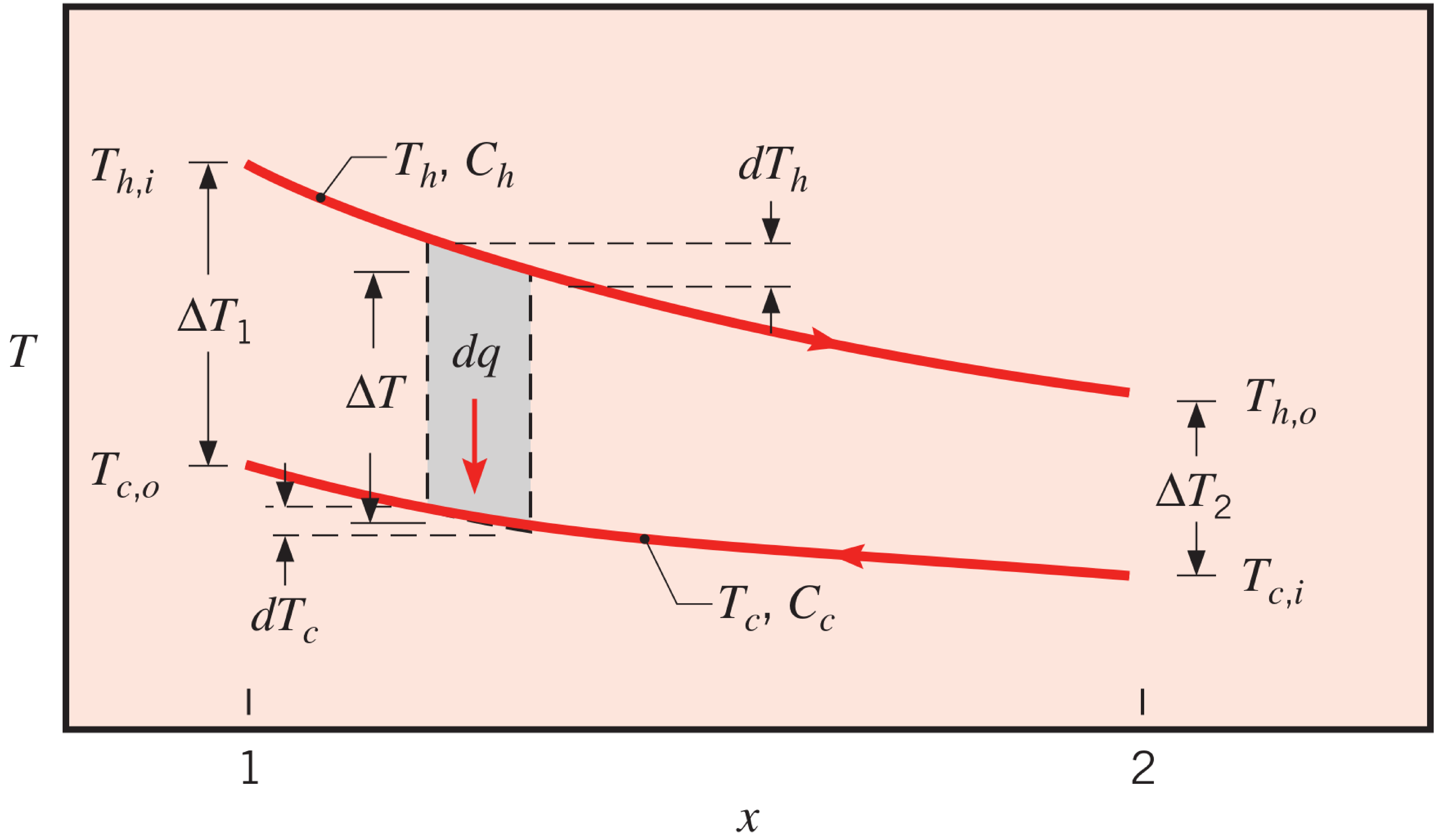


Figure: Incropera, Dewitt, *Fundamentals of Heat and Mass Transfer.*

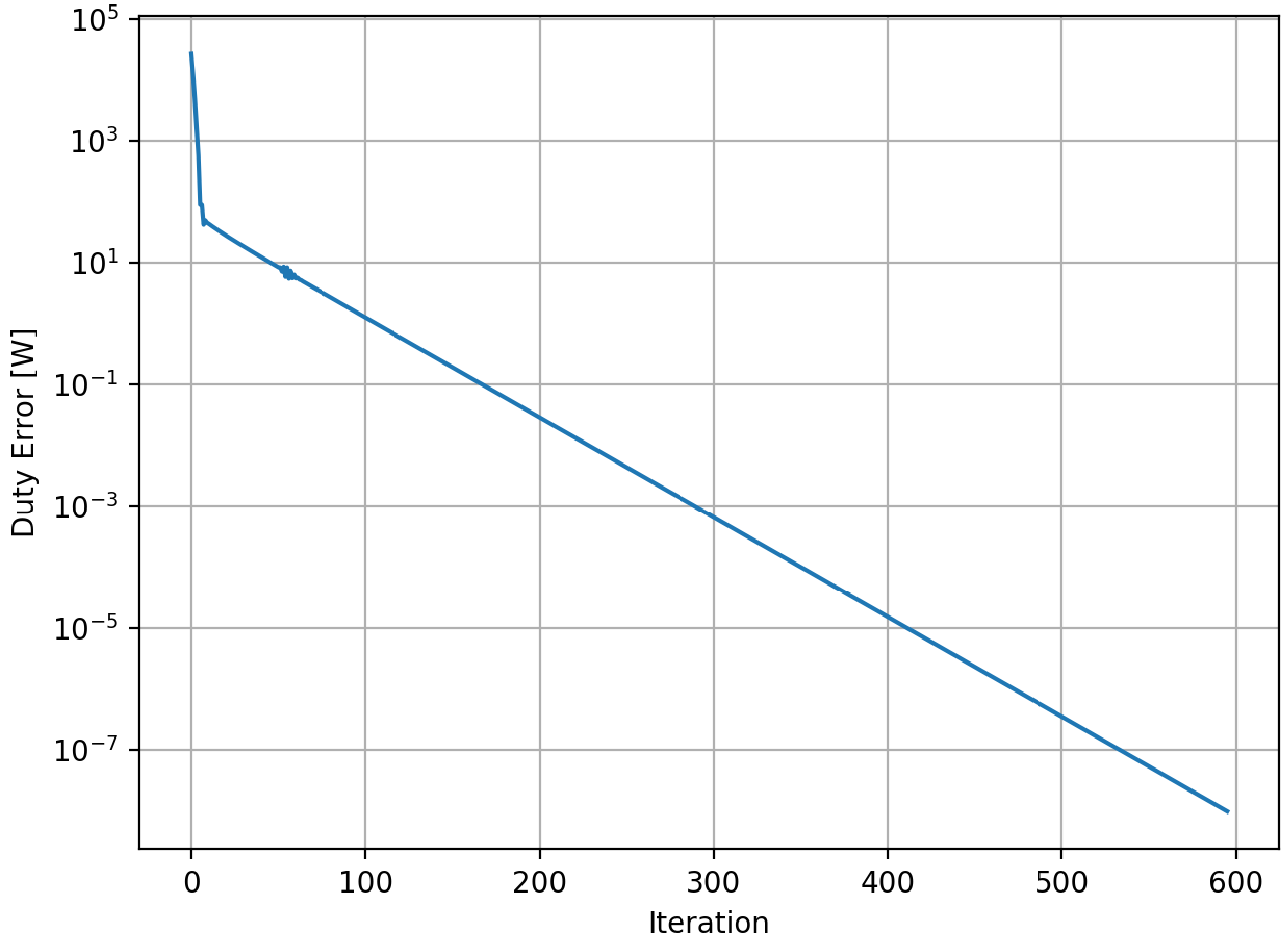
Energy conservation

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.*

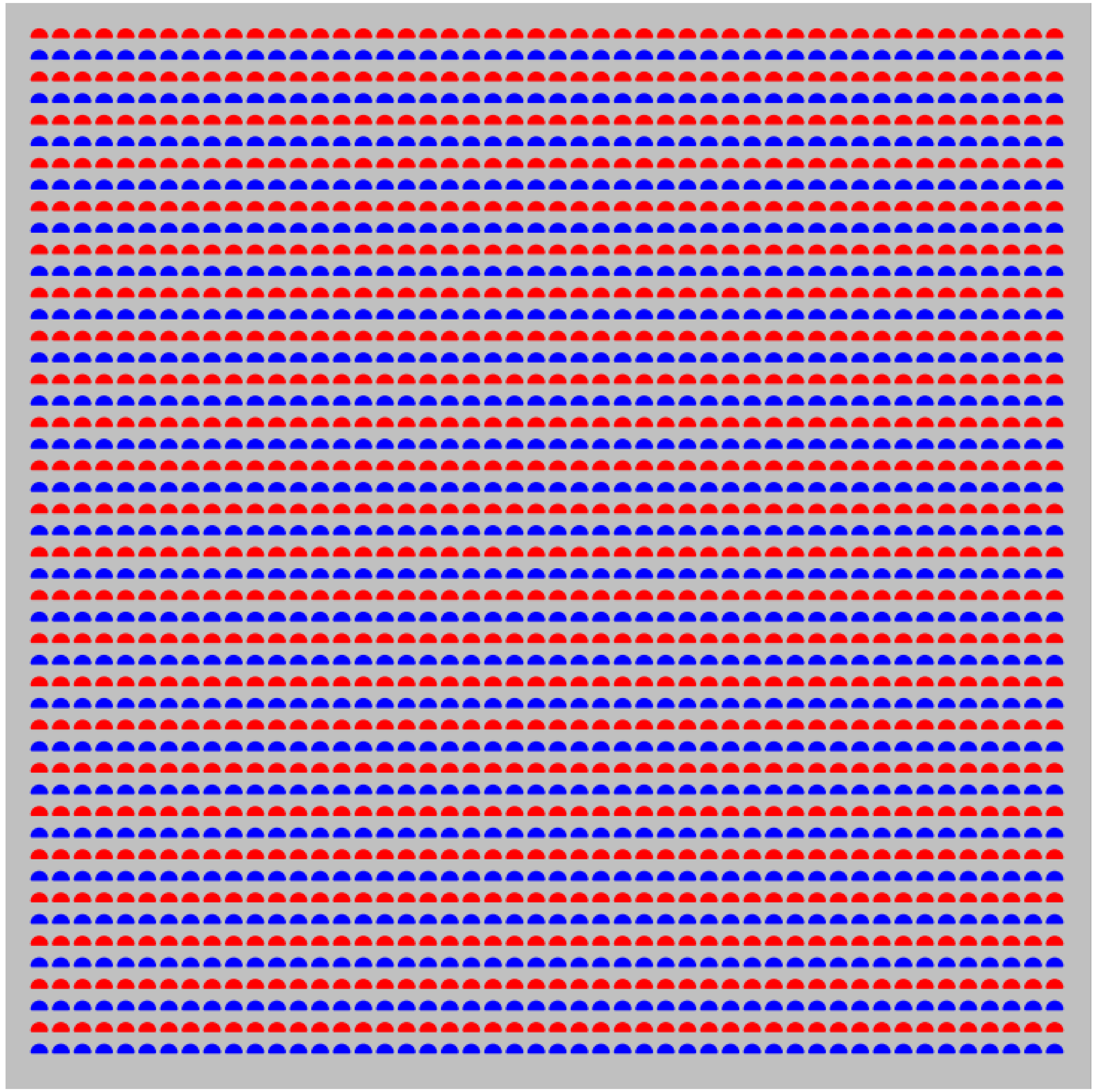
Strategy:
-Divide heat exchanger into divisions
-Guess initial temperature distribution

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

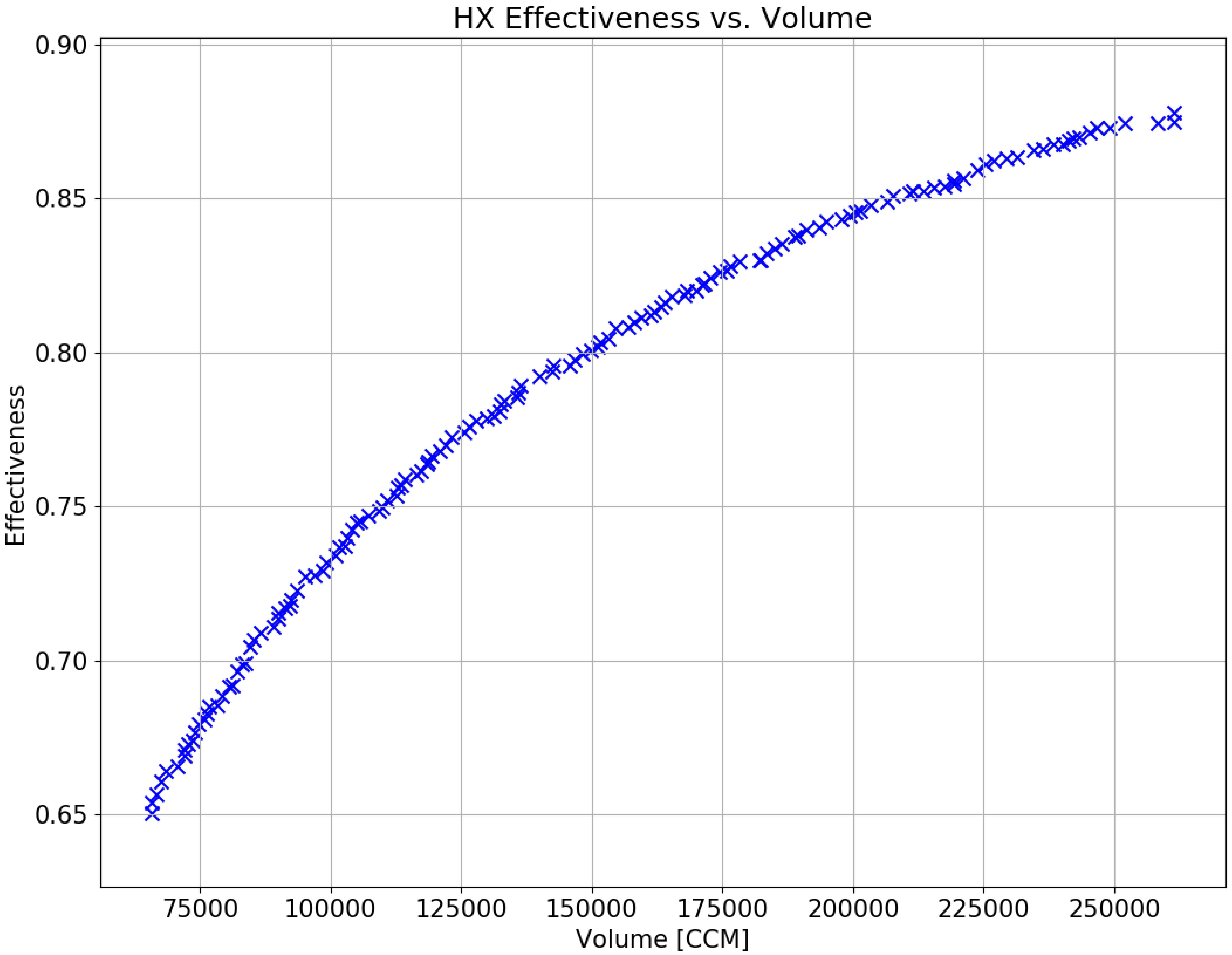
Set Objectives

- 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.

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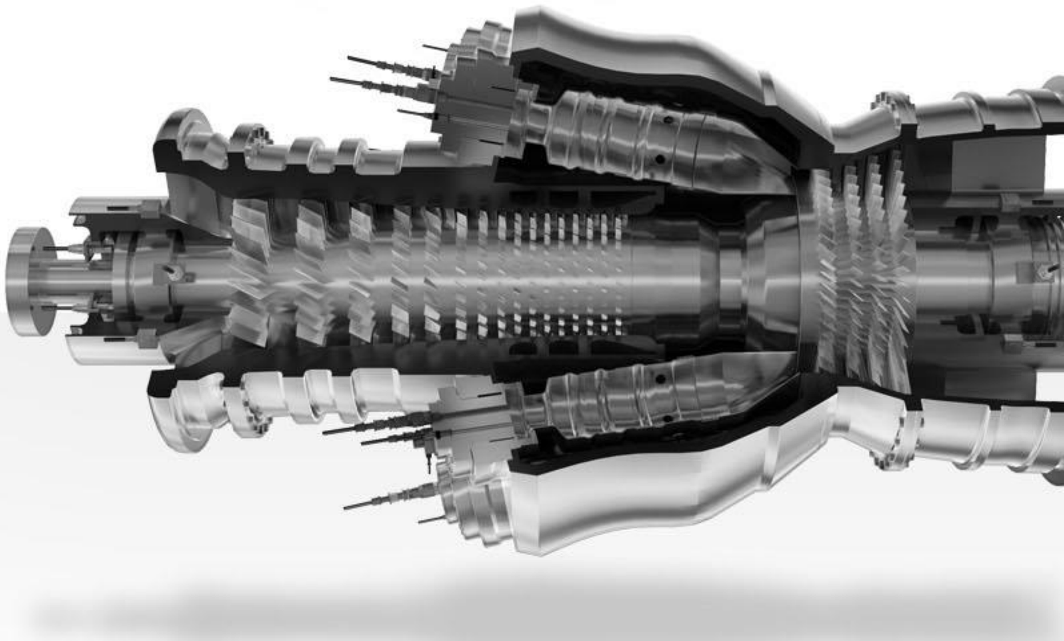

presented by:
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June 2021

1 | **Examples of PCHEs globally delivered for Power Cycles**

2 | **Economic feasibility of PCHEs for sCO2 power cycles**

3 | **Benefits of PCHEs**

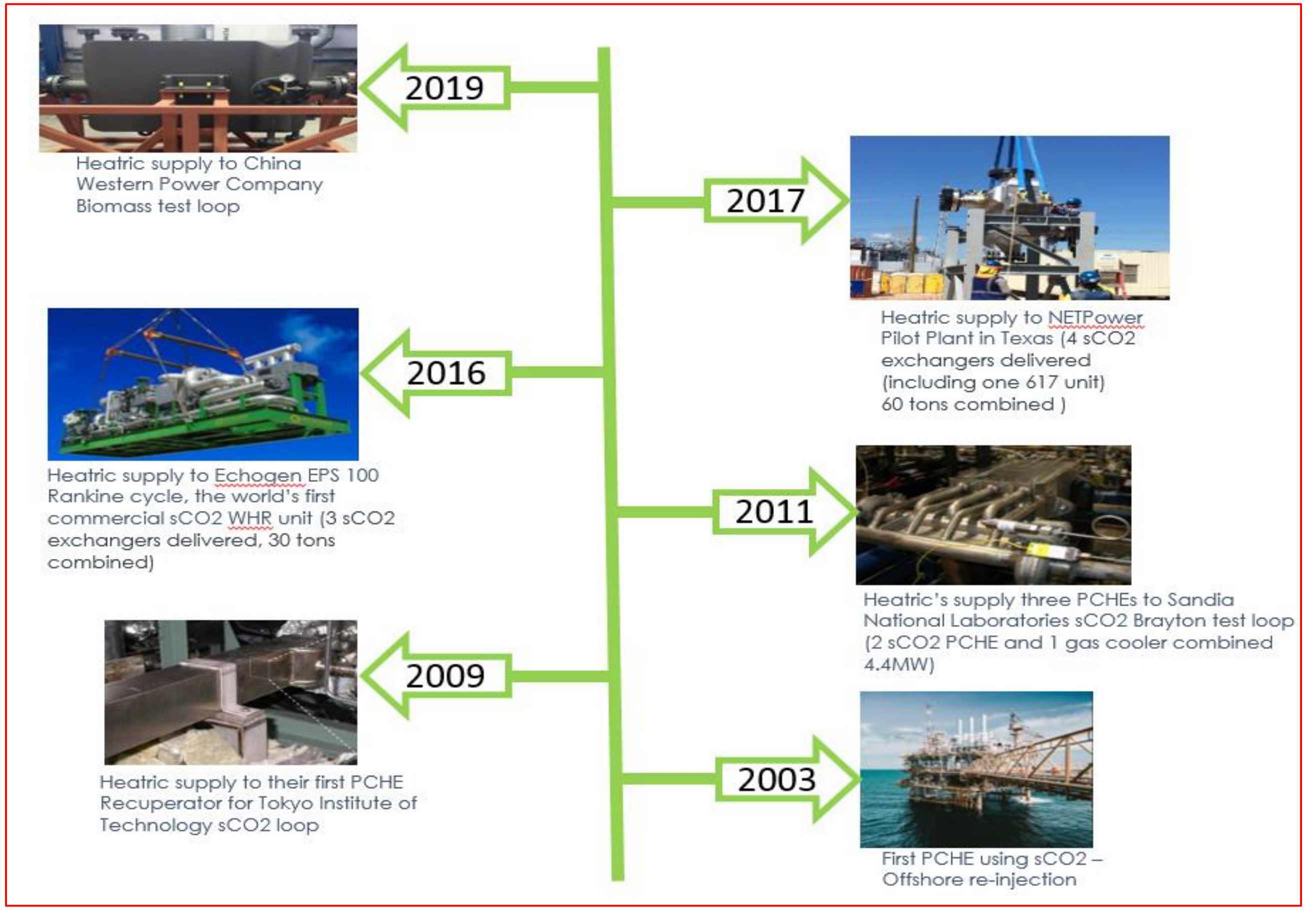
4 | **PCHEs design and construction**

1

Examples of PCHEs globally delivered for Power Cycles

Examples of PCHEs globally delivered for Power Cycles

PCHEs Globally Delivered Projects for sCO2 Cycles



2019

Heatric supply to China Western Power Company Biomass test loop

2017

Heatric supply to NETPower Pilot Plant in Texas (4 sCO2 exchangers delivered (including one 617 unit) 60 tons combined)

2016

Heatric supply to Echogen EPS 100 Rankine cycle, the world's first commercial sCO2 WHR unit (3 sCO2 exchangers delivered, 30 tons combined)

2011

Heatric's supply three PCHEs to Sandia National Laboratories sCO2 Brayton test loop (2 sCO2 PCHE and 1 gas cooler combined 4.4MW)

2009

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

2003

First PCHE using sCO2 – Offshore re-injection

	USA	Australia	U.K.	Germany	Canada	China	Japan	Korea
N° Project	10	1	2	1	1	1	1	1
N° Units	21	3	2	2	2	2	1	1

- sCO2 power cycles (Recuperator, coolers and supper heaters)
- Combined Cycle Gas Turbine (fuel gas heaters and Rotor Air Coolers, condenser, evaporator
- Energy storage
- Waste heat recovery (WHR), Nuclear, concentrating solar, fossil energy

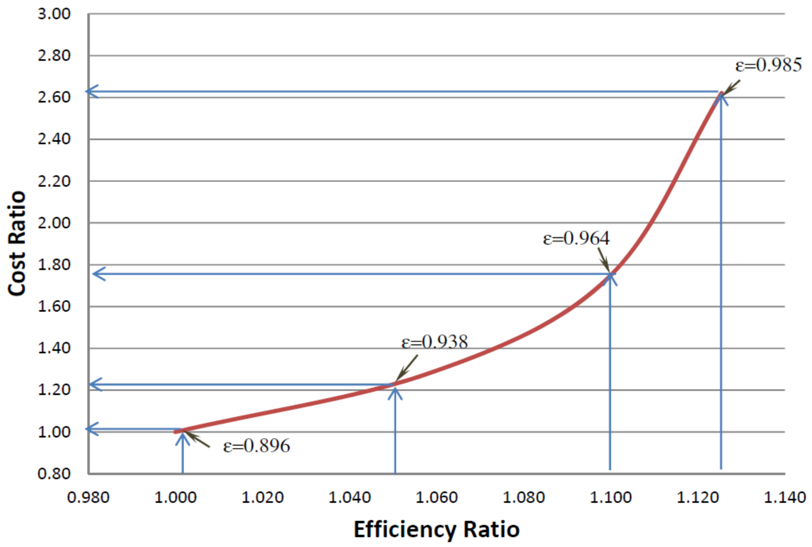
2 Economic feasibility of PCHEs for sCO2 power cycles

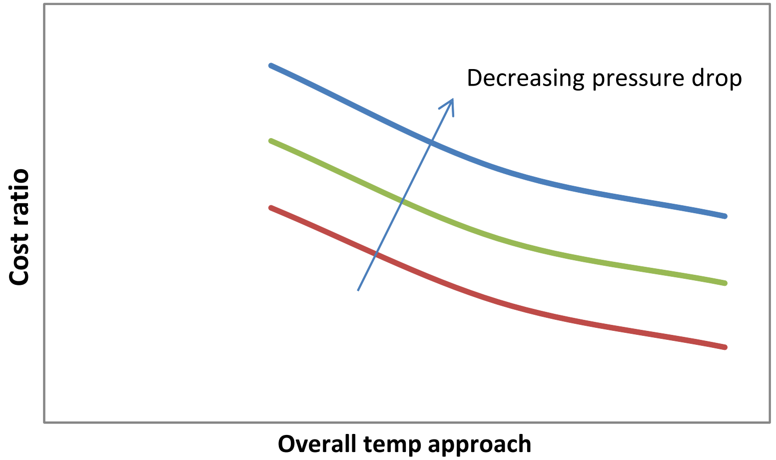
Economic feasibility of PCHEs for sCO2 power cycles

Economic feasibility – effectiveness of exchangers versus cost and cycle efficiency

- **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**





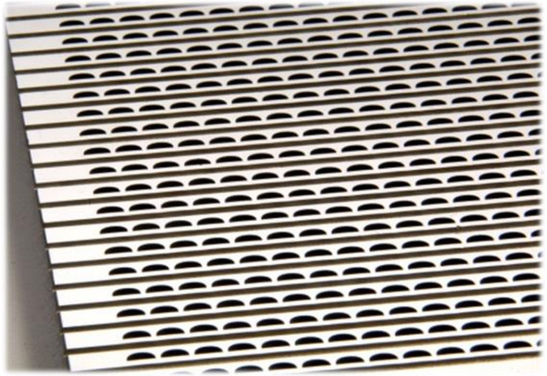
3

Benefits of PCHEs

Benefits of PCHEs

Printed Circuit Heat Exchangers

Superior Performance

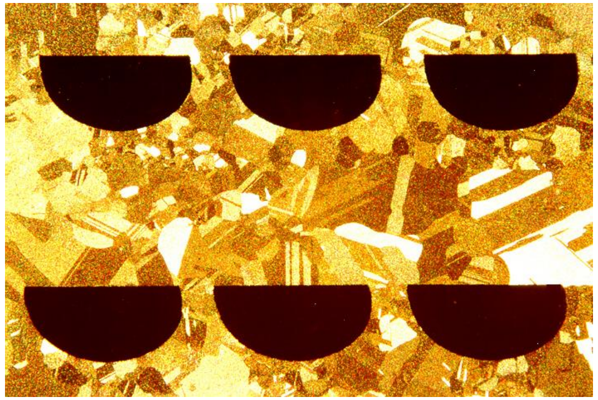


OPEX saving across wide range of processes

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 983°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 and Modular

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

Benefits of PCHEs

Printed Circuit Heat Exchangers

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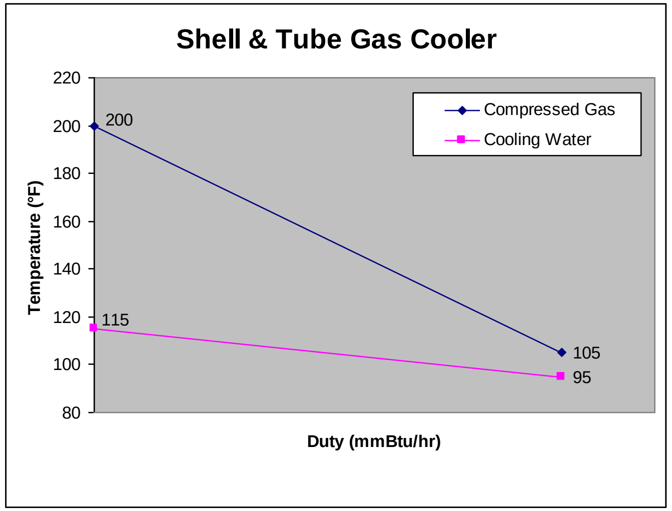
Coolant flow reduction - Temperature optimization

Reduced pumping requirements ➔ Lower capital & operating costs

Smaller diameter piping system ➔ Lower capital costs Reduced weight & space

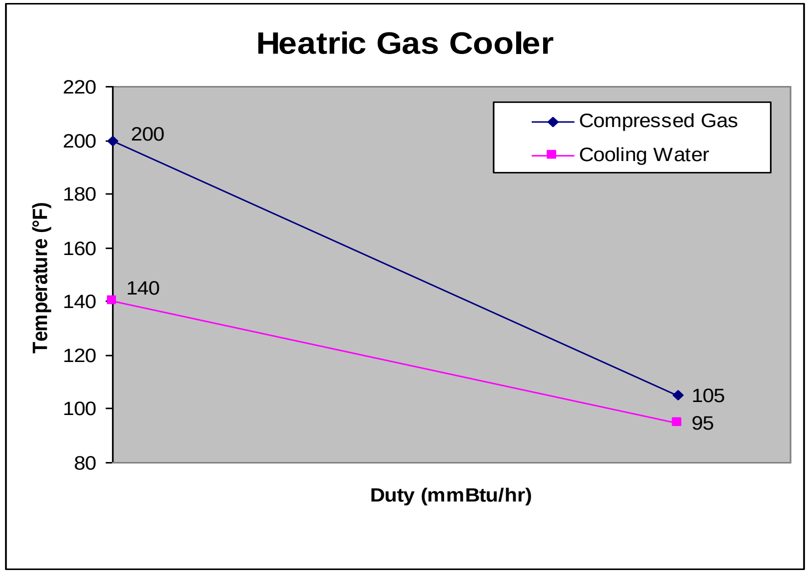
Greater mechanical & routing flexibility

Smaller coolant inventory ➔ Lower operating weight



$Q = m_1\ Cp\ \Delta T_1$

$Q = m_1\ Cp\ (115\text{-}95)$



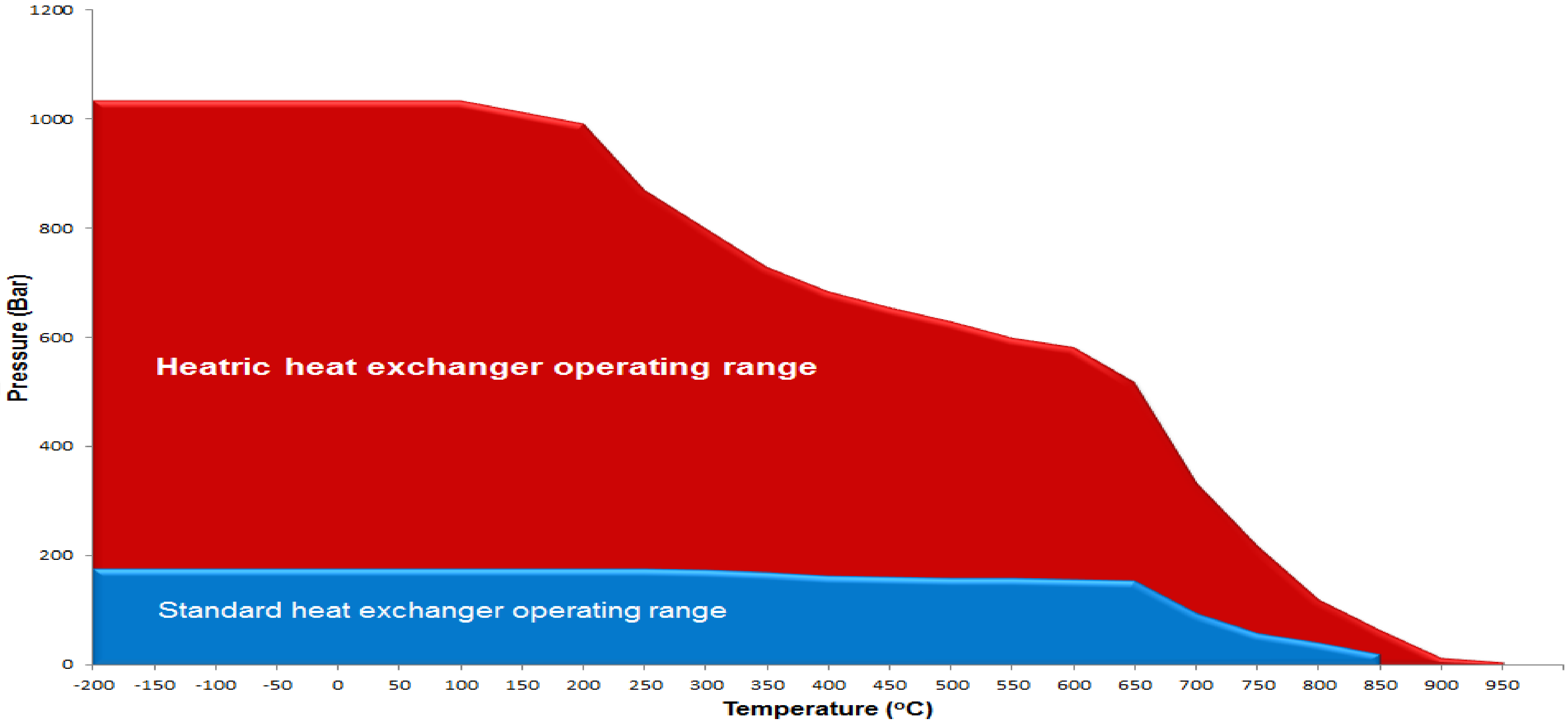
$Q = m_2\ Cp\ \Delta T_2$

$Q = m_2\ Cp(140\text{-}95)$

55% saving in coolant flow

Benefits of PCHEs

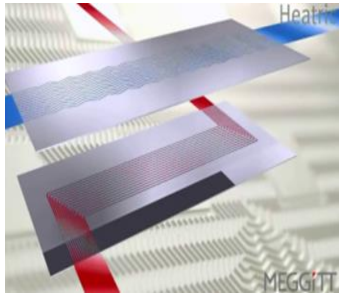
Mechanical capability



4 PCHE design and construction

PCHEs design and construction

Construction process

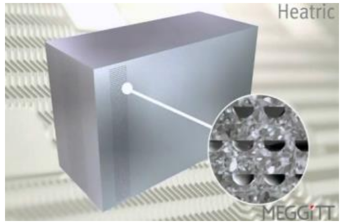


- **Design:**

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.

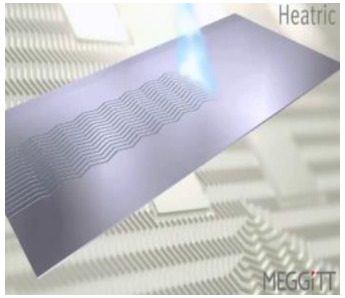


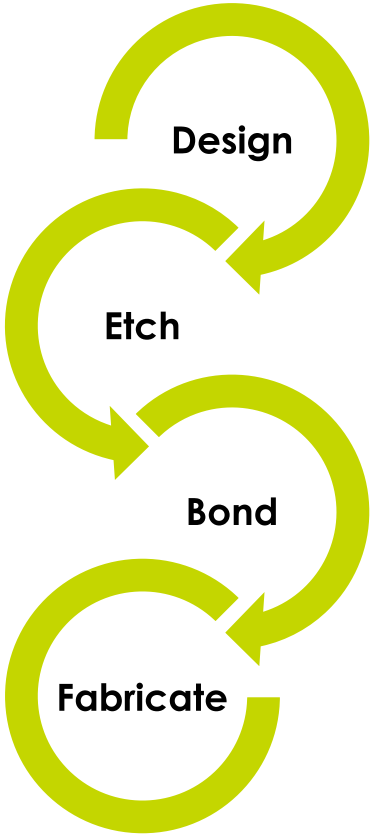
- **Bonding:**

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

- **Fabrication:**

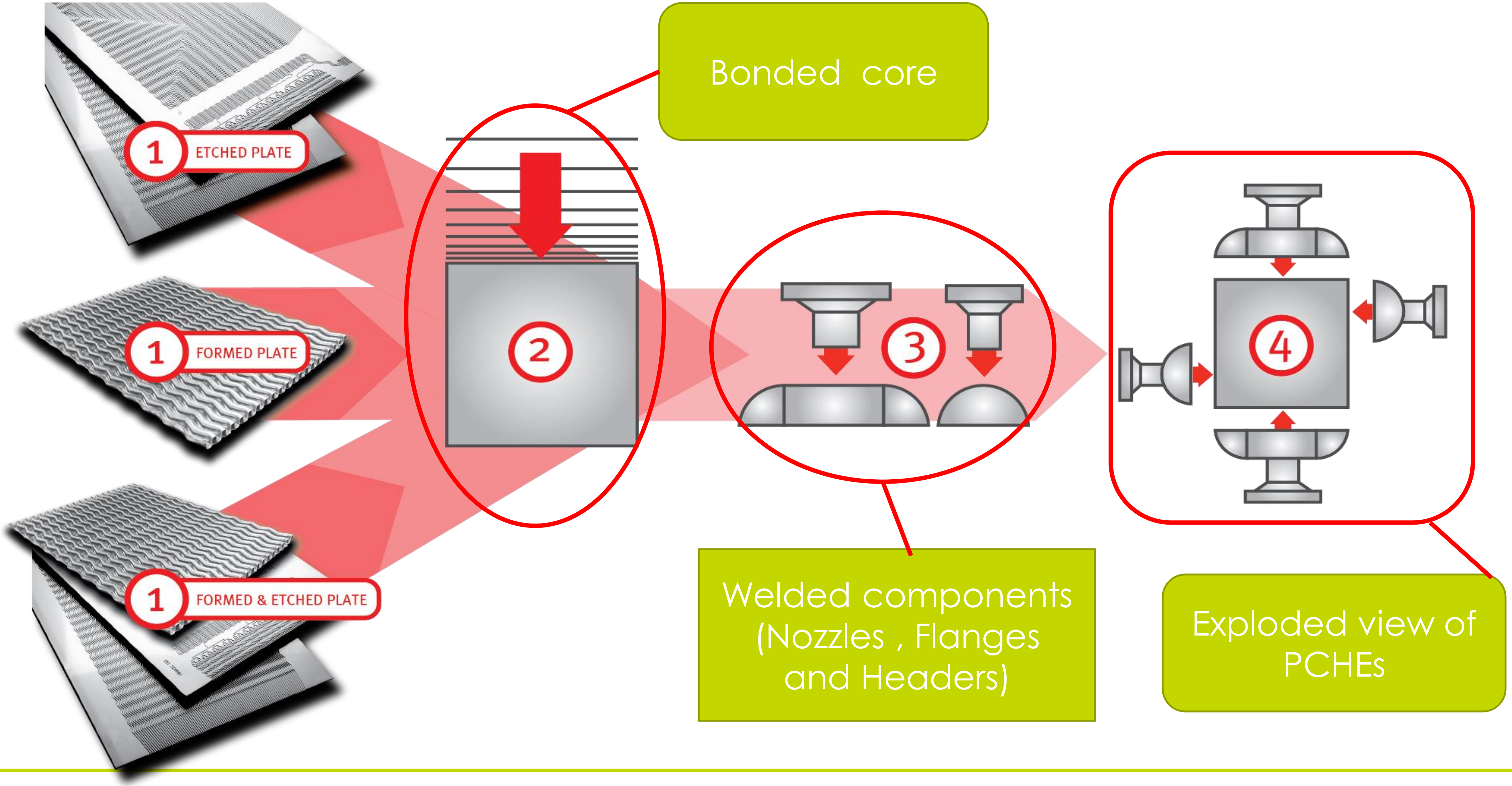
The cores are then welded together, with headers and flanges attached as required to produce the completed exchanger





PCHEs design and construction

Production process



Bonded core

Welded components (Nozzles , Flanges and Headers)

Exploded view of PCHEs

PCHEs design and construction

PCHEs design process

PCHE Design process

Hydraulic design

- Mass flow rate

- Overall pressure drop calc

- Component loss (Core, nozzle and headers)

- loss of Manifolds, elbow, glycol or liquid injection and two phase distributors if any)

Mechanical design

- Design as per code (ASME)

- Component minimum wall thickness

- Nozzle loads

- NDT if required

- FEA if not covered by code

- Combined load flange ratings

- Creep and Fatigue life analysis

Material selection

- Availability

-Cost

- Mechanical and thermal strength

- Corrosion resistant

- Manufacturability

- Weldability and Formability

Thermal design

- All required thermal calc and Fouling

- Plate sizing and core sizing

- Flow pass configuration

-design with manifolds if requires

- Design with multi-streamers if requires

- Endure maldistribution is avoided

Optimizing to minimize cost

PCHEs design and construction

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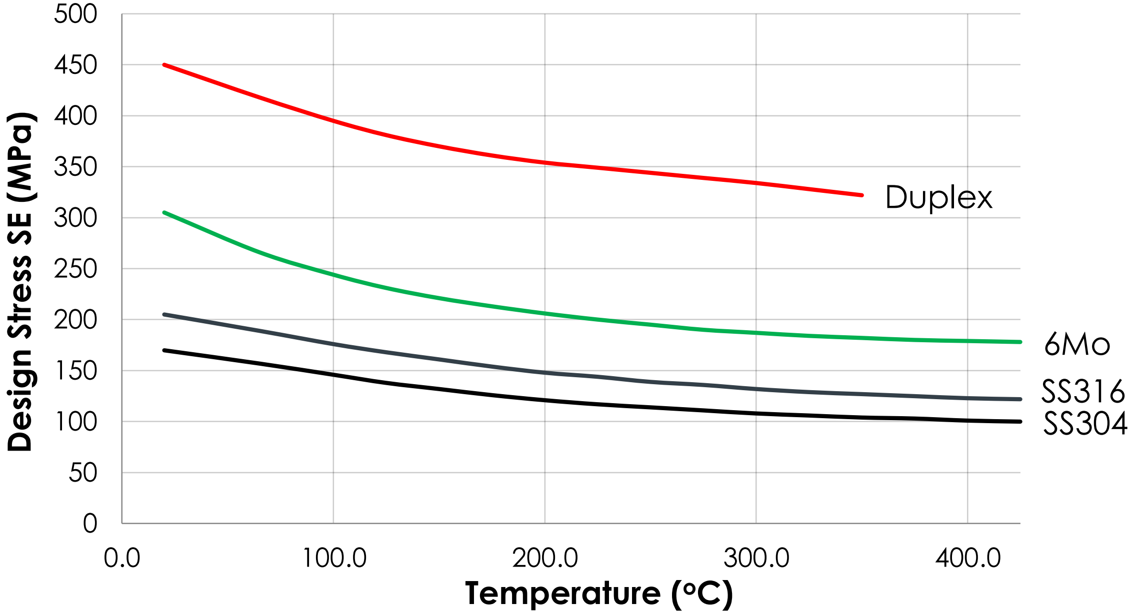
Material process

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:

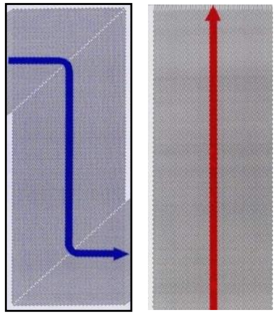
- SS304 @ 425°C = 100MPa ASME II Part D
- Duplex @ 150°C = 370MPa ASME II Part D
- 6Moly @ 275°C= 190MPa ASME II Part D

PCHE design and construction

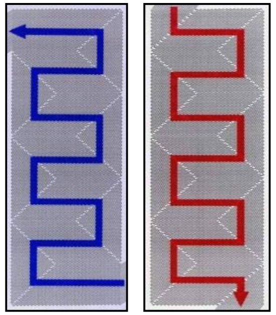
Thermal design considerations

Thermal contact arrangement (2 streamers)

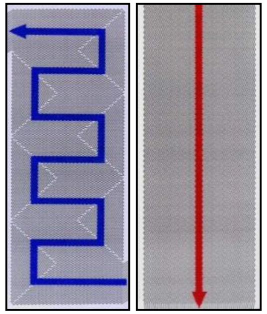
- Counter flow



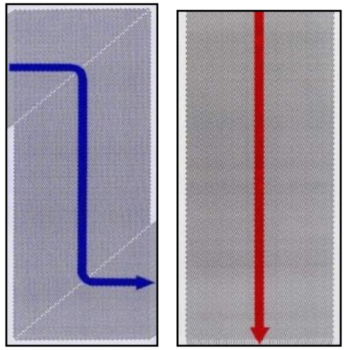
- Multipass counter flow



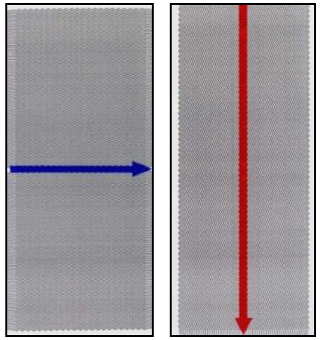
- Multipass counter -cross flow



- Parallel flow

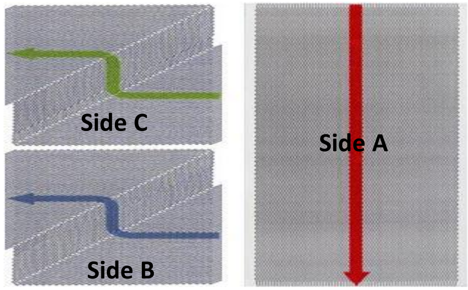


- Cross flow

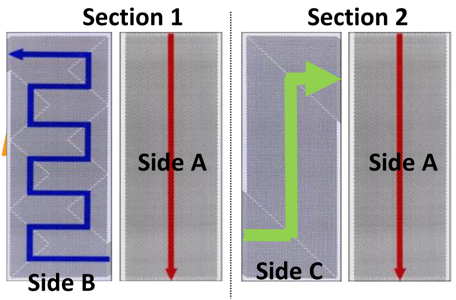


Thermal Contact (multi-streamers)

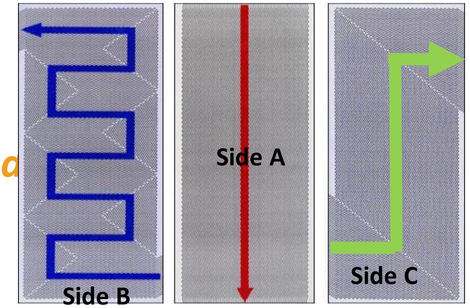
In Series



In parallel



Interleaved



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 *(ƒ)*and *Re*.

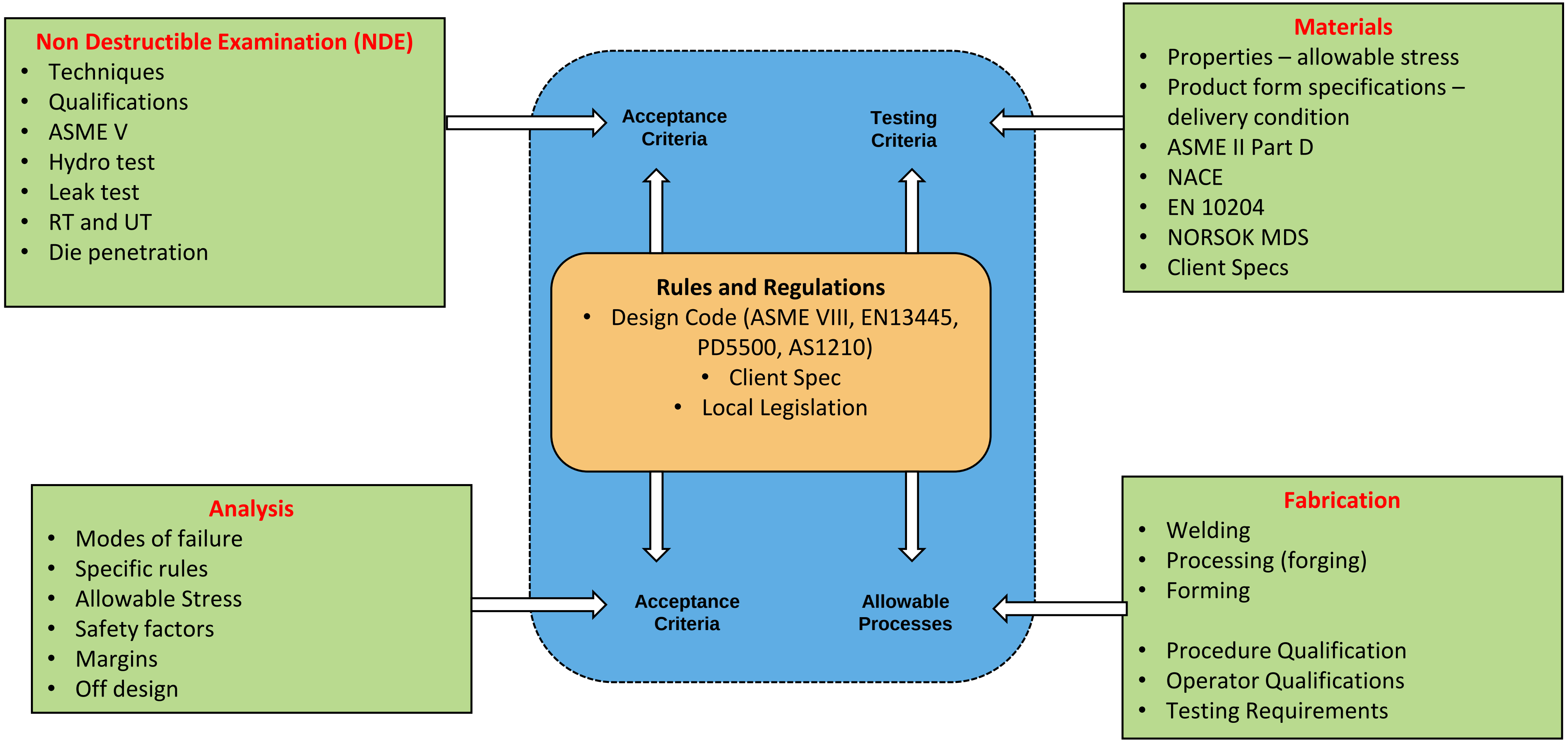
$$\boxed{\Delta P = \frac{\rho V^2 fL}{2D}}$$

- 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

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

PCHE design and construction

Mechanical design Code & Certifications



Non Destructible Examination (NDE)
- Techniques
- Qualifications
- ASME V
- Hydro test
- Leak test
- RT and UT
- Die penetration

Materials
- Properties – allowable stress
- Product form specifications – delivery condition
- ASME II Part D
- NACE
- EN 10204
- NORSOK MDS
- Client Specs

Rules and Regulations
- Design Code (ASME VIII, EN13445, PD5500, AS1210)
- Client Spec
- Local Legislation

Analysis
- Modes of failure
- Specific rules
- Allowable Stress
- Safety factors
- Margins
- Off design

Fabrication
- Welding
- Processing (forging)
- Forming

- Procedure Qualification
- Operator Qualifications
- Testing Requirements

7^{th} *International*
Supercritical CO_2 Power Cycles Symposium
San Antonio, TX U.S.A.
February 21-24, 2022

Heat Exchangers for Supercritical CO_2 Power Cycle Applications Tutorial

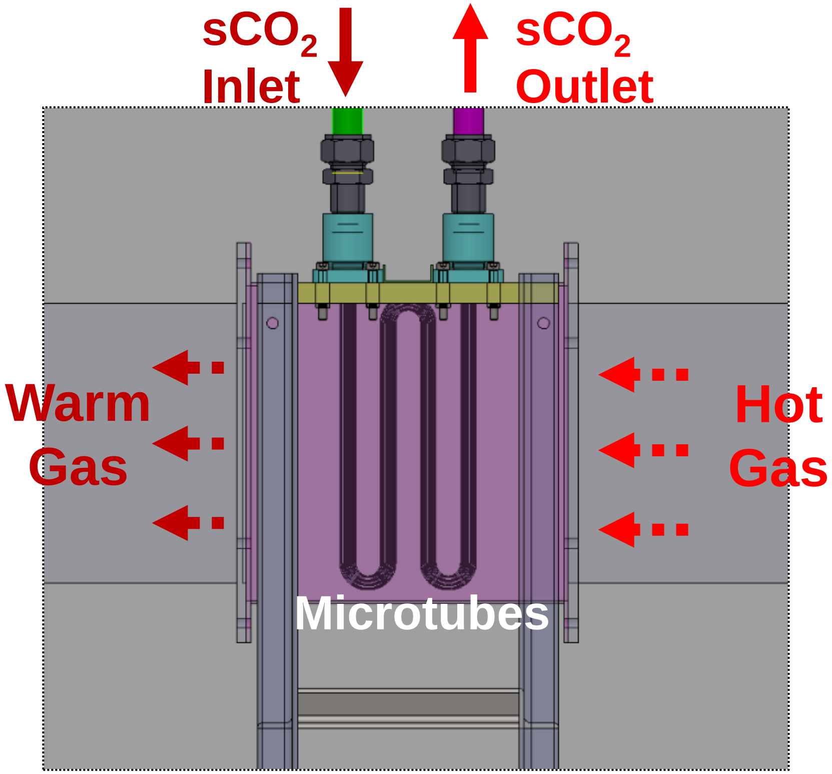
Compact Heat Exchangers
Design Considerations, Operations & Testing

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

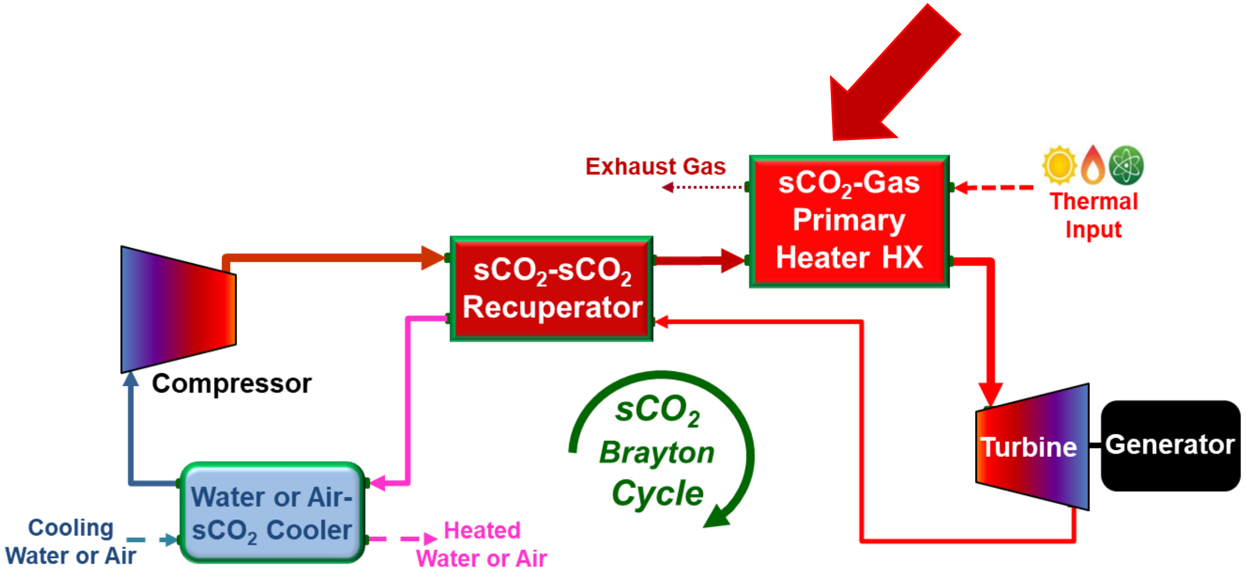
TharEnergy

Primary Heat Exchanger

Hot gas to sCO_2



Cross Flow, Counter-current Microtube Heater



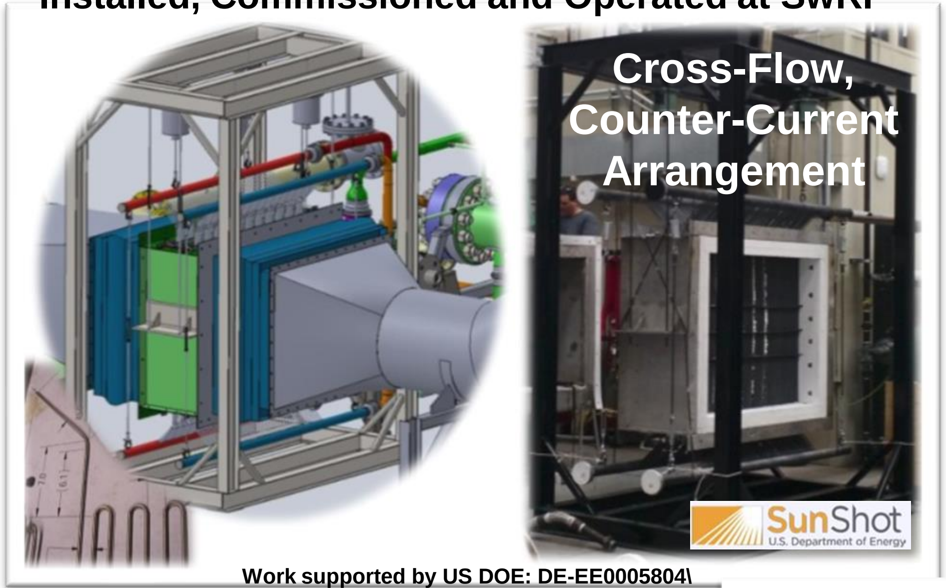
- **Heats up the pressurized sCO_2 to high temperature prior to entering the turbine**
- **Particle contaminants are a concern – size for periodic cleaning**

Work supported by US DOE NETL: DE-FE0024012

Primary Heat Exchanger – Design Considerations

Thar Energy's sCO$_2$ Primary Heater

Installed, Commissioned and Operated at SwRI



Work supported by US DOE: DE-EE0005804\

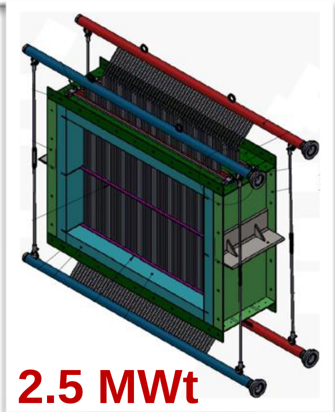
Design Conditions:

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 yield strength**

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**

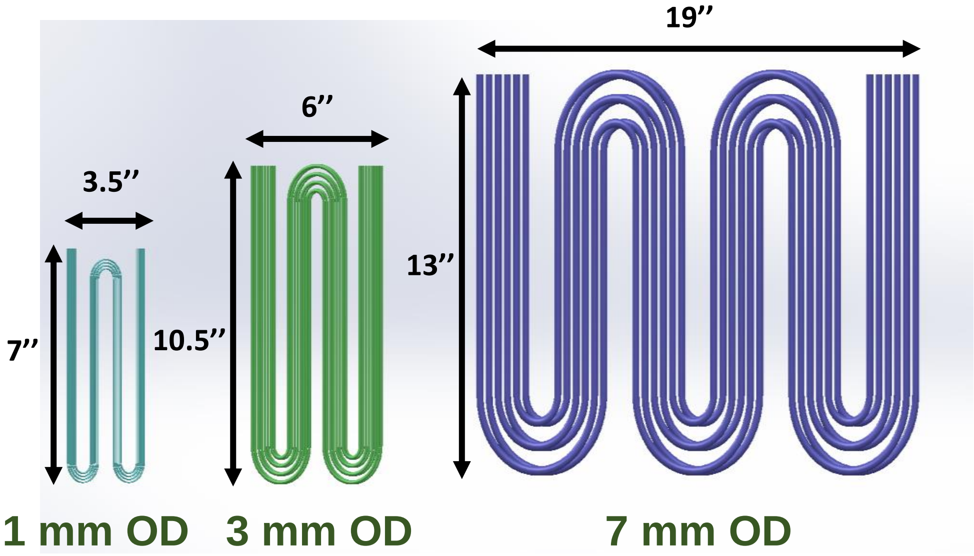
4

Air Side Pressure Drop

- **Air side pressure drop sized to be under limit to ensure overall efficiency**

Primary Heat Exchanger

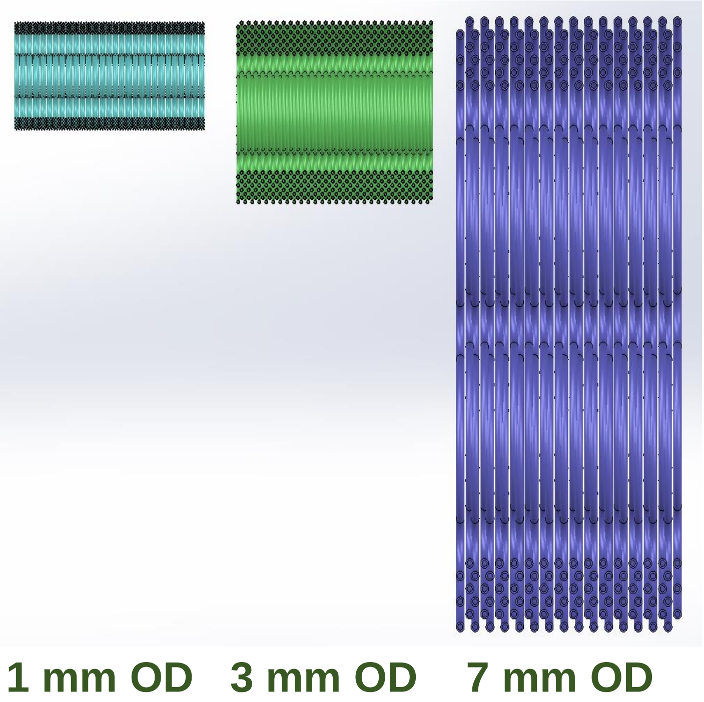
Cross flow, Counter-current Microtube Heat Exchanger



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

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



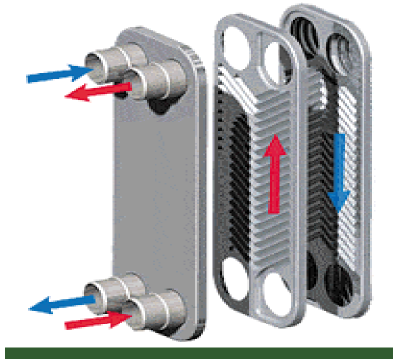
Water Cooler: Water to sCO_2
Gas or Air Cooler: Air to sCO_2

Air Cooled

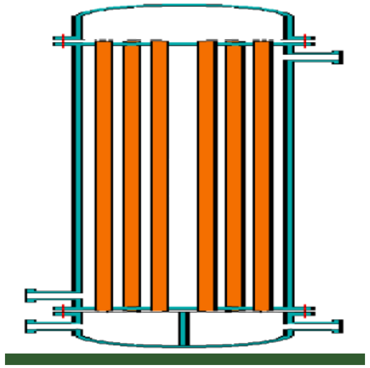
Finned-Tubes

Micro-channel

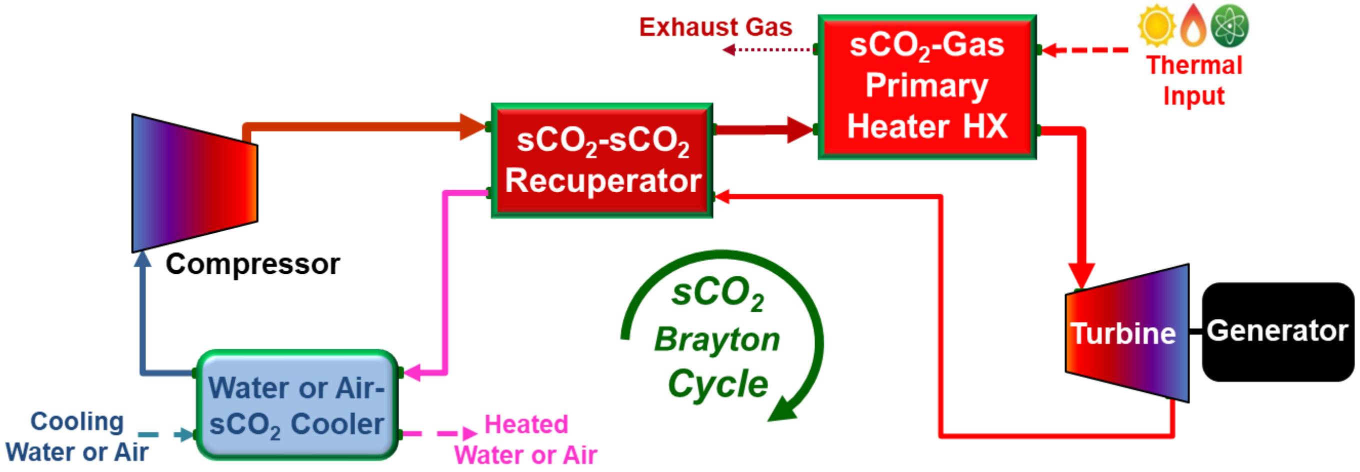
Water Cooled



Brazed-Plate



Tube/ Microtube



Exhaust Gas

sCO_2-Gas Primary Heater HX

Thermal Input

sCO_2-sCO_2 Recuperator

Compressor

sCO_2 Brayton Cycle

Turbine

Generator

Cooling Water or Air

Water or Air-sCO_2 Cooler

Heated Water or Air

- Cool sCO_2 to increase density and reduce compressor energy

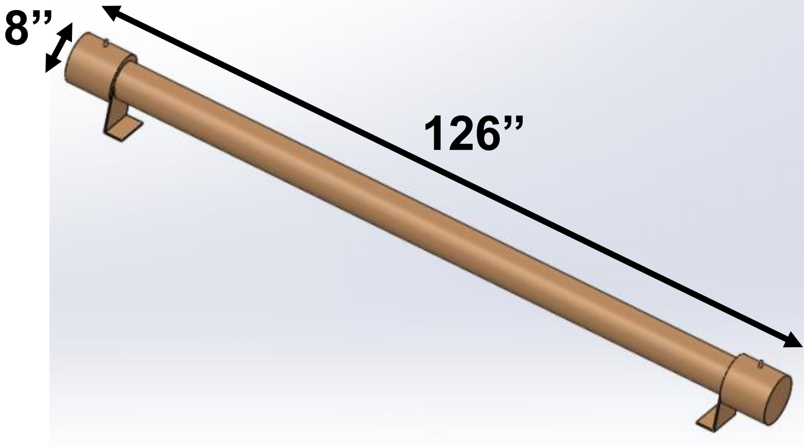
Trade off between water vs. air cooling

- 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

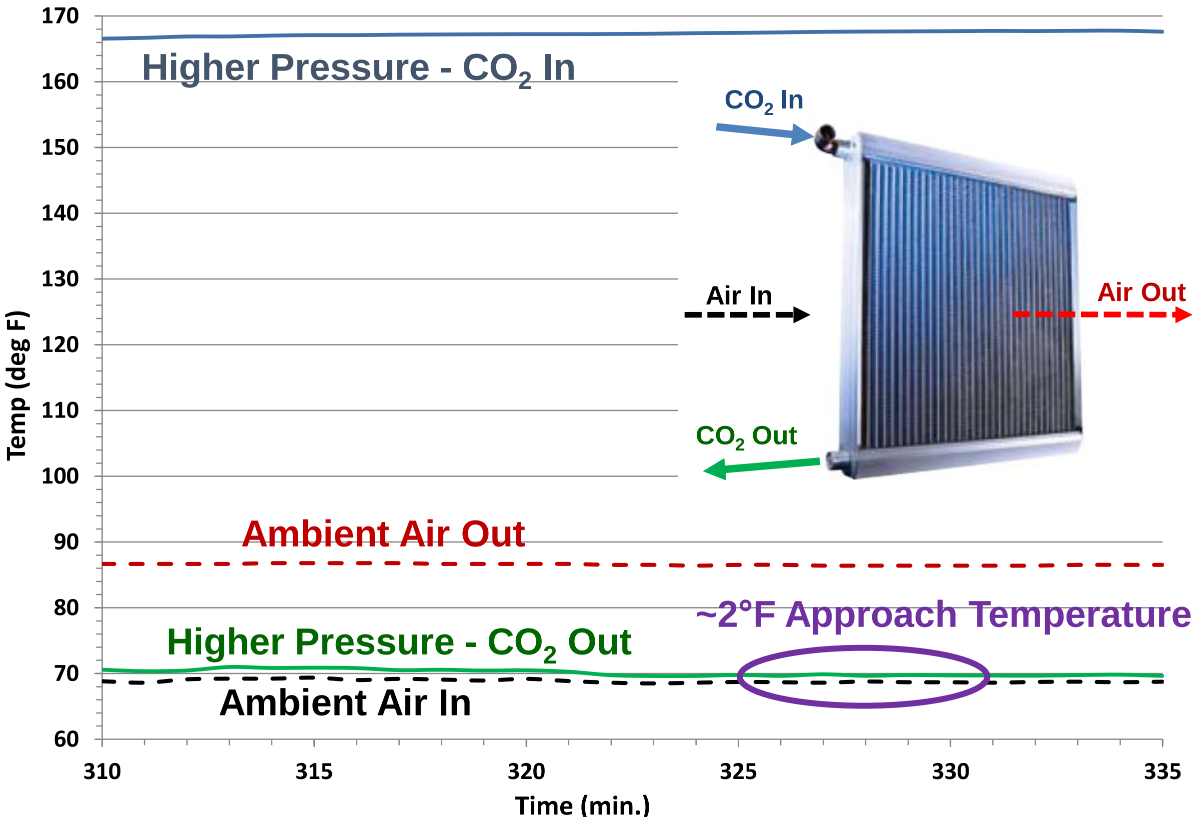
Material: Stainless Steel 304

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 regular maintenance

sCO_2 Gas - Air Cooler – Design Considerations



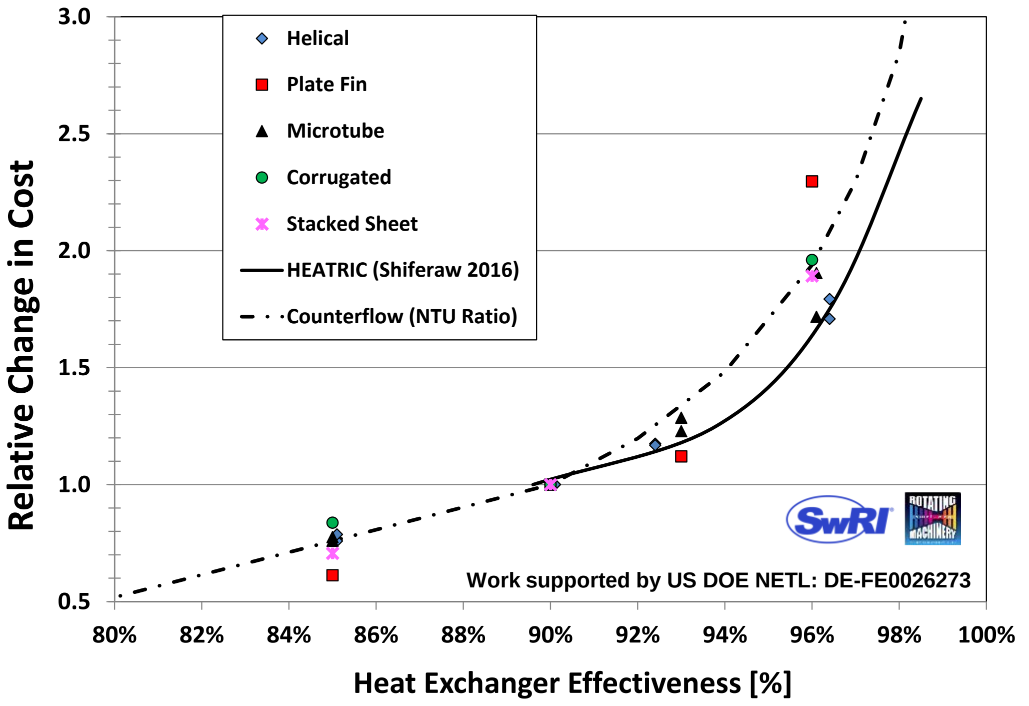
Micro-channel coils are
- **40% more efficient**
- **40% smaller**
- **50% less refrigerant**
- **Lower air side ΔP**

than standard tube & fin coils

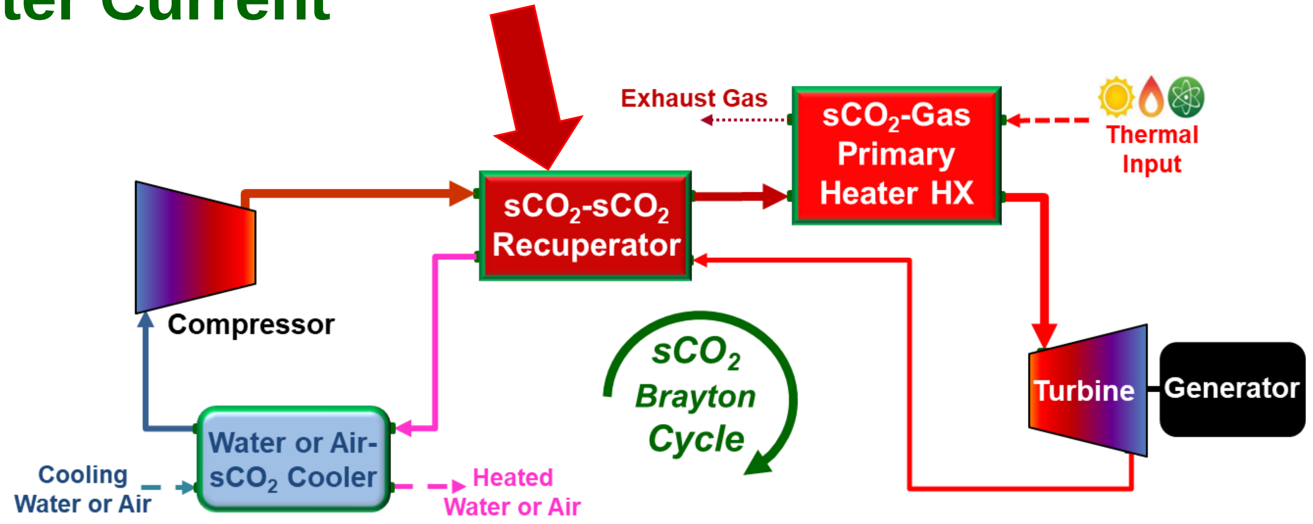
At Thar’s test facility, air and CO_2 approaching temperature as low as 2°F was achieved using micro-channel coil.

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**

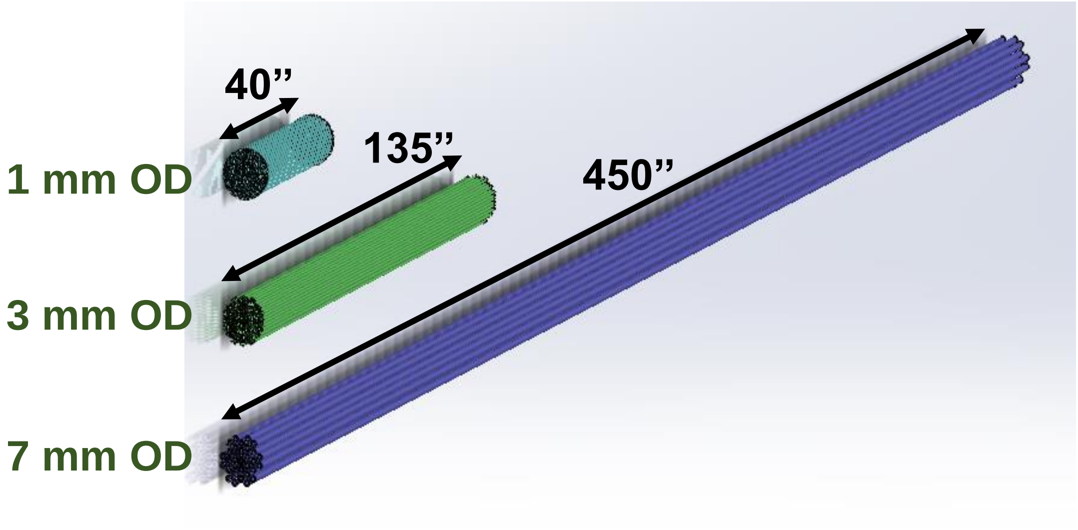
Relatively independent of the heat exchanger concepts evaluated

Recuperator specifications influence cost

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

Microtube Recuperator

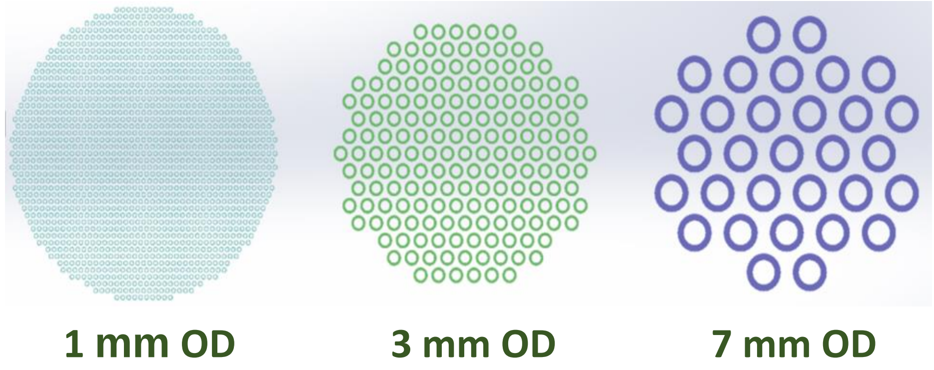
Counter- current



Overall Size Comparison

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

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

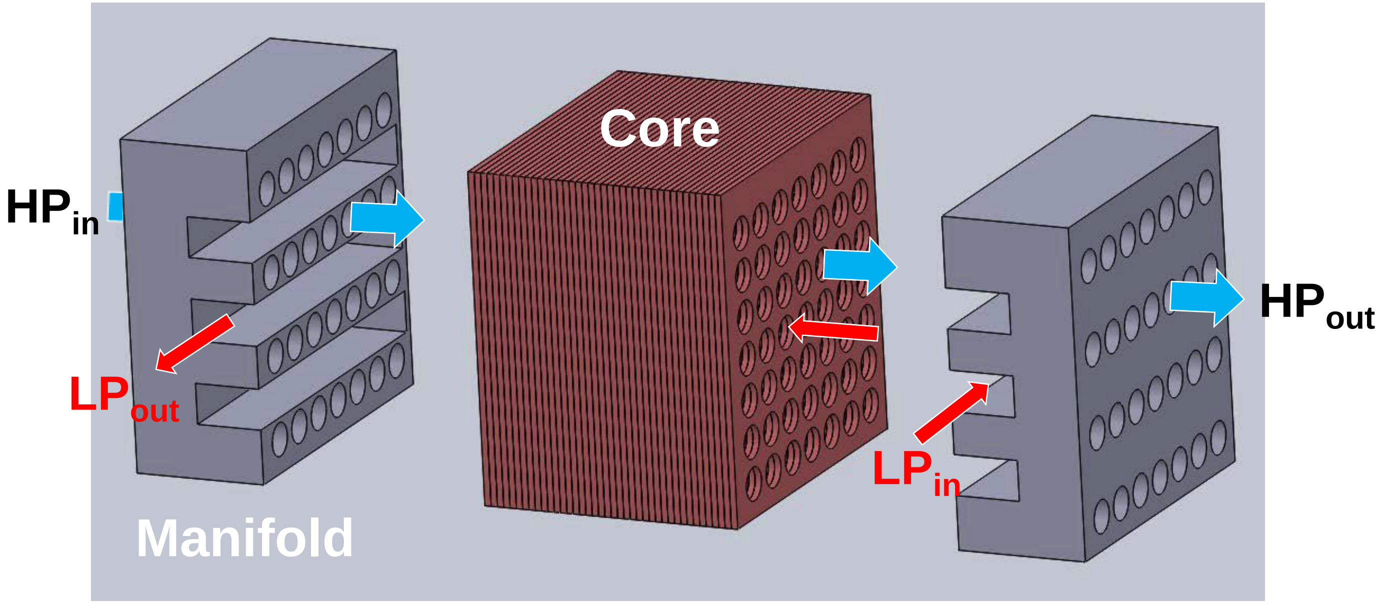


Thar Energy and SwRI conducted a multi-year study focused on building cost effective recuperators, at the MWt scale.

- 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
  - ❖ Vacuum bonding
  - ❖ Advanced CMM QA/QC methods

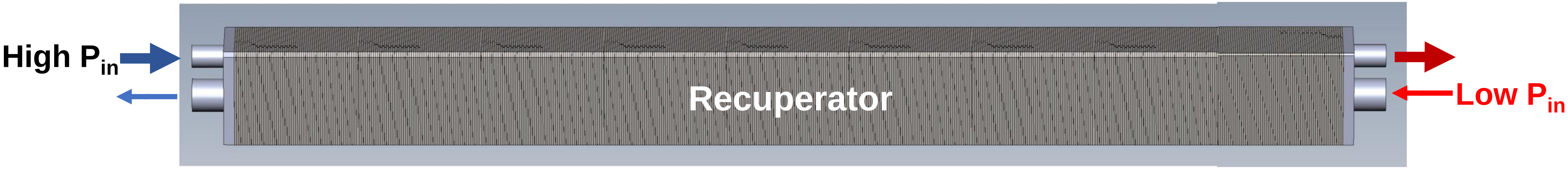
Stacked-sheet Recuperator Concept (SSHX)



- **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 sheets is parallel to the mechanical stresses & perpendicular to the thermal stresses

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

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

Different from Standard Loop

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

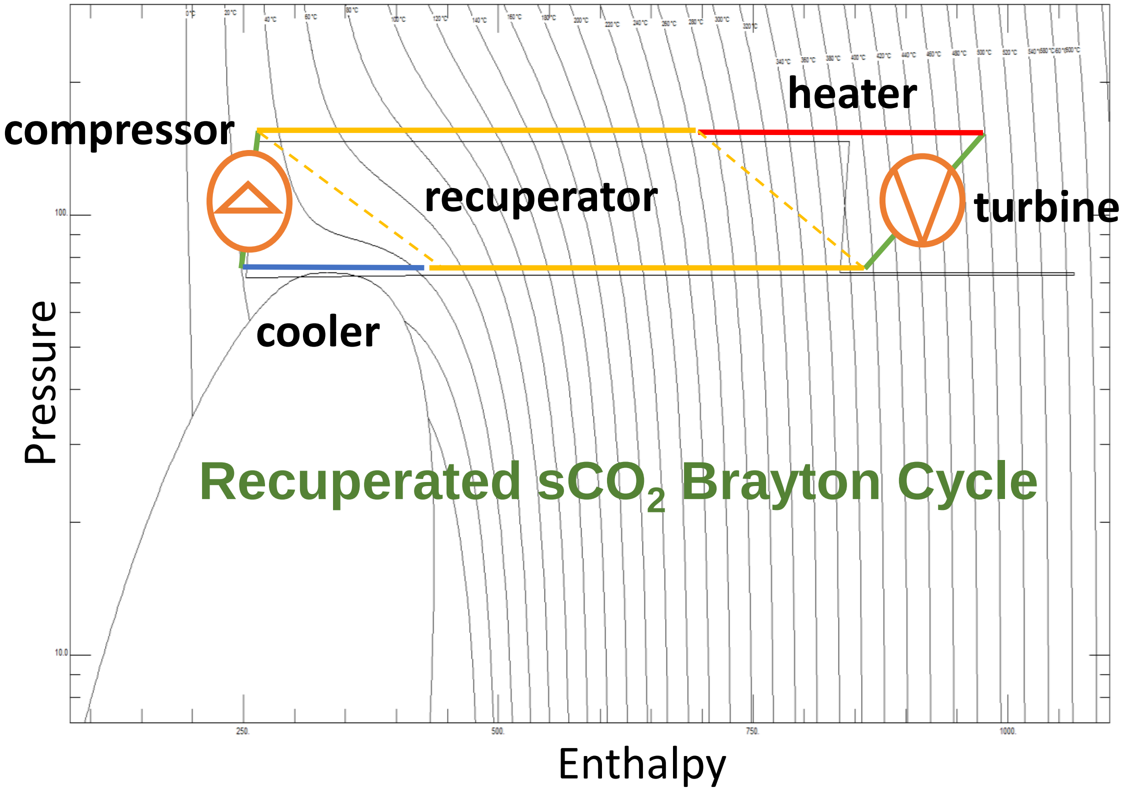
Test Condition

Supercritical Carbon Dioxide

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

Combustion Gas

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



Thar Loop Compared to Standard Brayton Cycle

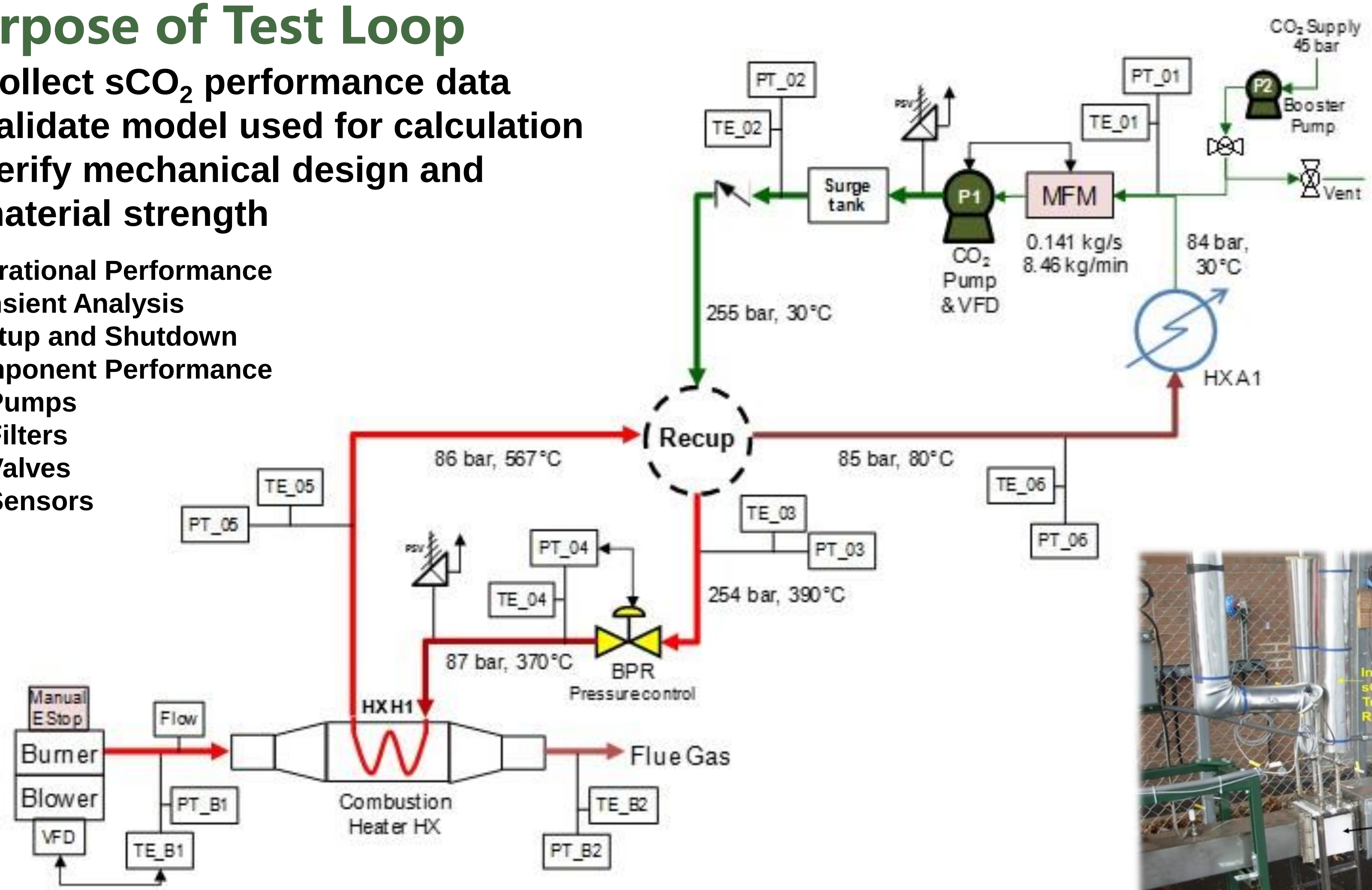
Work supported by US DOE NETL: DE-FE0024012, DE-FE0026273

Thar sCO_2 HX Test Loop

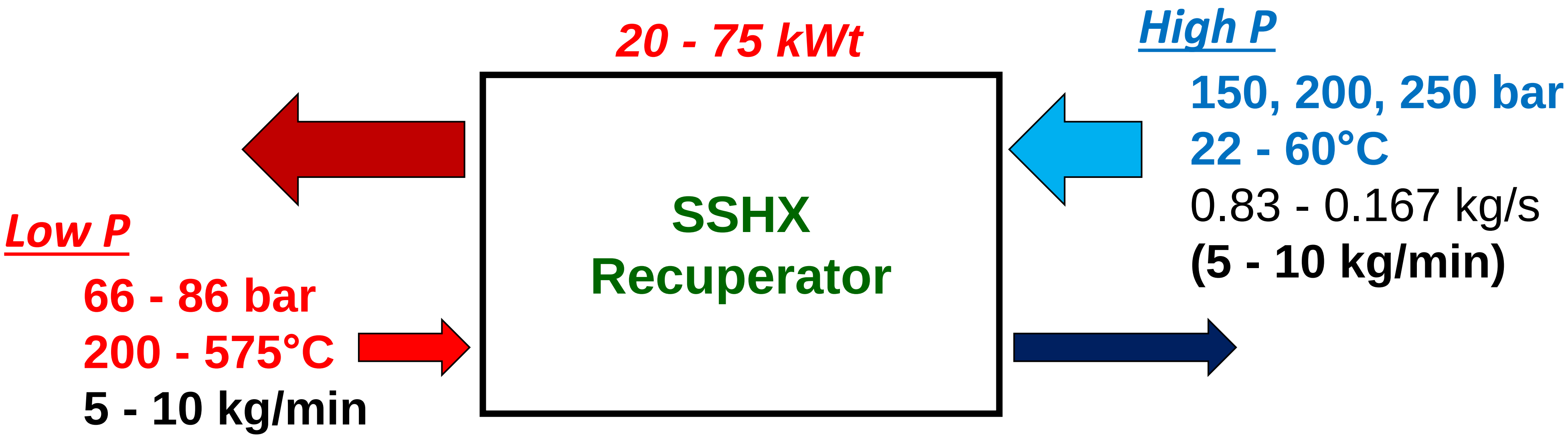
Purpose of Test Loop

1. Collect sCO_2 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



Test Conditions - SSHX Recuperator Prototypes



20 - 75 kWt

SSHX Recuperator

Low P

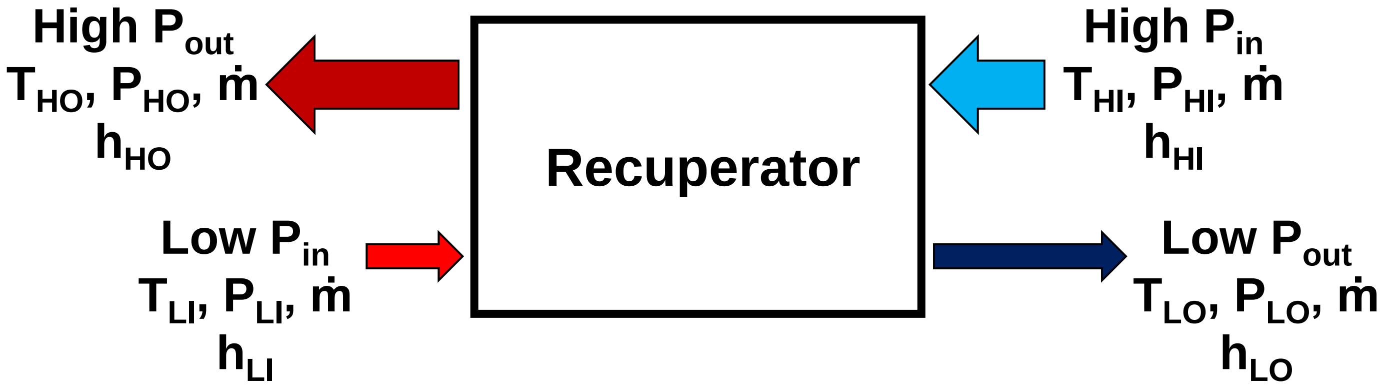
66 - 86 bar
200 - 575°C
5 - 10 kg/min

High P

150, 200, 250 bar
22 - 60°C
0.83 - 0.167 kg/s
(5 - 10 kg/min)

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

HX Performance Heat Transfer Equations



Effectiveness, $\epsilon = Q_{act} \div Q_{max}$

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

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

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

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

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

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

$UA = Q_{act} \div T_{Ln}$

$T_{Ln} = (\Delta T_i - \Delta T_{ii}) \div LN\ (\Delta T_i \div \Delta T_{ii})$

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

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

Approach Temperature = $T_{LO} - T_{HI}$

% Pressure Drop

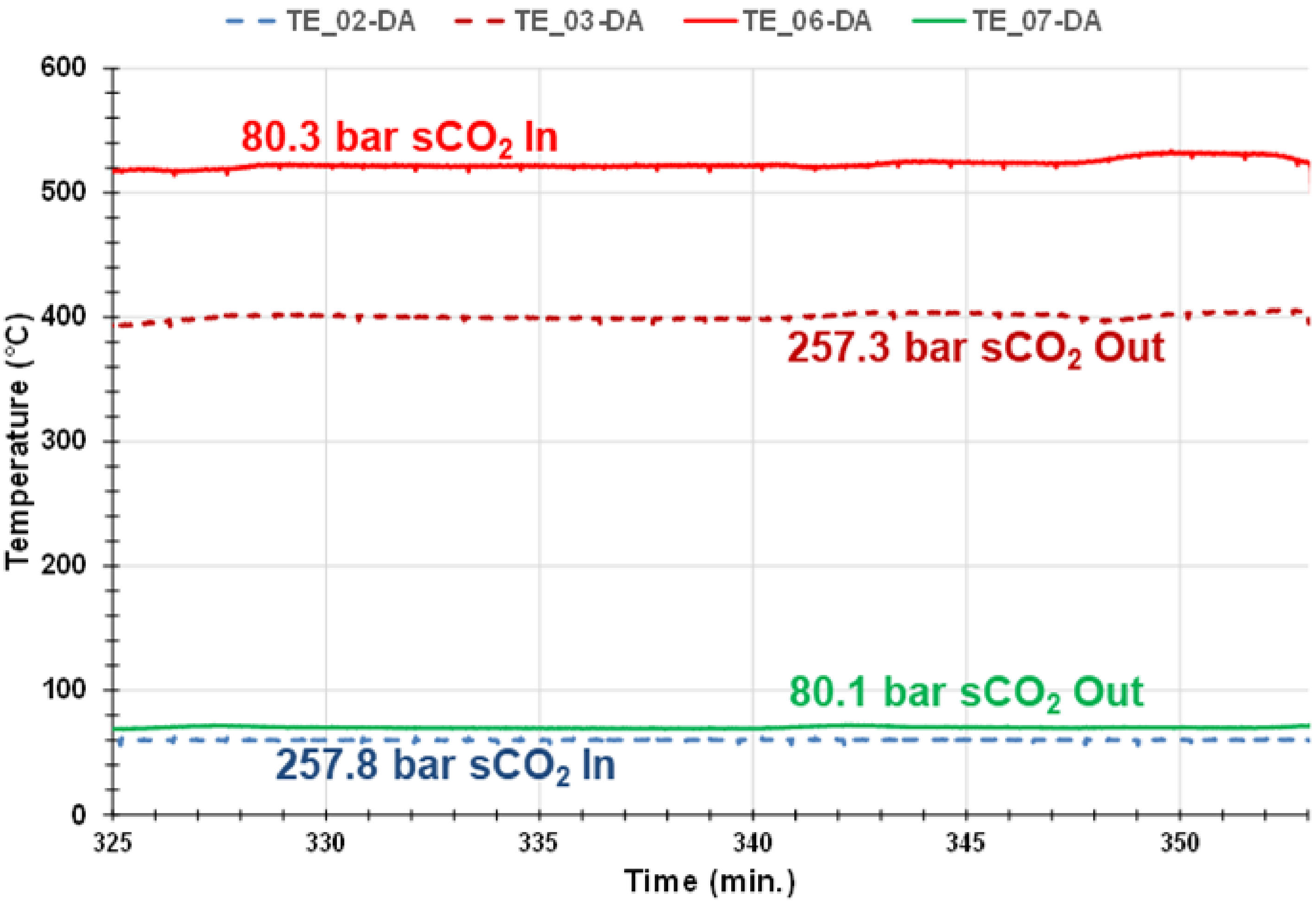
$\%\Delta P = (Pin - Pout) / Pin$

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

Steady State Time vs. Temperature Plot

Prototype SSHX Recuperators

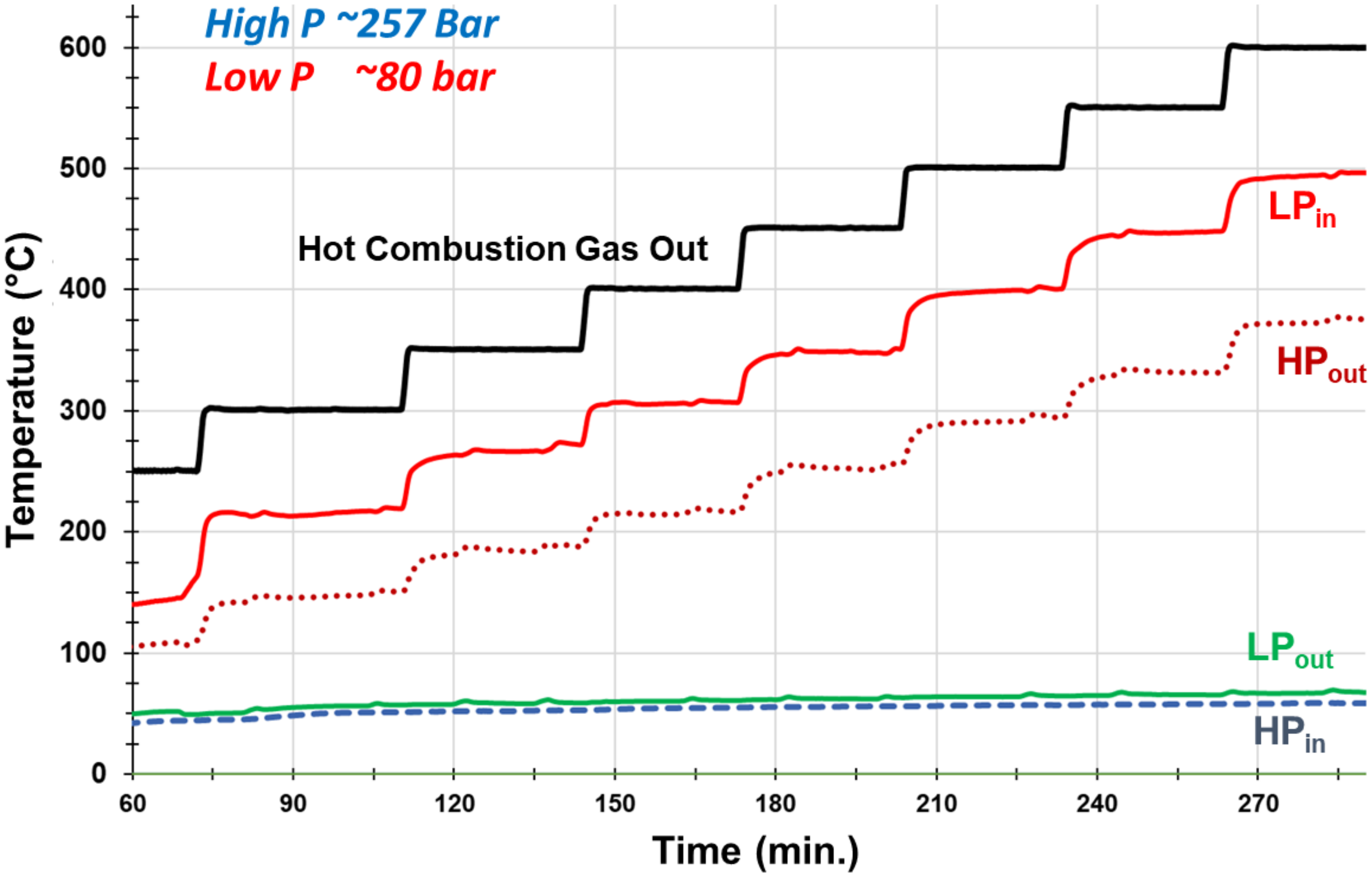
3D-SSHX – Steady State Plot



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

Temperature vs. Time Plot

Good Energy Balance, < 2% error



Approach T, < 10°C

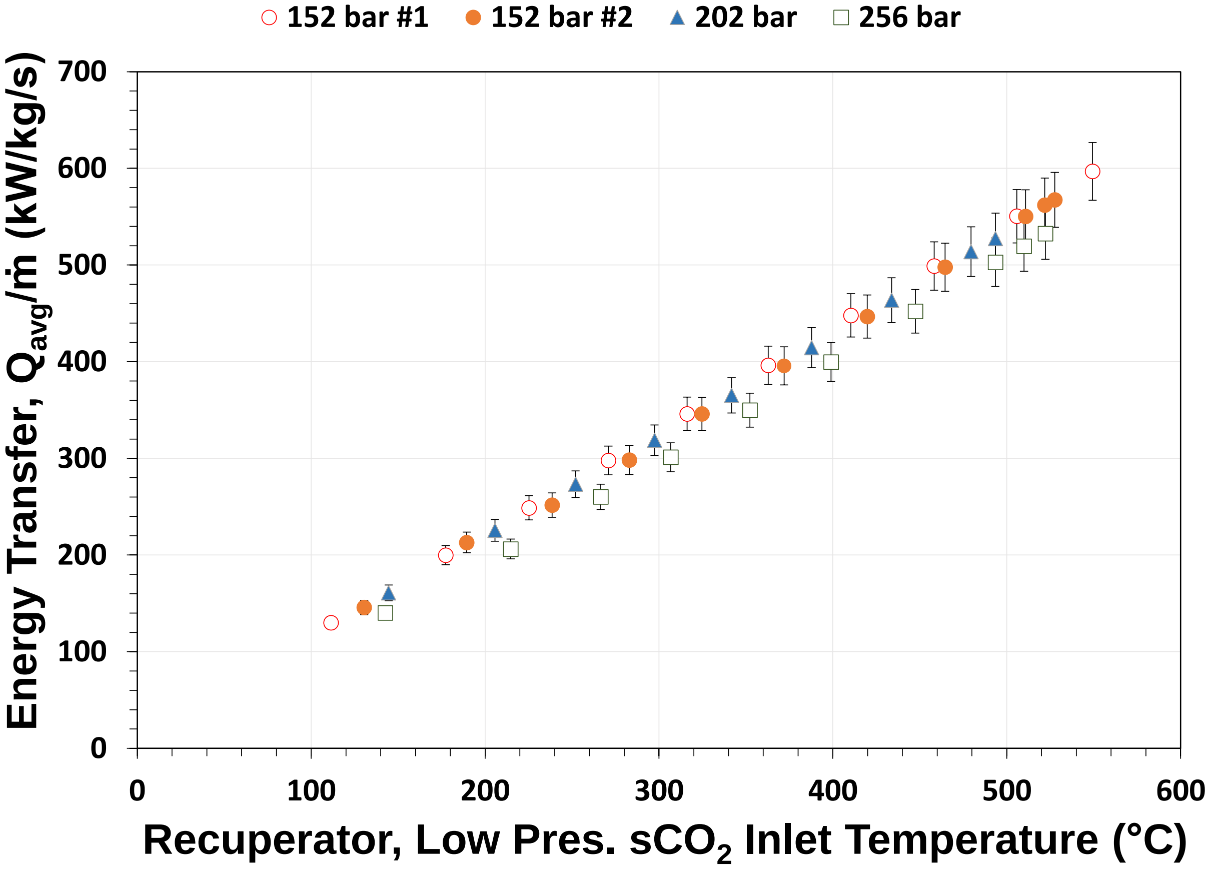
Work supported by US DOE NETL: DE-FE0024012, DE-FE0025348 , DE-FE0026273

Energy Transfer Plots

SSHX Recuperator Prototypes

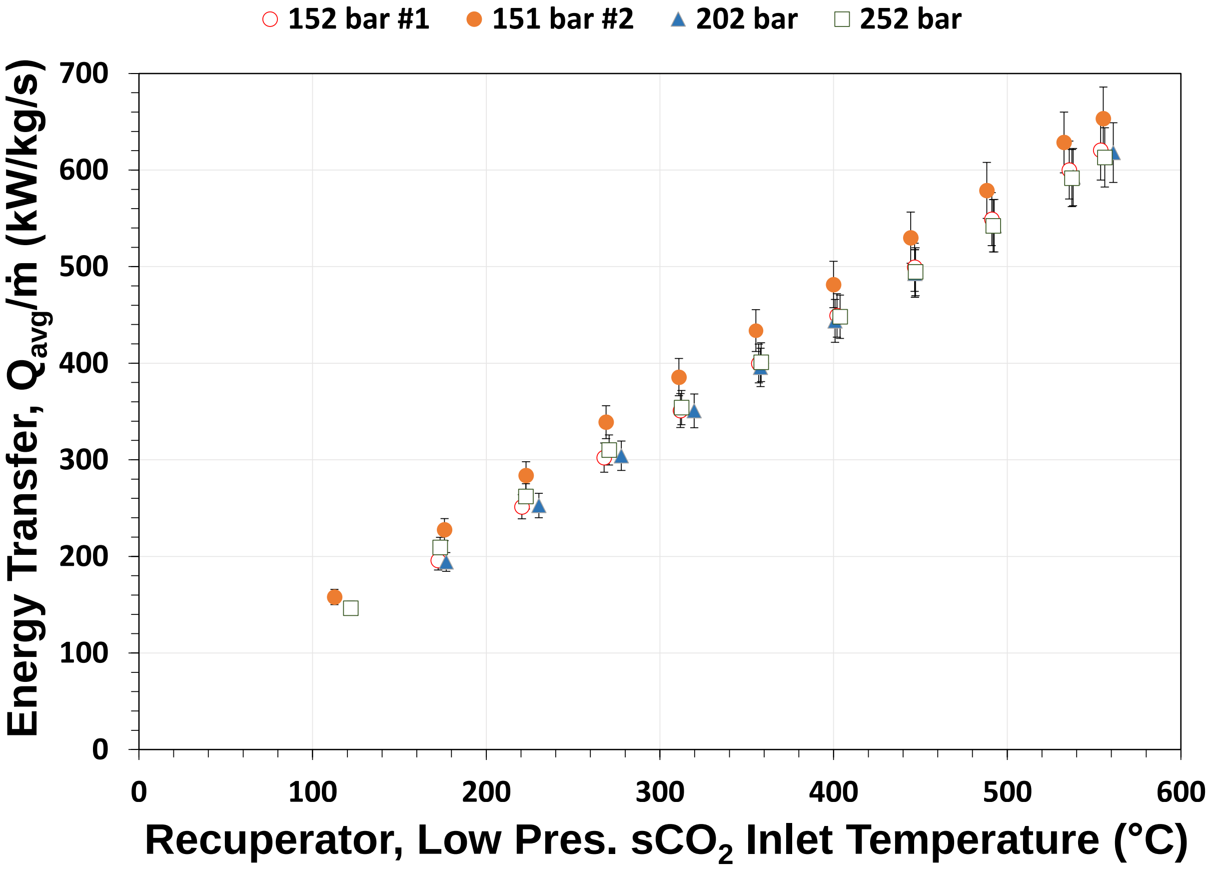
3D-SSHX

Inconel 625



Laser-SSHX

347H Stainless Steel

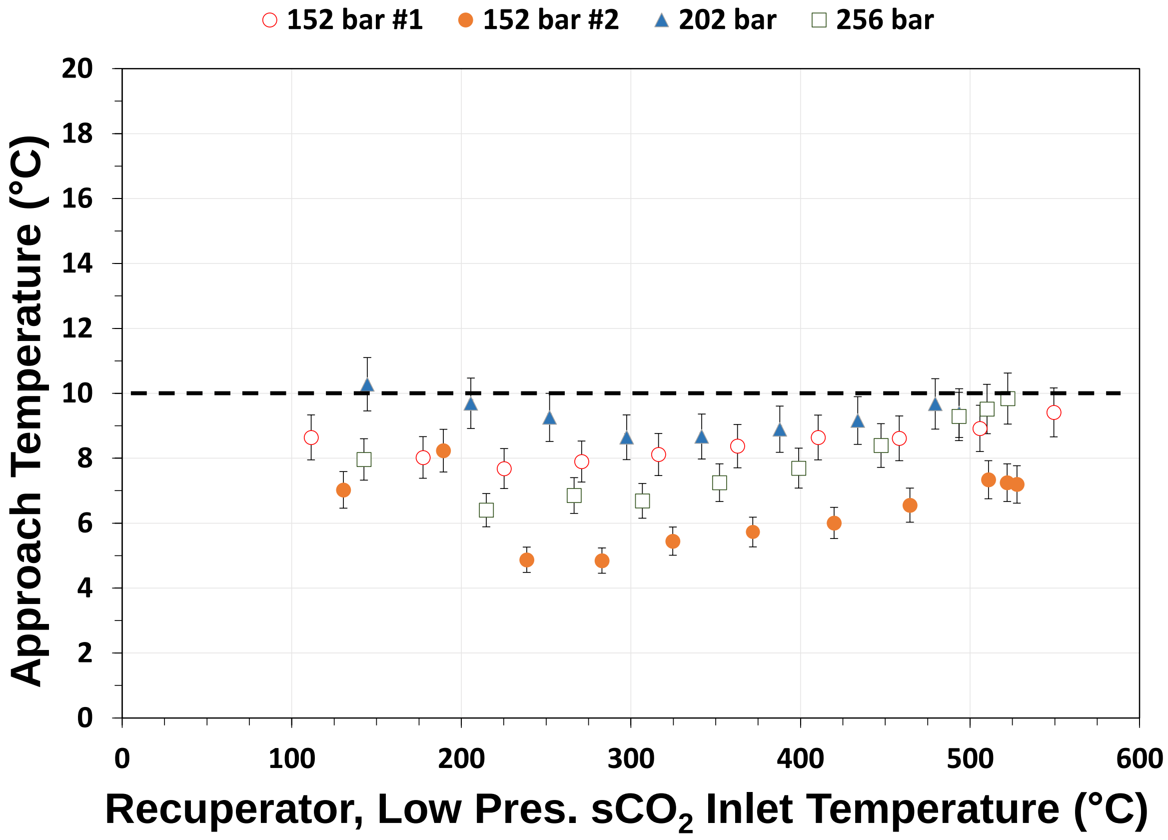


Linear Response

Work supported by US DOE NETL: DE-FE0026273

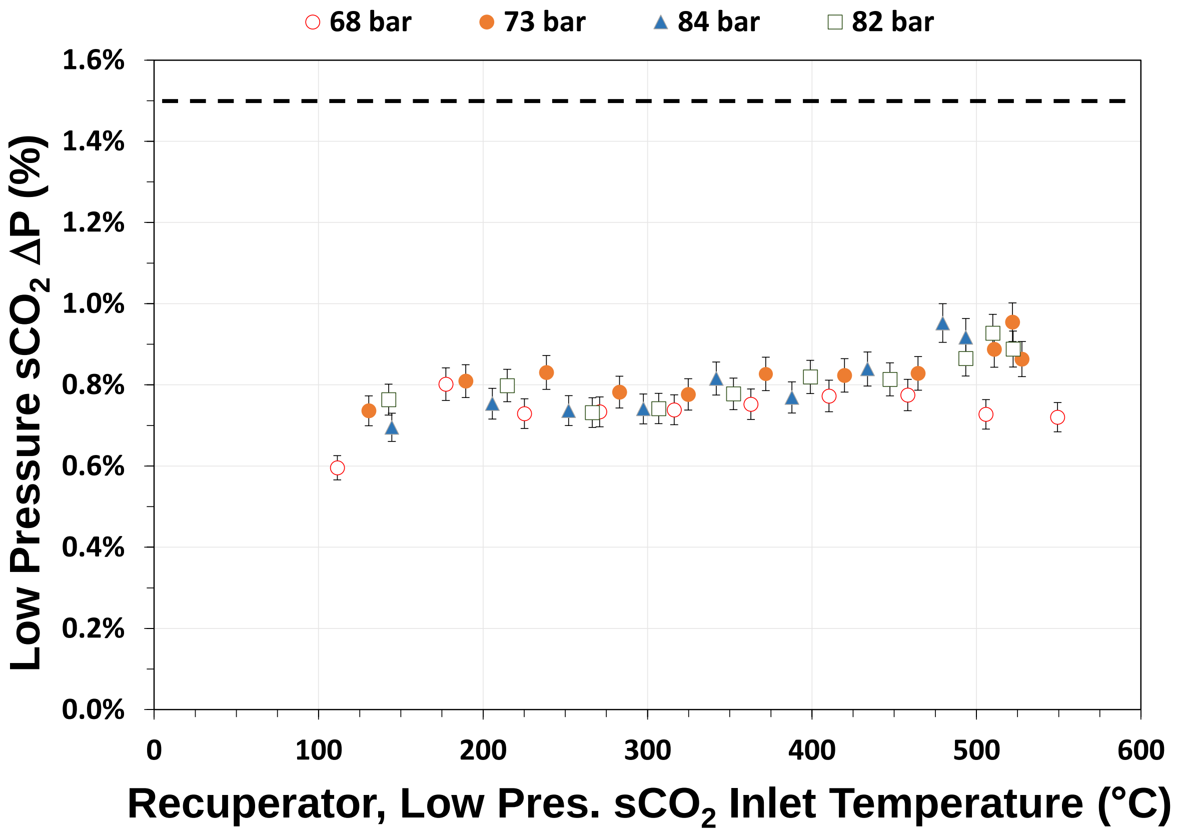
3D-SSHX Prototype Recuperator

Approach Temperature Plot



Approach T, < 10°C

sCO$_2$ ΔP Plot



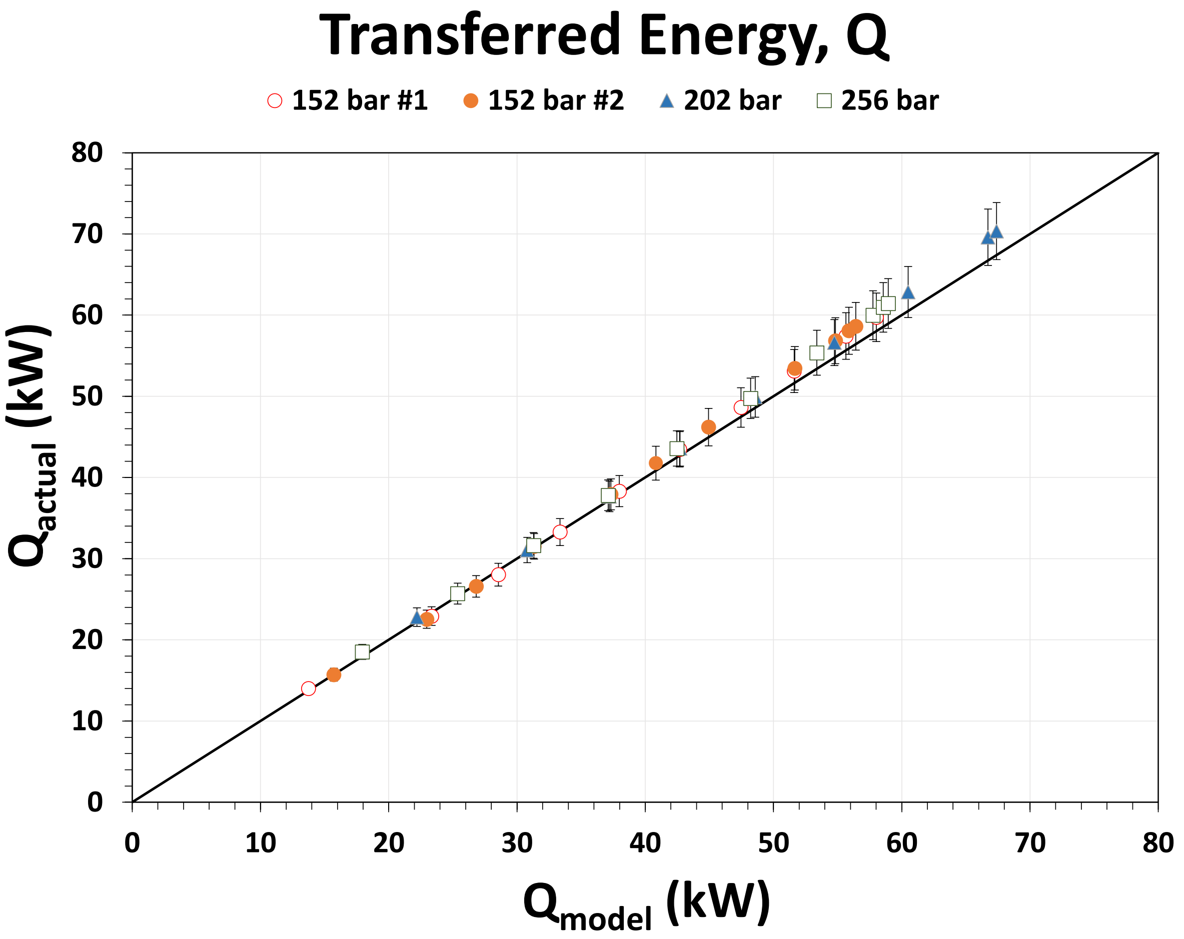
$\Delta P_h < 1.5\%$

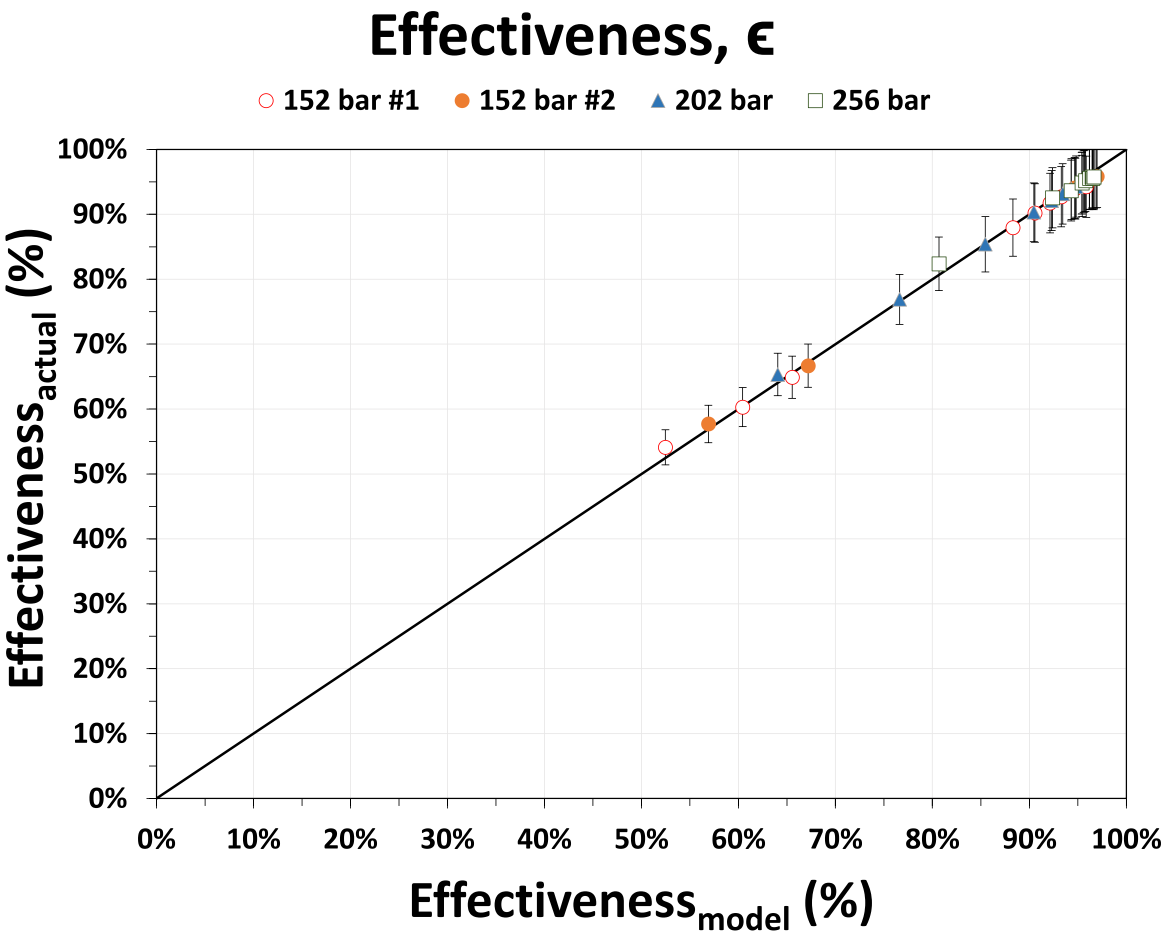
Meets design specifications

Work supported by US DOE NETL: DE-FE0026273

3D-SSHX Prototype Recuperator

Good correlation between Design & Actual HX performance data

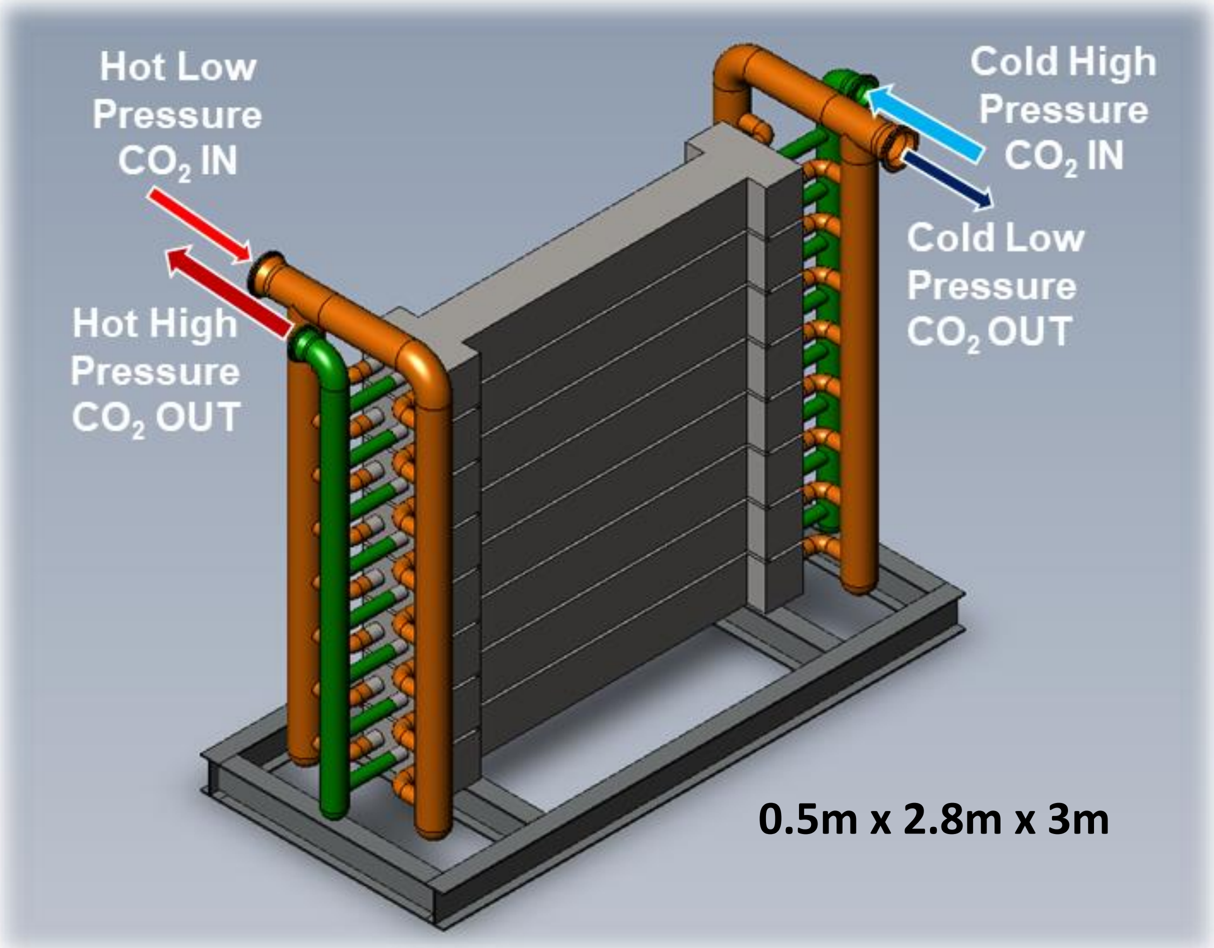




Work supported by US DOE NETL: DE-FE0026273

46 MWt Laser-SSHX Recuperator

Parallel Modular Design, Factory Fabricated



3D-SSHX
57% volume decrease

Example: Eight stacked Laser-SSHX sub-modules

Work supported by US DOE NETL: DE-FE0026273

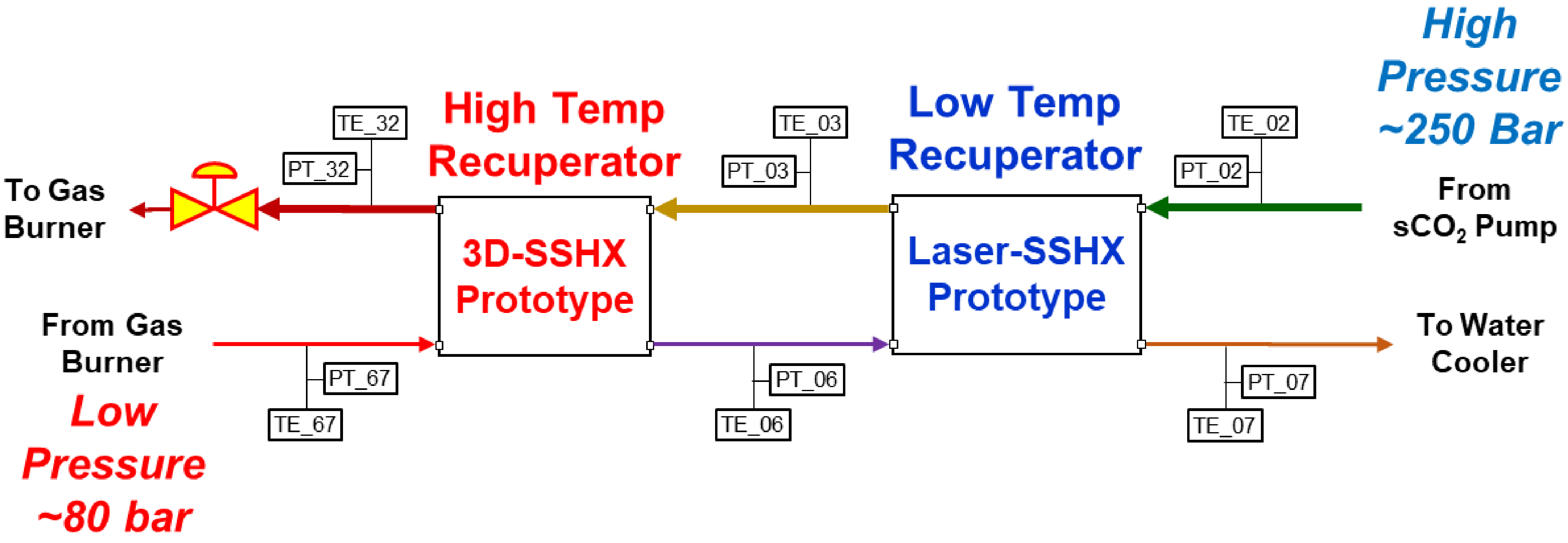
Data confirms SSHX Recuperator Performance

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	ΔP_h < 1.5% (1.3 bar)	✓
	ΔP_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	✓

Transient Tests

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

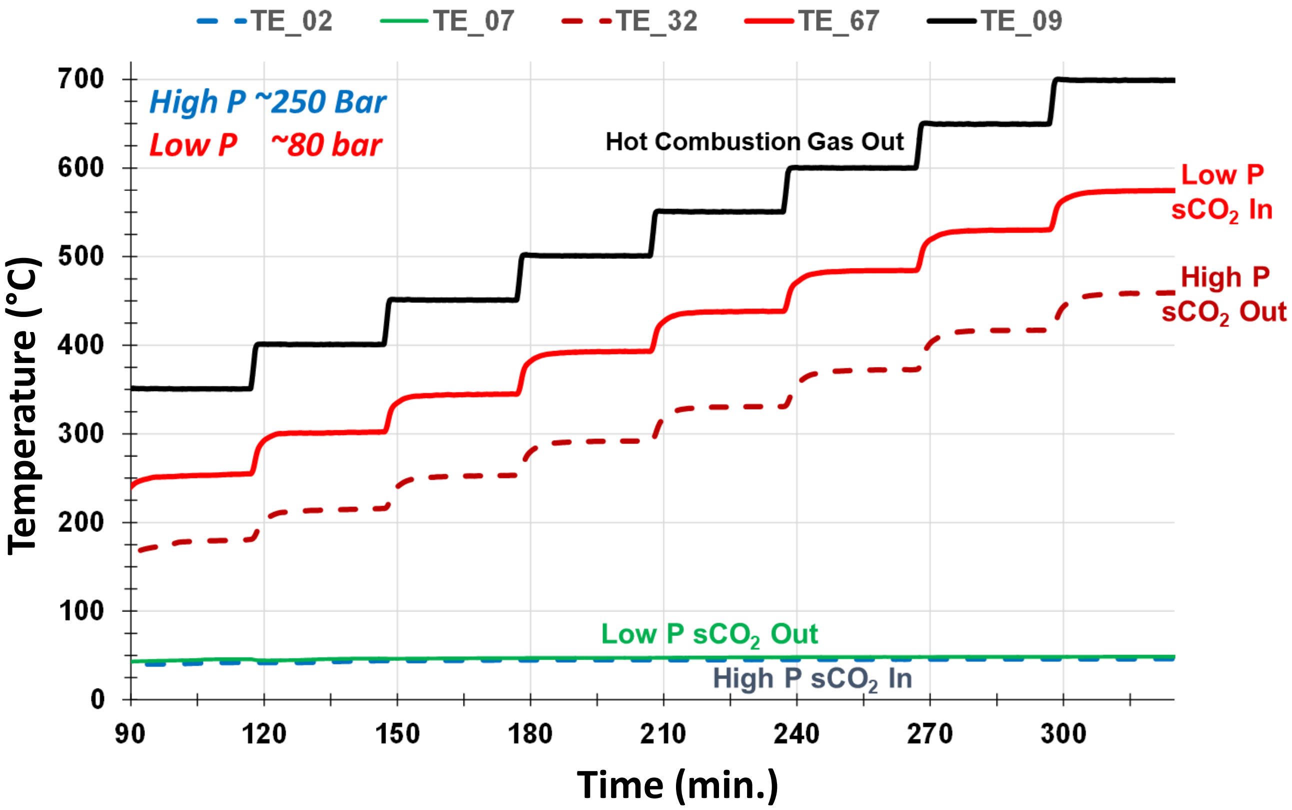


Test & Energy Balance Plots

COMBO-SSHX Recuperator

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

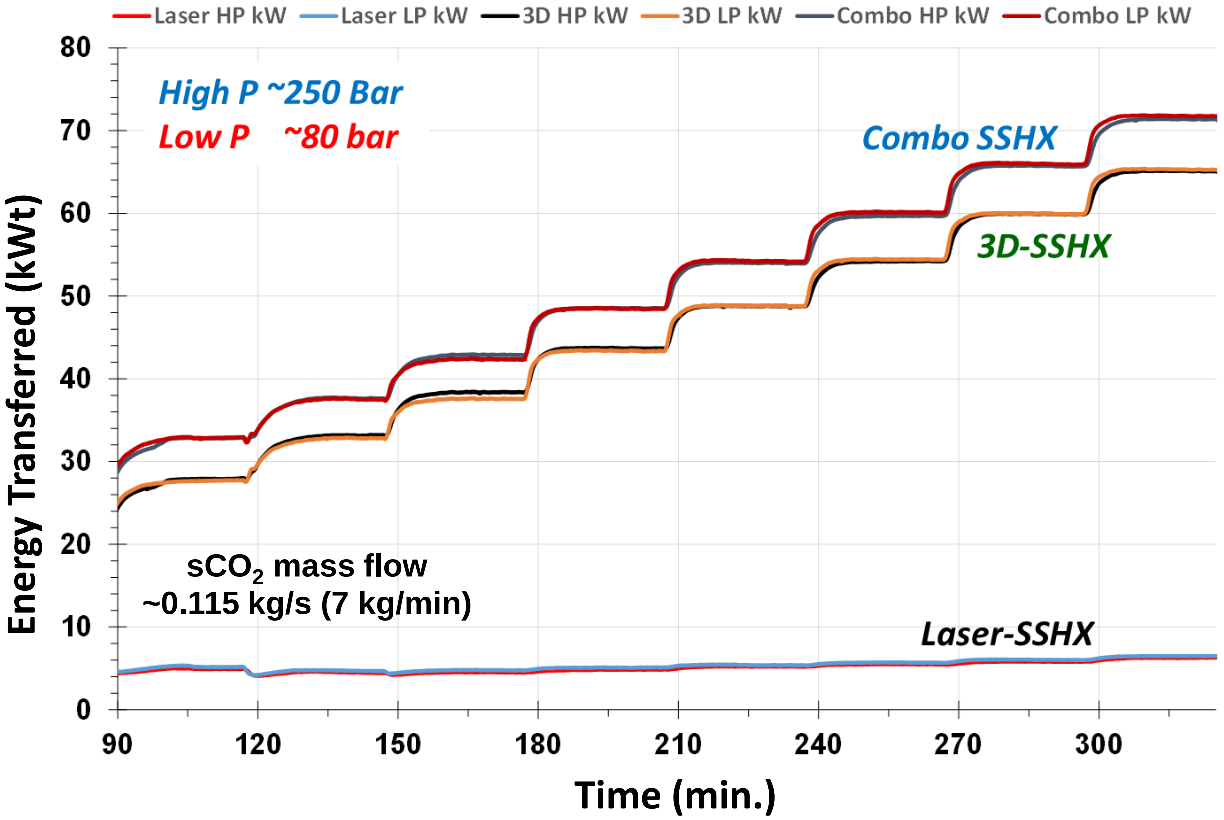
Combo-SSHX Time vs. Temperature Plot



Approach T: < 5°C

Effectiveness: > 98%

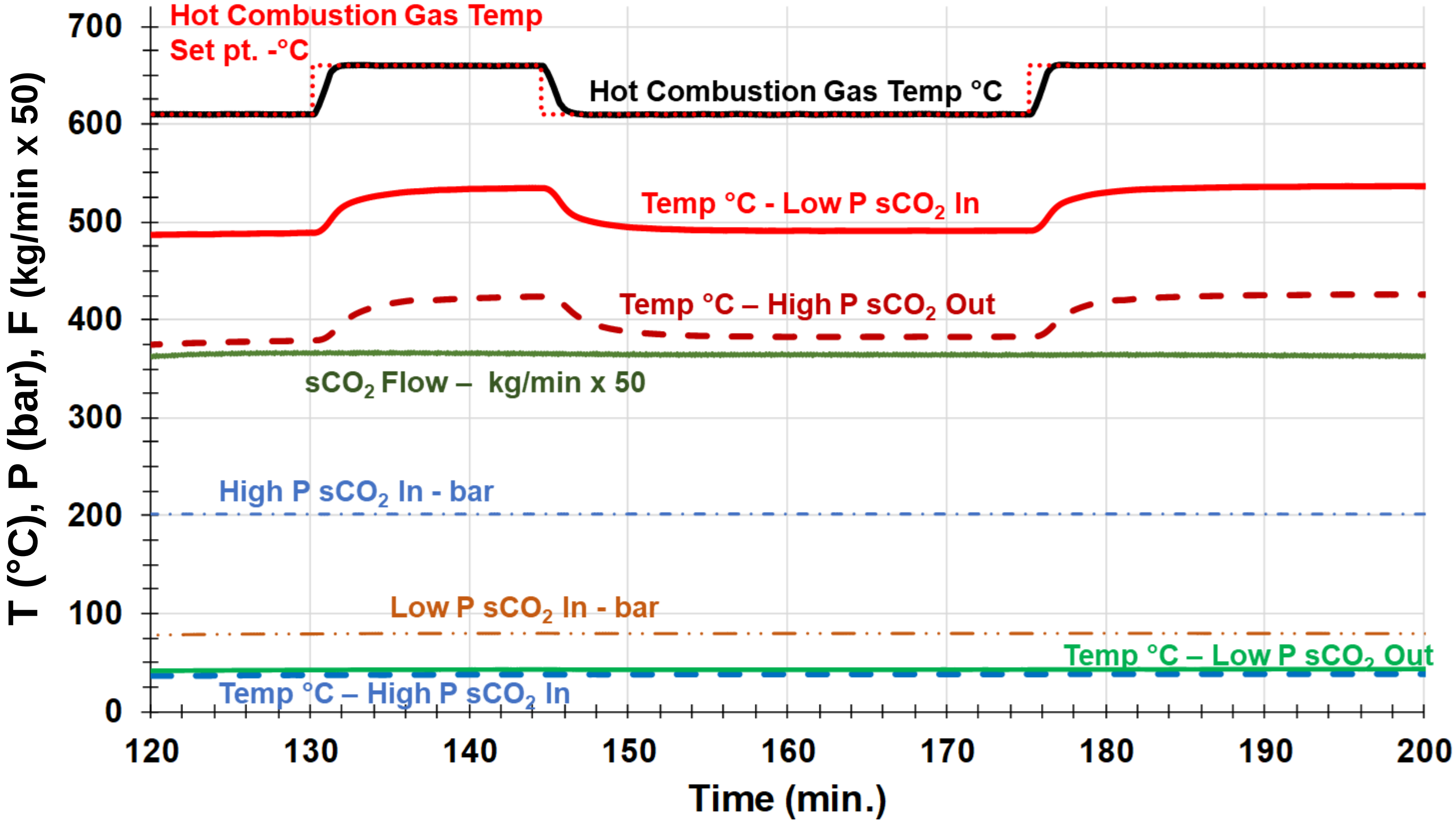
Energy Balance Plot



Good Energy Balance, < 2% error

COMBO-SSHX

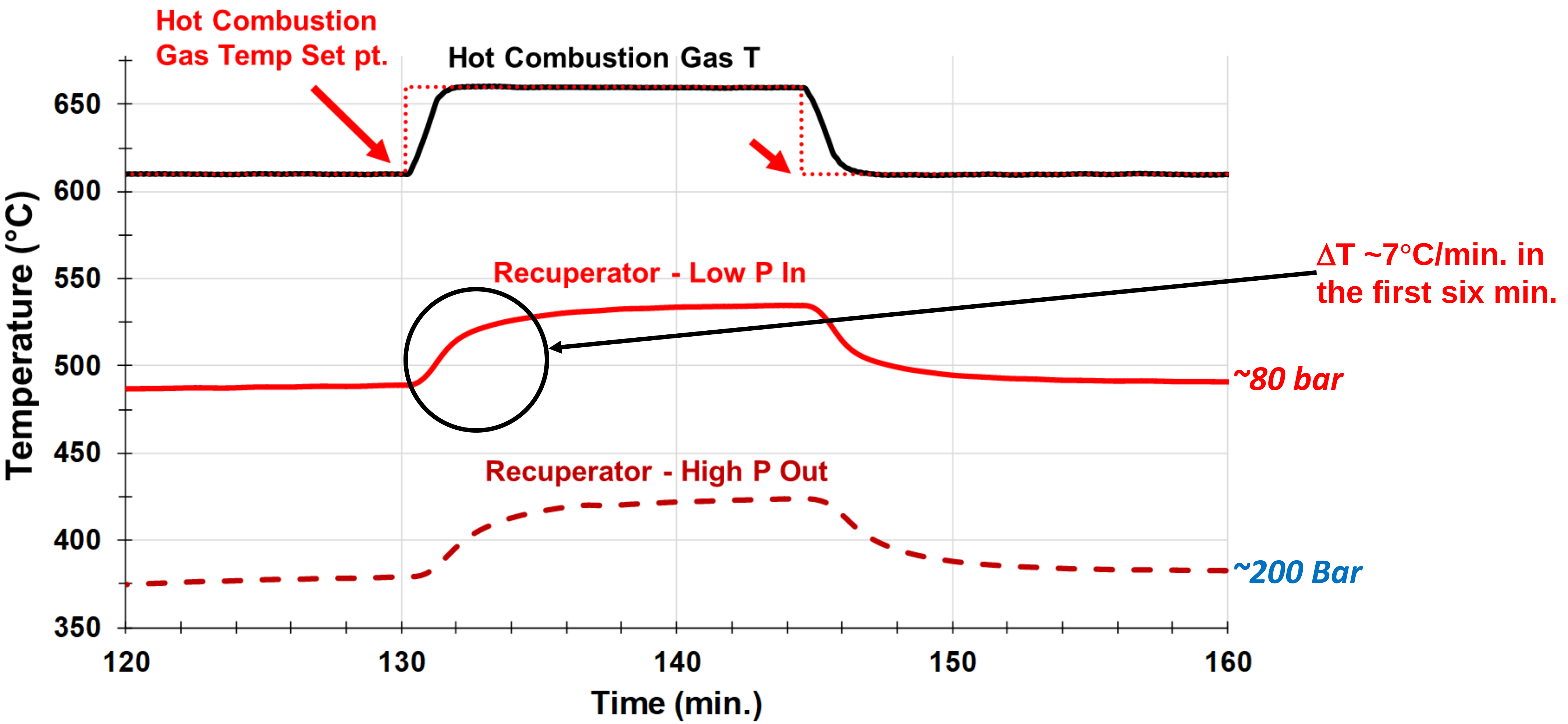
Temperature Transient Plot



Pressure and flow remain stable

COMBO-SSHX

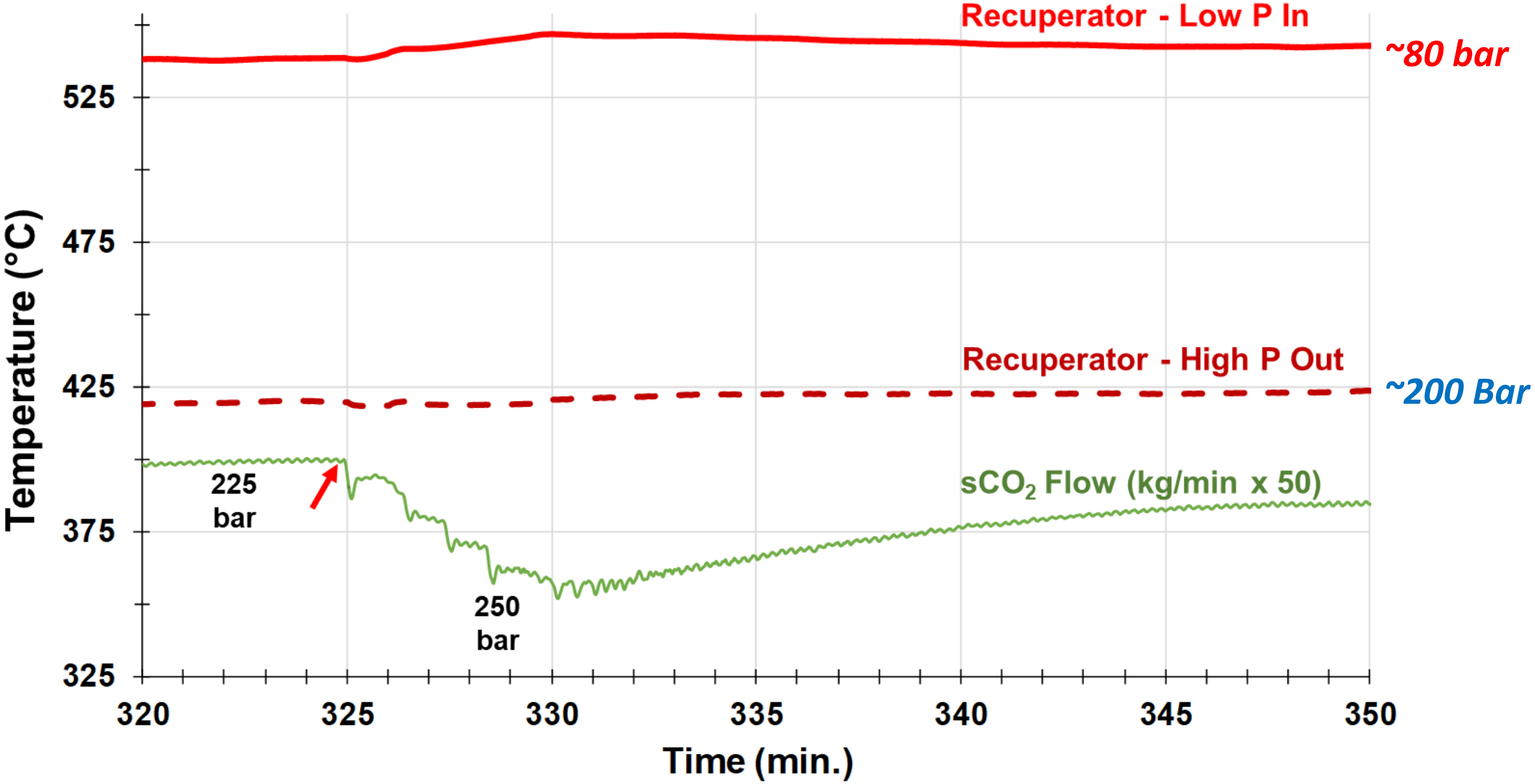
Temperature Transient Plot - expanded



Hot combustion gas adjusts in ~2 min; sCO$_2$ streams take ~10-15 min.

COMBO-SSHX

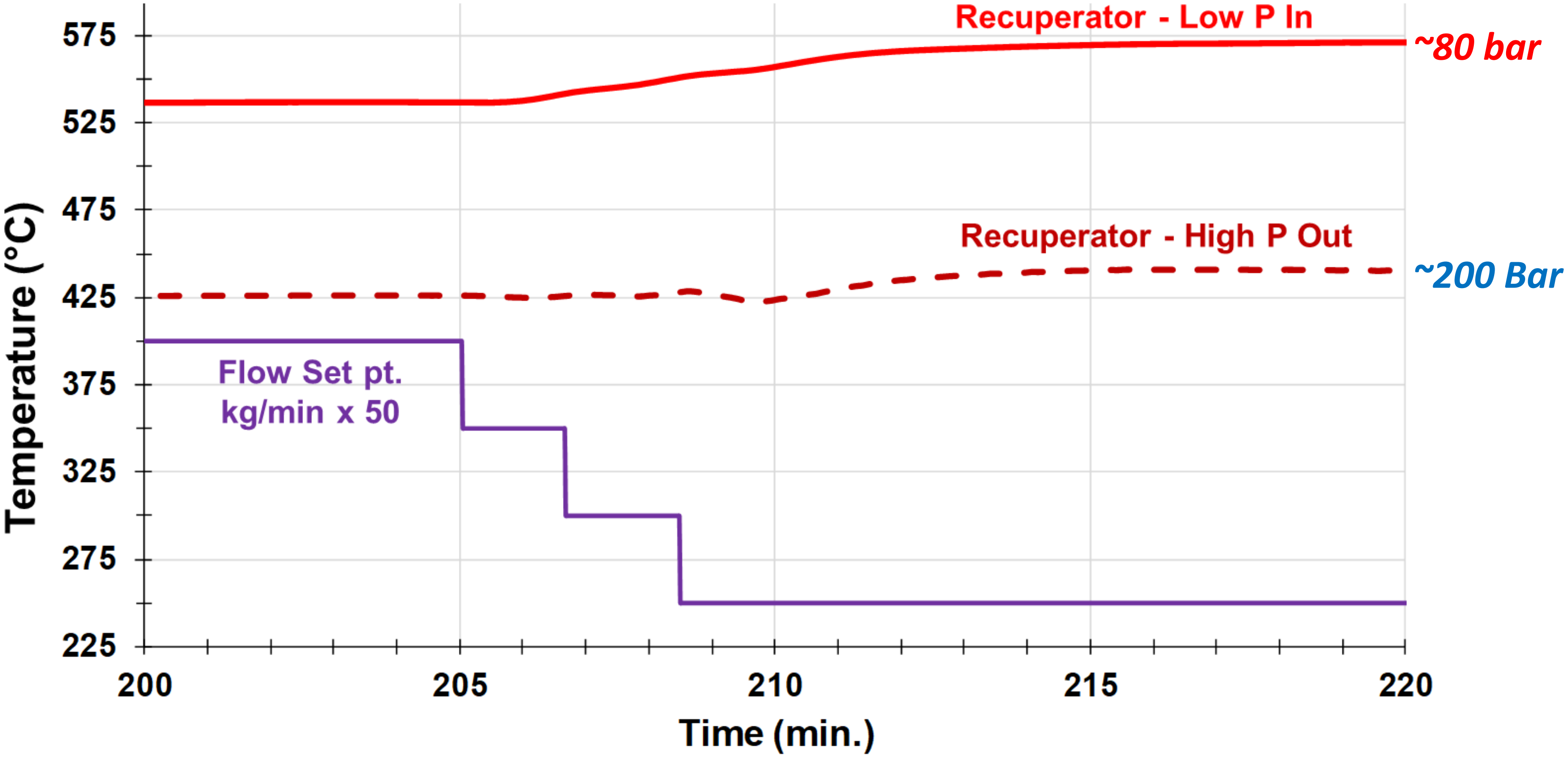
Pressure Transient Plot



As High P is increased, sCO$_2$ flow decreases, & Low P Recuperator T increases

COMBO-SSHX

Flow Transient Plot



As sCO_2 flow decreased, Low P Recuperator T increases, & High P increases slightly

(not shown)

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Thank you for your kind attention!

Thar Energy's new Pittsburgh location

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