# Introduction to Heatric PCHEs

9th International sCO2 Energy Technologies Symposium - 20 March 2026

Heat Exchangers for Supercritical CO2 Power Cycle Applications Tutorial

Heatric

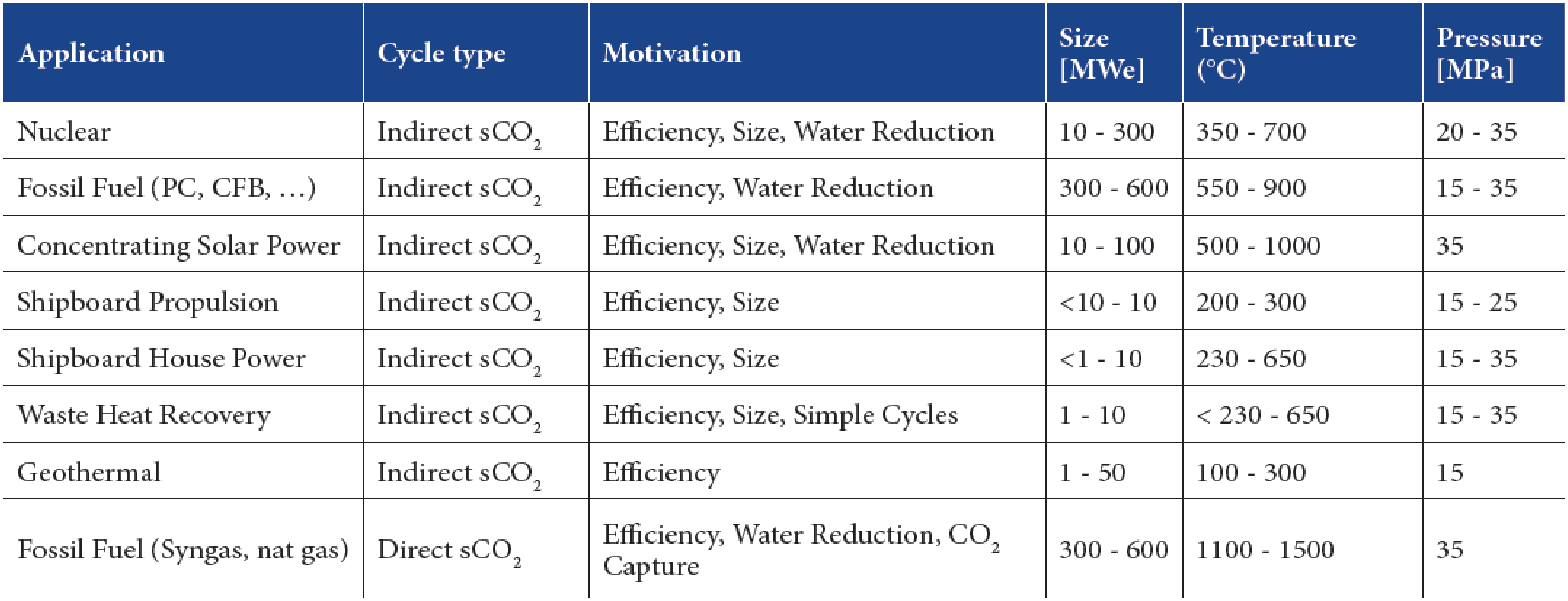
Parker

Renaud Le Pierres – Business Development Engineer

ENGINEERING YOUR SUCCESS.

# 1 | Why Heatric PCHEs?

## Heat Exchangers for **Supercritical CO2 Power Cycle Applications**



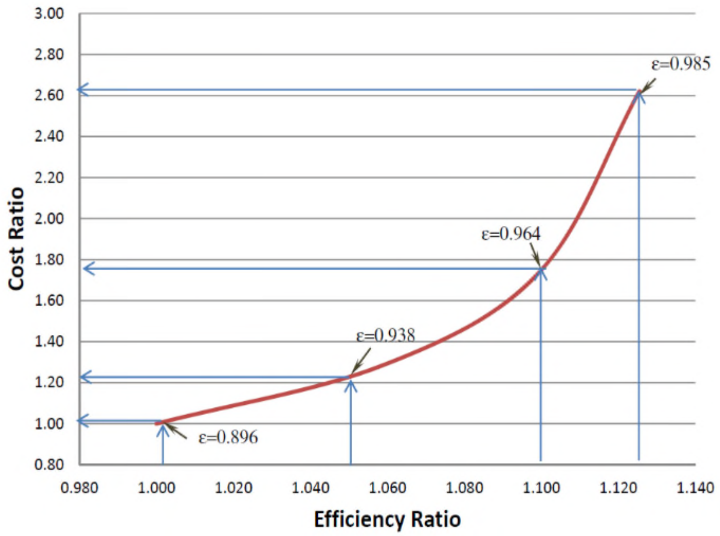
| Application | Cycle type | Motivation | Size [MWe] | Temperature (°C) | Pressure [MPa] |
|---|---|---|---|---|---|
| Nuclear | Indirect sCO$_2$ | Efficiency, Size, Water Reduction | 10 - 300 | 350 - 700 | 20 - 35 |
| Fossil Fuel (PC, CFB, …) | Indirect sCO$_2$ | Efficiency, Water Reduction | 300 - 600 | 550 - 900 | 15 - 35 |
| Concentrating Solar Power | Indirect sCO$_2$ | Efficiency, Size, Water Reduction | 10 - 100 | 500 - 1000 | 35 |
| Shipboard Propulsion | Indirect sCO$_2$ | Efficiency, Size | <10 - 10 | 200 - 300 | 15 - 25 |
| Shipboard House Power | Indirect sCO$_2$ | Efficiency, Size | <1 - 10 | 230 - 650 | 15 - 35 |
| Waste Heat Recovery | Indirect sCO$_2$ | Efficiency, Size, Simple Cycles | 1 - 10 | < 230 - 650 | 15 - 35 |
| Geothermal | Indirect sCO$_2$ | Efficiency | 1 - 50 | 100 - 300 | 15 |
| Fossil Fuel (Syngas, nat gas) | Direct sCO$_2$ | Efficiency, Water Reduction, CO$_2$ Capture | 300 - 600 | 1100 - 1500 | 35 |

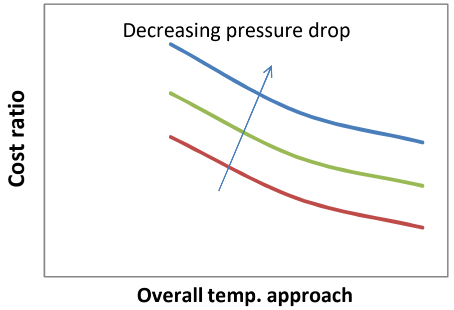
# 2 | Economic feasibility of PCHEs for sCO2 power cycles

## Key optimisation factors (cost vs. efficiency)

- **Increasing design temperature** → Change from 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).
- **Reducing temperature approaches** → Diminish efficiency returns versus exchanger potentially doubling in size for minimum gains (Q=U·A·LMTD).
- **Reducing allowable pressure drop** → Very high free flow area required (increase size of HE) potentially beyond compressor / pump cost savings.

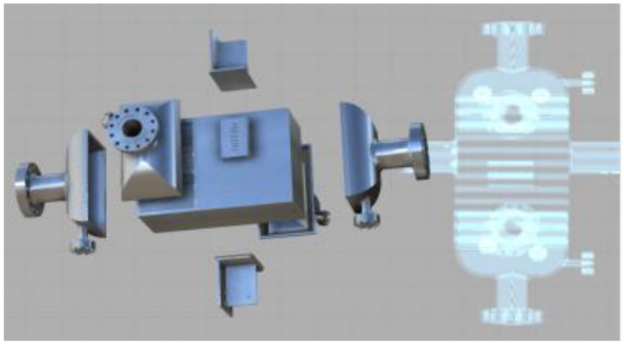
**Hence sCO2 process design must be balanced between equipment cost and efficiency gain.**





# 3 | Benefits of PCHEs

## Superior Performance

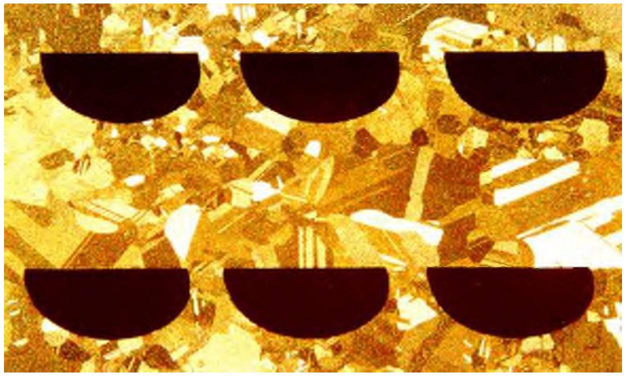


### OPEX saving across wide range of processes

PCHEs are bespoke diffusion bonded compact heat exchangers providing:

- close temperature approaches (>2°C)
- very high thermal performance (13.6MWth/m3 sCO2 recuperator)
- high pressure capability (>1,000 Bar)
- widest range of temperatures (-254°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 40 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

# 3 | Heatric sCO2 Key Delivered Project Timeline

**1994**

First PCHE using sCO2 offshore re-injection

**2003**

First PCHE recuperator for Tokyo Institute of Technology sCO2 loop

**2009**

3 PCHEs to Sandia National Laboratories sCO2 Brayton test loop

**2011**

3 PCHEs to Echogen EPS 100, the world’s first commercial sCO2 WHR unit

**2016**

Recuperator to NET Power Pilot Plant in La Porte, Texas

**2019**

3 PCHEs to GTI / SWRI for the STEP facility

**2021**

2 PCHEs for first Everllence HPU commercial plant in Denmark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Heatric

# 5 | PCHEs design and construction

**Design**

Heatric PCHEs are designed in-house by specialised engineering team, bespoke to customer requirements.

**Etching**

Heatric PCHEs are typically 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 heat exchanger core with the same integrity as a block of steel.

**Fabrication**

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

# 5 | PCHEs design and construction

## Design process

### Material selection

- Client requirement
- Availability of product form and grade
- Cost
- Mechanical and thermal strength
- Corrosion resistant
- Manufacturability (weldability and formability)

### Hydraulic design

- Mass flow rate
- Overall pressure drop calculation
- Component losses (core, nozzles, headers)
- Other losses on components (manifolds, elbows), due to glycol or liquid injection and two-phase distributors if any)

### Thermal design

- All required thermal calculations and fouling
- Plate and core sizing
- Flow pass configuration
- Design with multi-streams, if required
- Ensure maldistribution is avoided
- Optimizing to minimize cost vs. performance

### Mechanical design

- Thermal and hydraulic design input
- Client design requirements
  - Basic design condition (pressure, temperature)
  - External loads (nozzle loads, wind, snow, motion)
- Design to Code rules (e.g. ASME BPVC VIII-1)
- FEA - if required or design not covered by Core rules
- Creep and Fatigue analysis, if required
- Other specific loading condition

# 5 | PCHEs design and construction

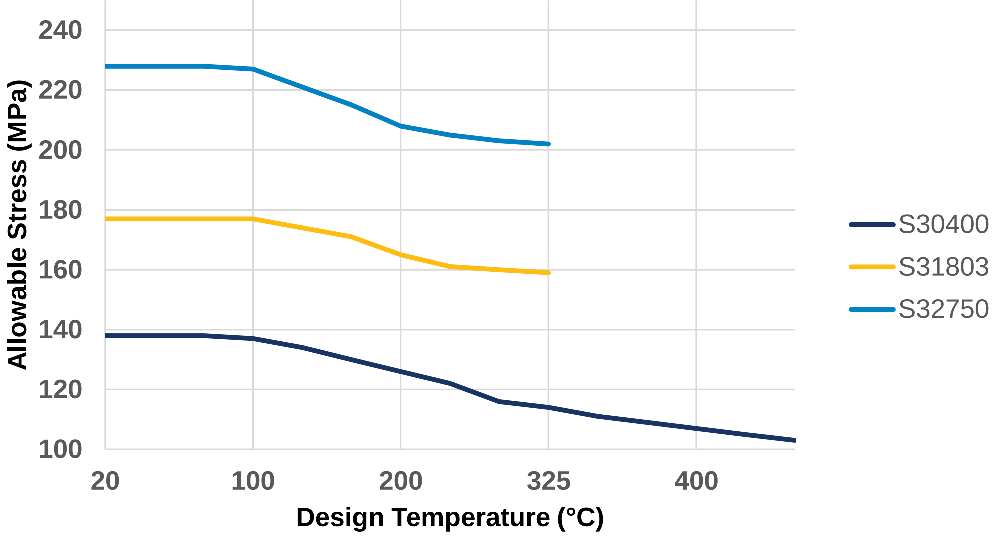
## Material selection

Qualified:

- Stainless steels 304/304L (S30400, S30403)
- Stainless steels 316/316L (S31600, S31603)
- Duplex (S31803/S32205)
- Super duplex (S32750/S32760)
- 6 Moly (N08367)

Examples of previously qualified:

- Titanium Grade 2 (R50400)
- Alloy 617 (N06617)



Material Allowable Stress @ 200°C (ASME II-D)

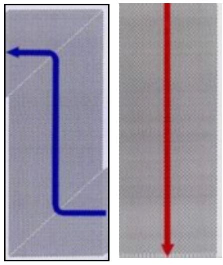
- Super duplex (S32750) = 208 MPa
- Duplex (S31803) = 165 MPa
- SS 304 (S30400) = 126 MPa

# 5 | PCHEs design and construction

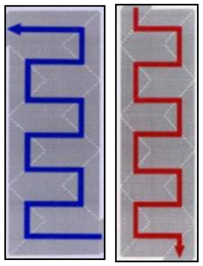
## Flow arrangement

### Thermal contact - 2 streamer

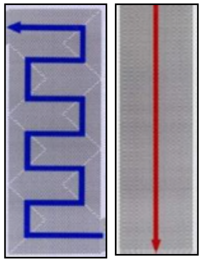
**Counter flow**



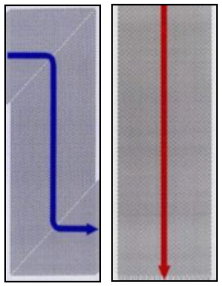
**Multipass counter flow**



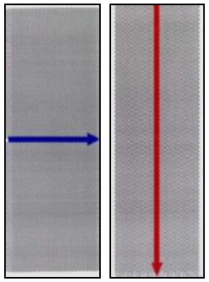
**Multipass counter-cross flow**



**Parallel flow**

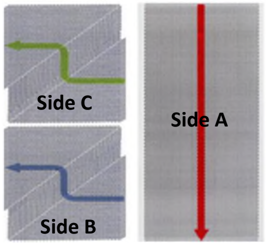


**Cross flow**

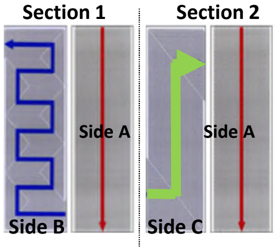


### Thermal contact - multi-streamer

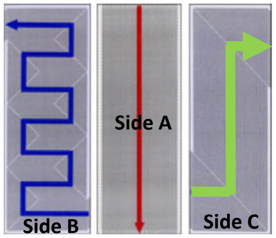
**Series**



**Parallel**

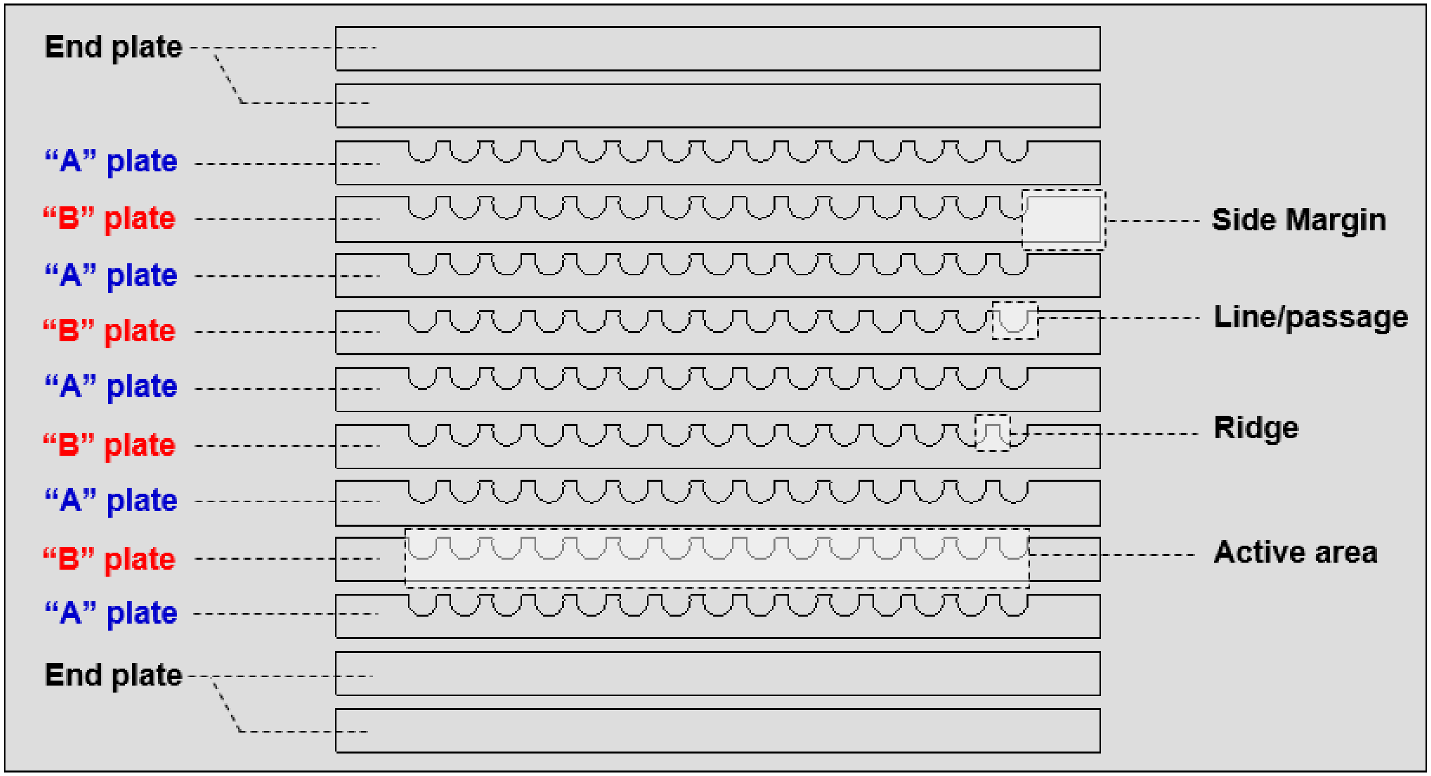


**Interleaved**



# 5 | PCHEs design and construction

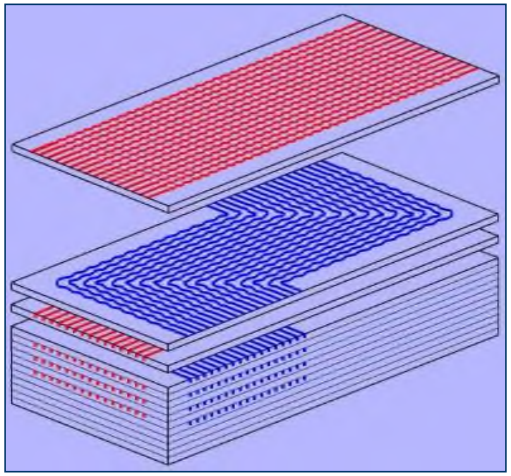
## Stacking arrangement

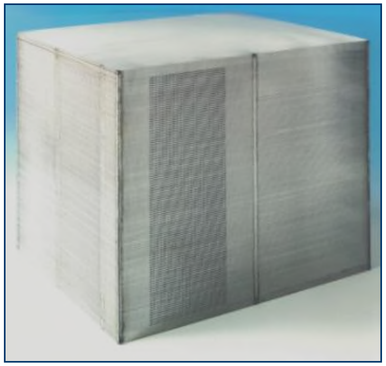


# 5 | PCHEs design and construction

## Core construction

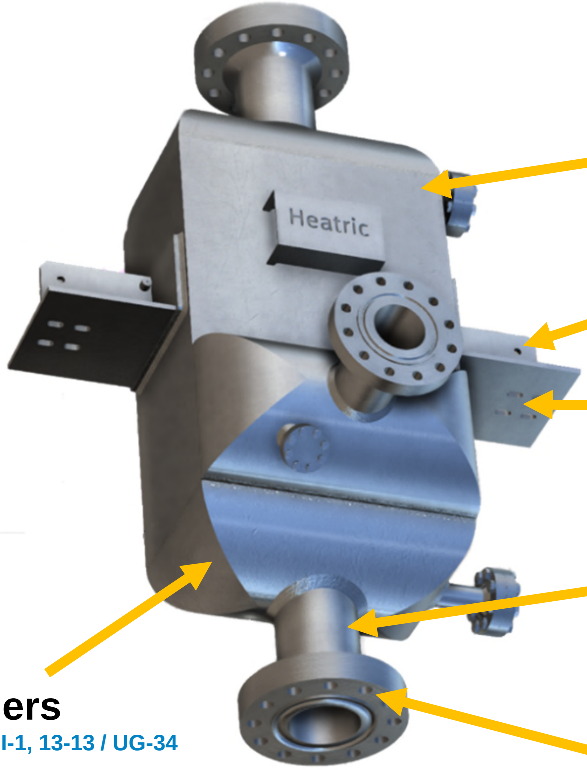
- Plates typically 1.65 mm thick
- Semi-circular flow channels with diameter of typically 2 mm
- Produced by chemical etching
- Custom design of flow channels to optimize heat transfer and pressure drop performance
- Solid state joining process giving parent metal strength
- Clean high temperature process
- No melting or deformation
- No braze, flux or filler
- Metal grain growth occurs
- Design to ASME Sec. VIII Div. 1

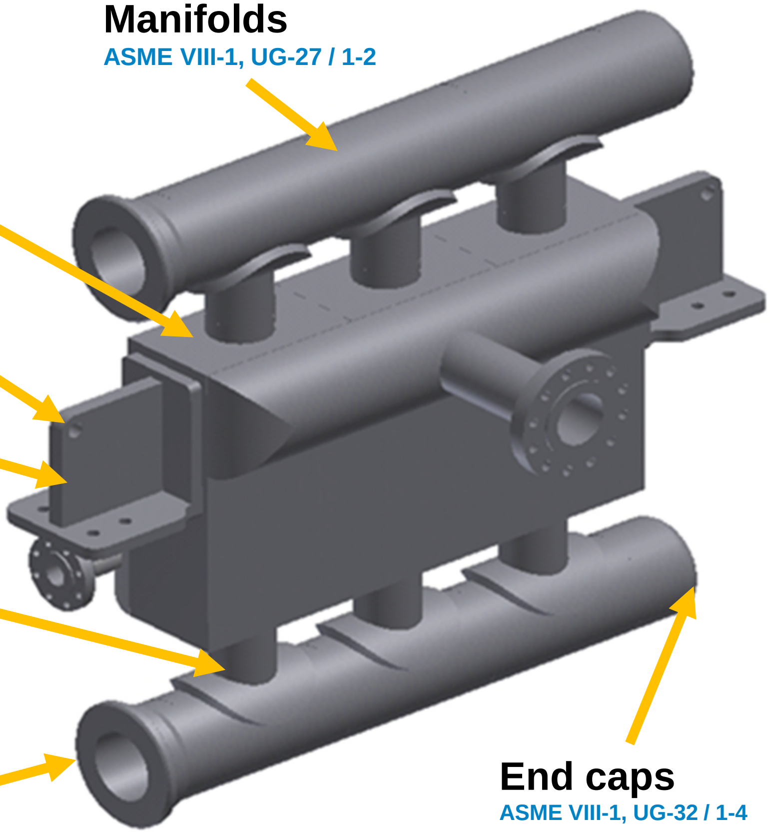




# 5 | PCHEs design and construction

## Mechanical design and key components





**Manifolds**
ASME VIII-1, UG-27 / 1-2

**Core**
ASME VIII-1, MA-13, 13-9

**Lifting Lugs**
Structural Design Rules
DNV 2-7.3

**Supports**
Structural Design Rules

**Nozzles**
ASME VIII-1
- **Reinforcement:**
  ASME VIII-1 and ASME VIII-2, Part 5 - FEA
- **External loads:**
  ASME B31.3, ASME VIII-2, Part 5 - FEA

**Headers**
ASME VIII-1, 13-13 / UG-34

**Flanges**
ASME B16.5
ASME VIII-1, MA-2
SPO
Teklok

**End caps**
ASME VIII-1, UG-32 / 1-4

# 6 | Operation challenges in heat exchangers

## Structural, Performance and Metallurgical problems of HEs

**Structural**

- Failures caused by flow induced vibration
- Leakage from bolted connections

**Performance**

- The excessive tube fouling
- Thermal stresses in the internal of the heat exchanger

**Metallurgical**

- Stress corrosion
- Galvanic corrosion
- Erosion corrosion
- Pitting corrosion

# 6 | Operation challenges in heat exchangers

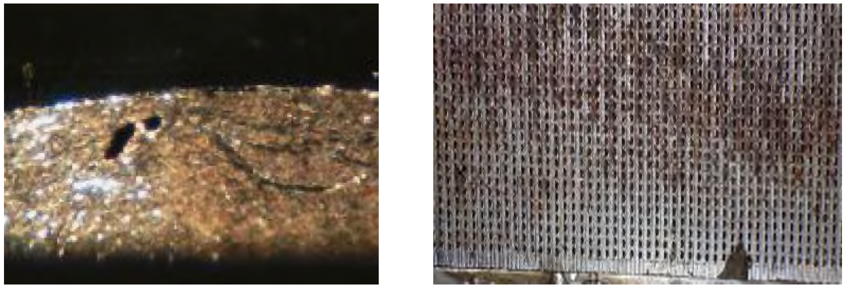
## Corrosion

- Corrosion of a PCHE is uncommon due to the materials used in their construction (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)**

# 6 | Operation challenges in heat exchangers

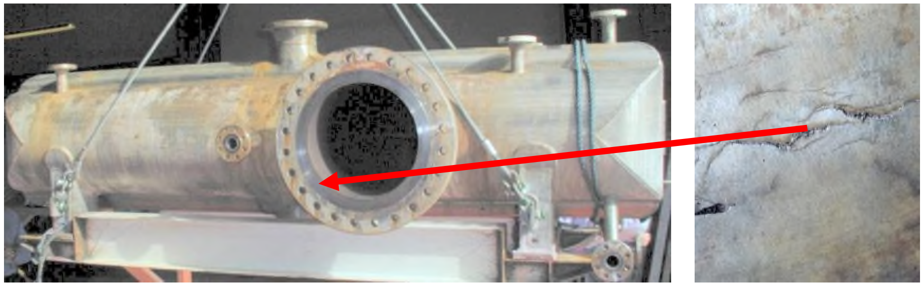
## Corrosion

### Pitting Corrosion



- It’s a form of localised corrosion that leads to the creation of small holes in the metal.
- Typically occurs in alloys that are protected by a tenacious (passivating) oxide film, such as stainless steels.
- It also occurs in the presence of surface defects or foreign materials and substances that are left in contact with exposed surfaces.
- Oxidisation of the protective surface layers leads to increased acidity and on set of corrosion.

### Chloride Stress Corrosion Cracking (CSCC)



- CSCC is the growth of crack formation in a corrosive environment i.e. coastal locations where higher levels of chlorides are present
- It can lead to failure of normally ductile metals subjected to a tensile stress, especially at elevated temperatures

# 7 | 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

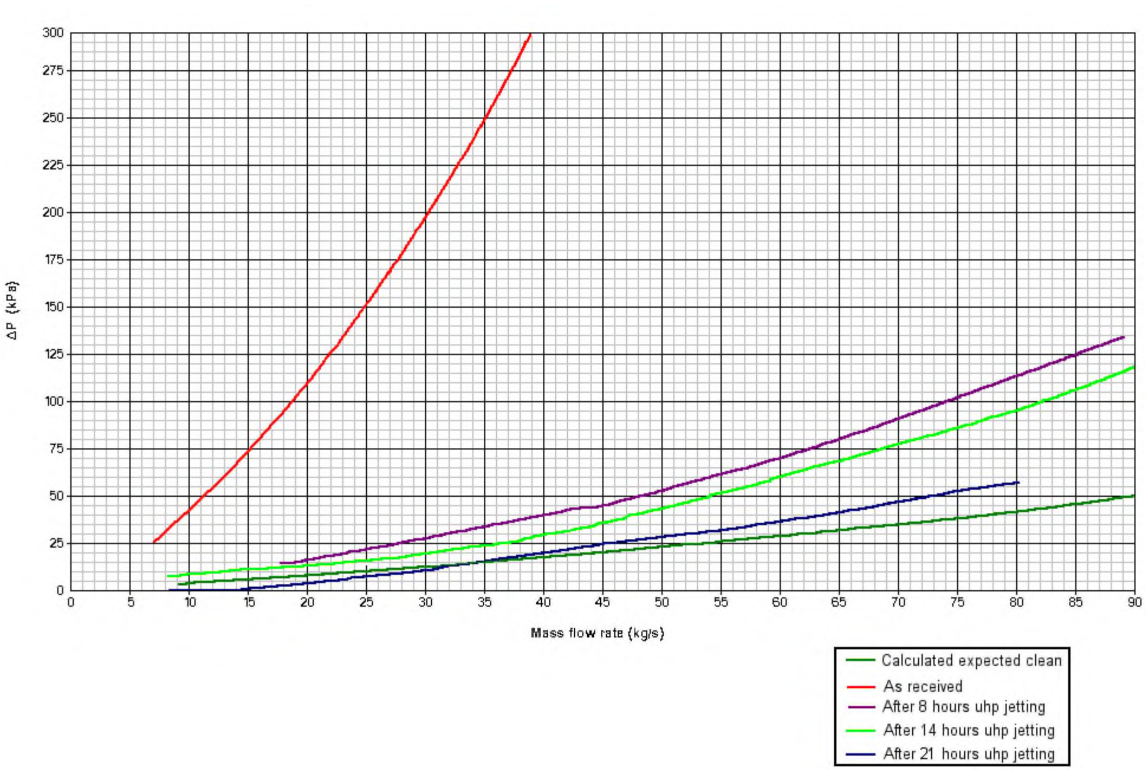
- Weld repair
- Re-core
- Failure investigation
- Maintenance nozzle retrofit

### 4. Additional Offerings

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

# 7 | Preventative Measures & Maintenance

## UHP Cleaning Example



**Before**

**After**

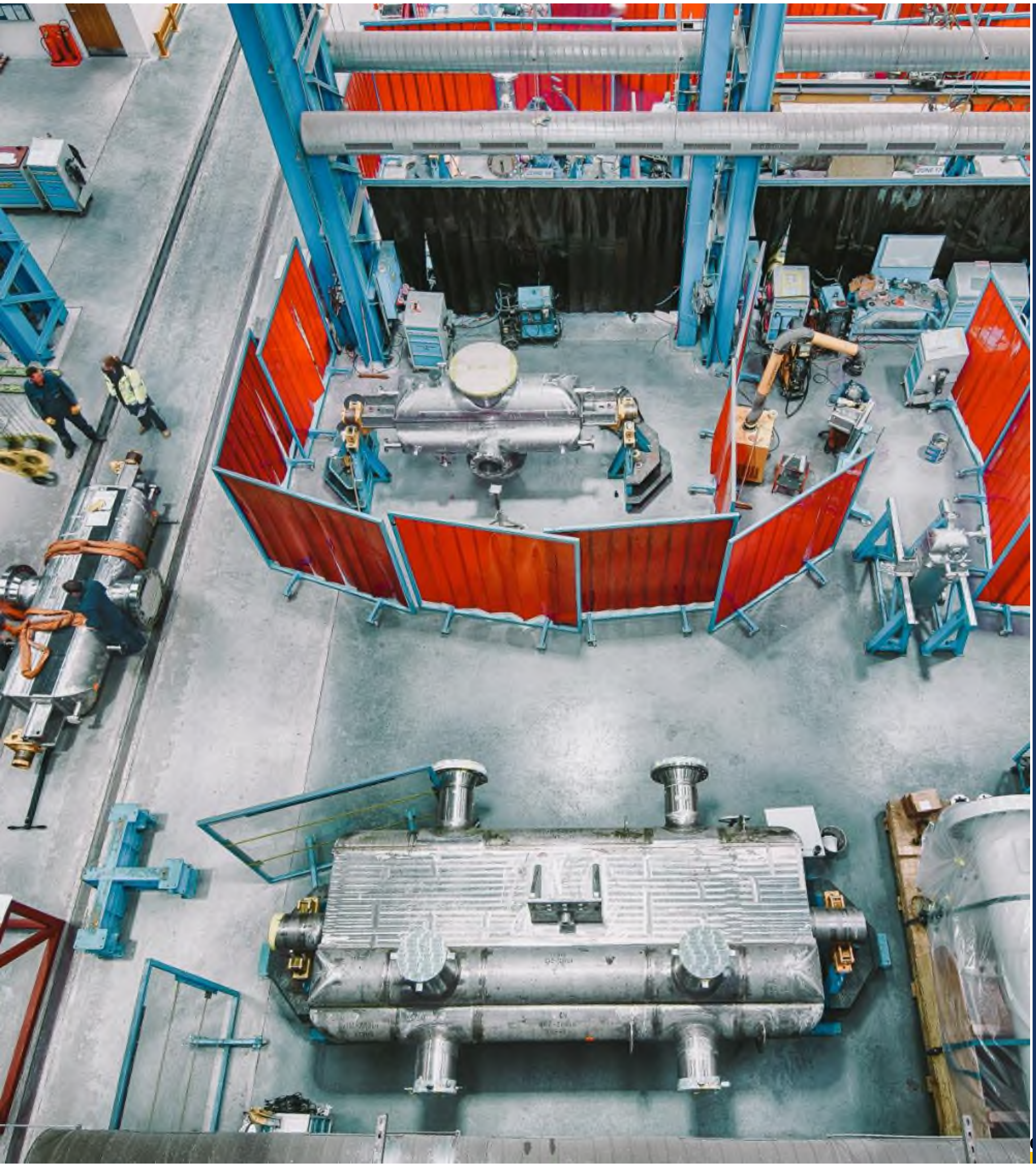
Heatric

# 8 | PCHEs application & troubleshooting

## PCHEs application & advantages compared to other HEs

- Combined Cycle Gas Turbine (fuel gas heaters and Rotor Air Coolers, condenser, evaporator (GE)
- sCO2 power cycles (Recuperator, coolers and supper heaters) (Net power)
- Energy storage (Highview)
- Waste heat recovery (WHR), Nuclear, concentrating solar, fossil energy (Sandia)
- Electro thermal energy storage (Everllence)
- Intercooler to improve efficiency of compressor
- CCS (Carbon capture storage)

| Troubleshooting | S&T | PCHE |
|---|---|---|
| Tube vibration | X | ✓ |
| Tube-to-tubesheet joint leakage | X | ✓ |
| Tube impingement erosion | X | ✓ |
| Baffle plate erosion | X | ✓ |
| Tube overstress & rupture | X | ✓ |
| Thermal fatigue | X | X |
| Corrosion | X | X |
| Fouling / Blockage | X | X |



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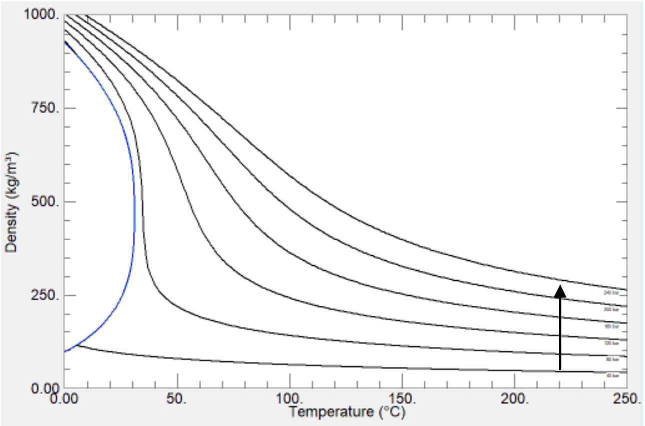
# GENERAL INTRODUCTION
# HEAT EXCHANGERS AND SCO2 POWER CYCLES

Michael Marshall

# 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 enhanced heat transfer.

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



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240
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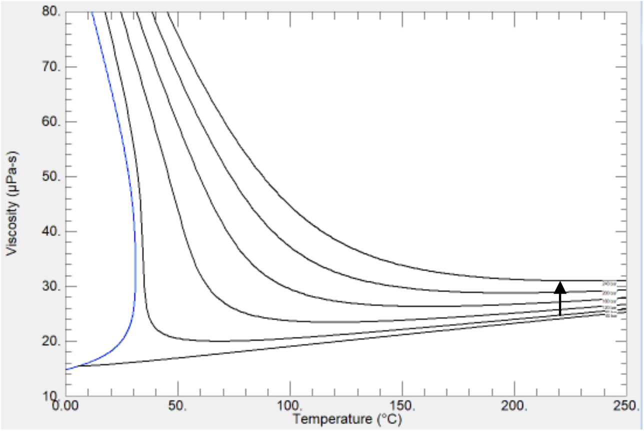
160
120
80
40



Isobars (bara):
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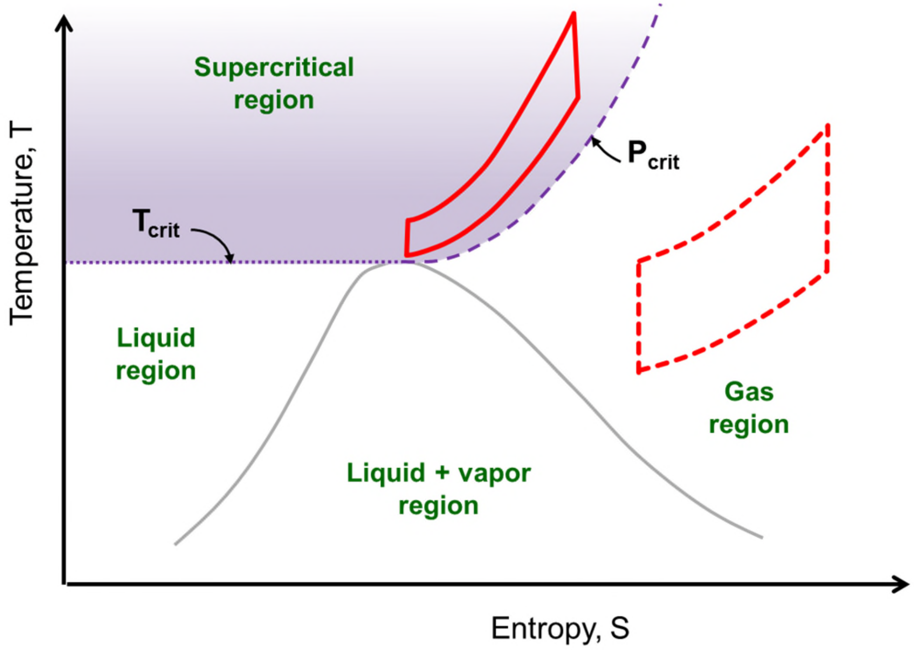
Figures: NIST REFPROP, v9.1

# Supercritical power cycles are unique in their operating region compared to Brayton or Rankine cycles.



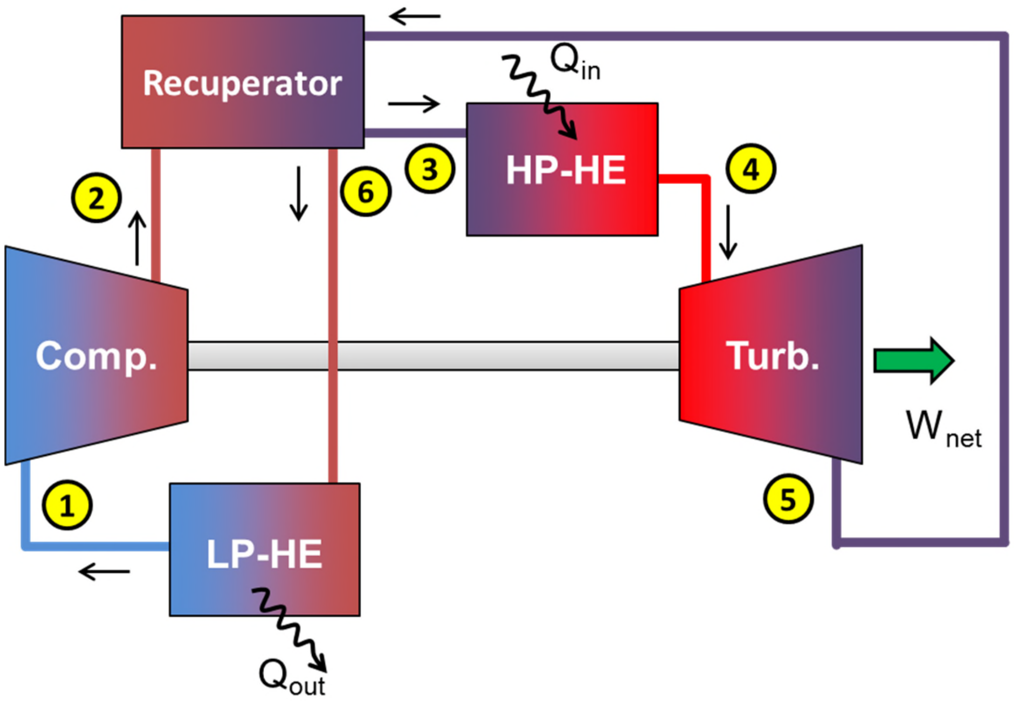
**Heat Input:**

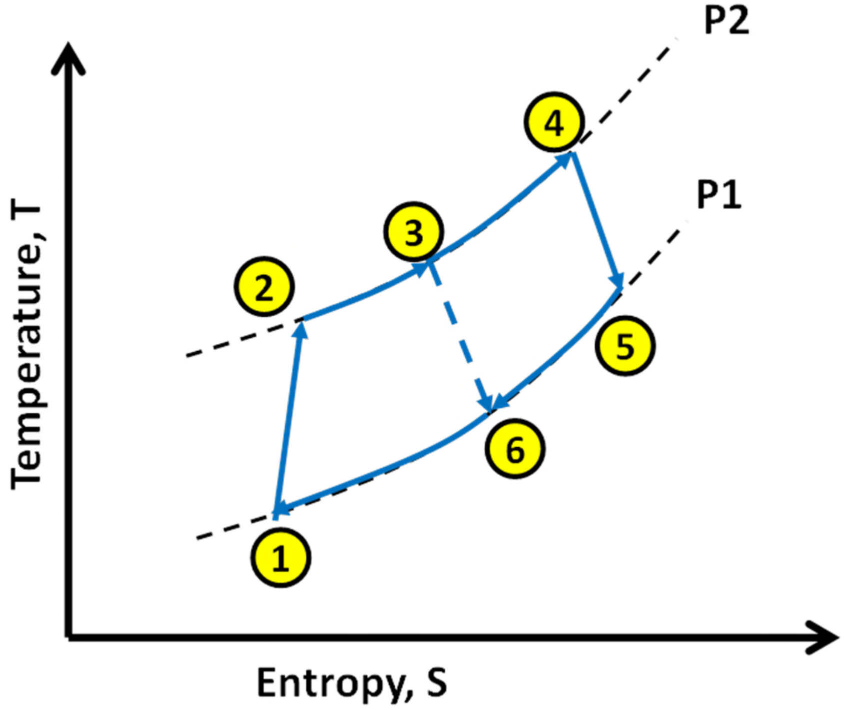
- Direct-fired (oxy-combustion)
- Indirect-fired (primary heat exchanger, secondary fluid from variety of sources)

**Heat Rejection:**

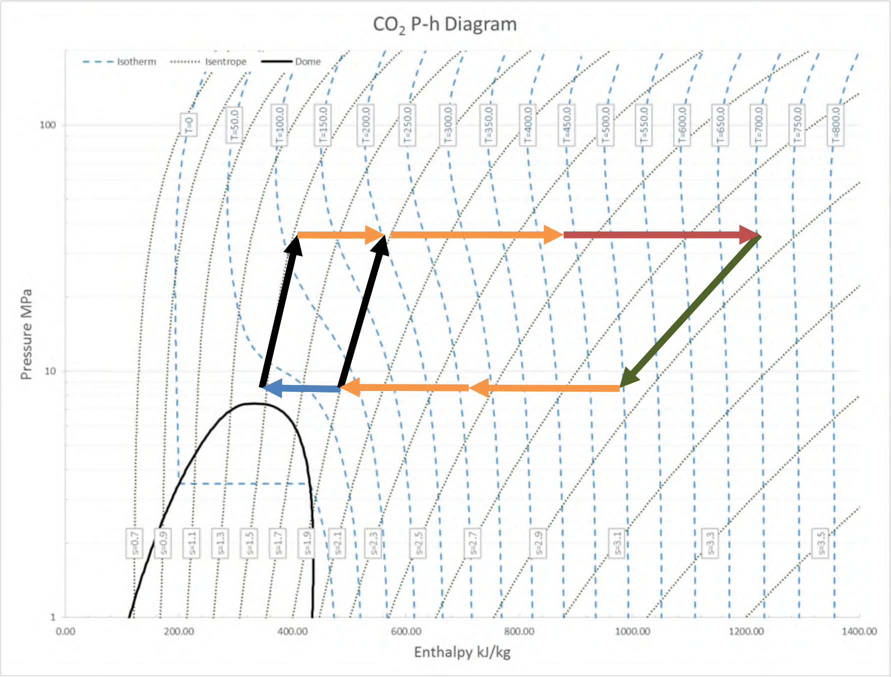
- Non-condensing: Dry (air) or water cooling.
- Condensing: Typically water cooling.

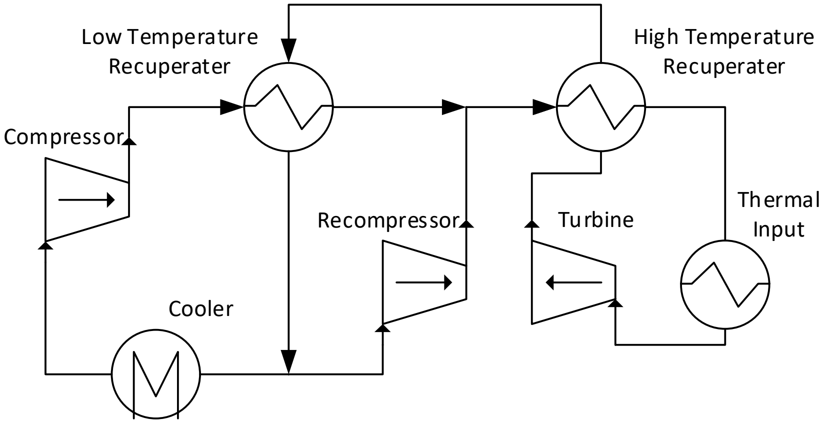
# A recuperator exchanges heat within the cycle to improve overall cycle thermal efficiency





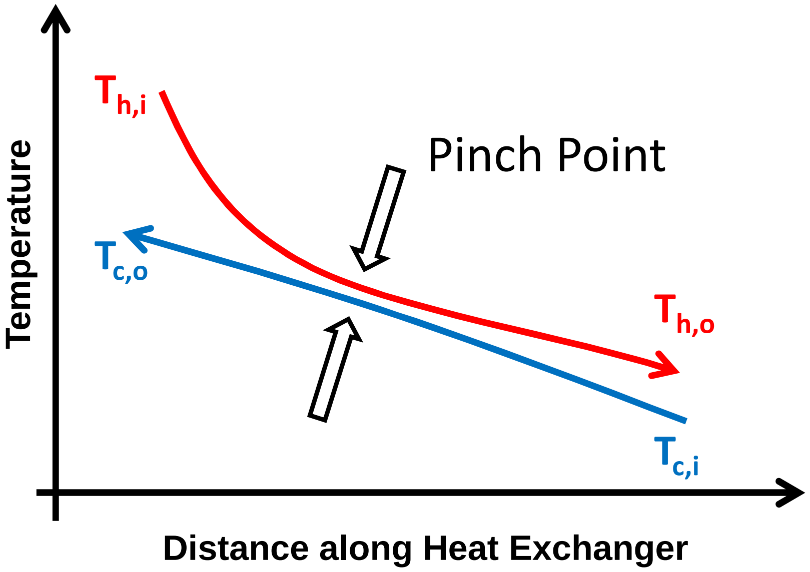
# Recompression cycle is benchmark for indirect fired cycles.

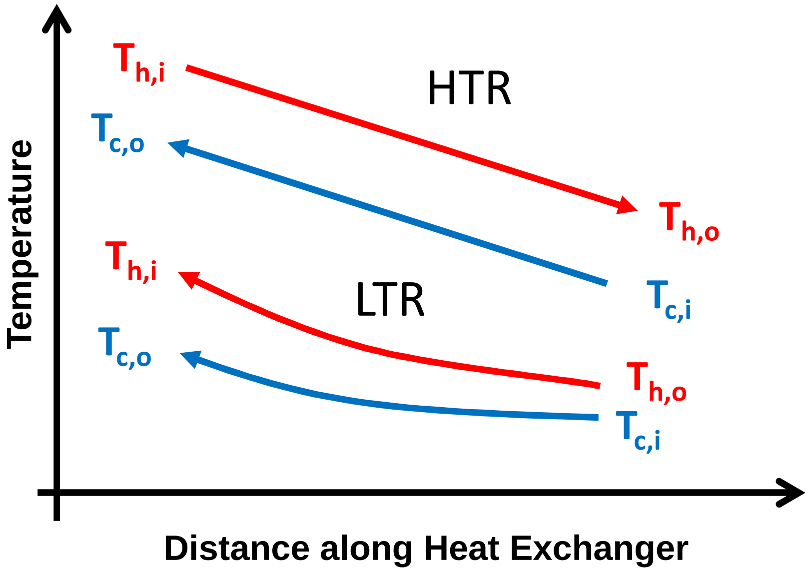




Main HX (Thermal Input) and Cooler can take on several forms, highly recuperated nature of cycle helps to drive up thermal efficiency.

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

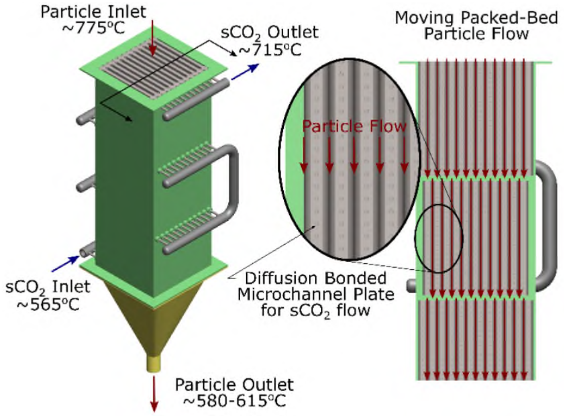




Splitting recuperator into Low Temperature (LTR) and High Temperature (HTR) units and employing cycle flow splits can get around pinch point issue.

# Cycle Heat Exchangers – Primary Heater

- Primary 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.



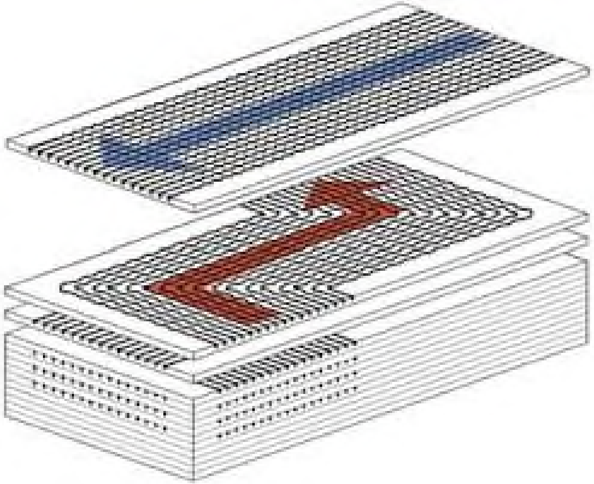
CSP particle-to-$sCO_2$ HX
(Albrecht, Ho, 2019)

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 $CO_2$ 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.



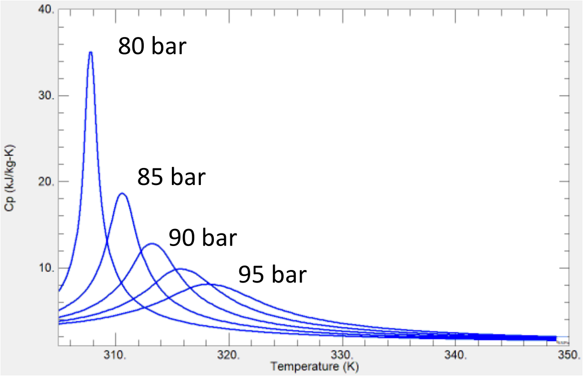
PCHE flow schematic [1]

PCHE Recuperator for STEP program

*[1] Heatric*

# Cycle Heat Exchangers - Coolers

- With a critical temperature around 88°F, $sCO_2$ 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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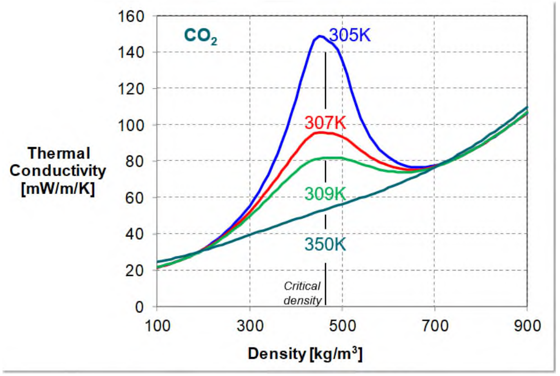

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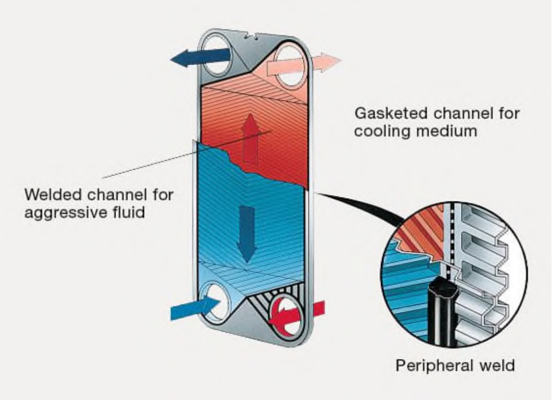


*[3]*

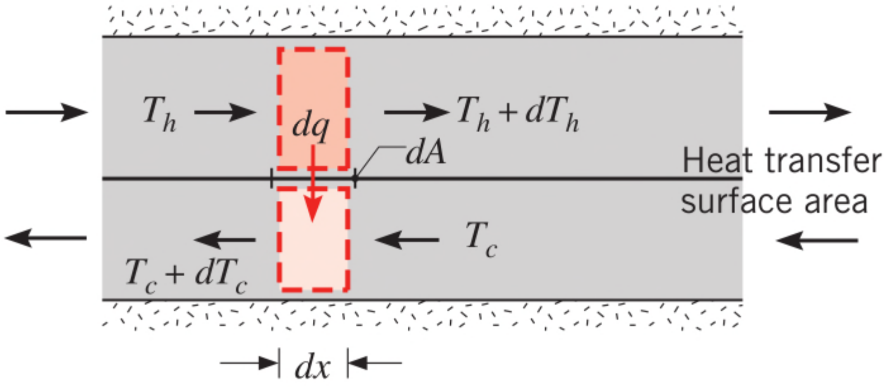
*[4]*

*[1]* NIST REFPROP, v9.1 *[2]* NIST REFPROP, v9.1
*[3] Alfa Laval*; *[4] Goodway Technologies*

# DESIGN APPROACH

Michael Marshall

# Heat Exchanger Thermal Design Overview



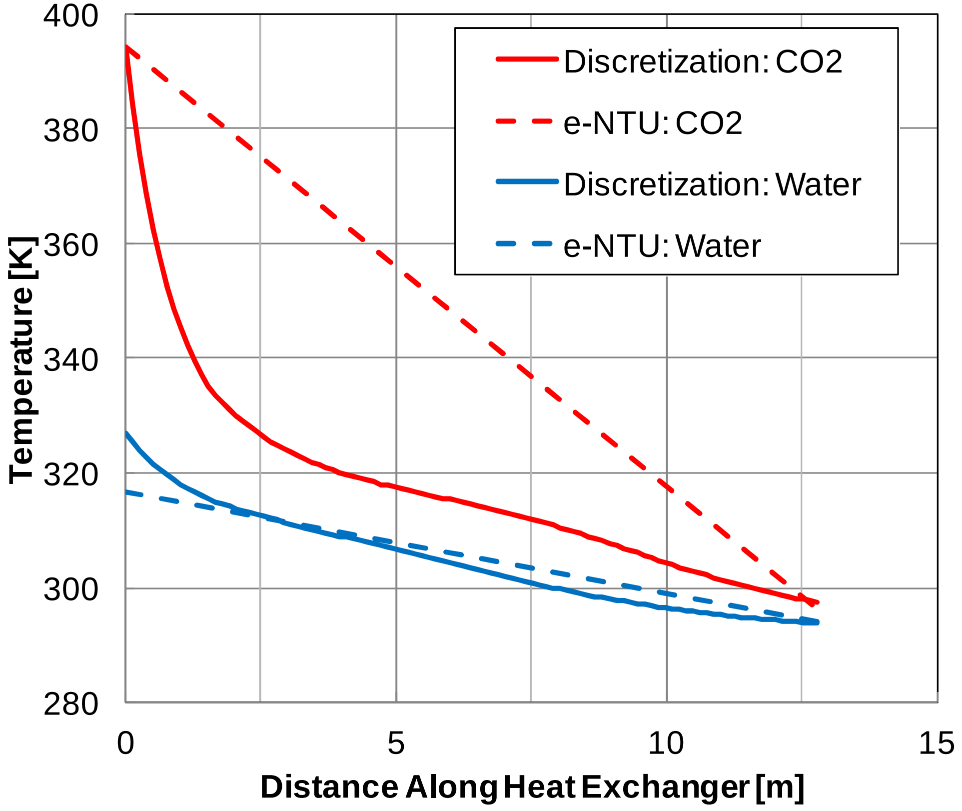
Once the cycle has established heat exchanger design conditions, detailed design can begin.

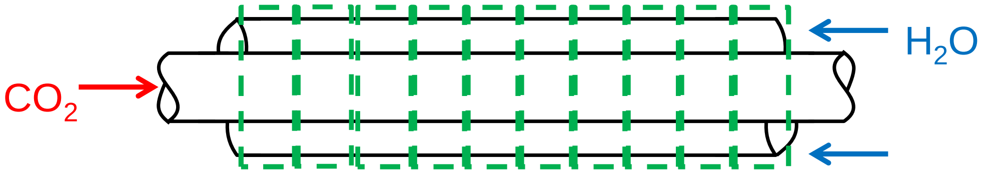
The overall approach is to determine the heat exchanger Unit Cell and correlations for HTC, dP and conduction resistance.

A discretized model finds 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.

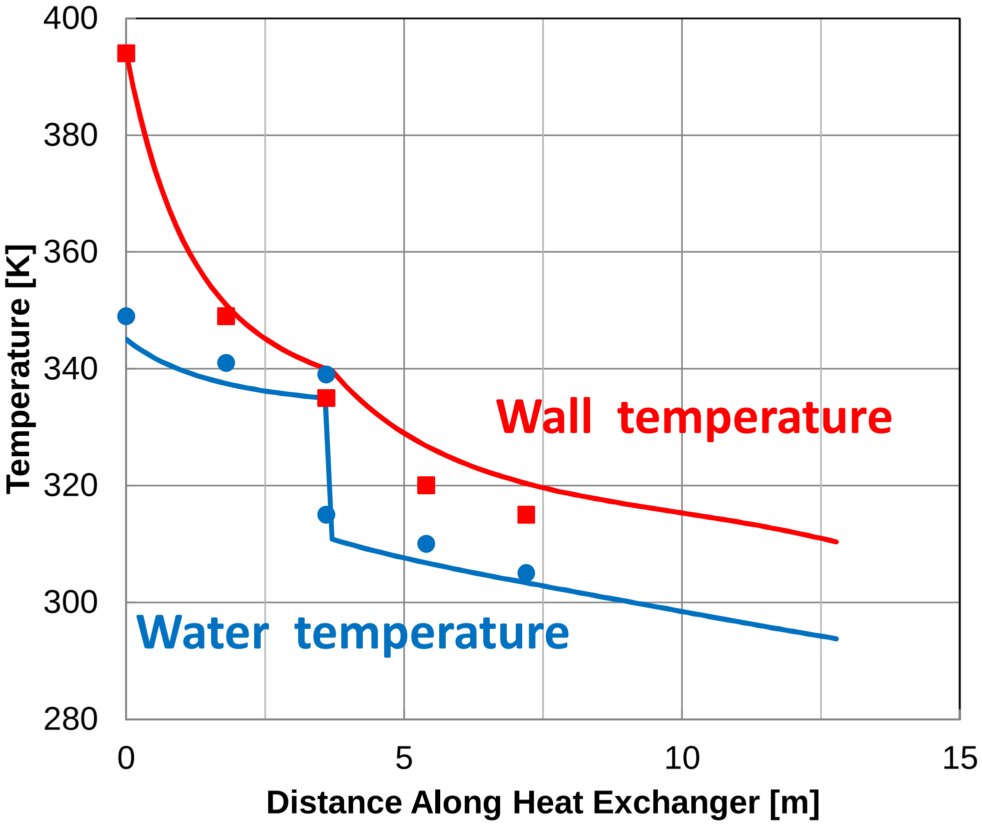
# Discretizing the heat exchanger accounts for property differences that affect fluid temperature.

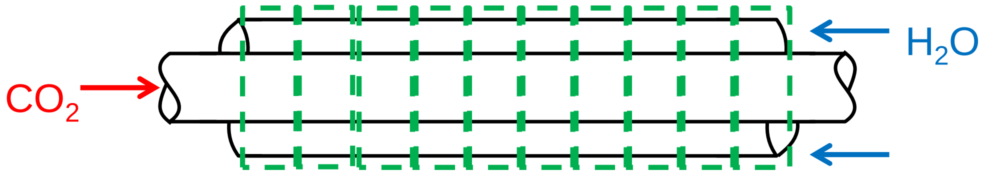




*Operating conditions and geometry from:*
*Pitla, S., Groll, E., and Ramadhyani, S., 2001, "Convective Heat Transfer from In-Tube Cooling of Turbulent Supercritical Carbon Dioxide: Part 2—Experimental Data and Numerical Predictions," HVAC&R Research,* ***7****(4), pp. 367–382.*

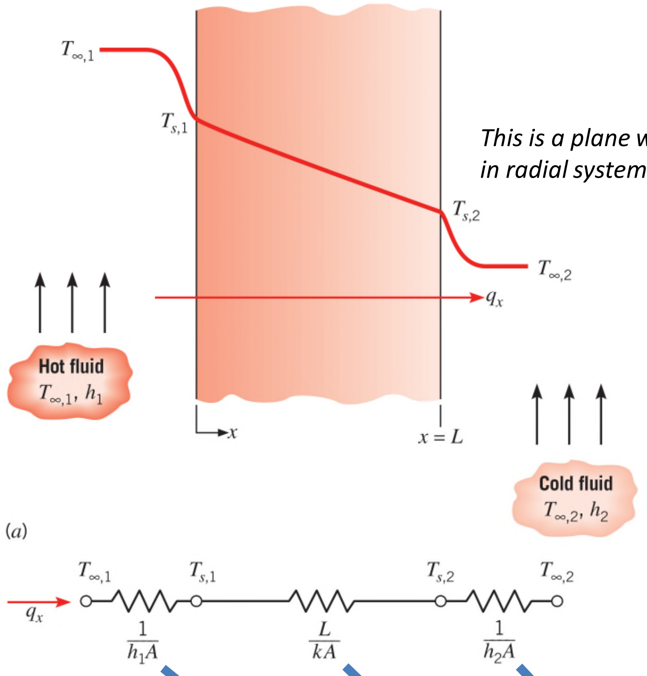
# 1D prediction methods match well with experimental measurements when the HX is discretized.





*Pitla, S., Groll, E., and Ramadhyani, S., 2001, "Convective Heat Transfer from In-Tube Cooling of Turbulent Supercritical Carbon Dioxide: Part 2—Experimental Data and Numerical Predictions," HVAC&R Research,* ***7****(4), pp. 367–382.*

# 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:

$$Q = UA * \Delta\mathrm{T}$$

In this equation $\Delta T$ 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.

Image: 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)*

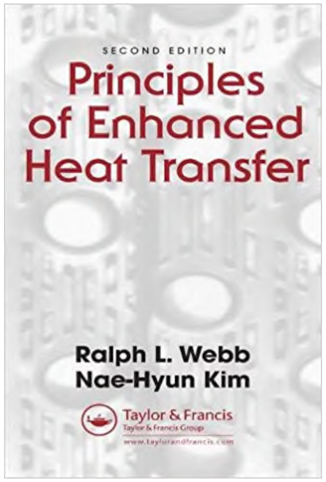
To calculate the required $UA$ term we need the hot and cold side heat transfer coefficients. These can be derived from experiments, CFD, or from correlations.

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?

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

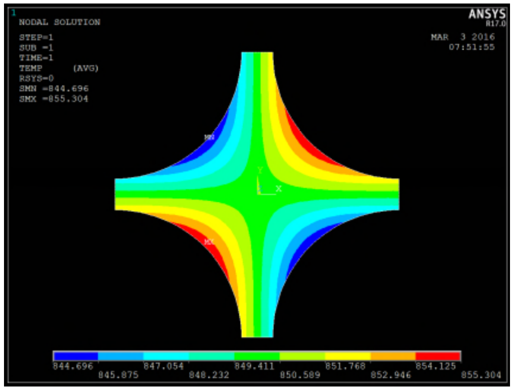
# Wall Resistance

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

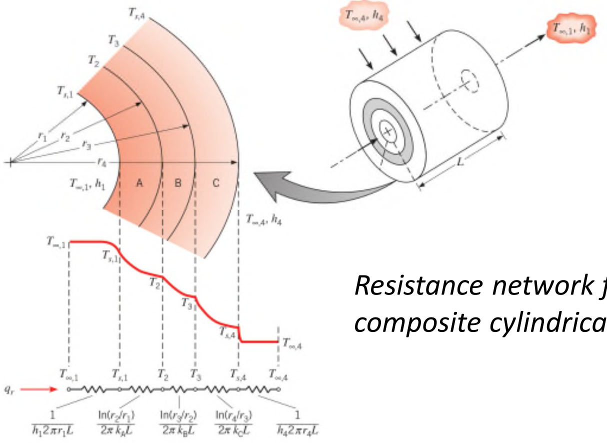
Wall resistance inhibits heat flow between the fluids. The value of $R_w$ can be obtained from FEA, analytically, or from experiment.

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

| Configuration | UA per m | Percent |
|---|---|---|
| No wall resistance | 26.6 | 100 |
| Equivalent Plane Wall | 25.4 | 95.3 |
| Checkerboard | 24.6 | 92.3 |
| Staggered | 21.9 | 82.2 |

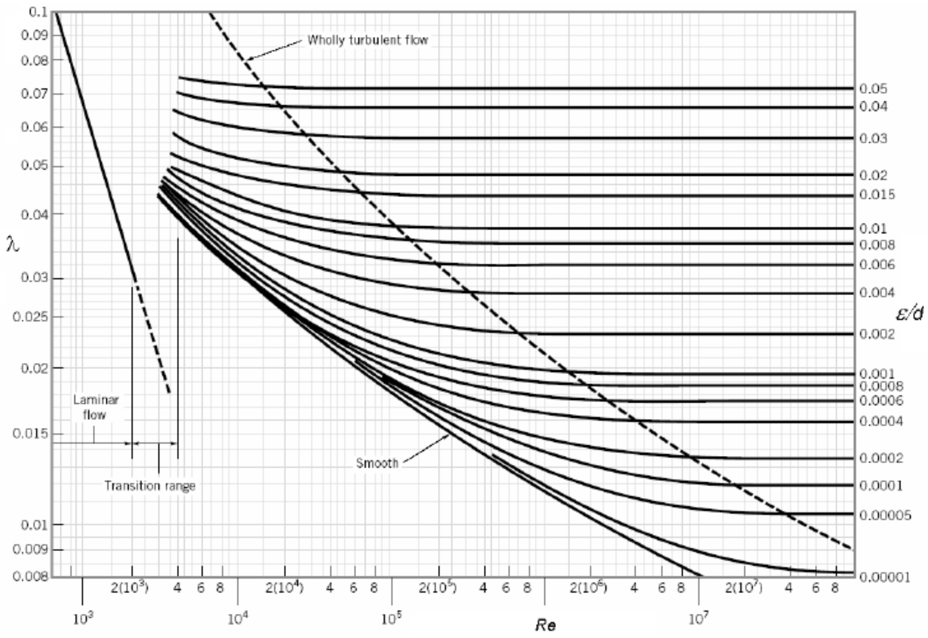


*FEA used to calculate equivalent wall resistance for checkerboard circular channels*



*Resistance network for composite cylindrical wall*

# Pressure Drop



*Moody Chart*

Image: 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:

$$DP = f * \frac{l}{D} * \frac{\rho V^2}{2}$$

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

# Energy Conservation

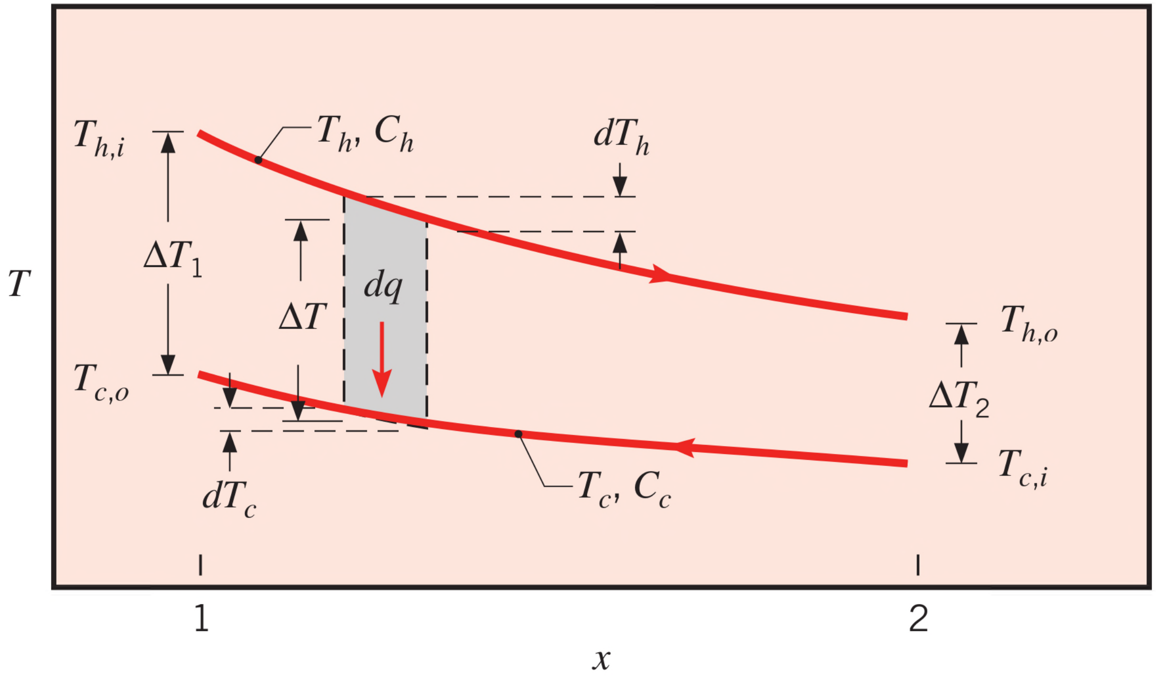


Image: Incropera, Dewitt, *Fundamentals of Heat and Mass Transfer.*

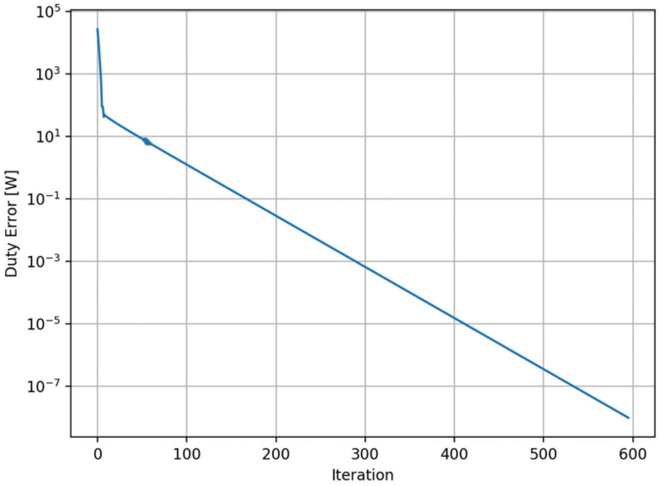
**Energy conservation**

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 | 0.25 s | 0.022 s |
| 15 | 0.93 s | 0.081 s |
| 50 | 10.3 s | 0.871 s |
| 250 | 256.3 s | 22.2 s |

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)

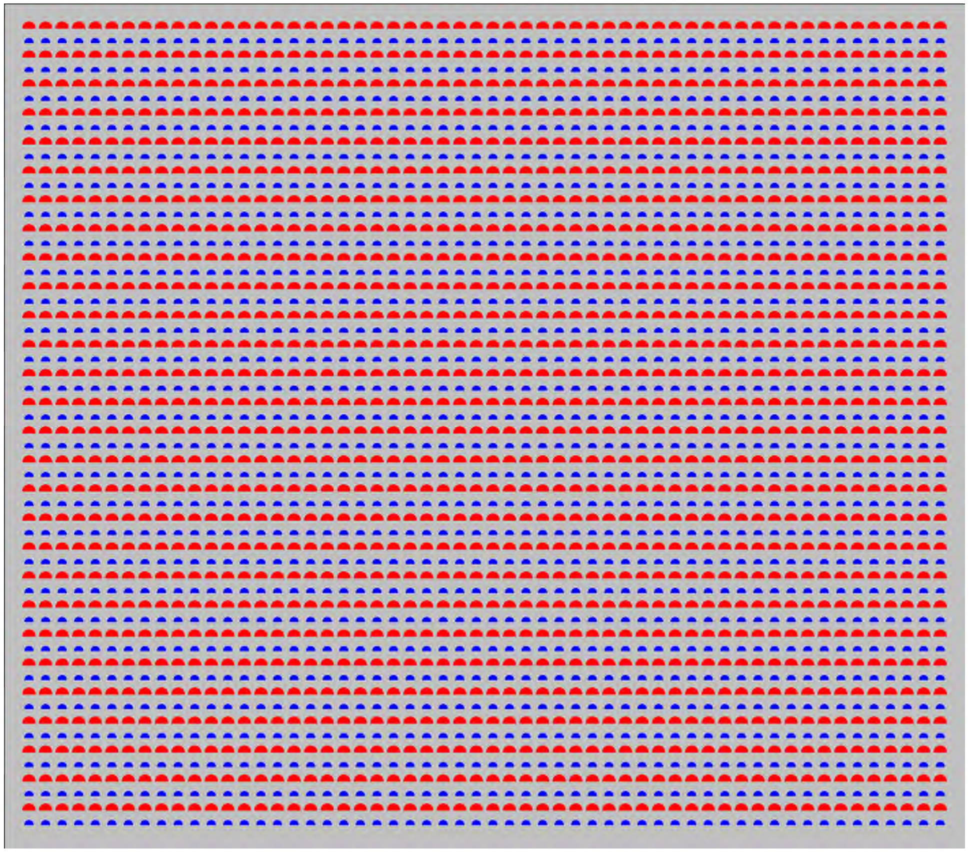
-Update fluid properties

-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]

Establish Basic Geometry and Material

- Semi-circular passages in counterflow arrangement, SS316

Set Independent Variables

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

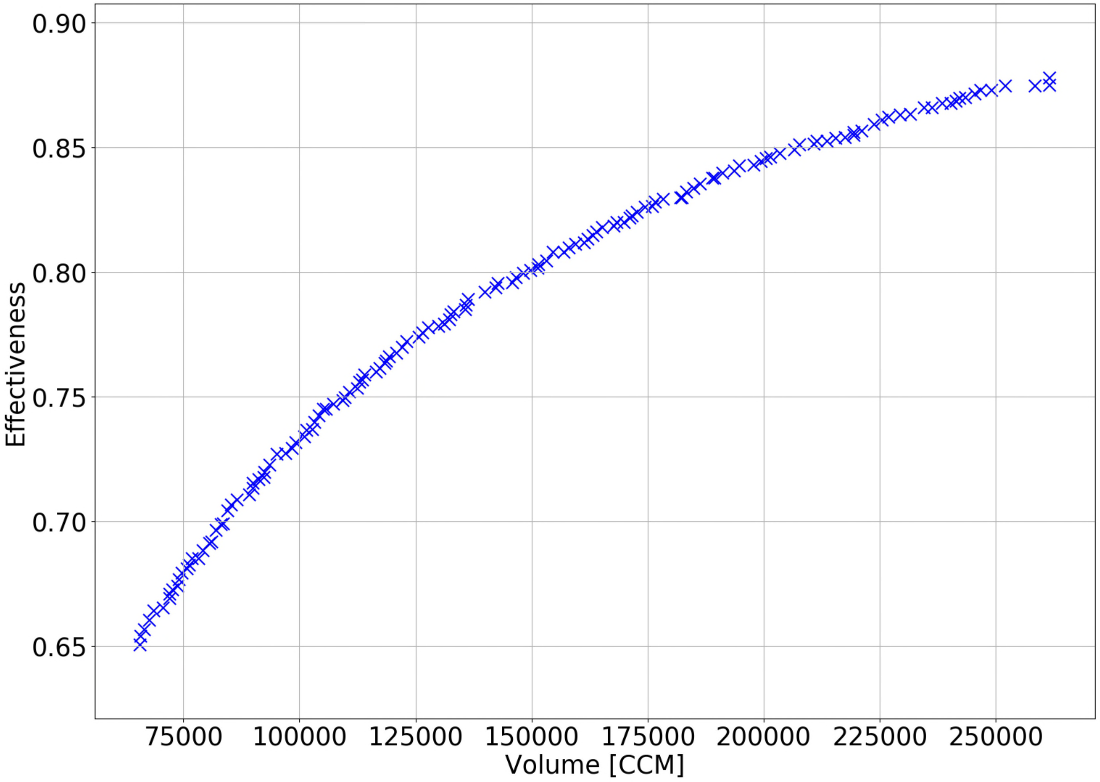
Set Objectives

- 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.

The International Supercritical $CO_2$ Energy Technologies Symposium
Pittsburgh, PA U.S.A.
March 2, 2026

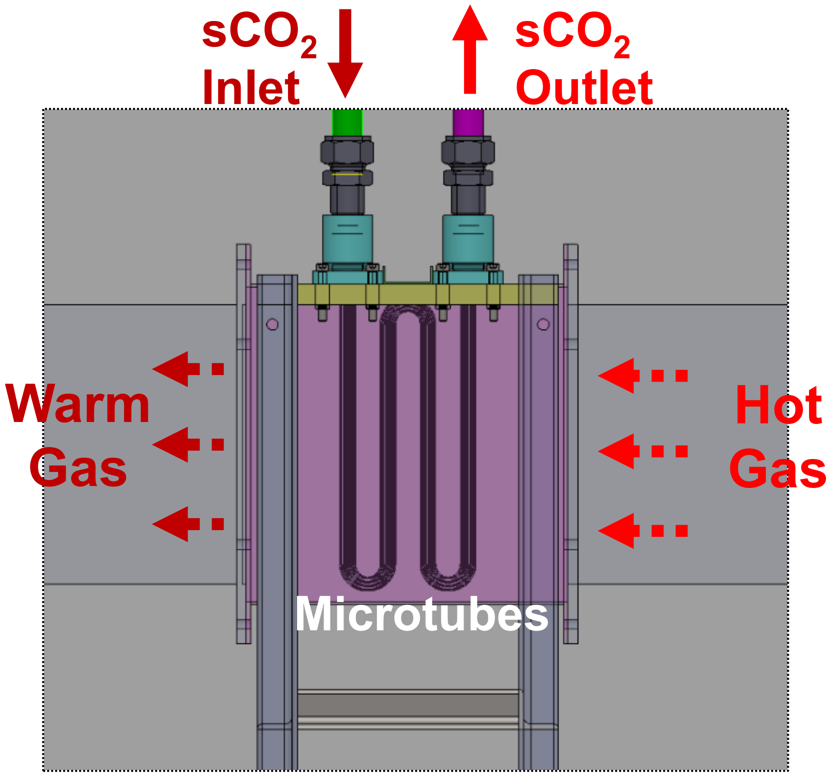
# Heat Exchangers for Supercritical $CO_2$ Power Application

## Compact Heat Exchangers
## Design & Additive Manufacturing
### Addendum: Operations & Testing

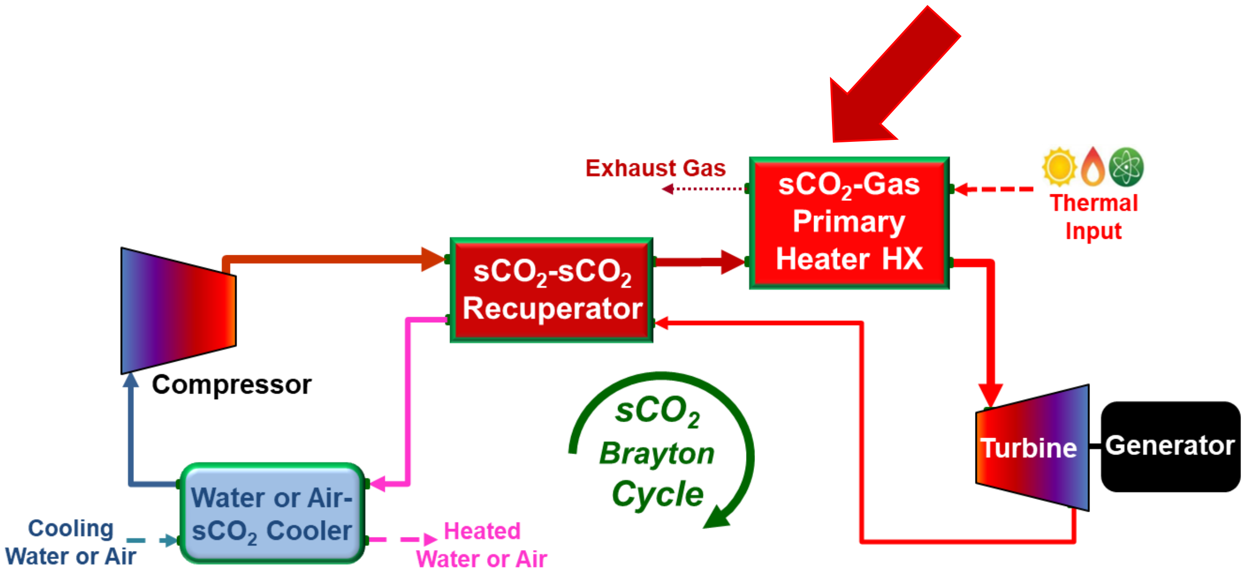
Lalit Chordia, PhD, Vahid Vahdat, PhD, Kevin Glunt, **Marc Portnoff**
TharEnergy

# Primary Heater Heat Exchanger

## Hot gas to $sCO_2$



Cross Flow, Counter-current Microtube Heater

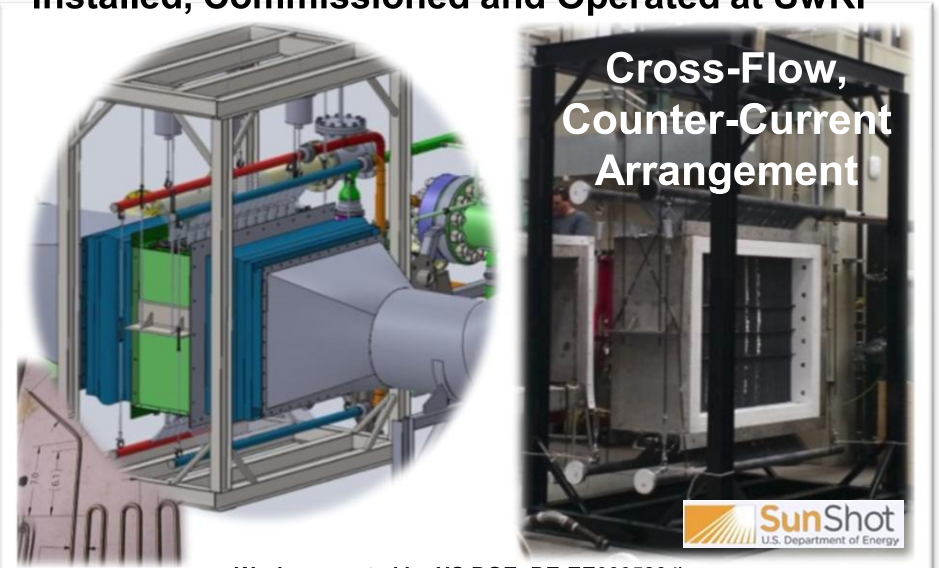


- Heats up the pressurized $sCO_2$ to high temperature prior to entering the turbine

# Primary Heater– Design Considerations

*Thar Energy's $sCO_2$ Primary Heater*

**Installed, Commissioned and Operated at SwRI**



Work supported by US DOE: DE-EE0005804\

## Design Conditions:

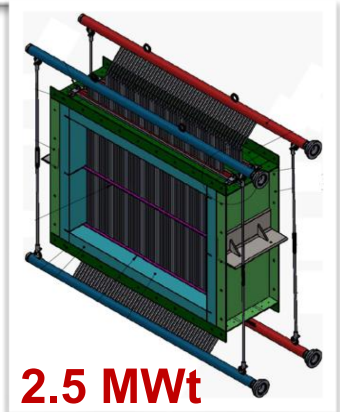
**Gas Fired Burner/Blower Outlet**

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 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

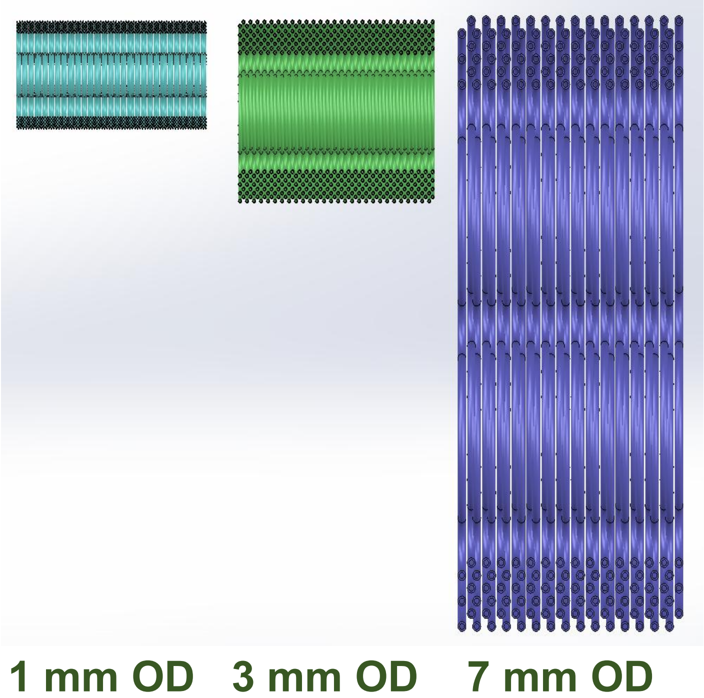
- Air side pressure drop sized to be under limit to ensure overall efficiency
- Particle contaminants can be a concern – size for periodic cleaning

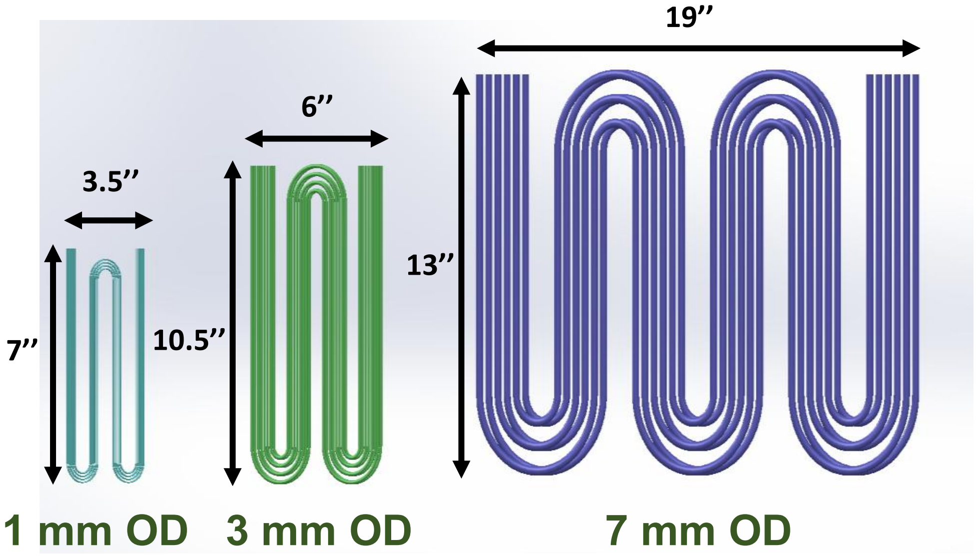
# Primary Heater

## 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





| 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 $in^2/in^3$ |

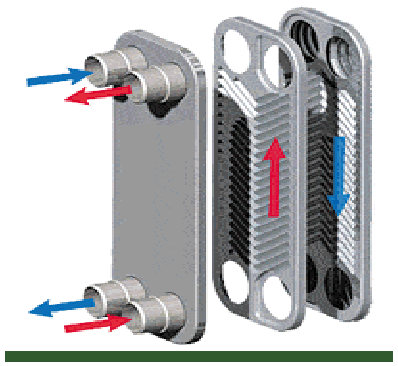
# Air Cooler: Air to $sCO_2$
# Water Cooler: Water to $sCO_2$

## Air Cooled

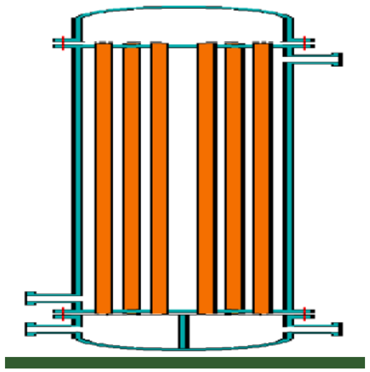
Finned-Tubes

Micro-channel

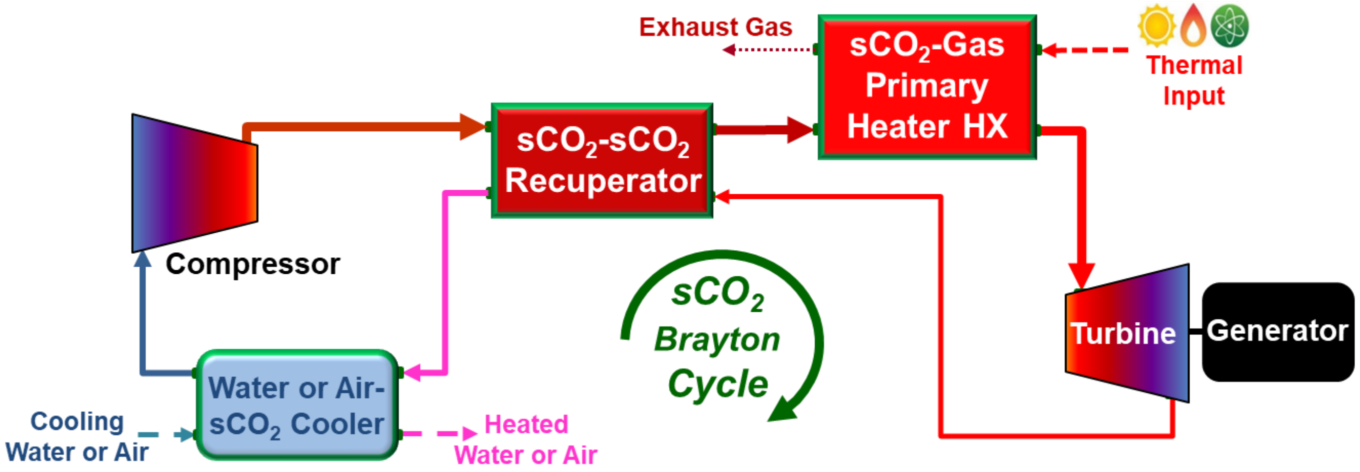
## Water Cooled



Brazed-Plate



Tube/ Microtube



- Cool $sCO_2$ to increase density and reduce compressor energy

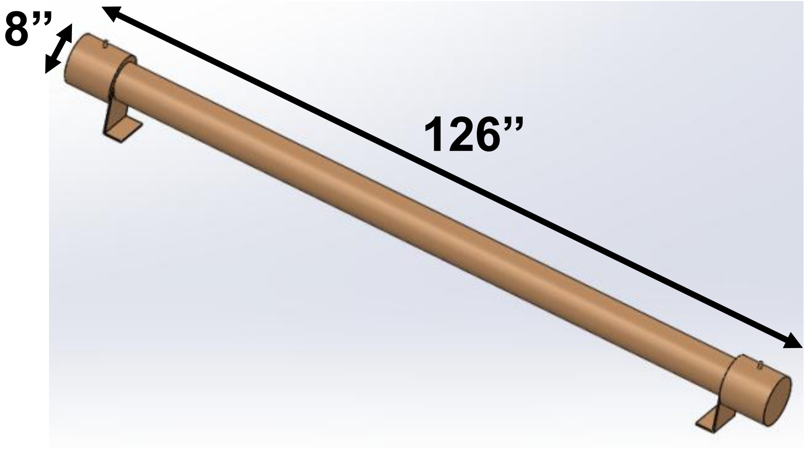
## Trade off between water vs. air cooling

- 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

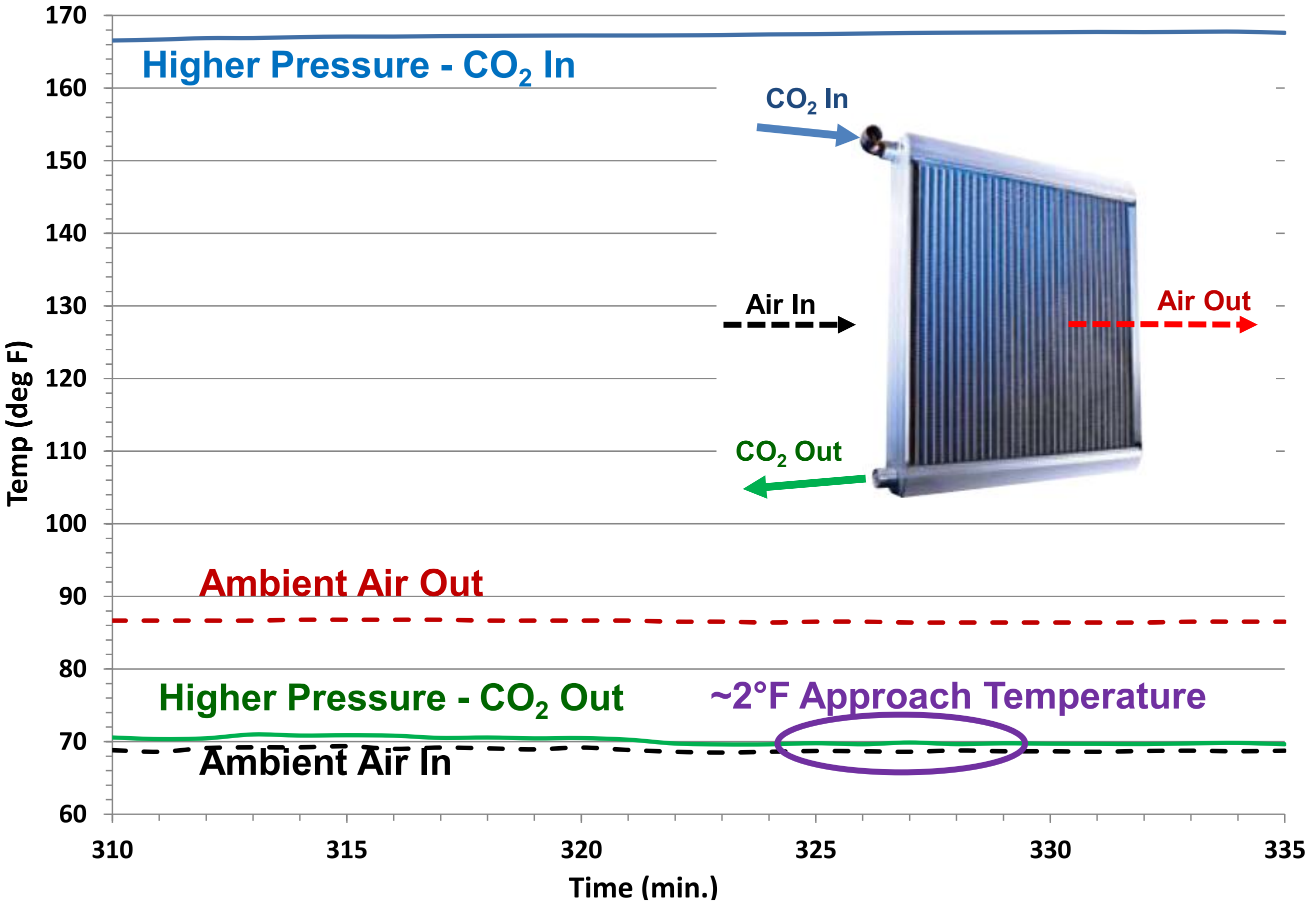
- Water-cooled heat exchanger requires occasional maintenance

# $sCO_2$ 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

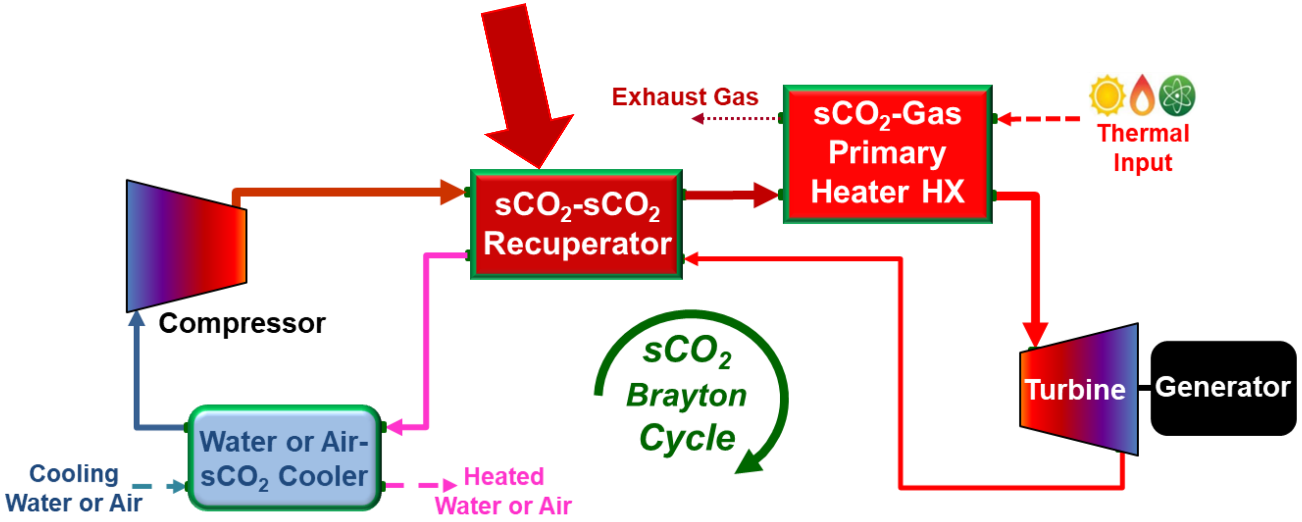
At Thar's test facility, air and $CO_2$ approaching temperature as low as **2°F** was achieved using micro-channel coil.



***$CO_2$ (R744) refrigerant is now readily available.***

# Recuperator - $sCO_2$ to $sCO_2$

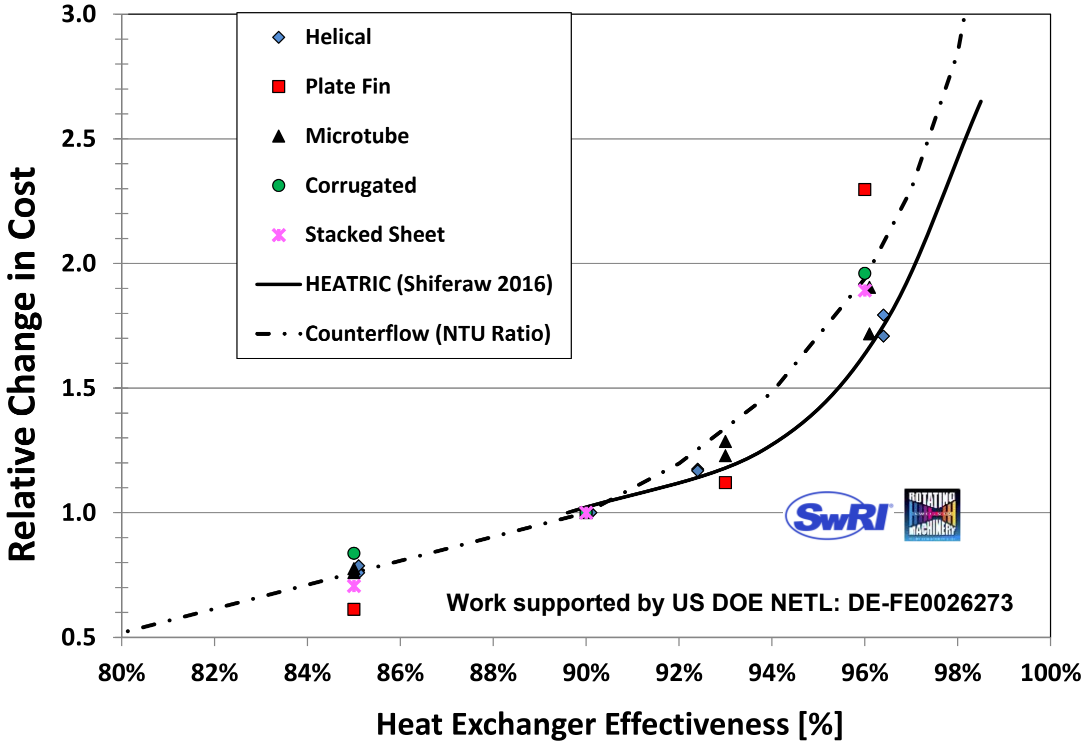
## Counter-current



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

*Recuperator specifications influence the cost:*

- Approach Temperature / Effectiveness
- Pressure Drop



Work supported by US DOE NETL: DE-FE0026273

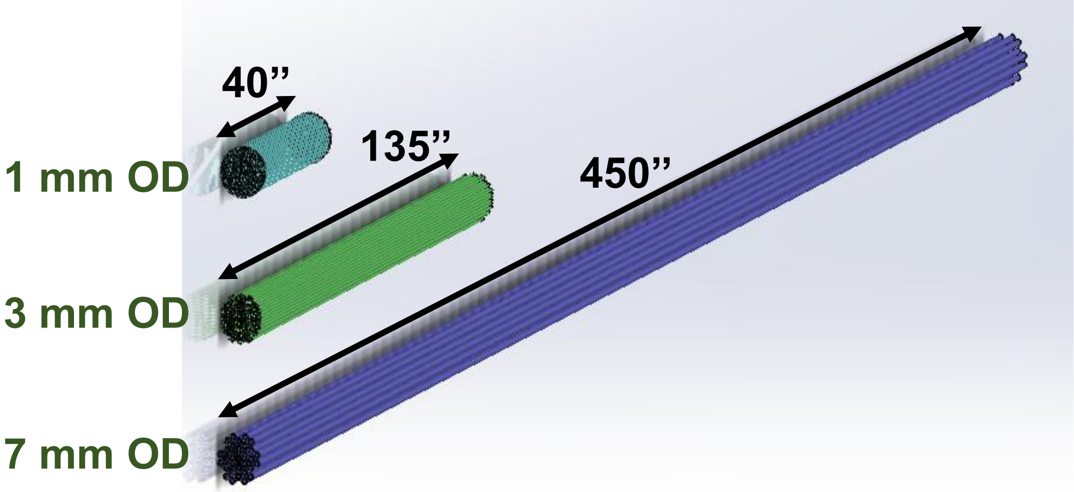
*Relatively independent of the heat exchanger concepts evaluated*

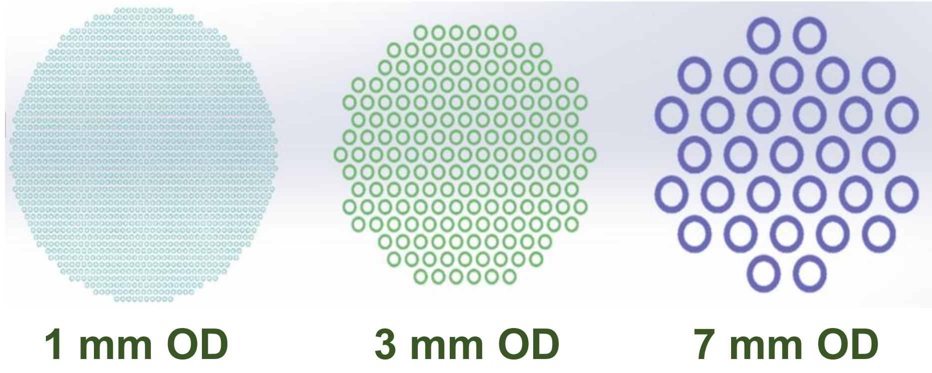
# Microtube Recuperator

## 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





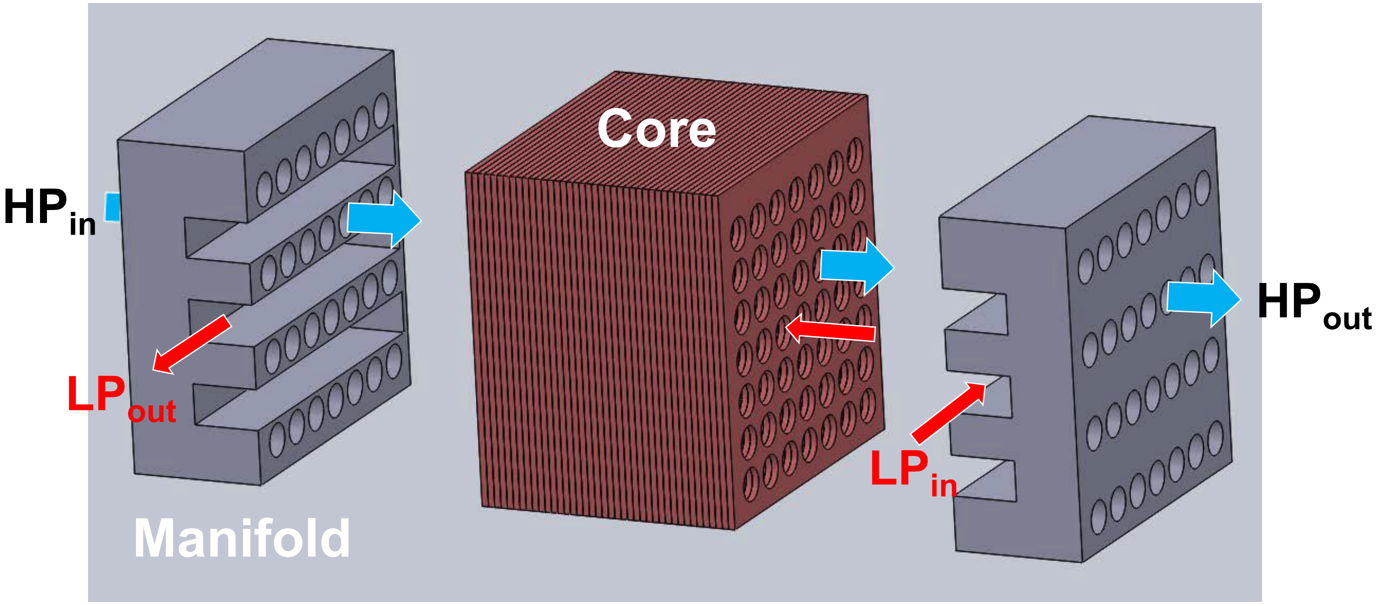
| Tube OD | 1 mm | 3 mm | 7 mm |
|---|---|---|---|
| **Tube Length** | 40" | 135" | 450" |
| **Tube Number** | 1500 | 175 | 30 |
| **Bundle Weight** | 17 lb | 59 lb | 244 lb |
| **Surface Density** | 76 $in^2/in^3$ | 30 $in^2/in^3$ | 12 $in^2/in^3$ |

# 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

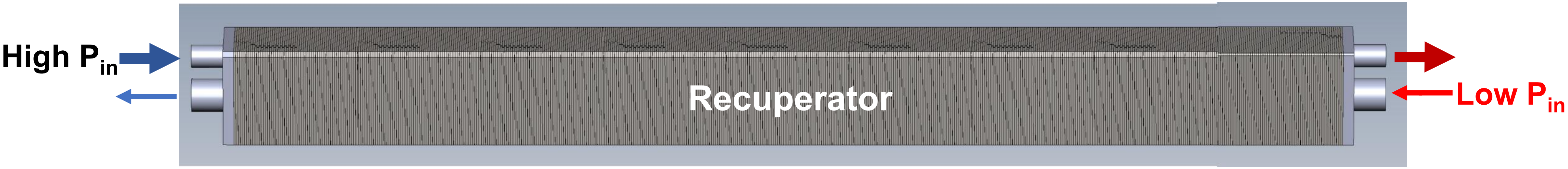
# Stacked-sheet Recuperator Concept (SSHX)



- **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% |

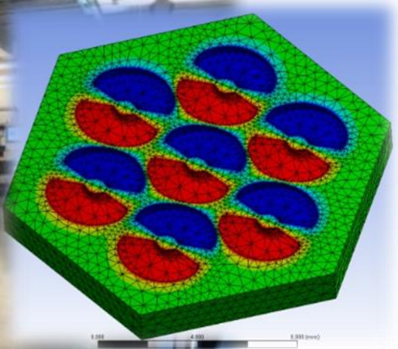
See Addendum for Test Data

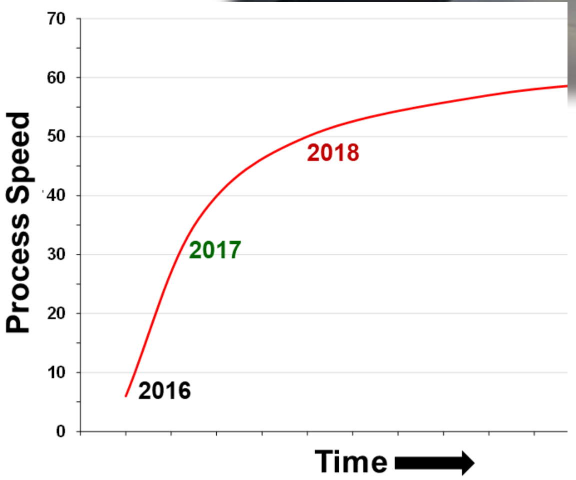
Work supported by US DOE NETL: DE-FE0026273

# Manufacturing technologies are advancing at a rapid pace

## *Subtractive Manufacturing*
## *Additive Manufacturing*
## *QA/QC Methods*

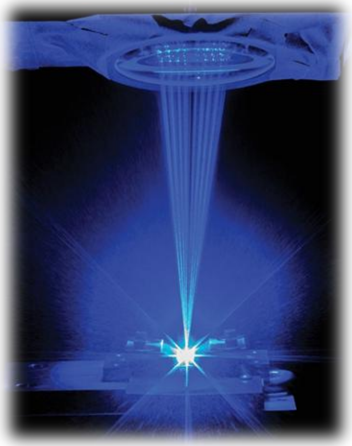
- Laser cutting
- Laser welding
- Water jet cutting
- 3D metals printing
- Electrochemical etching
- Electrochemical machining (ECM)
- Electro discharge machining (EDM)
- EDM wire cutting
- Sheet bending/forming
- Metal plating
- Stamping
- Brazing
- Welding
- Diffusion bonding





# 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

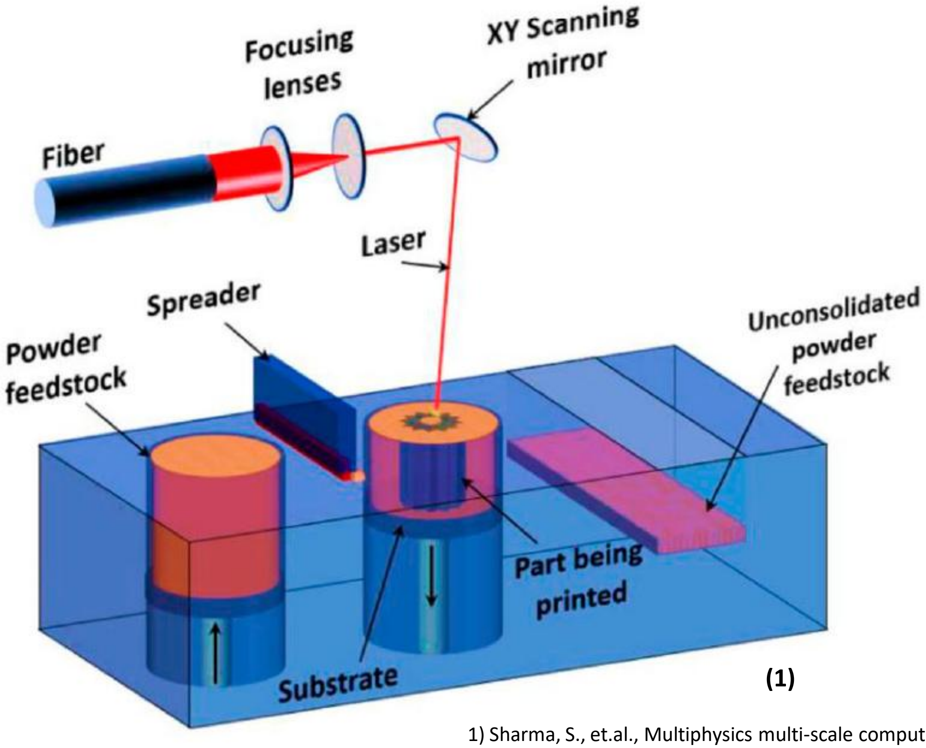
***Costs increase the longer it takes to identify a problem***

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**

**$sCO_2$-$sCO_2$ Recuperator**



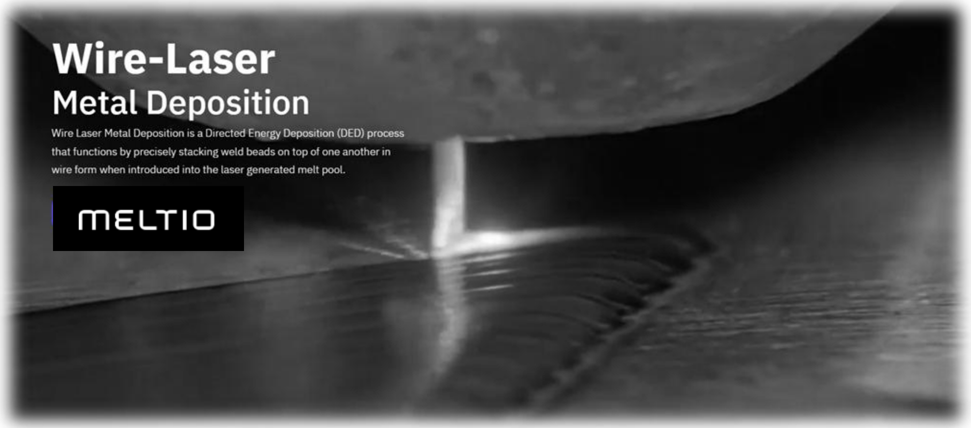
(1)

**DLMS – H282 3D-SSHX Recuperator**

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

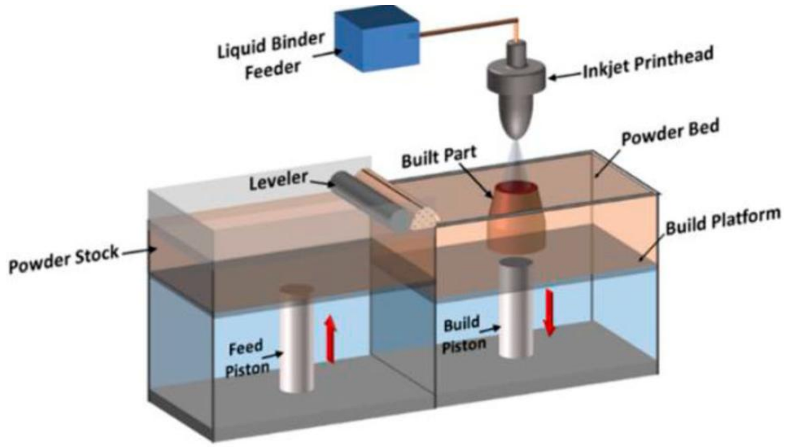
- **Wire melting (arc discharge or laser)**
  - ○ **No special facility requirements**
  - ○ **Lower resolution but with high part density**
  - ○ **Simpler operation**
  - ○ **Faster build rate**
  - ○ **More cost effective than DMLS**
  - ○ **Larger part builds**
  - ○ **More alloy compositions available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

- **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

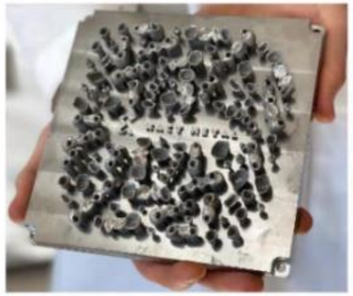
# Additive Manufacturing Overview

## 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

## *DED systems are getting larger - 10' tall*

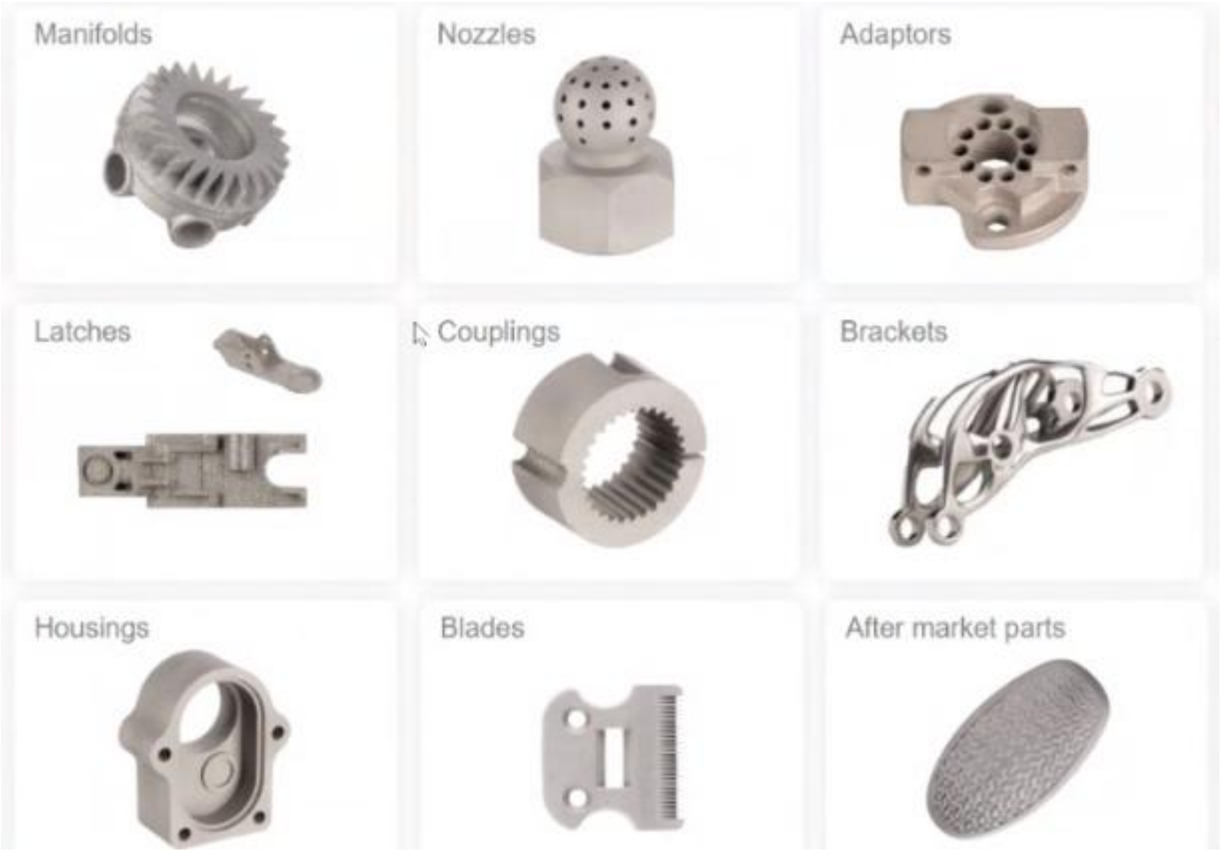
- **Mid to Large Part Printing**
- **Repair & Remanufacturing**
- **Multi-Material Mfg - Cladding**

DM3D Technology, LLC
dm3dtech.com

# Additive Manufacturing Overview

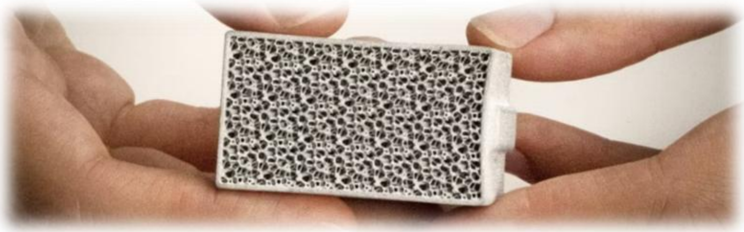
## Desktop Metals – Binder jet

https://www.desktopmetal.com/



## HP Metal Jet – Binder jet

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



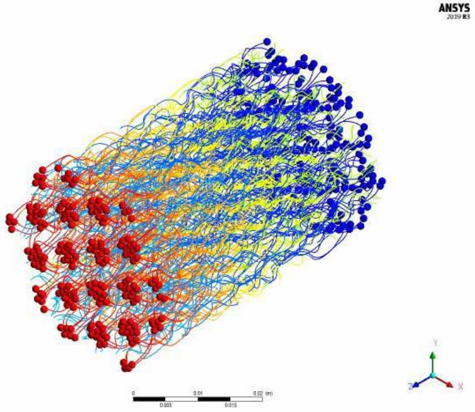
**Air Filter - 690V**
**Circuit breaker**
**SS 316L**

**Engine Component**
**SS 17-4PH**

**Fluidic Manifold**
**SS 316L**

# GE DMLS Additive - ex. AM303 Heat Exchanger

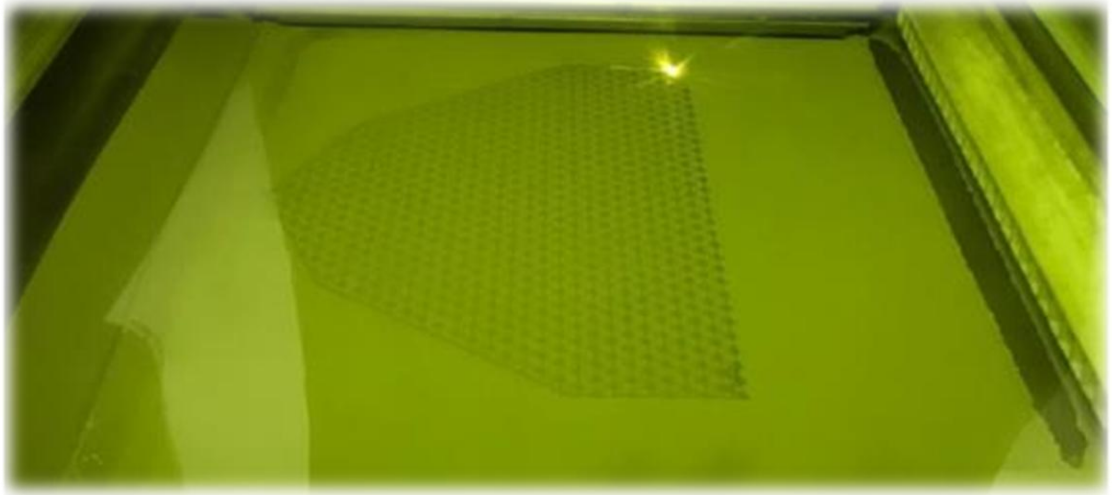
GE VERNOVA
Our portfolio of energy businesses



**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**

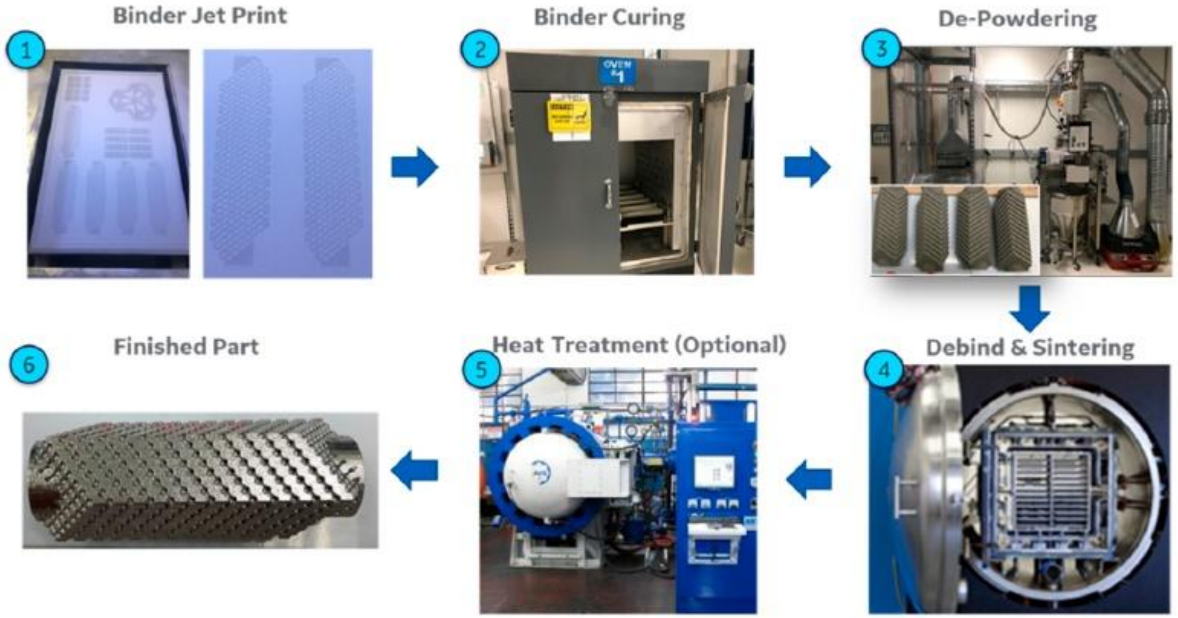
**Hole Diameter: 2 mm**

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

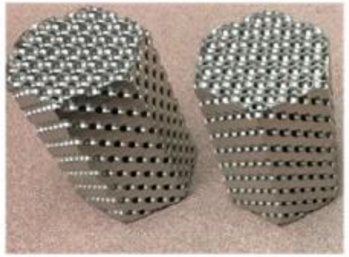
# Binder Jet Additive - ex. SS316L Heat Exchanger

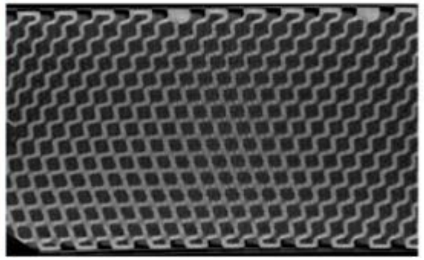
## *Trifurcating Flow Path Design*

### Process Steps



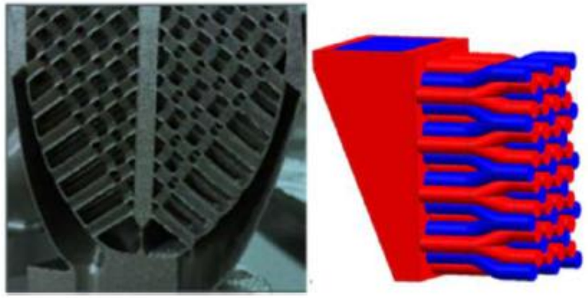
Printed heat exchanger core





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

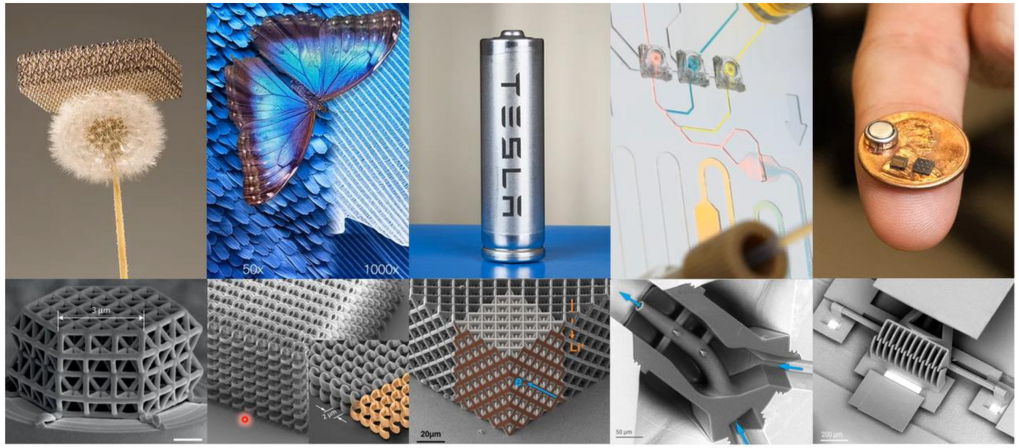
# The Future?

## Massively Parallel Two-Photon Lithography using Metaoptics

**Lawrence Livermore National Laboratory Center for Engineered Materials and Manufacturing**

### 3D Printing at the Diffraction Limit

**Enables nanoscale breakthrough performance and novel functionality**



Mechanics
Strong & resilient[1]

Metamaterials
Light[2] & acoustics

Electrochemistry
Reaction-diffusion[3,4]

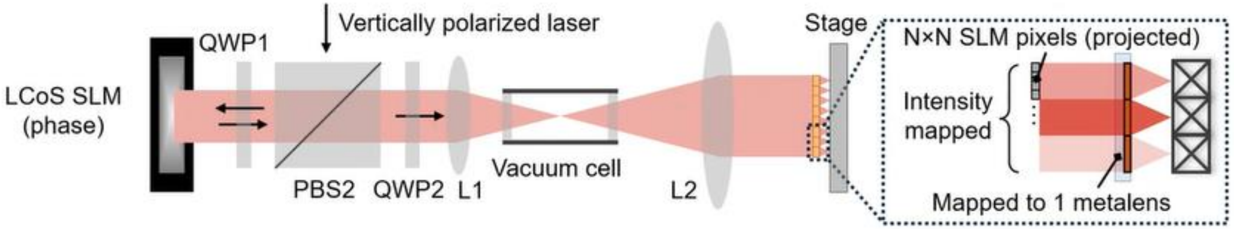
Microfluidics
Gas/liquid flow[5]

Microelectronics
MEMS array[6]

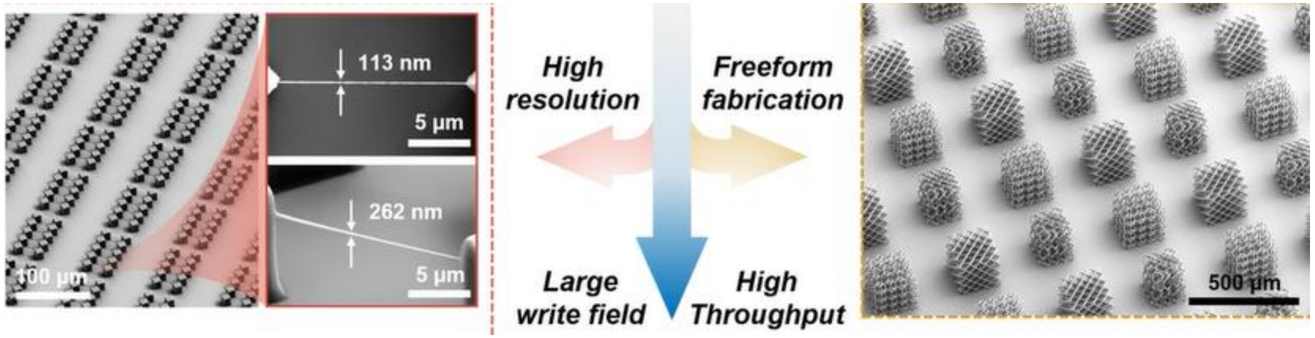
***Limited to small scale production***

### Massively parallel 3D nanolithography

***Potential for commercial scale production***



### 120k+ metalenses (well-spaced miniature printers)



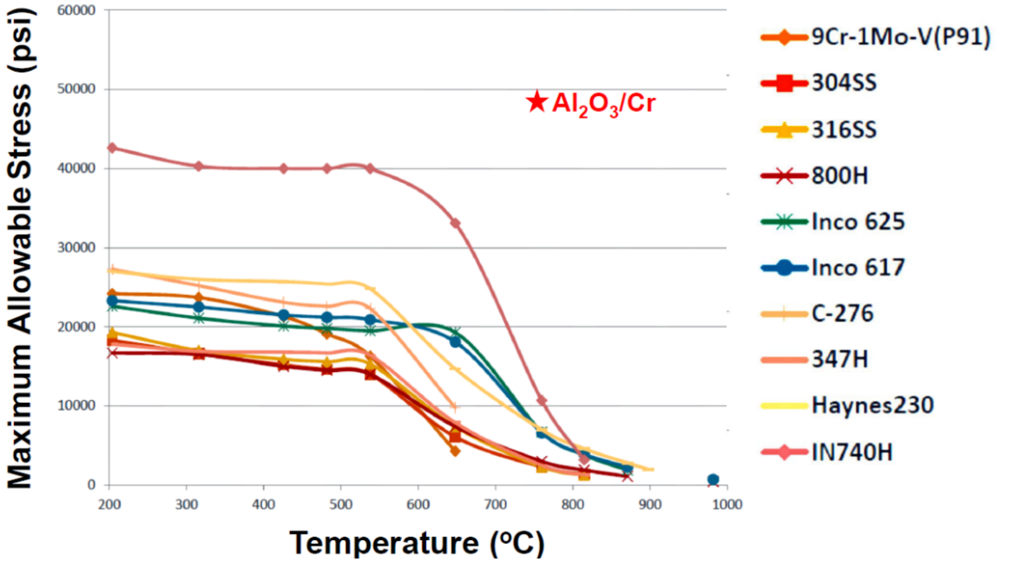
***Print time reductions from months to hours***

Xia, X., Smith, A., Massively Parallel Two-Photon Lithography (TPL) Using Metooptics, Lawrence Livermore National Laboratory, DOE OTC National Lab Discovery Series, IM Release Number: LLNL-PRES-2016012, February 24, 2026

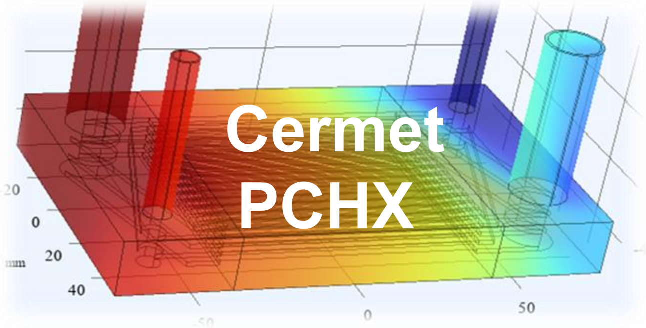
# Ceramic Heat Exchanger ex. $Al_2O_3$/Cr Composite

## *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***

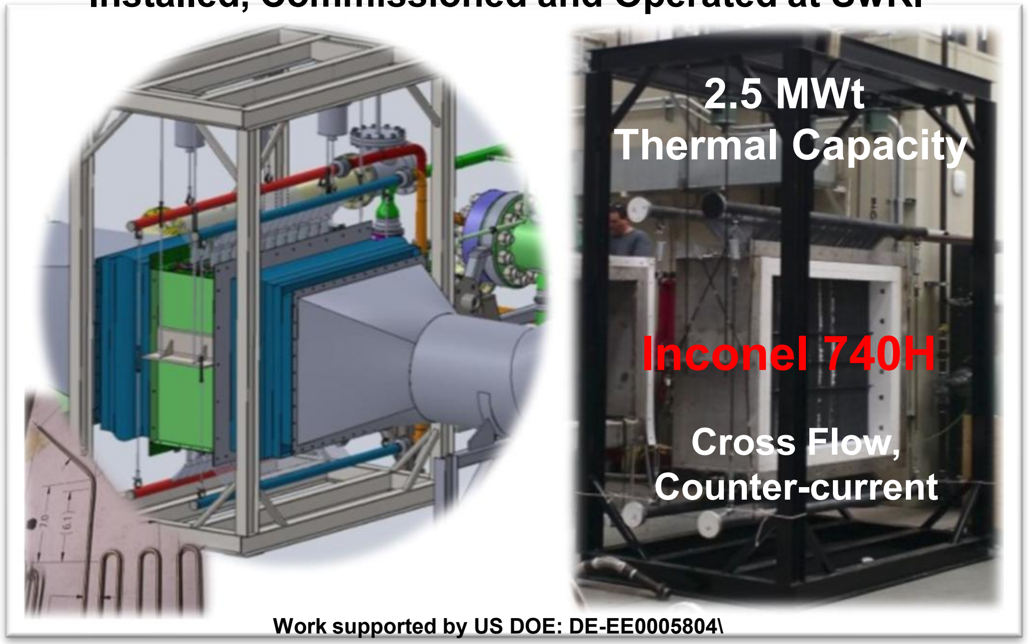
## Recuperators Primary Heater Gas/Air Coolers Water Coolers

- **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***

**Gas Cooler**

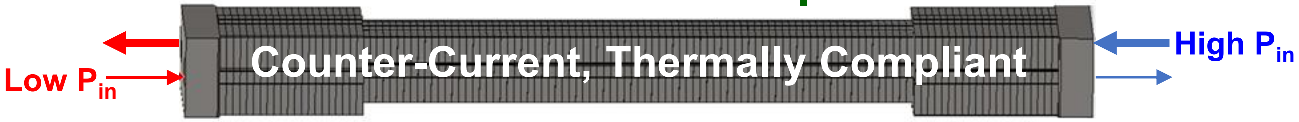
***$sCO_2$ Primary Heater***

**Installed, Commissioned and Operated at SwRI**



Work supported by US DOE: DE-EE0005804\

**Stacked Sheet Recuperator**



## *Thank you for your kind attention!*

**Contact:** **Marc Portnoff**

**Principal Engineer**
150 Gamma Drive, Pittsburgh, PA 15238
412-251-4615
mportnoff@tharenergy.com
tharenergy.com

***Delivering clean energy solutions - rooted in natures' design***

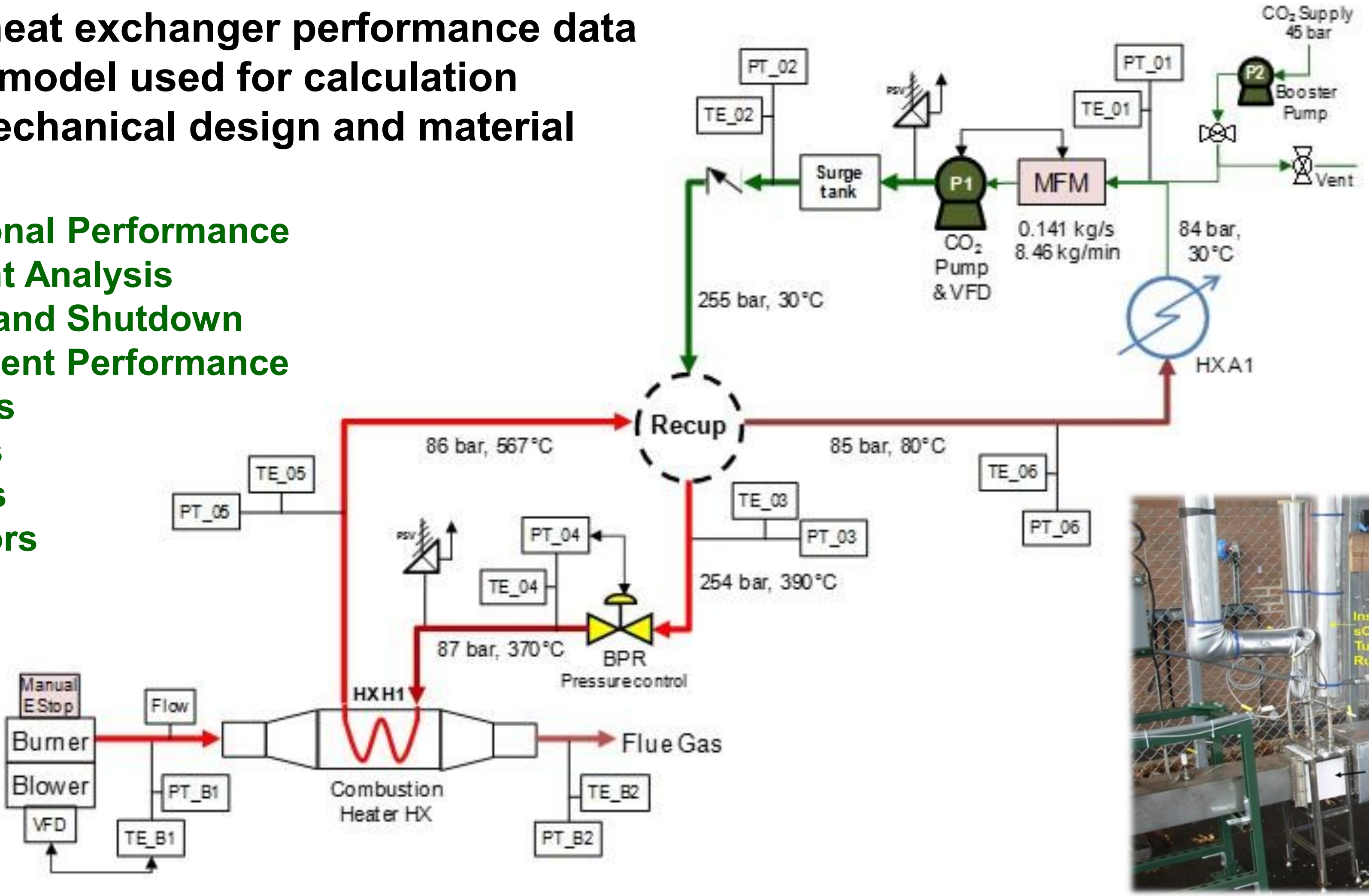
# Addendum

# 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



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

# 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)

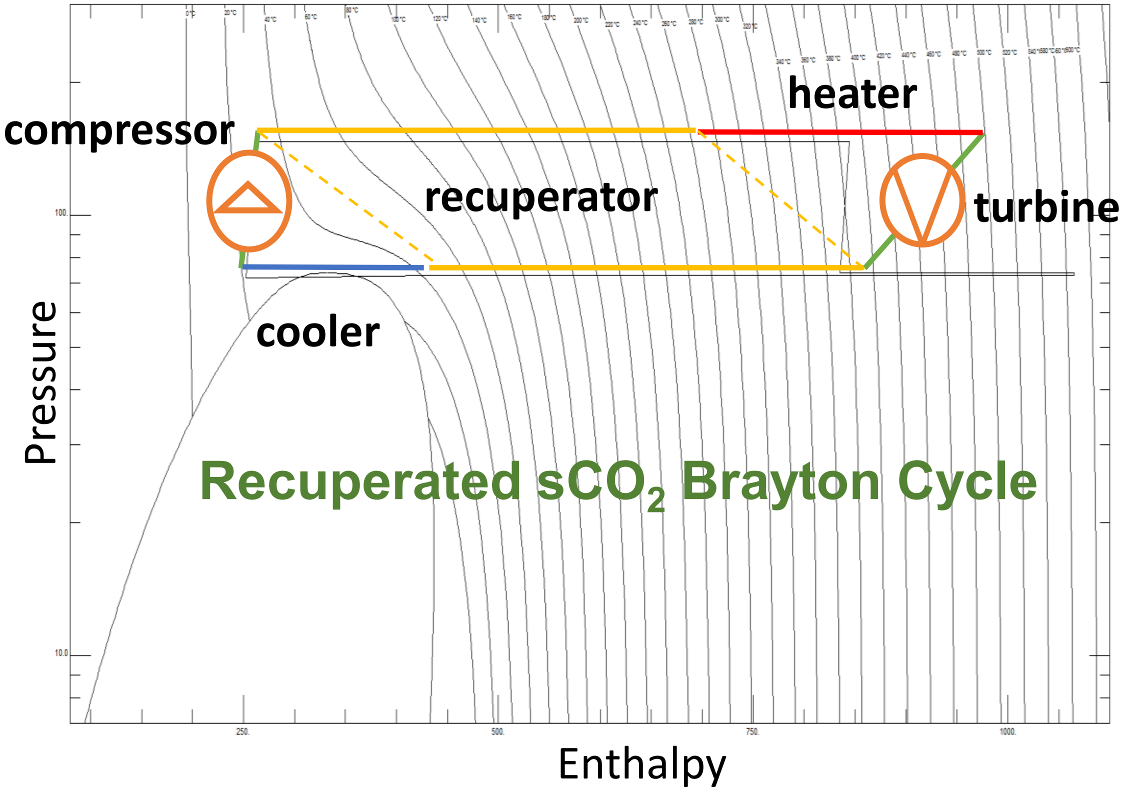
## Test Condition

**Supercritical Carbon Dioxide**

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

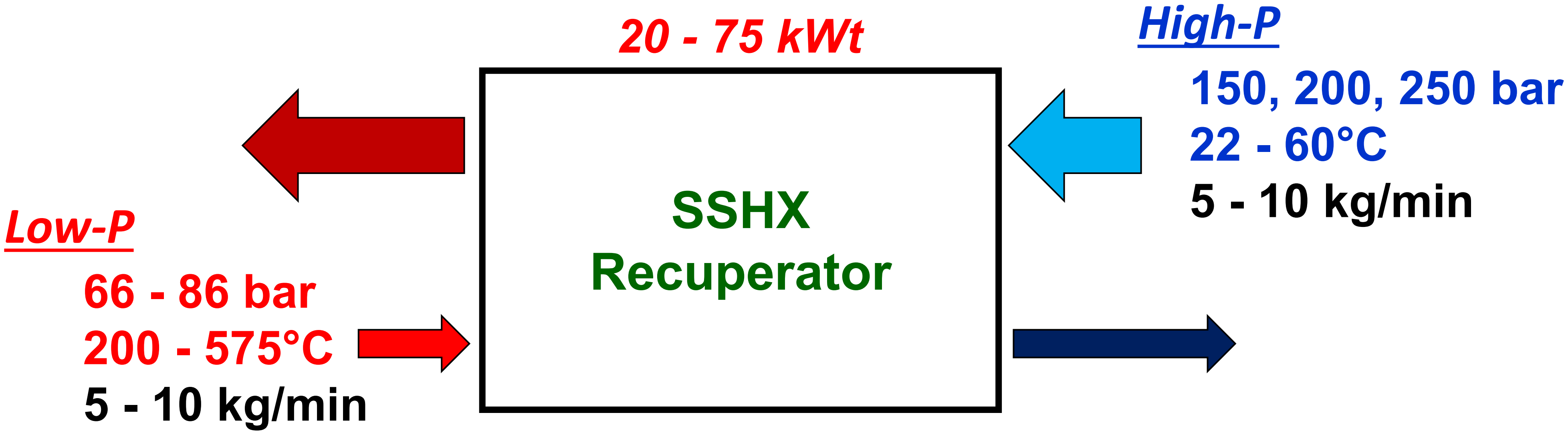
**Combustion Gas**

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



**Thar Loop Compared to Standard Brayton Cycle**

# Test Conditions - SSHX Recuperator Prototypes



*20 - 75 kWt*

**SSHX Recuperator**

***High-P***

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

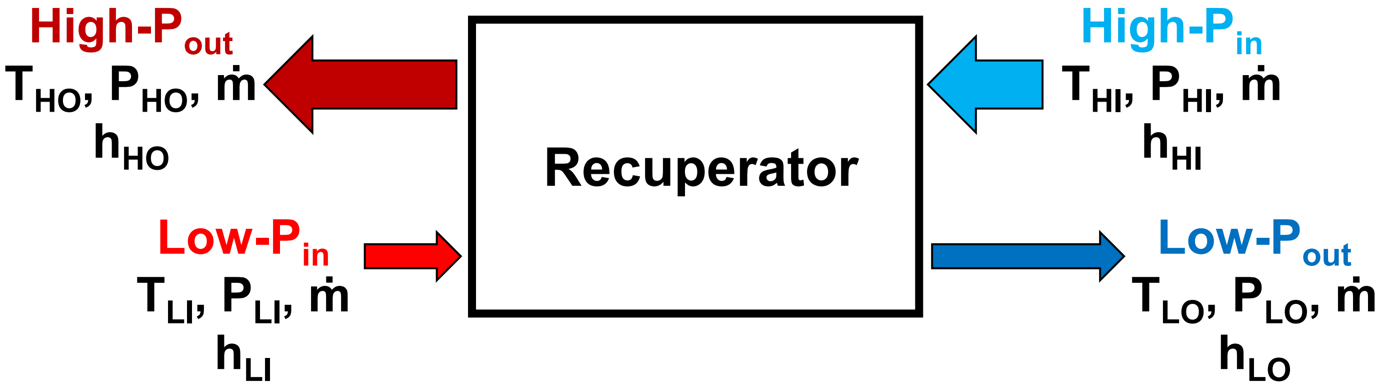
***Low-P***

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**

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

# HX Performance Heat Transfer Equations



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

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

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

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

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

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

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

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

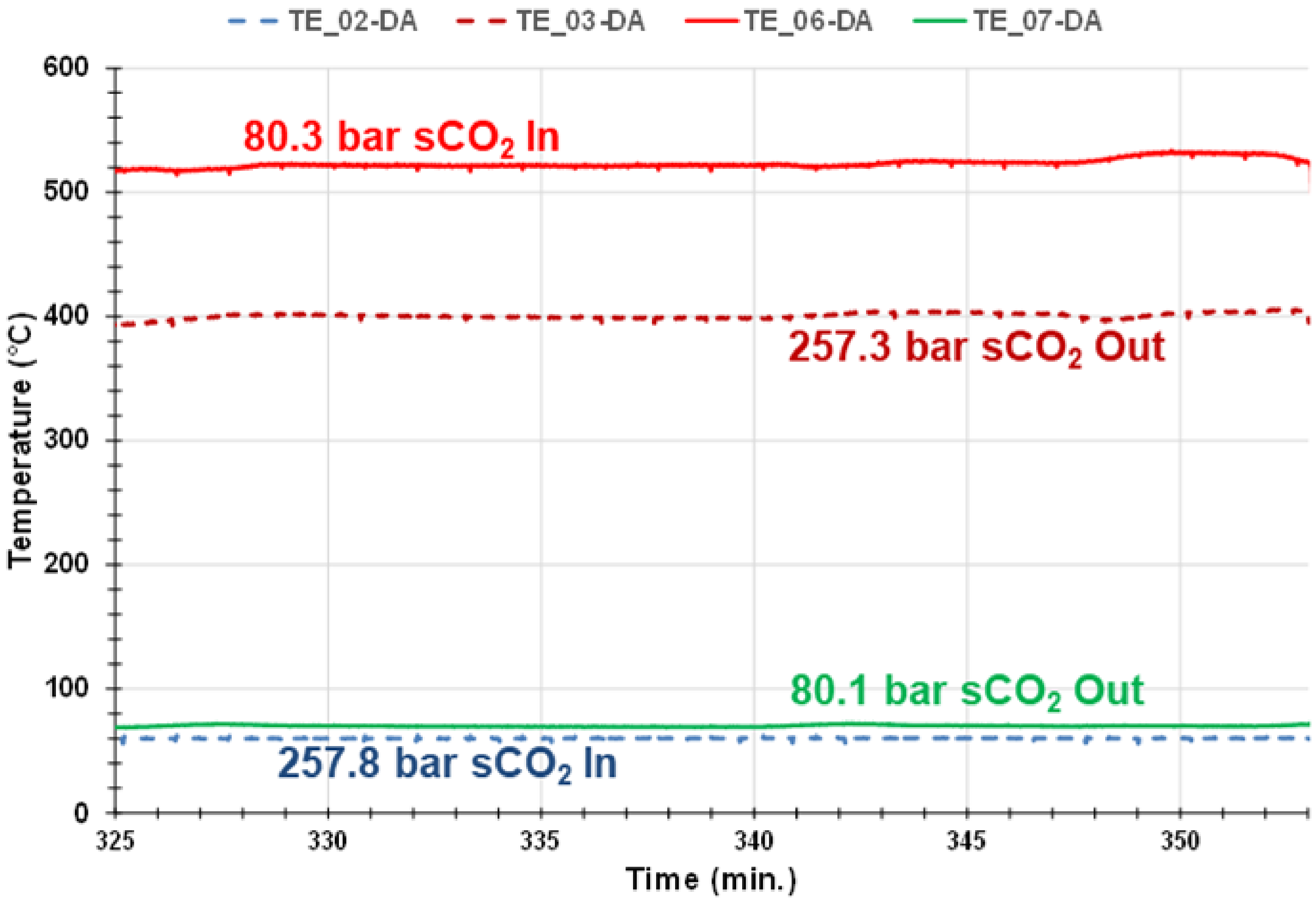
**% Pressure Drop:** $\%\Delta P = (P_{in} - P_{out})/P_{in}$

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

# Steady State Temperature Plot

## Prototype SSHX Recuperators

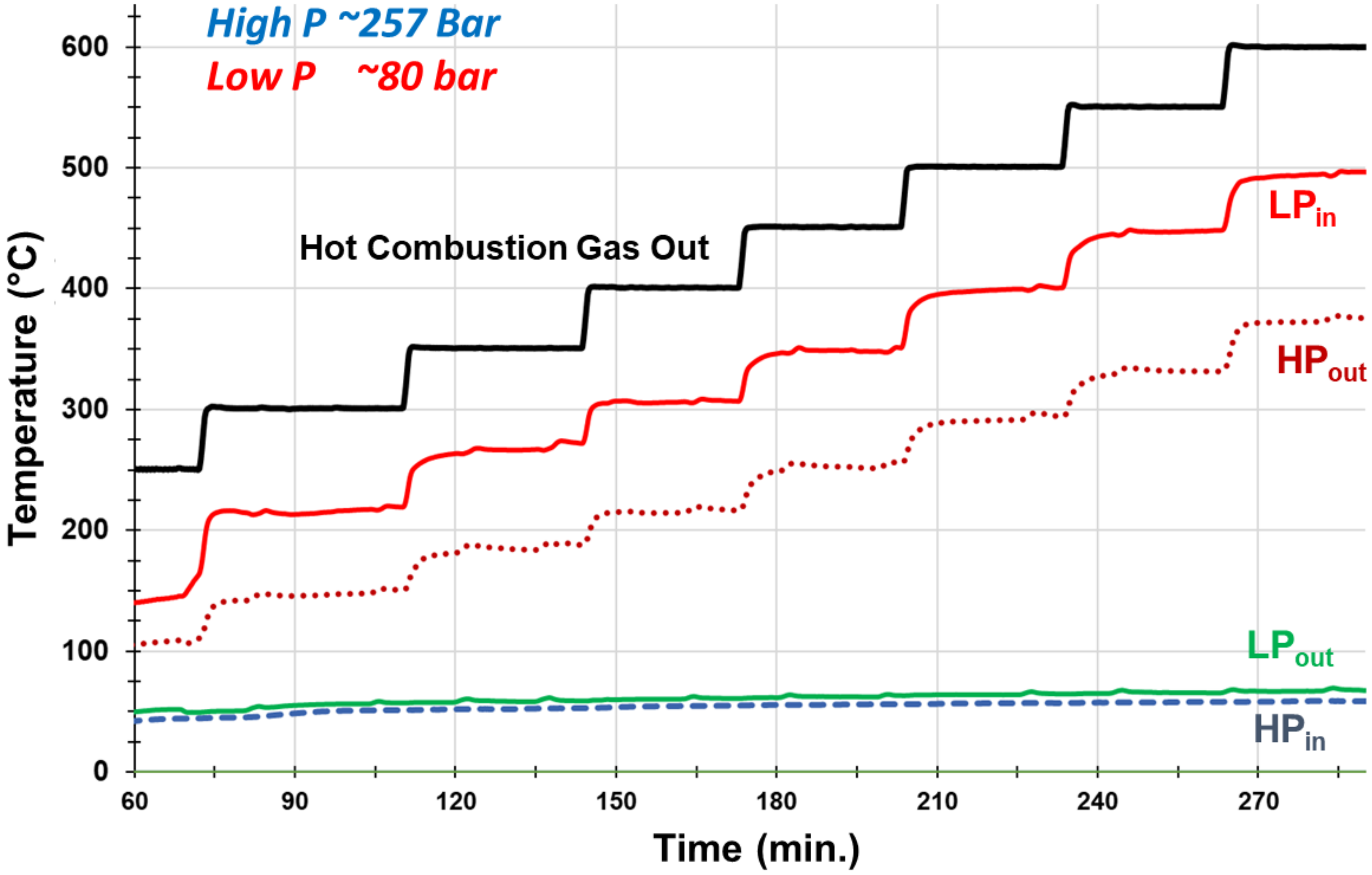
## 3D-SSHX – Steady State Plot



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

# Temperature Plot

## *Good Energy Balance, < 2% error*



*Approach T < 10°C*

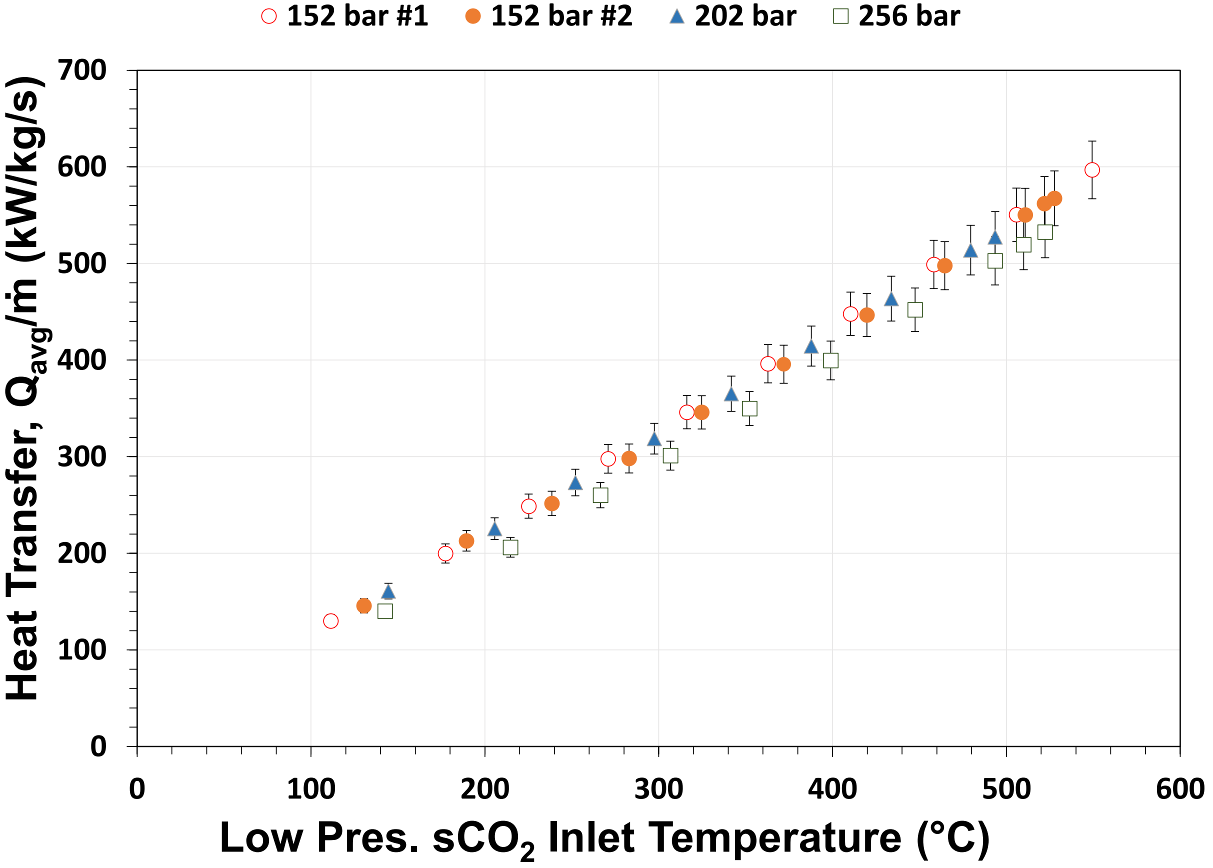
Work supported by US DOE NETL: DE-FE0024012, DE-FE0025348 , DE-FE0026273

# Energy Transfer Plots

## SSHX Recuperator Prototypes

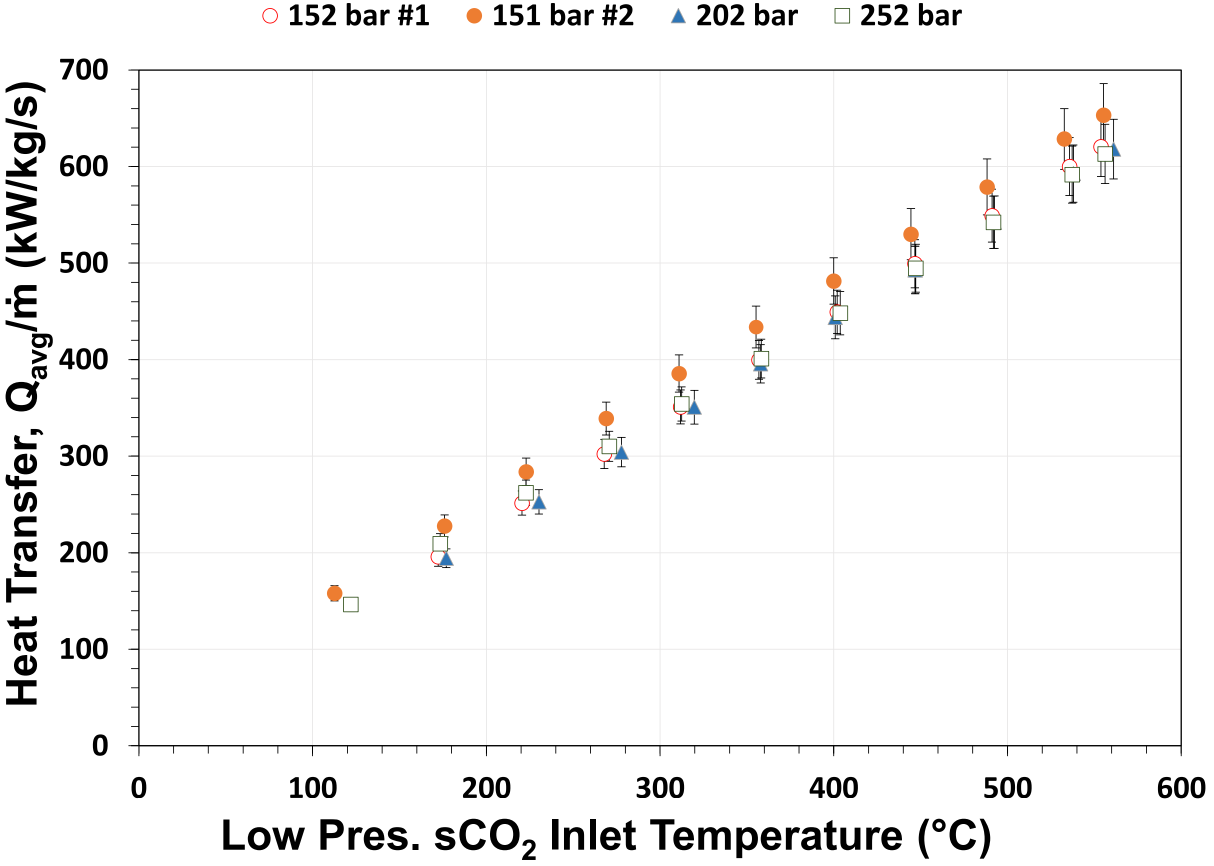
### 3D-SSHX

**Inconel 625**



### Laser-SSHX

**347H Stainless Steel**

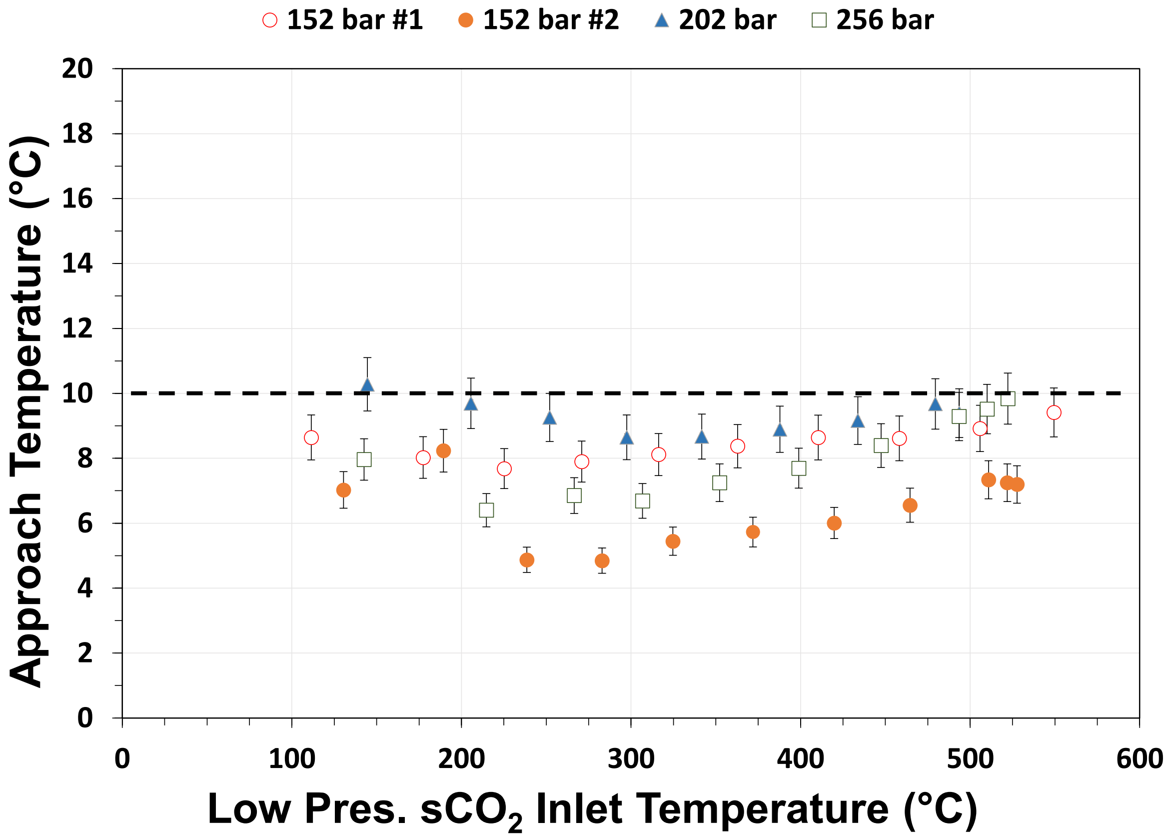


***Linear Response***

Work supported by US DOE NETL: DE-FE0026273

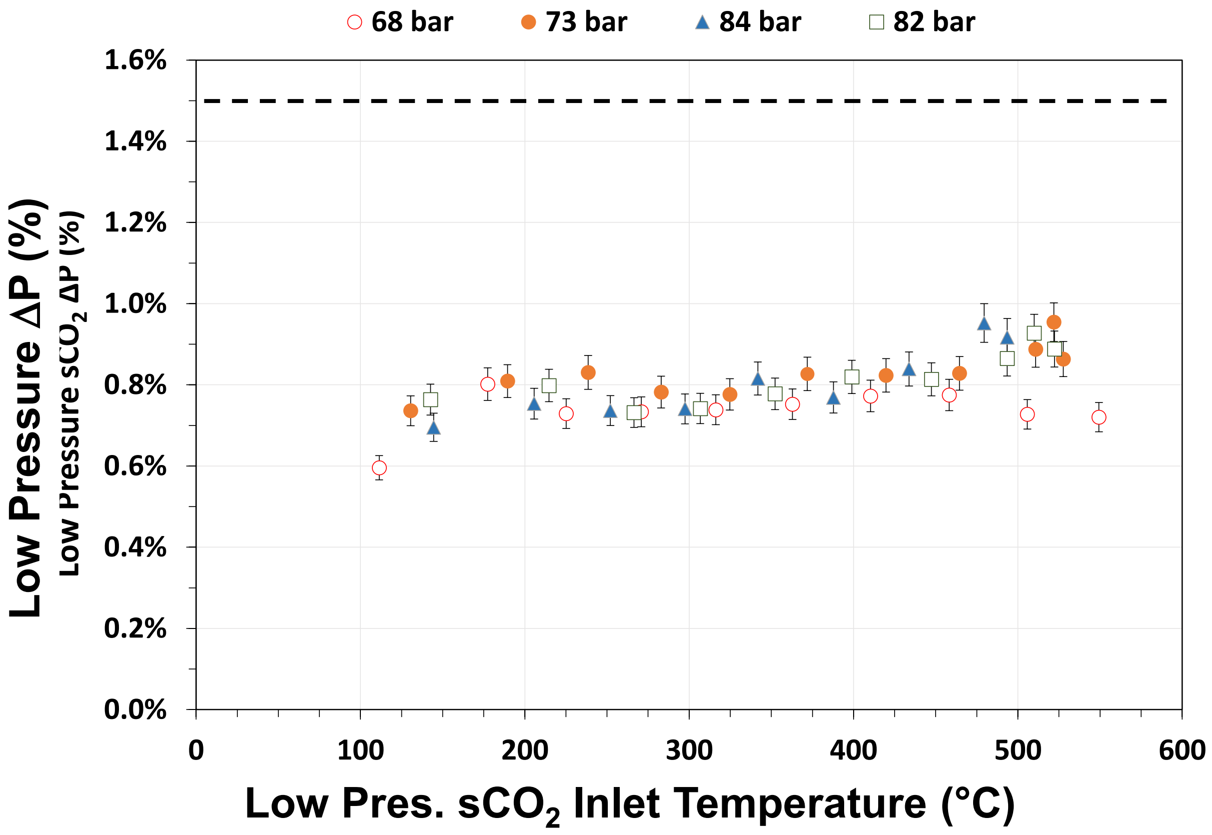
# 3D-SSHX Prototype Recuperator

## Approach Temperature Plot



*Approach T < 10°C*

## Pressure Drop Plot



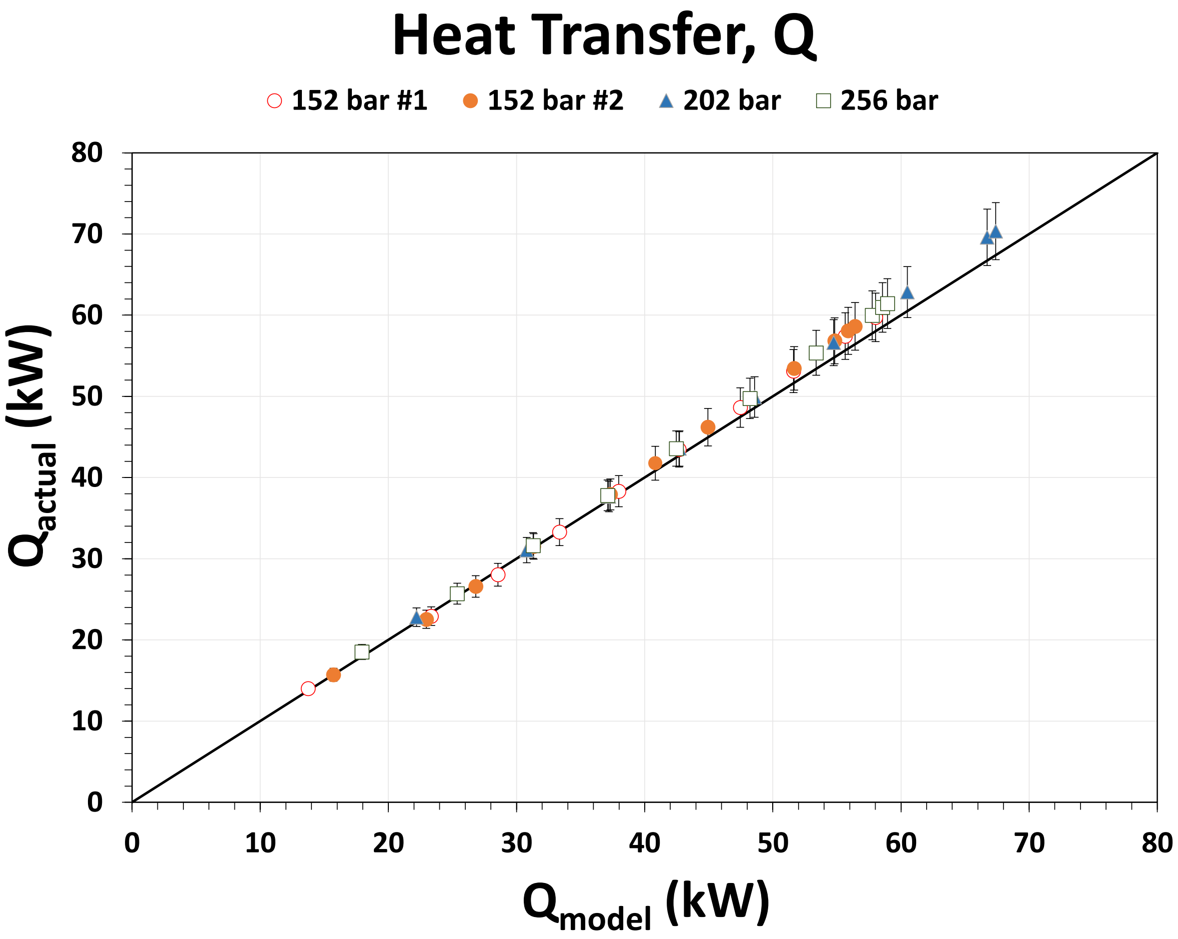
$\Delta P_h < 1.5\%$

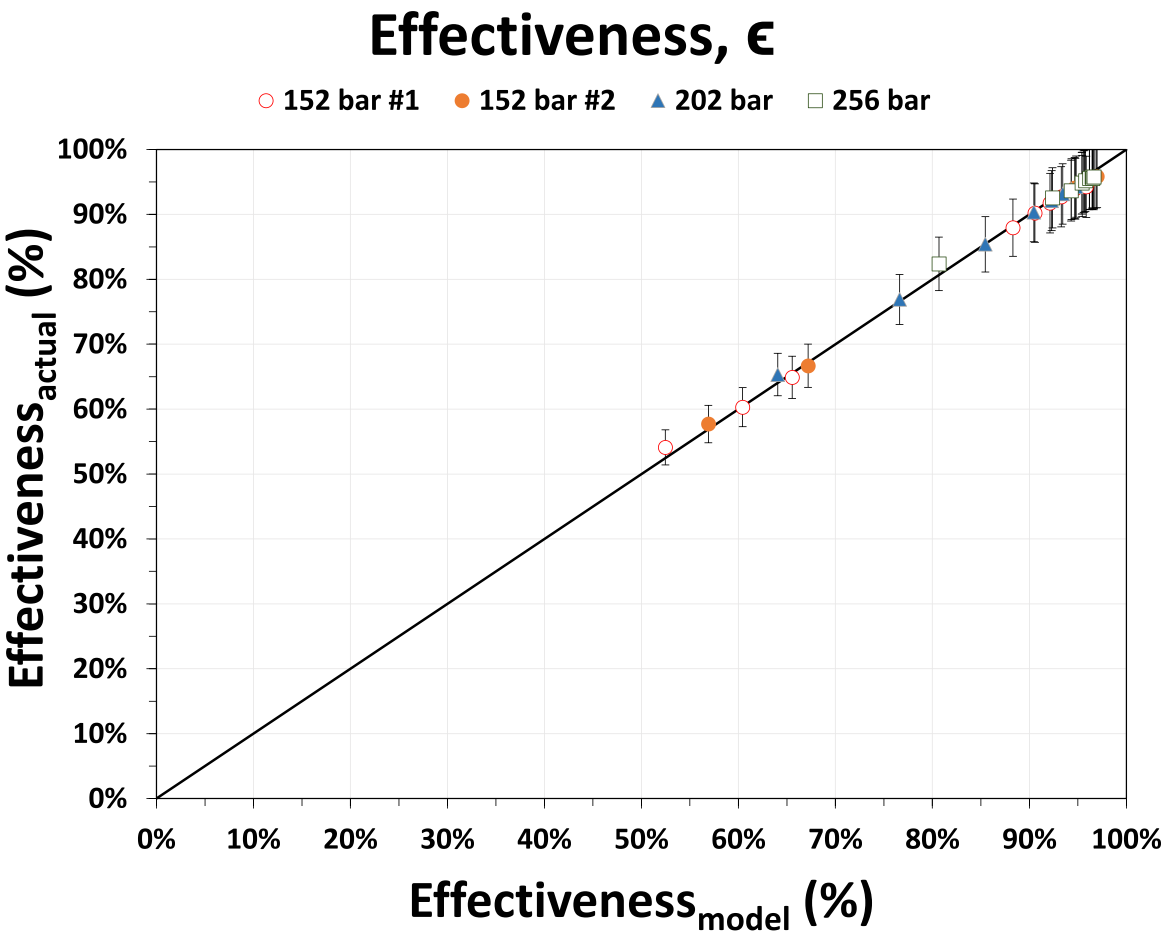
*Meets design specifications*

Work supported by US DOE NETL: DE-FE0026273

# 3D-SSHX Prototype Recuperator

## *Good correlation between Design & Actual HX performance data*

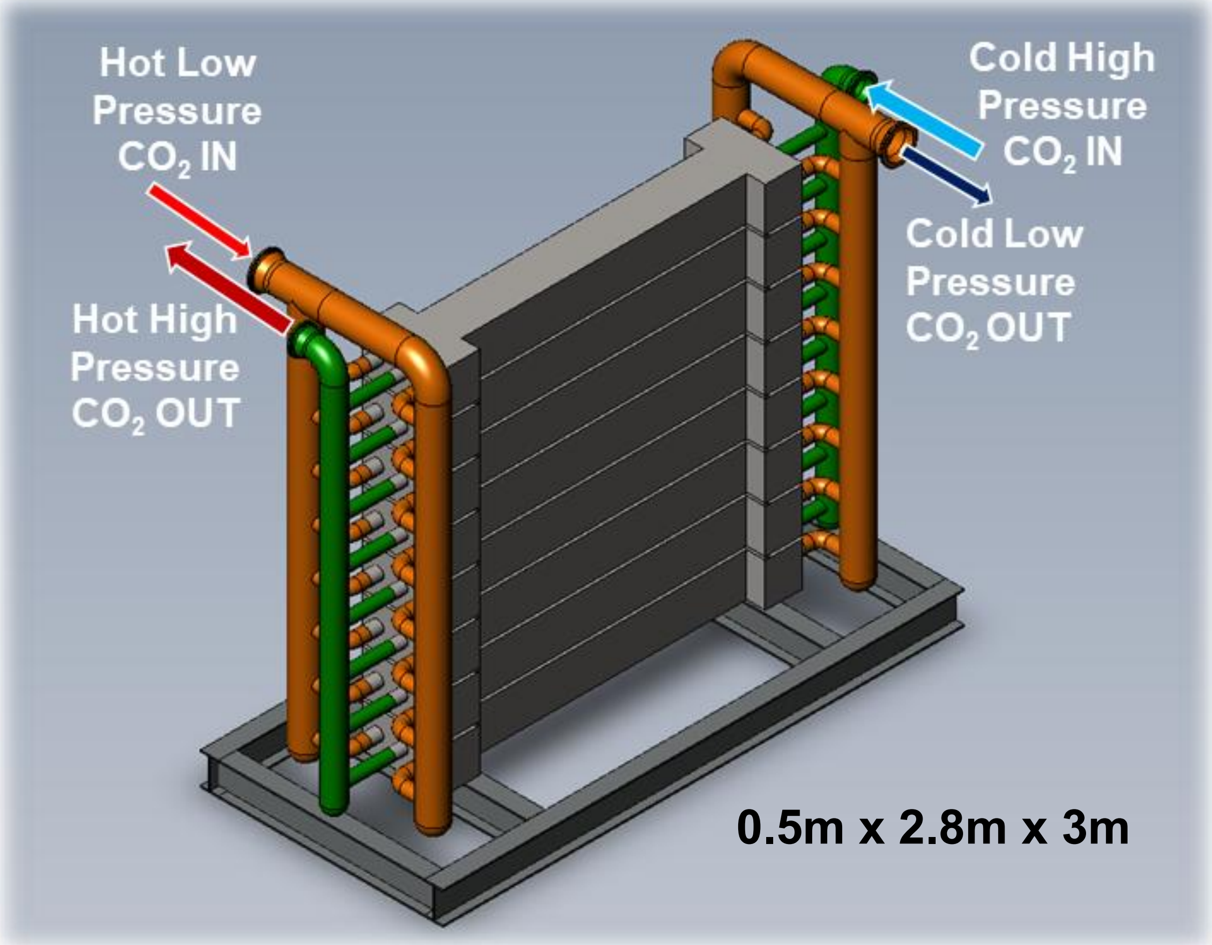




Work supported by US DOE NETL: DE-FE0026273

# 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

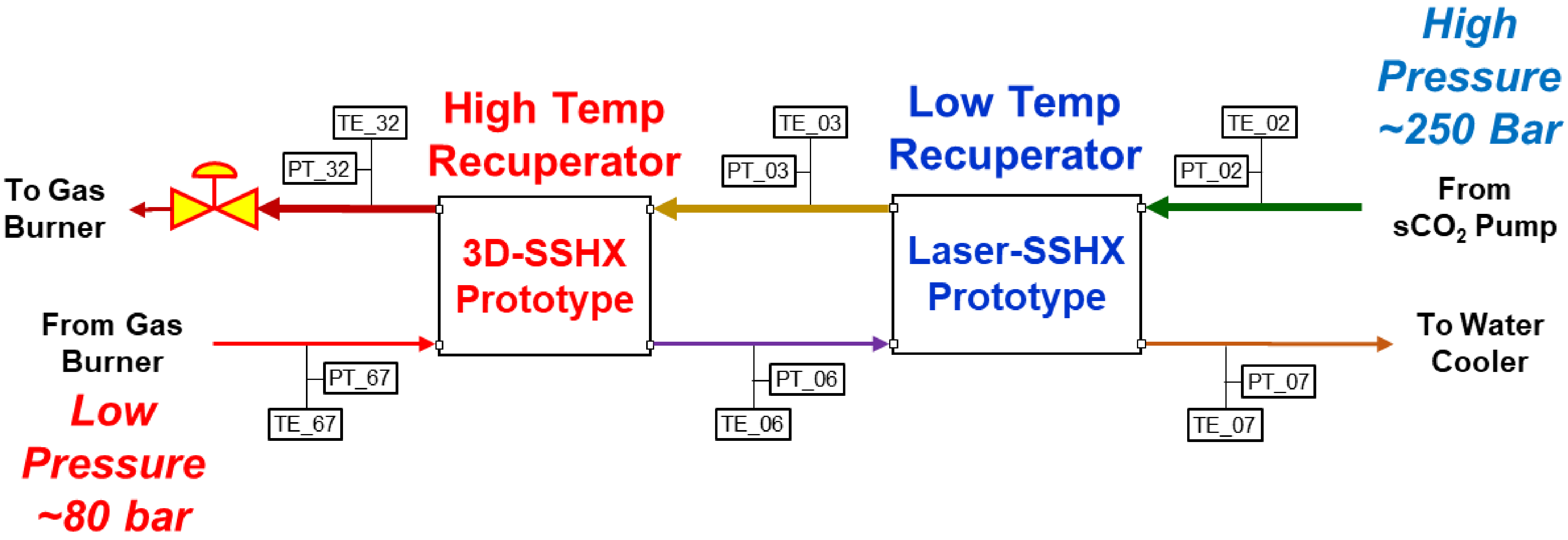
## *SSHX Recuperator*
## *meets or exceeds program requirements*

| Criteria | S.T.E.P. Target (Aug 2016) | SSHX Prototype |
|---|---|---|
| **Thermal Capacity** | **45.9 MWt** | ✓ |
| **Thermal Effectiveness** | **97%** | ✓ |
| **Pressure Loss** | $\Delta P_h$ < 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

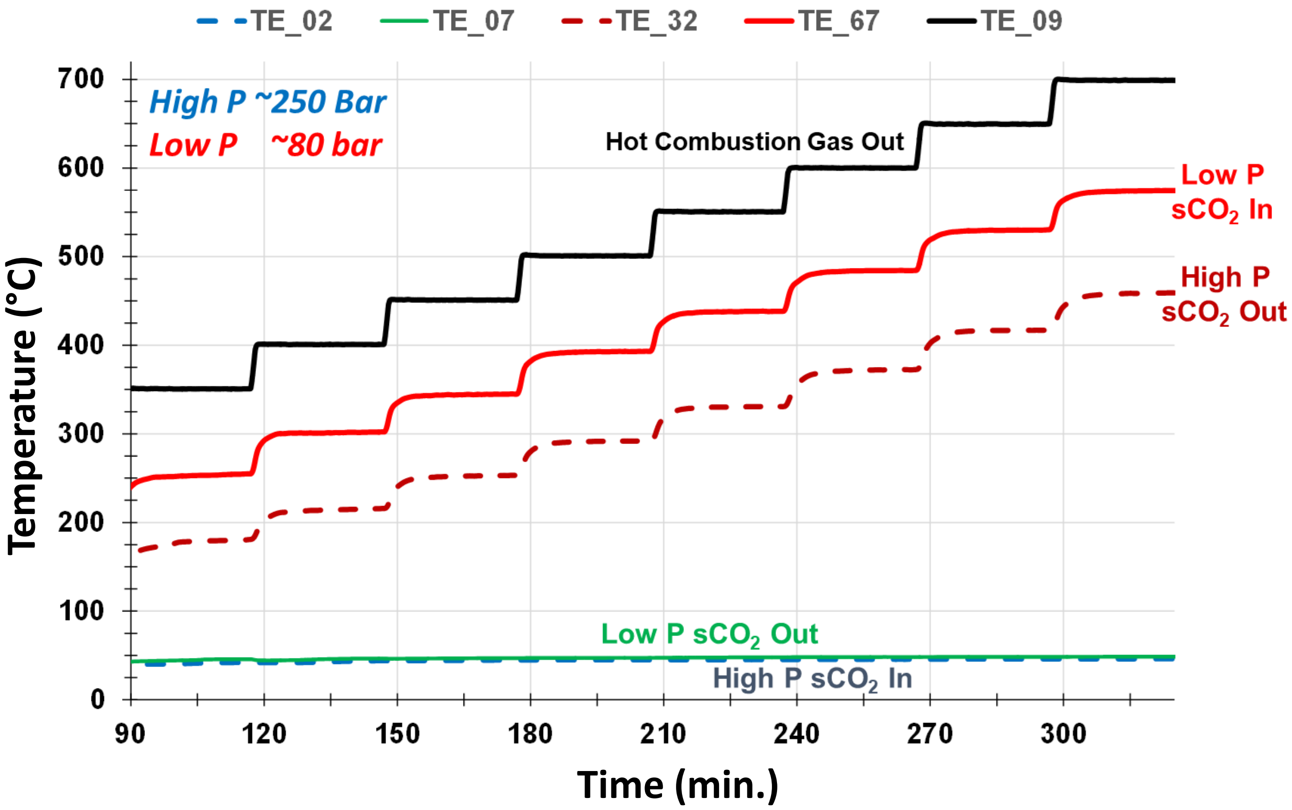


# Test & Energy Balance Plots

## COMBO-SSHX Recuperator

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

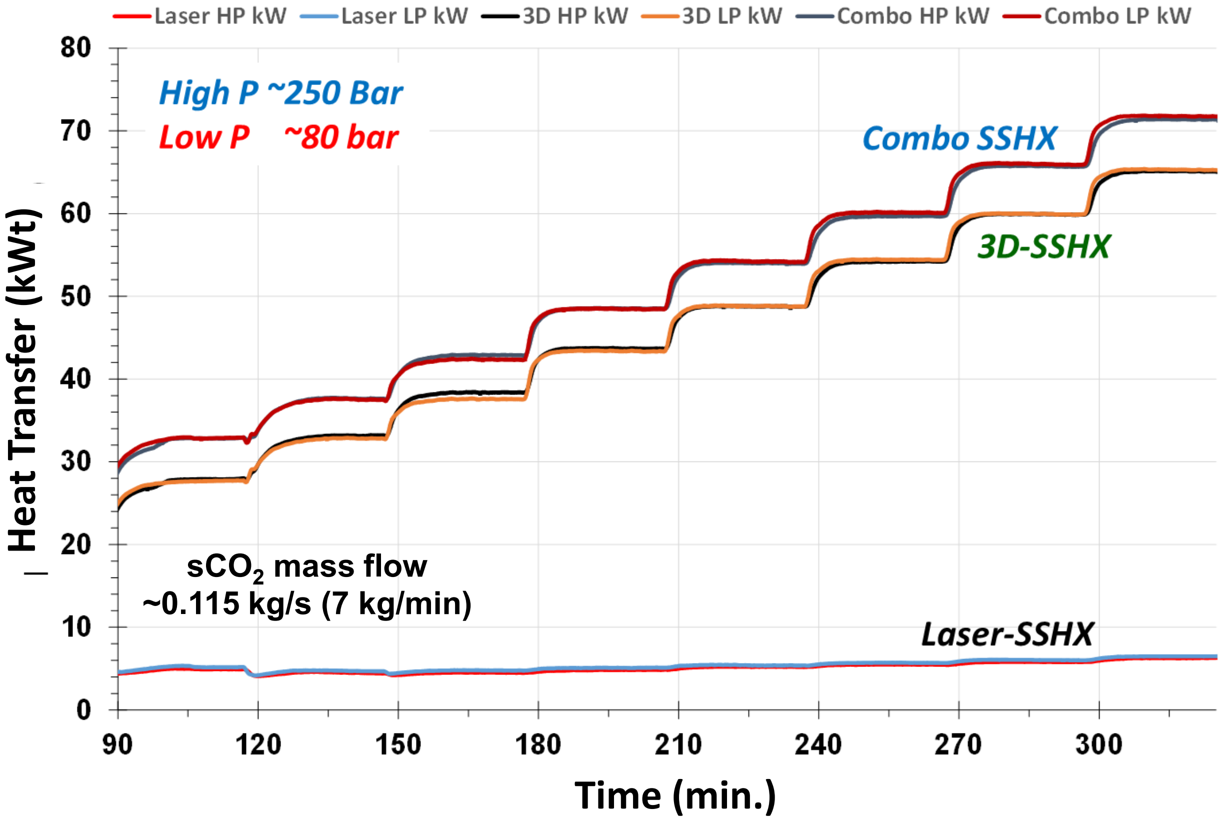
### Temperature Plot



*Approach T: < 5°C*

*Effectiveness: > 98%*

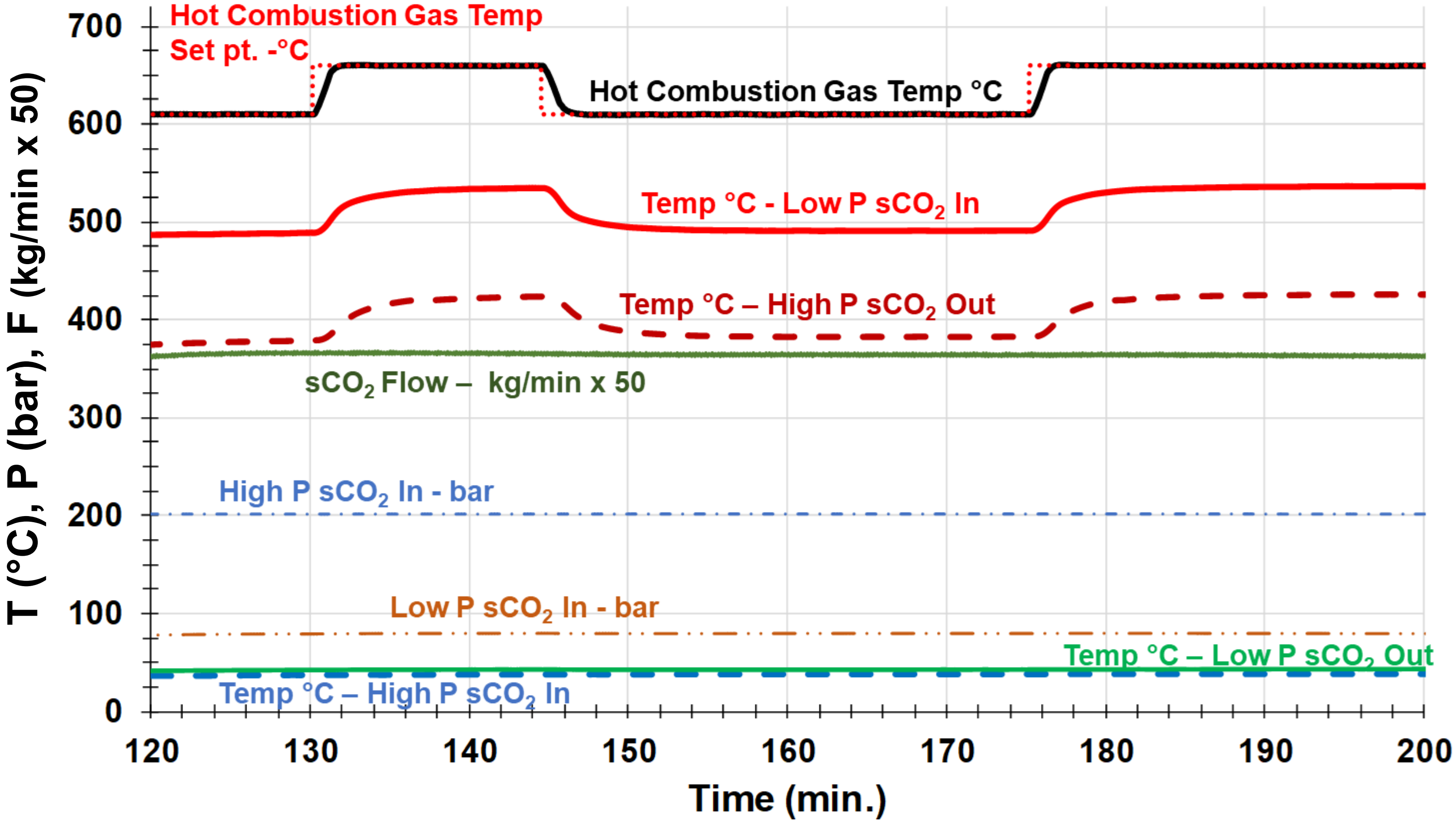
### Energy Balance Plot



*Good Energy Balance, < 2% error*

# COMBO-SSHX

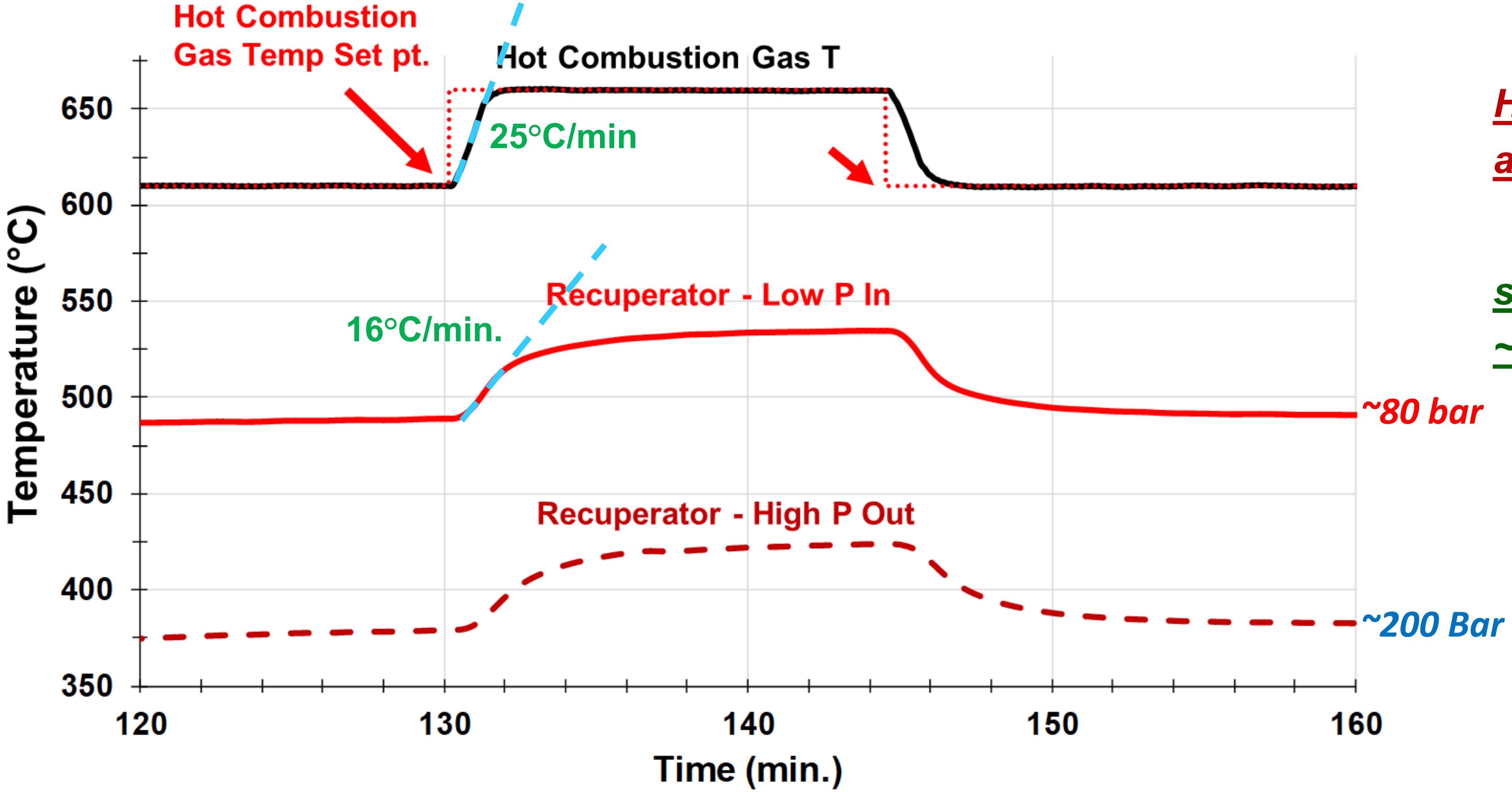
# Temperature Transient Plot



***Pressure and flow remain stable***

# COMBO-SSHX

## Temperature Transient Plot - expanded

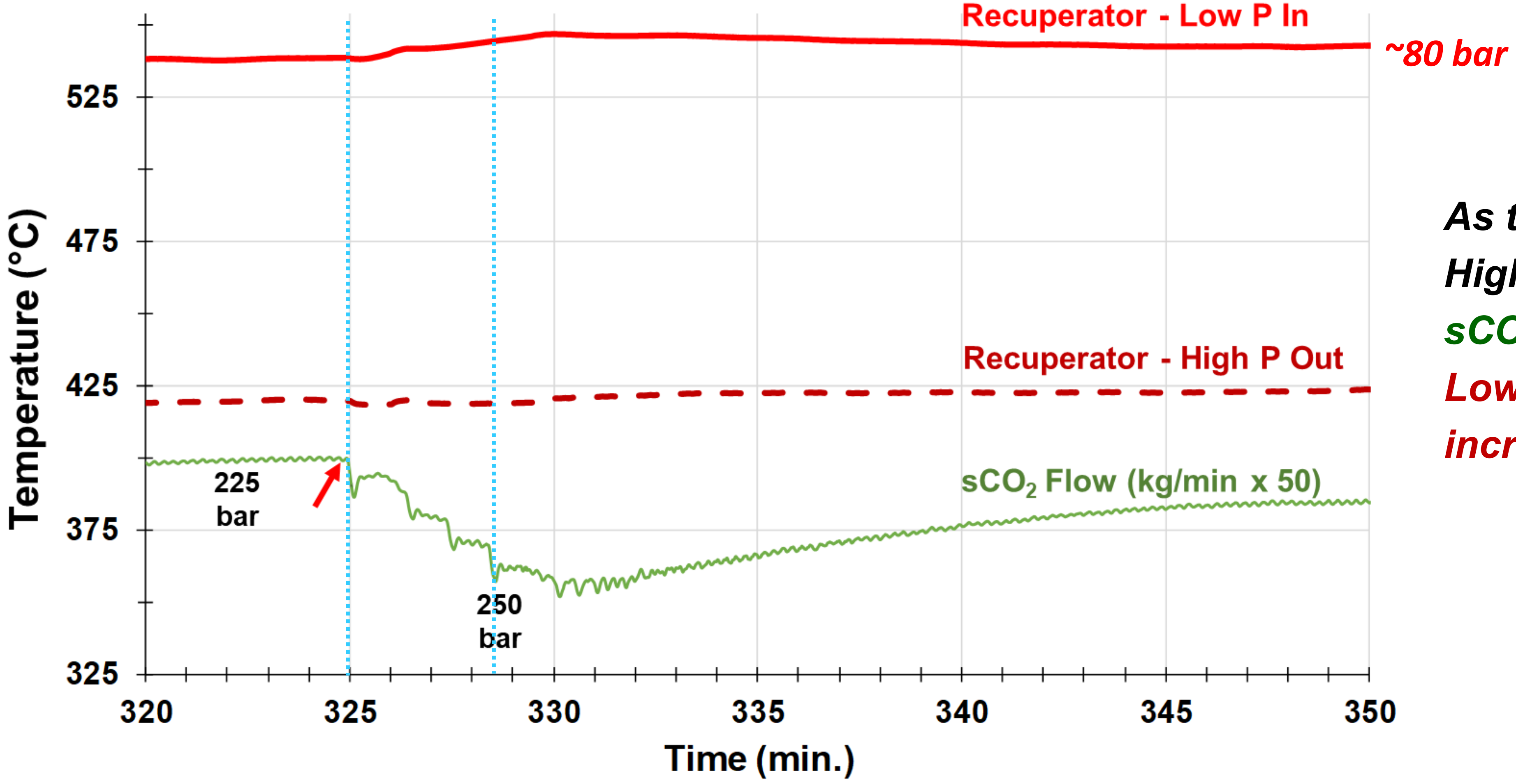


***Hot combustion gas adjusts in ~2 min***

***$sCO_2$ streams take ~10-15 min.***

# COMBO-SSHX

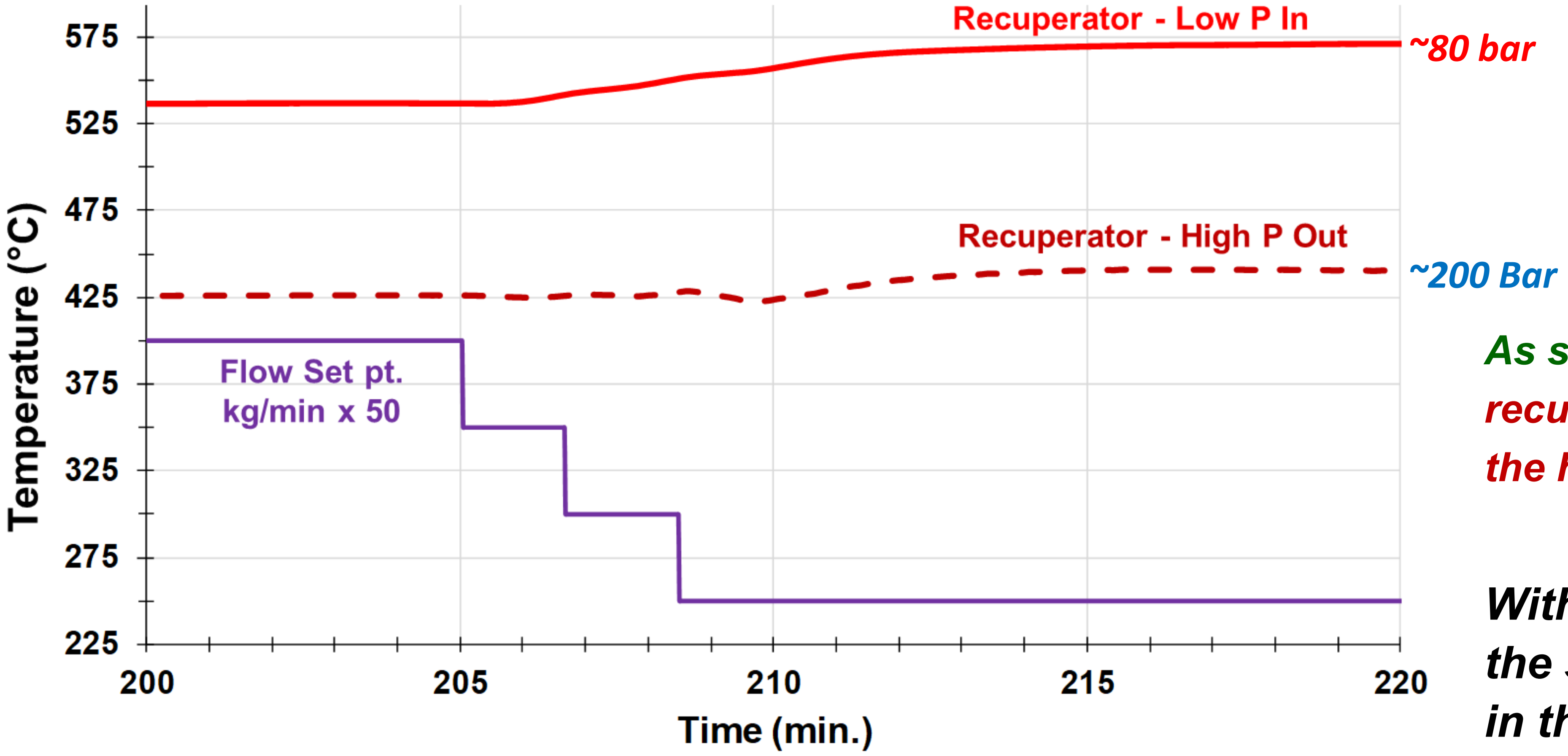
## Change of Pressure



***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.*