2019 UNIVERSITY TURBINE SYSTEMS RESEARCH PROJECT REVIEW MEETING

University of Central Florida

Orlando, Florida
November 6, 2019

Development of Modular, Low-Cost, High Temperature Recuperators for the sCO_2 Power Cycles – Prototype Performance Update

Lalit Chordia, PhD, Vahid Vahdat, PhD, Ed Hoppe,
Forest Sears, Peter Shipe, Tom Koger, **Marc Portnoff**

DE-FE0026273

150 Gamma Drive
Pittsburgh, PA 15238
www.tharenergyllc.com

Outline

- Introduction to Thar Energy
- Project Recap
  - STEP Recuperator Criteria
  - Recuperator Concept Down Select
  - Scaling Considerations
- Project Update
  - Prototype Design & Fabrication
  - Prototype Performance Testing
- Project Summary

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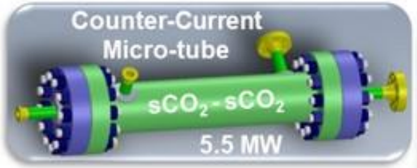
The Thar Brand

Over 25 years of Innovation with "Green" Supercritical Fluid Technologies

Timeline (recent past)

sCO_2 Brayton Power Cycle Development

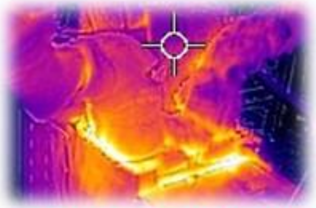
COMPACT Heat Exchangers for sCO_2 Power Cycles



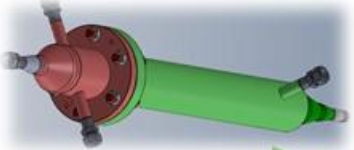
3D Printed, Inconel 718, sCO_2-sCO_2 Recuperator

Design – Construct – Install Primary Heater for Sunshot One MWe sCO_2 Test Loop

Design – Construct – Operate sCO_2 Heat Exchanger Test Loop



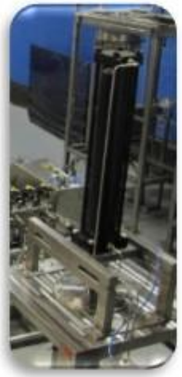
Superior Thermal Performance Confirmed



2014

Design – Construct – Operate Largest GMP sCO_2 Extraction System in USA

2015



Expands into Liquid Chromatography

2016

Oxy Combustion Test Facility
Design – Construct – Operate
Demonstrate auto-combustion

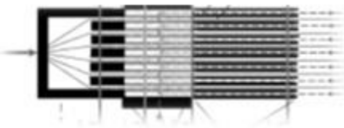
Thar Pharmaceuticals sold to GRUNENTHAL

2017

United States Patent and Trademark Office

Patent - Notice of Allowance

Counter Current Heat Exchanger/Reactor



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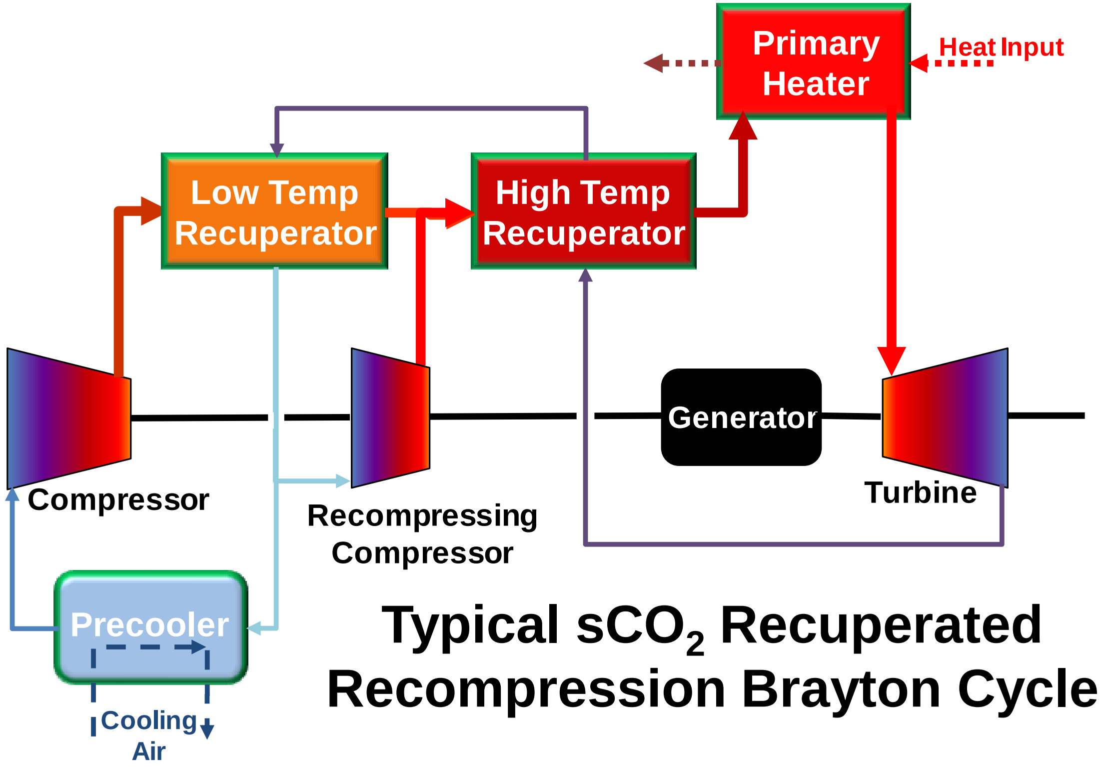
Heat Exchangers are key to improving sCO_2 power cycle efficiency and costs

Thar Energy - Manufacturer of

COMPACT Heat Exchangers for sCO_2 Power Cycles

- Recuperators
- Heaters
- Gas Coolers
- Water Coolers

kWt to MWt



Typical sCO_2 Recuperated Recompression Brayton Cycle

Optimized Material Use

- *Aluminum*
- *Carbon Steel*
- *Alloy Steel*
- *Stainless Steels*
- *Nickel Super Alloys*

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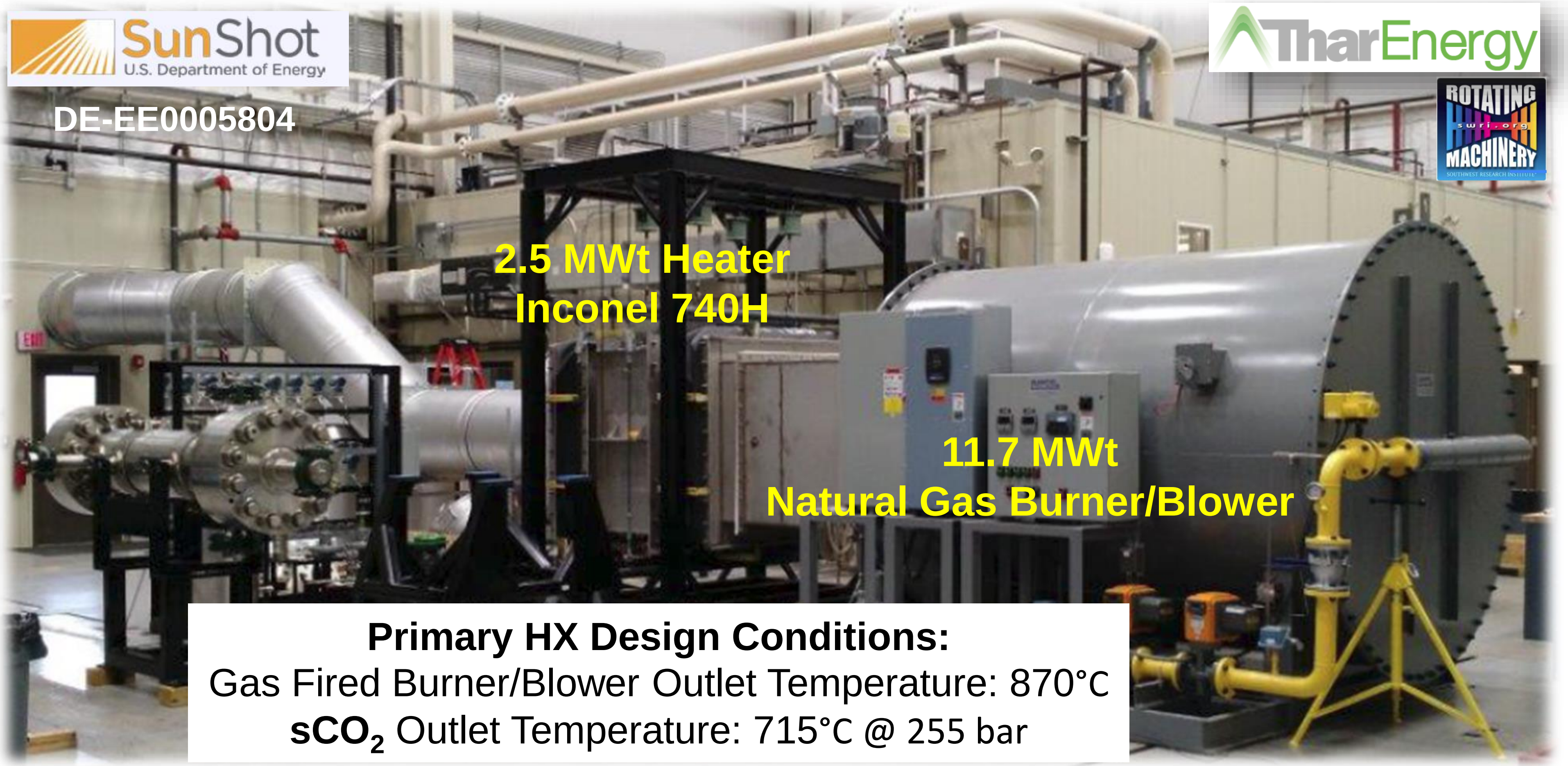
Installed, Commissioned and Operated at SwRI

Thar Energy's sCO_2 Primary Heater



Primary HX Design Conditions:
Gas Fired Burner/Blower Outlet Temperature: 870°C
sCO_2 Outlet Temperature: 715°C @ 255 bar

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Project Recap

- STEP Recuperator Criteria
- Recuperator Concept Down Select
- Scaling Considerations

Project Participants

Lalit Chordia, Vahid Vahdat, Danyang Li, Ed Green, Ed Hoppe, Peter Shipe, Andy Hessler, Tom Koger, Forest Sears, Marc Portnoff,

Grant Musgrove, Klaus Brun, Stefan Cich, C.J. Nolen, Anthony Costanzo, Kevin Hoopes, Shane Coogan, Griffin Beck, Larry Miller, Melissa Poerner, Matt James, Josh Schmitt, Elliott Bryner, Fang Pan, Nick Mueschke, David Ransom

Bruce Pint

Devesh Ranjan, Sandeep Pidaparti

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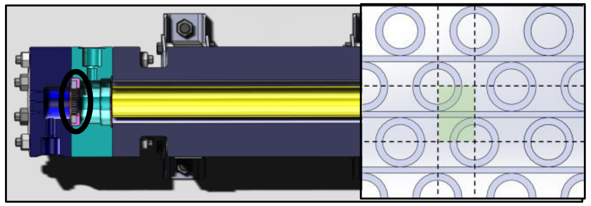
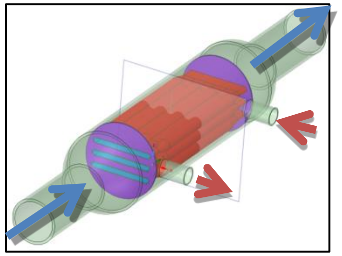
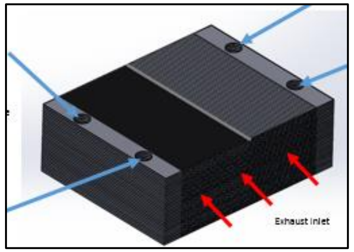
SOPO Tasks

A scaled prototype will verify the design process and technology before designing for 47 MWt

Task 1.0 — **Project Management and Planning**

Task 2.0 — **Engineering Assessment of Advanced Recuperator Concepts**

Other Concepts from brainstorm

Techno-Economic Analysis for selected recuperator concepts

Task 3.0 — **Preliminary design (detail design of 100 kWt prototype)**

Task 4.0 — **~75 kWt prototype fabrication and testing**

Go/No-Go Milestone for Budget Period 2

Task 5.0 — **Detail design of 47 MWt recuperator**

Task 6.0 — **Fabrication of 47 MWt recuperator**

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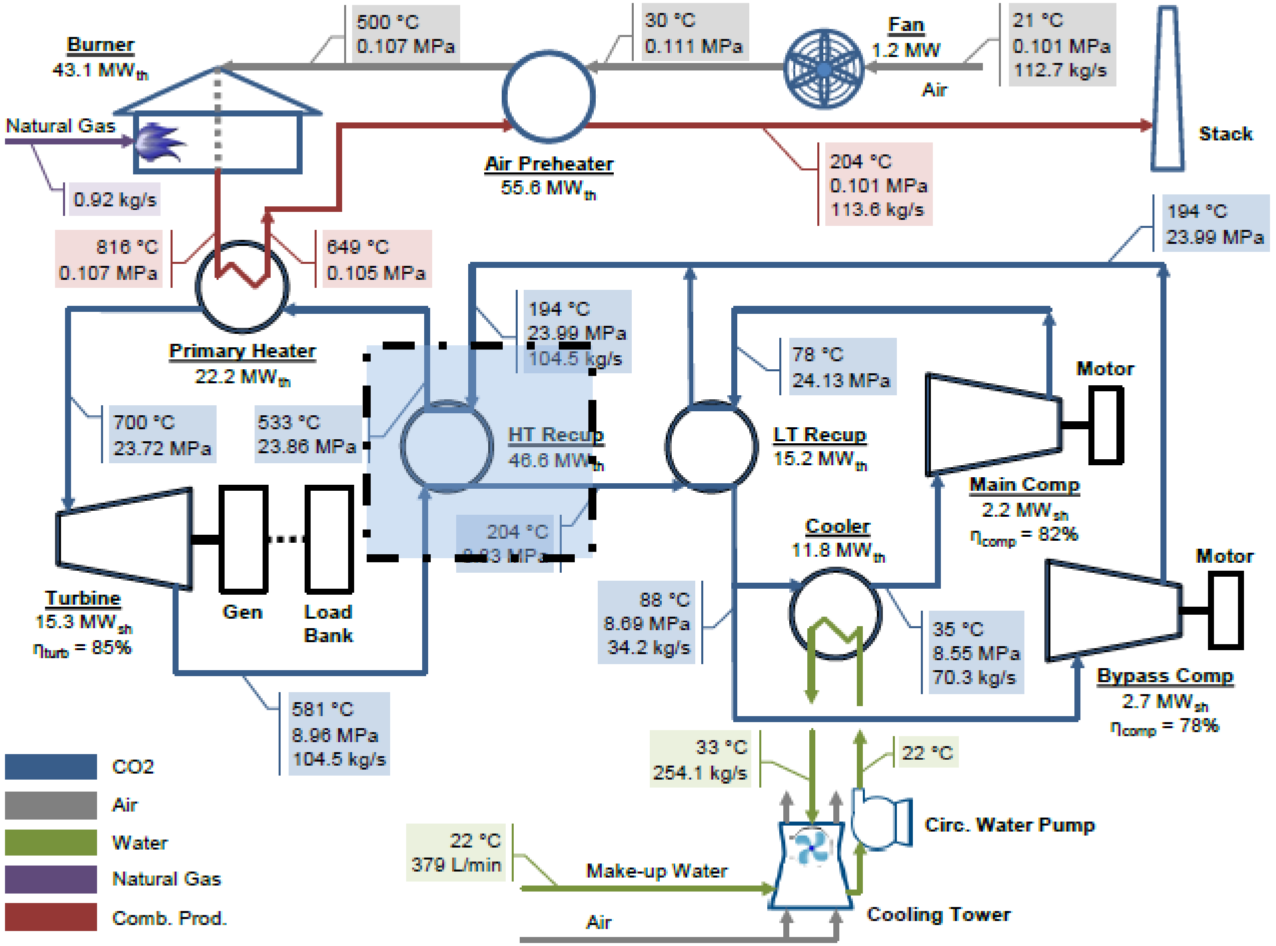
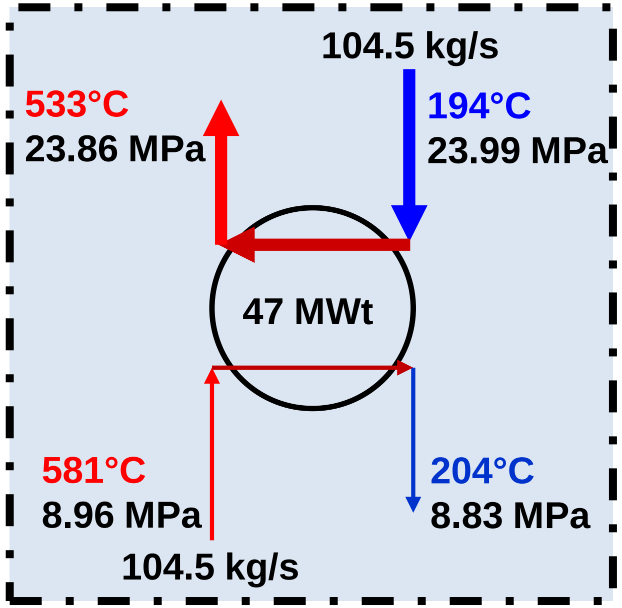
Develop a Scalable, High Temperature Recuperator for STEP Conditions



High Temperature Recuperator



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Comparison of Recuperator Design Criteria

Criteria	Initial	Updated
Thermal Capacity	**46.6 MWt**	**45.9 MWt**
Thermal Effectiveness	**96%**	**97%**
Pressure Loss	ΔP_h < 1.5% (1.3 bar) ΔP_c < 0.6% (1.3 bar)	
Temperature Limit	**581°C**	**577°C**
Differential Pressure	152 bar	
Life	30,000 hr	
Cost	< $100 / kWt	
Package Dimensions	8.8 x 3.6 x 2.6 m	

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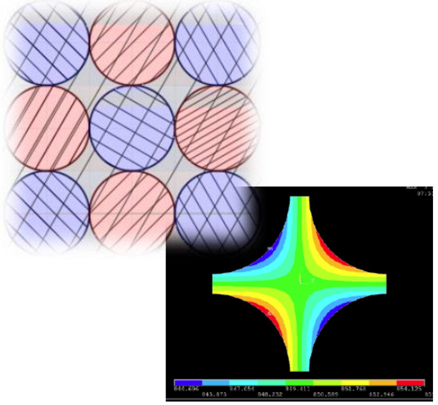
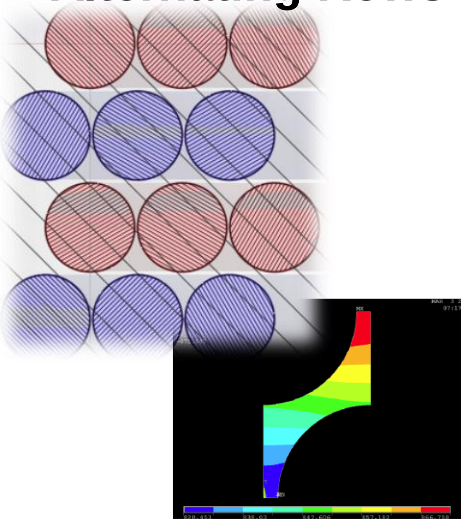
Heat Exchanger Design

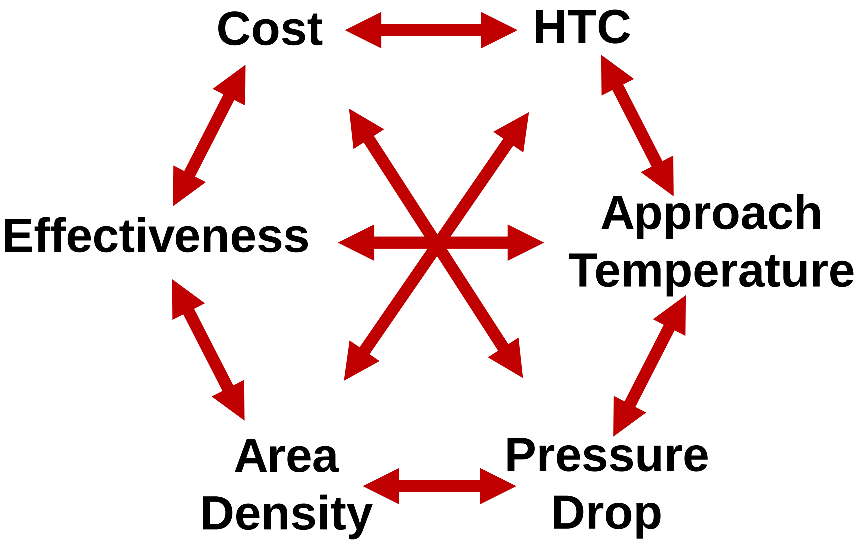
- Area Density (Microchannel passage size)
- Counter Current flow
- Checker Board Flow Pattern
- Passage Shape
- Surface Effects
- Turbulent vs Laminar flow

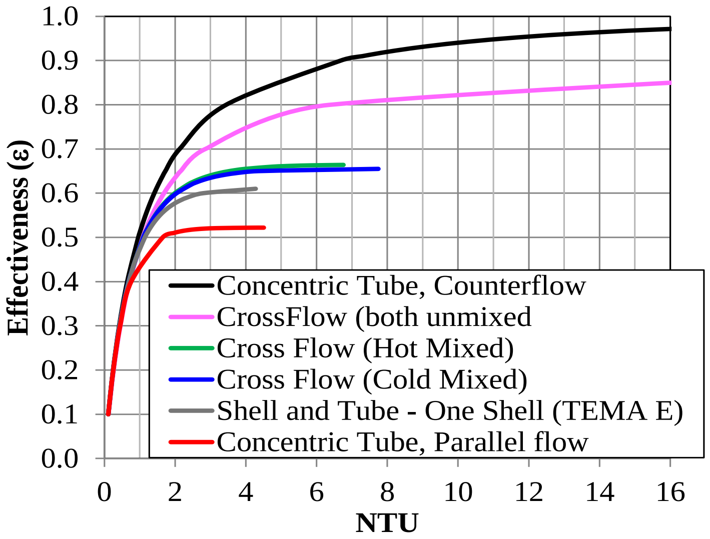
Checkerboard



Alternating Rows







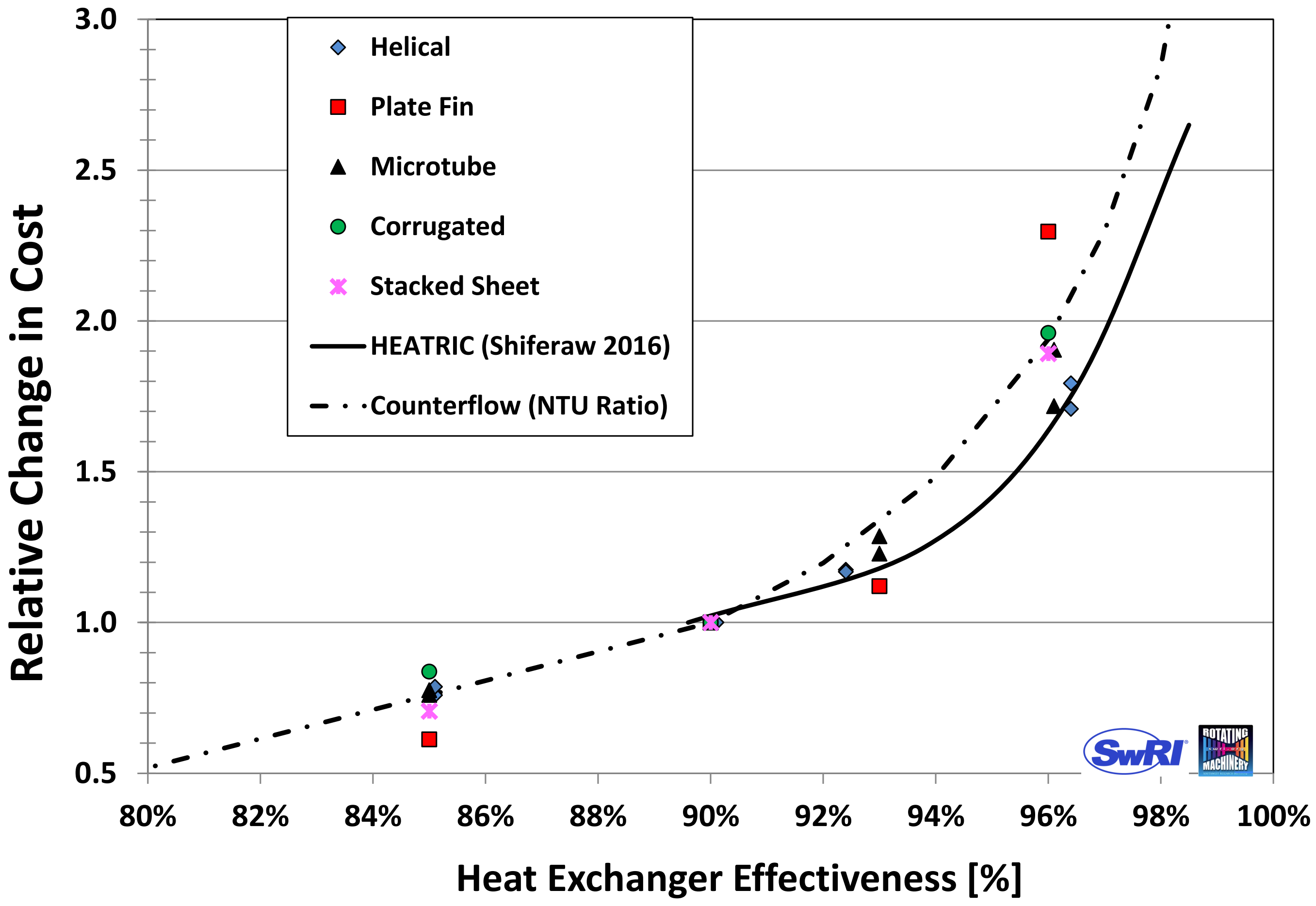
Recuperator specifications influence cost

Relatively independent for the heat exchanger concepts evaluated

- **Approach Temperature**
- **Effectiveness**

- **Pressure Drop**
- **Mass Flow**

- **Pressure**
- **Temperature**



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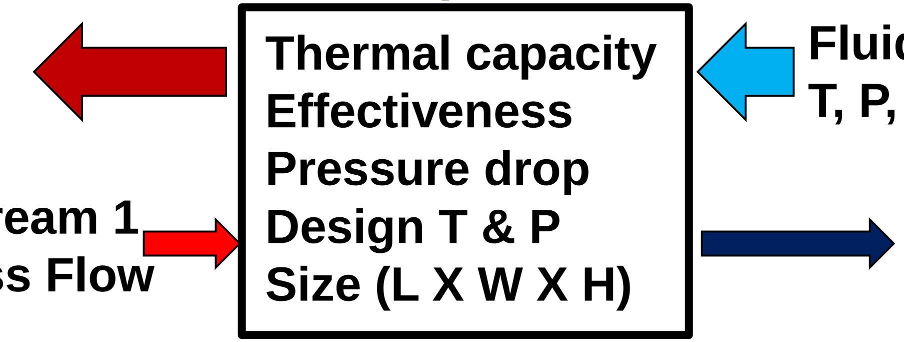
Recuperator Design

Recuperator



Fluid Stream 1
T, P, Mass Flow

Fluid Stream 2
T, P, Mass Flow

Material of Construction

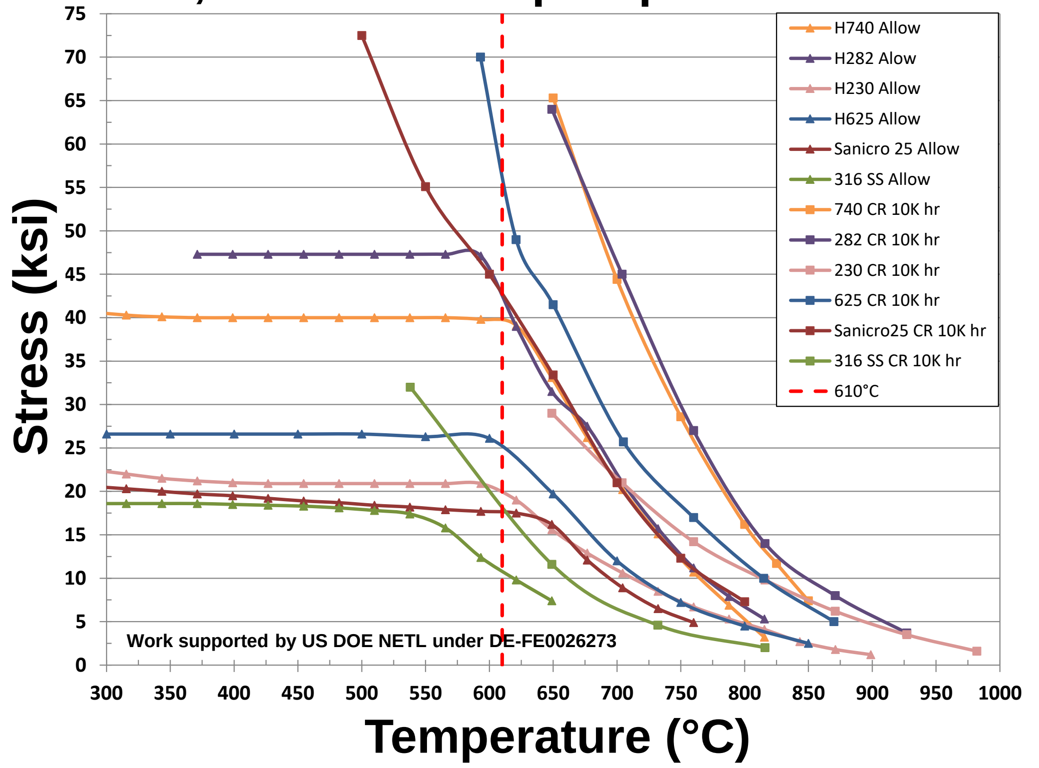
- Physical Properties
- Corrosion
- Contamination potential

ASME Code Stamp/Design

Fouling Factor

***Goal:** Meet performance requirements and provide margin of safety while minimizing over design*

ASME Allowable Stress and 10,000 Hour Creep Rupture Values



***Design T** ↑ **$** ↑*

As Design T increases, the material strength drops & corrosion rates increase

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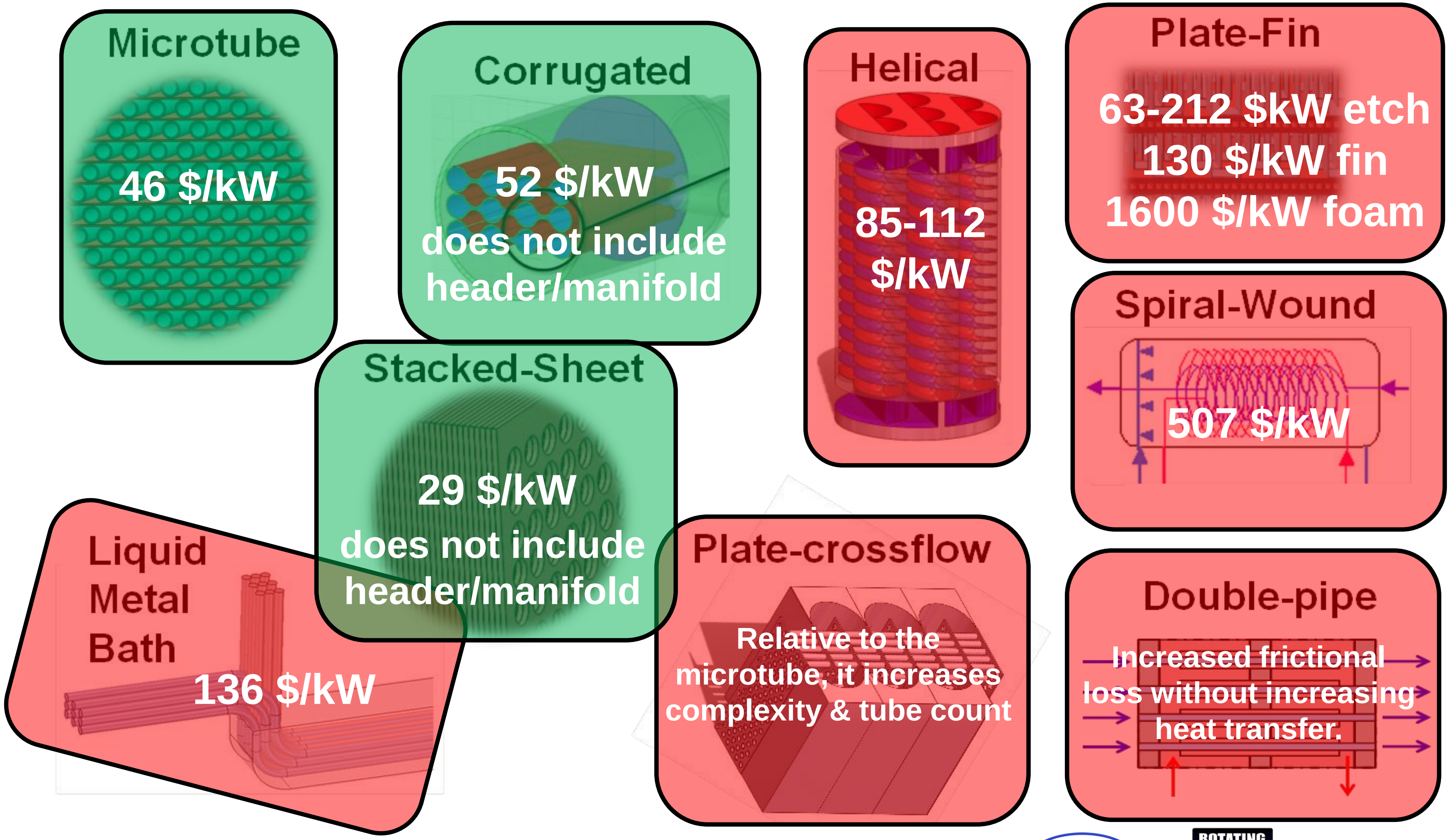
First Cost vs Life Cycle Costs

- Smaller passages are more susceptible to plugging, fouling and are harder to maintain
- Lower cost alloys can be more susceptible to corrosion
- HX design susceptibility to thermal fatigue at scale

The Microtube, Corrugated & Stacked-Sheet Recuperator Concepts were *down selected* for low complexity and cost

47MWt, 240 bar, 581°C, 96% Effectiveness, ΔP < 1.3 bar, <$100/kWt



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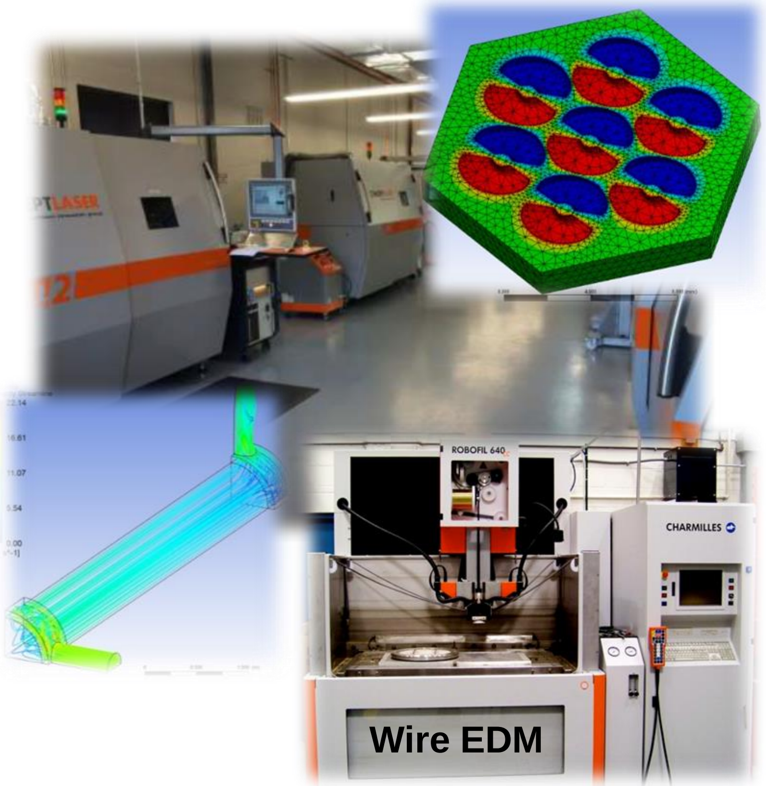
High Temperature Recuperator Concepts

Engineering Analysis & Down Select

- Thermal-Hydraulic performance modeling and analysis
- Advanced manufacturing methods and tolerance
- Fabrication cost analysis

Subtractive vs. Additive Manufacturing

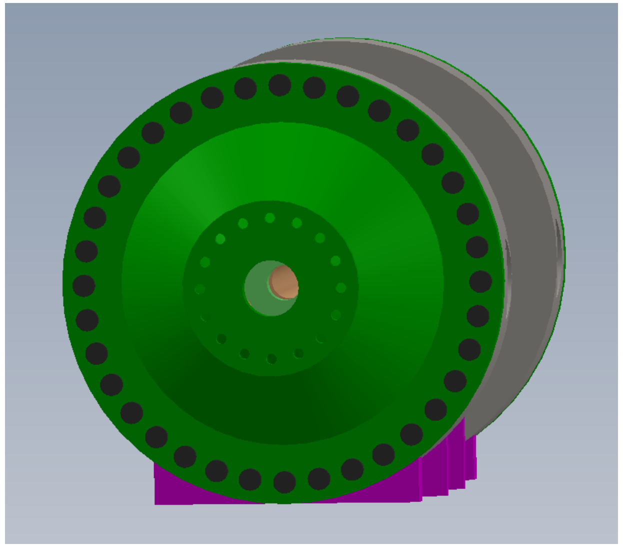
- Laser cutting
- Laser welding
- Water jet cutting
- 3D metals printing
- Electrochemical etching
- Electrochemical machining (ECM)
- Electro discharge machining (EDM)
- EDM wire cutting
- Sheet bending/forming
- Metal plating
- Stamping
- Brazing
- Welding
- Diffusion bonding



Recuperator Concepts
Engineering Analysis

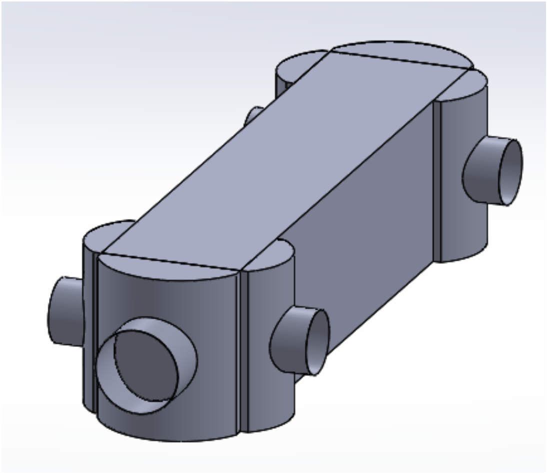
46 MWt, 280 bar, 610°C, 97% Effectiveness, ΔP < 1.3 bar, <$100/kWt

Microtube



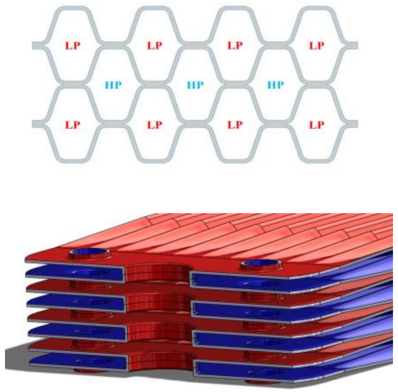
$51/kWt ✓

Stacked-Sheet



$47/kWt ✓

Corrugated



> $107-380 /kWt

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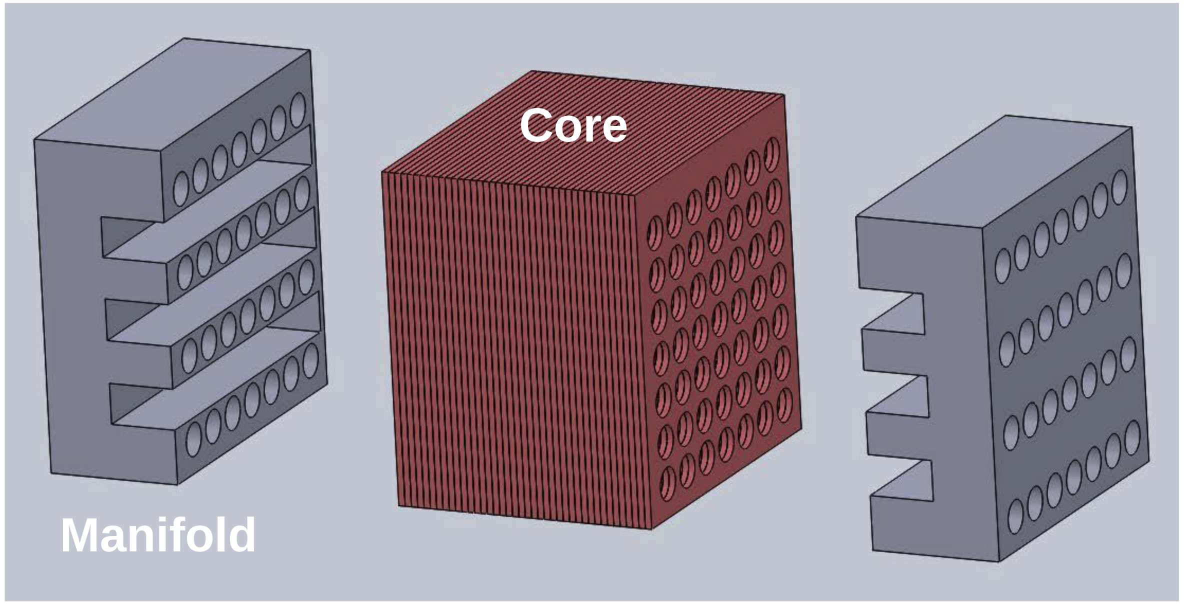
Project Update

- Prototype Design & Fabrication
- Prototype Performance Testing

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**

Opportunity for cost effective design enhancements

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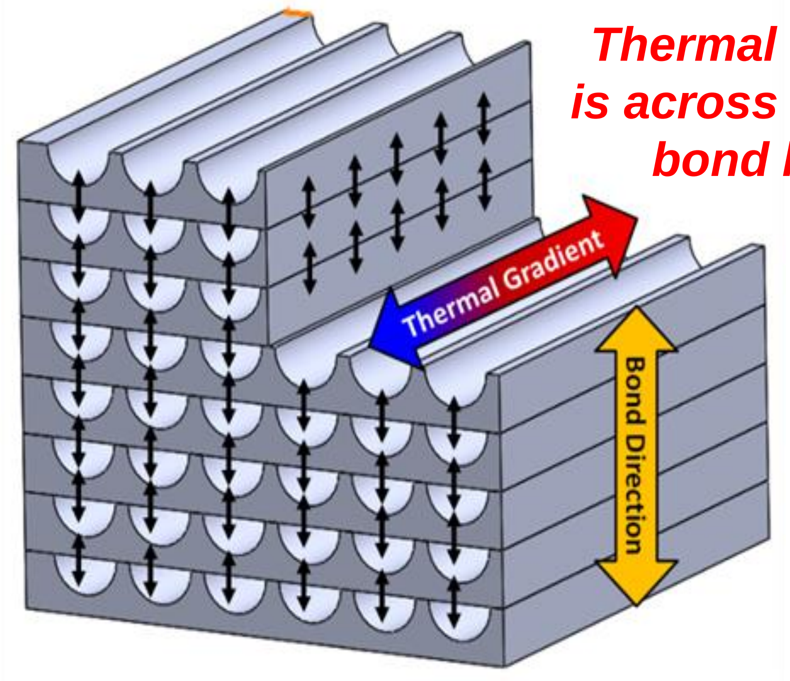
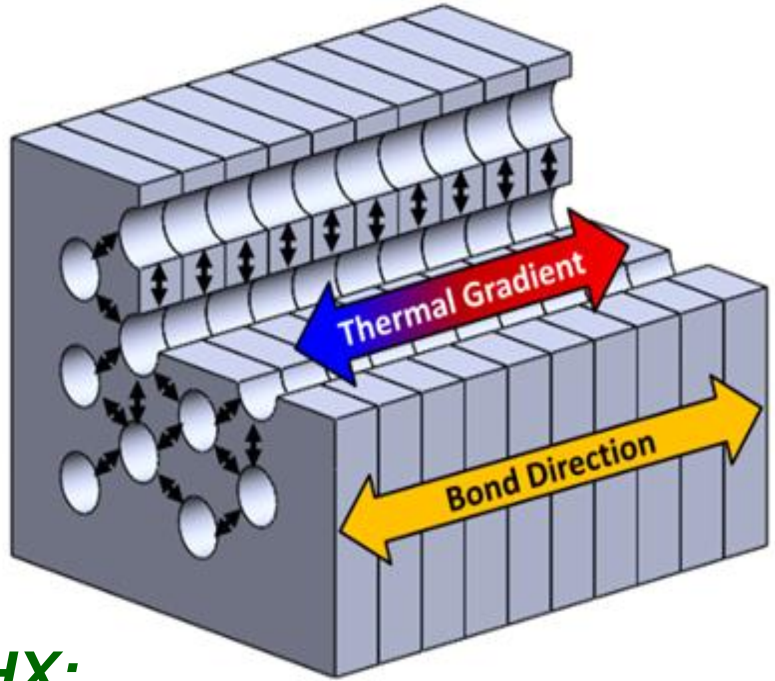
Mechanical & Thermal Stress Analysis - Printed-Circuit HX vs. SSHX



Thermal Gradient is across the entire bond length



Printed-Circuit HX:

The bond between sheets is:
perpendicular to the mechanical stresses & parallel to the thermal stresses

SSHX:

The bond between sheets is:
parallel to the mechanical stresses & perpendicular to the thermal stresses

Improves structural integrity and thermal compliance

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SSHX Manufacturing Options

Accommodates digital advances in Subtractive and/or Additive Manufacturing

- **Stamp or punch operations (Opacity ~73%)**
- **Laser Drilling**
- **Water Jet Drilling**
- **High Pressure Drilling**
- **Chemical etching**
- **Electrochemical machining**
- **Electro-polishing**
- **Mechanical Grinding**
- **Plate and Sheet Re-rollers**
- **Additive Manufacturing – 3D printing (Opacity ~38%)**

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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%

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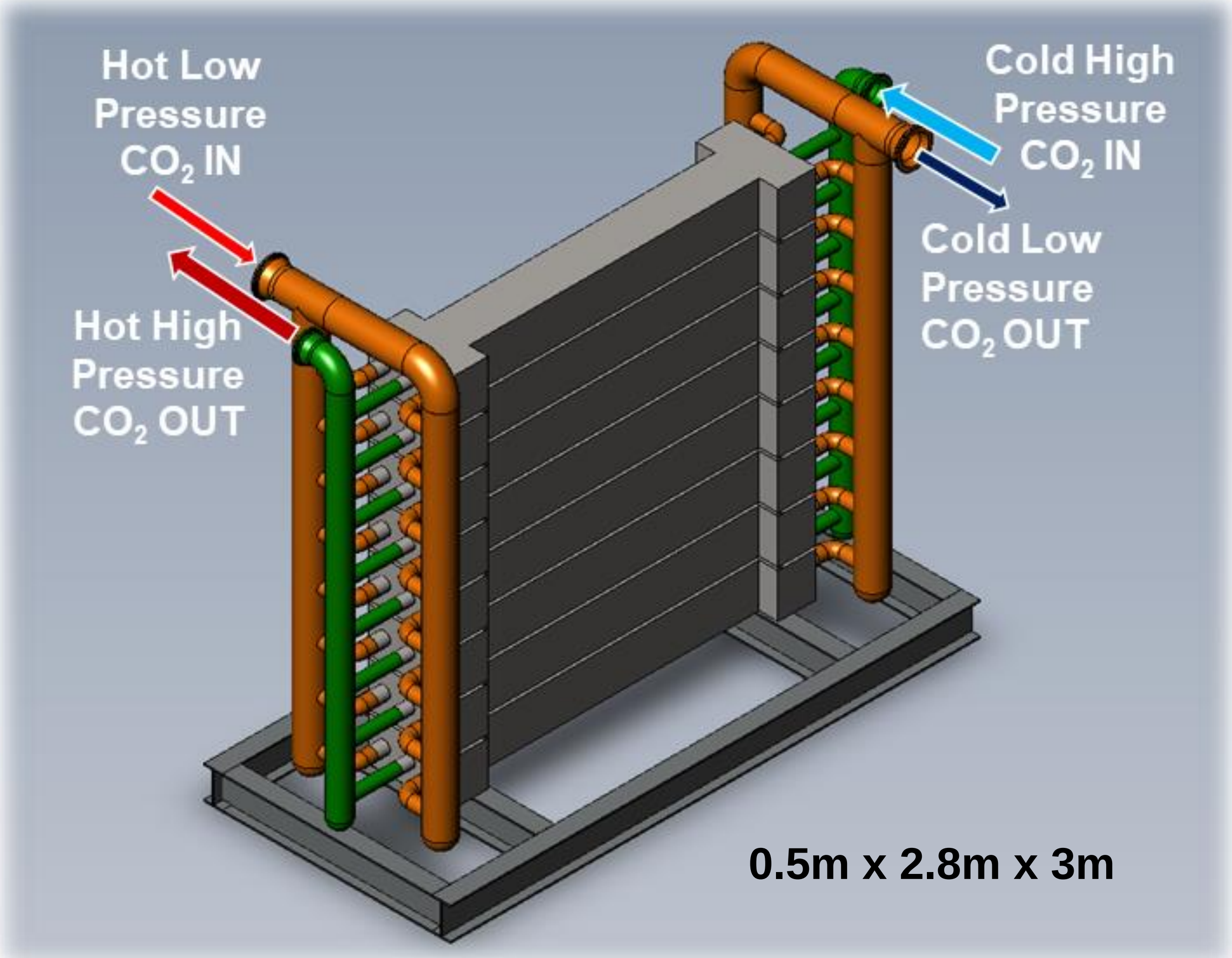
46 MWt Laser-SSHX Recuperator

Parallel Modular Design, Factory Fabricated



3D-SSHX 57% volume decrease

Example: Eight stacked Laser-SSHX sub-modules

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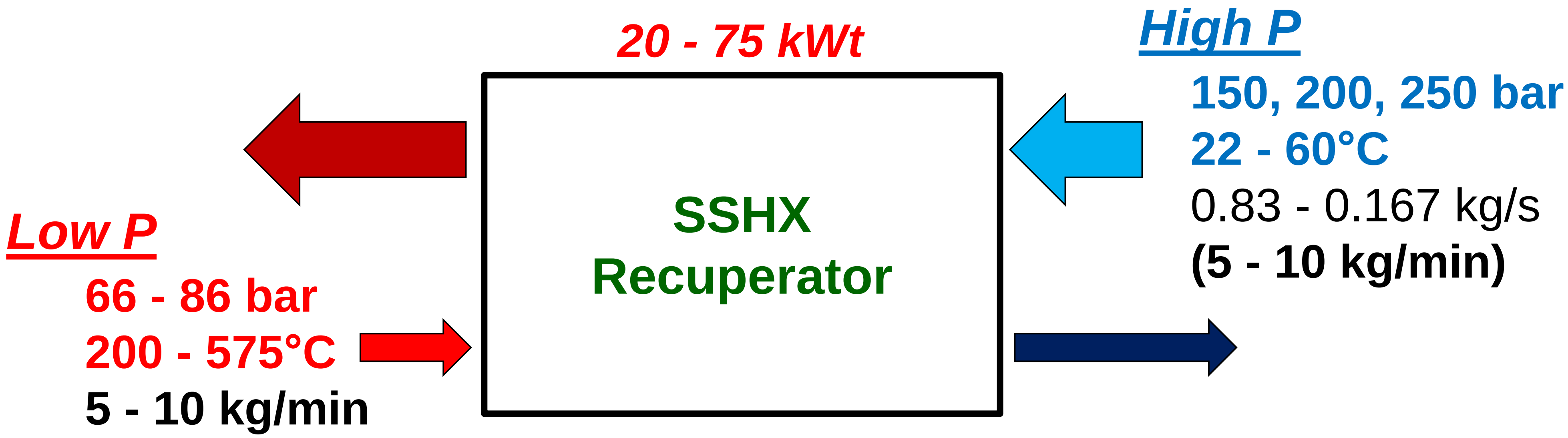
Test Conditions - SSHX Recuperator Prototypes



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

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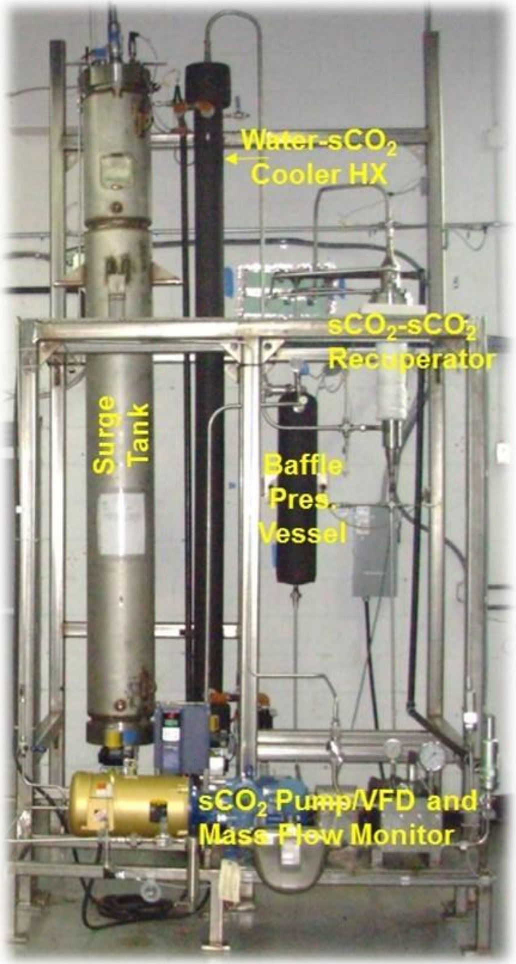
sCO_2 Brayton Power Cycle Heat Exchanger Test Facility

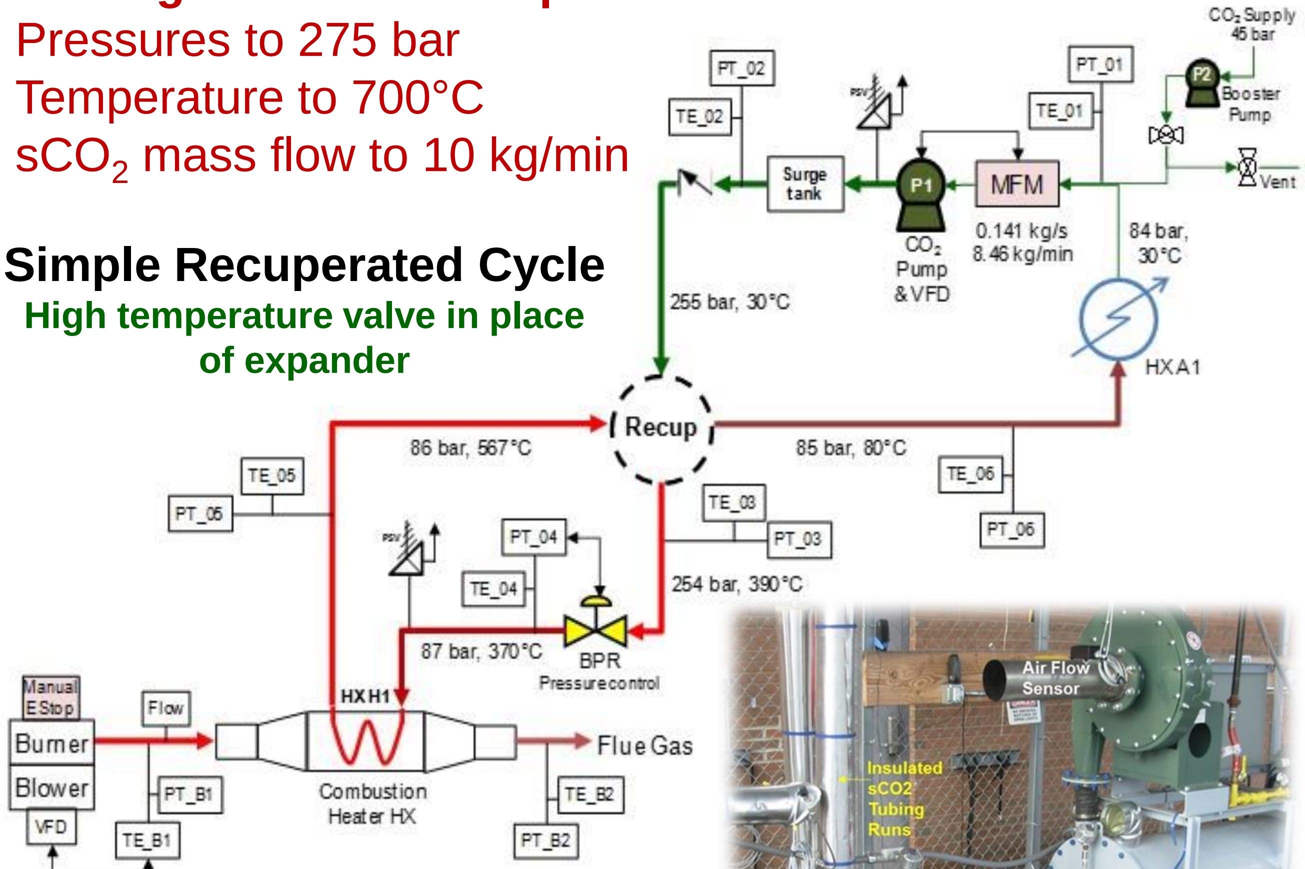


Reconfigurable Test Loop

- Pressures to 275 bar
- Temperature to 700°C
- sCO_2 mass flow to 10 kg/min

Simple Recuperated Cycle

High temperature valve in place of expander



Work supported by US DOE NETL under
DE-FE0024012 & DE-FE0025348

DE-FE0026273

HX Model Heat Transfer Equations

Models selected from established heat transfer and pressure drop equations for the best accuracy compared to testing data

1 CO_2 Side Nusselt Number

Petukhov (1970)

$$Nu_{CO_2} = \frac{(\frac{f}{2}) \times Re \times Pr}{1.07 + \frac{900}{Re} - \frac{600}{1 + 10\mathrm{Pr}} + 12.7\left(\frac{f}{2}\right)^{\frac{1}{2}}(Pr^{\frac{2}{3}} - 1)}$$

2 Air Side Nusselt Number

Martin (2002)

$$Lq = \begin{cases} 0.92Hg \times Pr_{air}(i) \times \left(\frac{\frac{4X_T}{\pi} - 1}{X_L}\right) & X_L \geq 1 \\ 0.92Hg \times Pr_{air}(i) \times \left(\frac{\frac{4X_T X_L}{\pi} - 1}{X_L X_D}\right) & X_L < 1 \end{cases}$$

$$Nu_{air}(i) = 0.404 \times Lq^{\frac{1}{3}}$$

3 CO_2 Side Pressure Drop

Bhatti and Shah (1987)

$$f = 0.00128 + 0.1143Re^{-0.311}$$

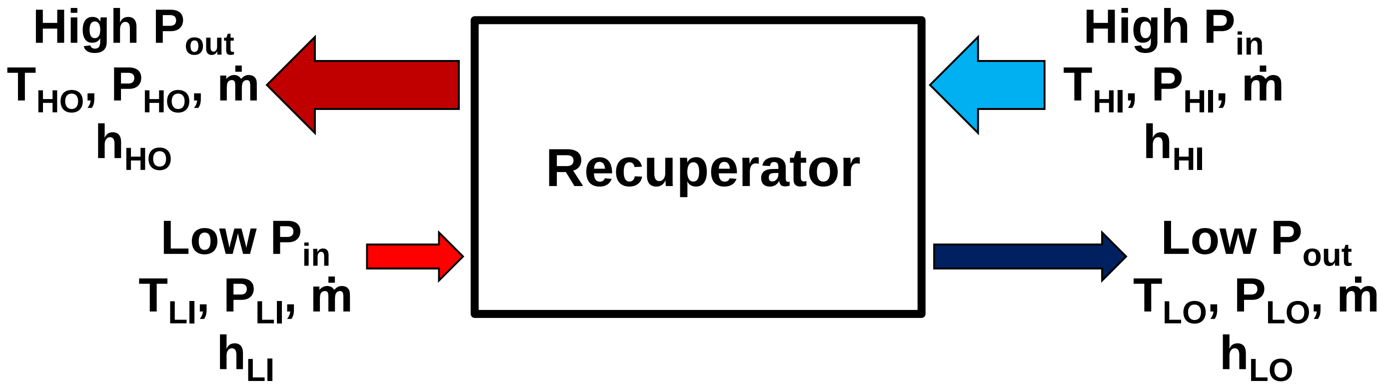
$$\Delta p_{co_2} = f\frac{L}{d_o}\frac{\rho\mu^2}{2}$$

4 Air Side Pressure Drop

Zukauskas (1988)

$$\Delta p_{air} = N_r X\left(\frac{\rho {u_m}^2}{2}\right)f$$

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

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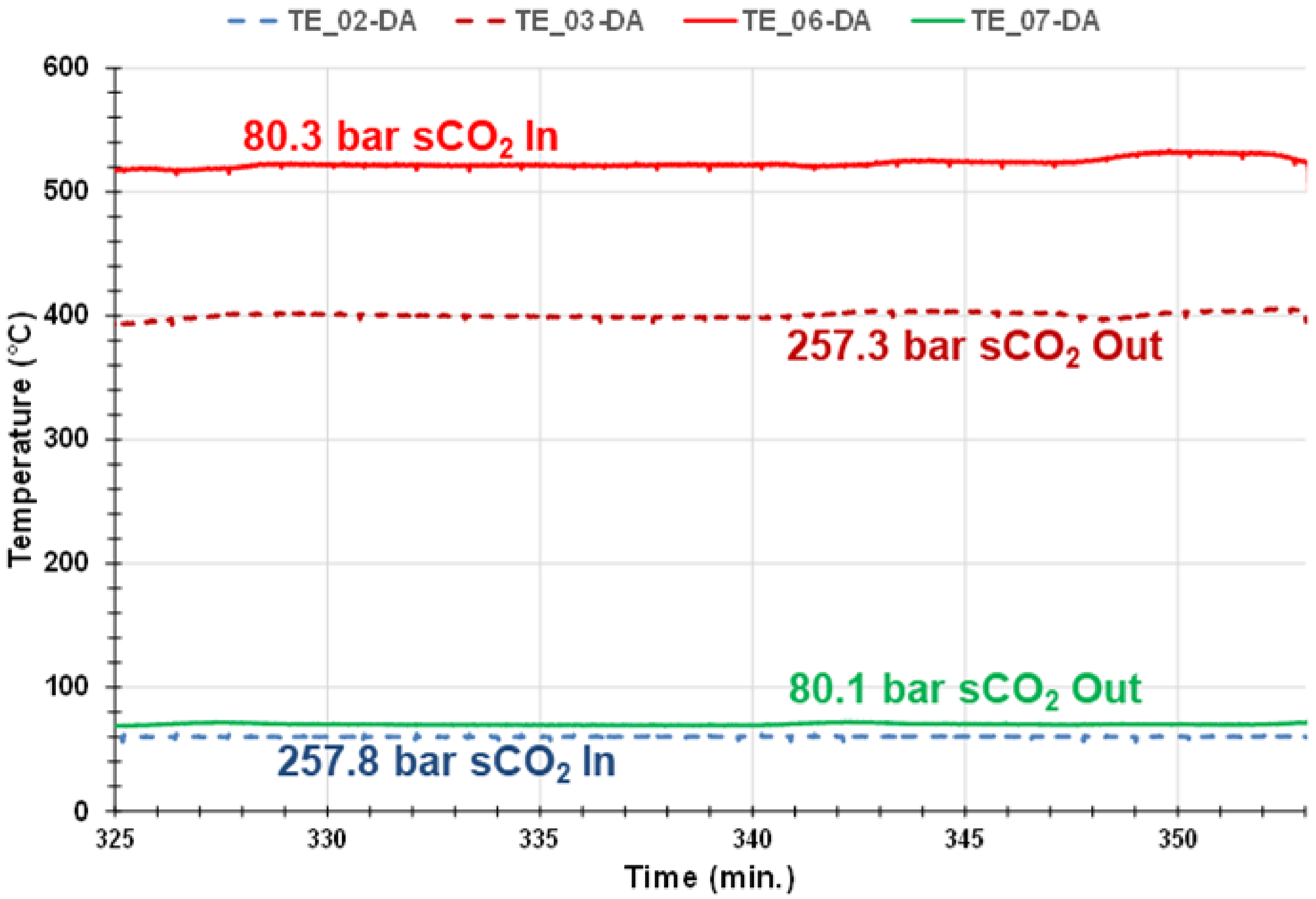
Steady State Time vs. Temperature Plot

Prototype SSHX Recuperators

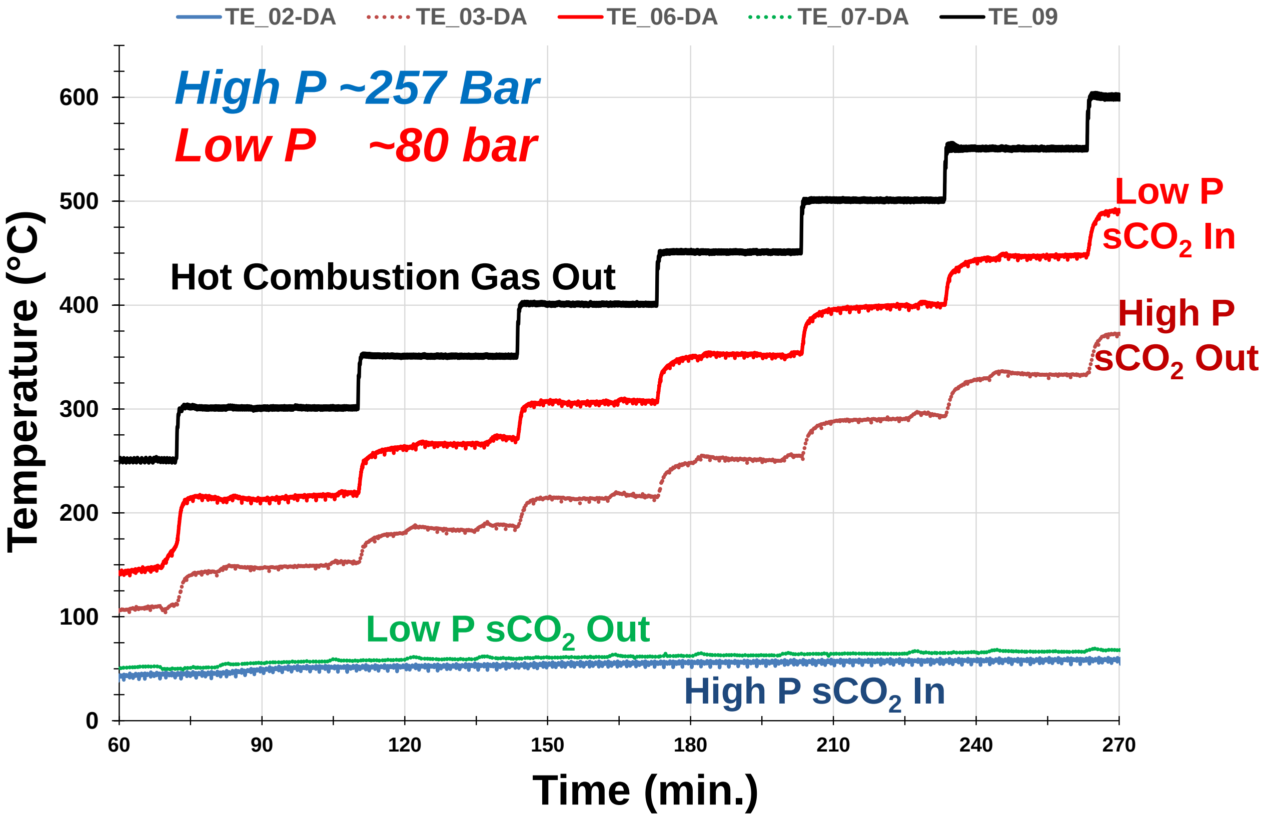
3D-SSHX – Steady State Plot



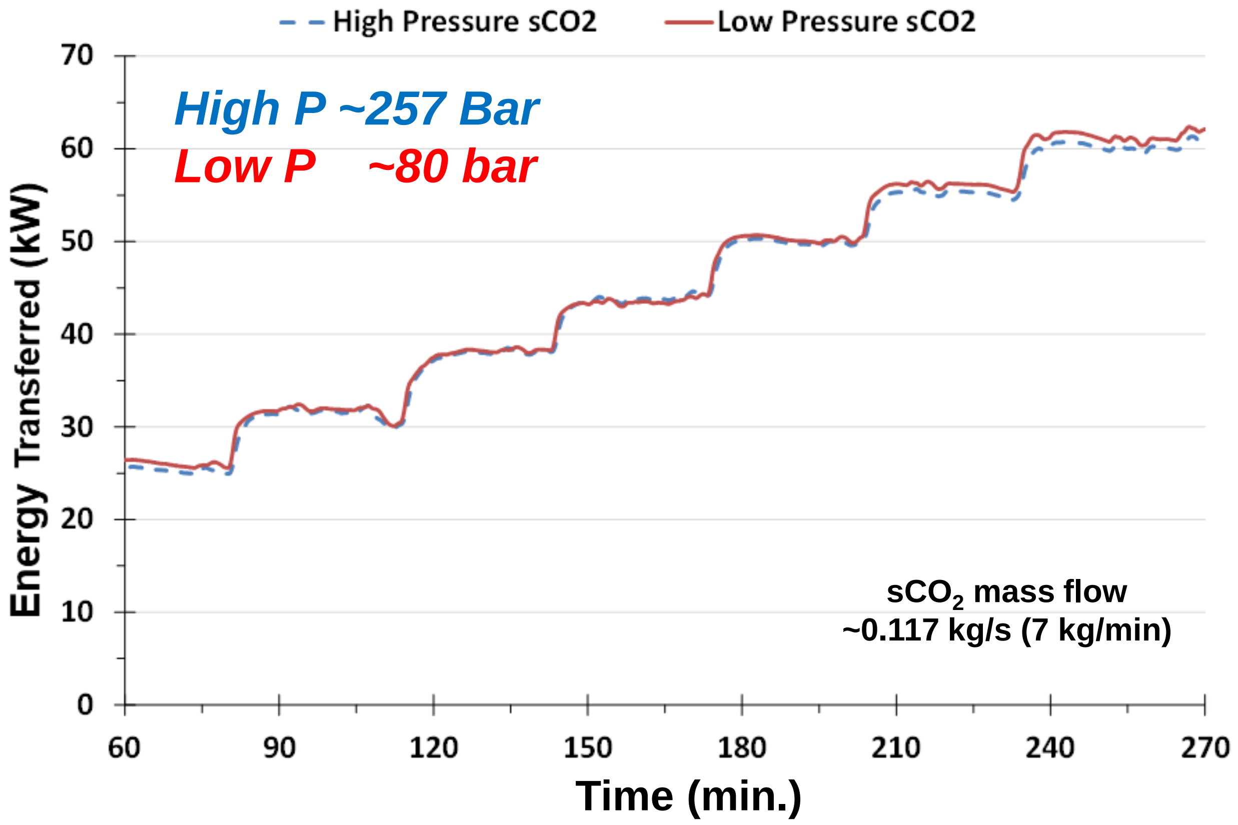
Test & Energy Balance Plots

Prototype 3D-SSHX Recuperator

Time vs. Temperature Plot



Energy Balance Plot



Approach T, < 10°C

Good Energy Balance, < 2% error

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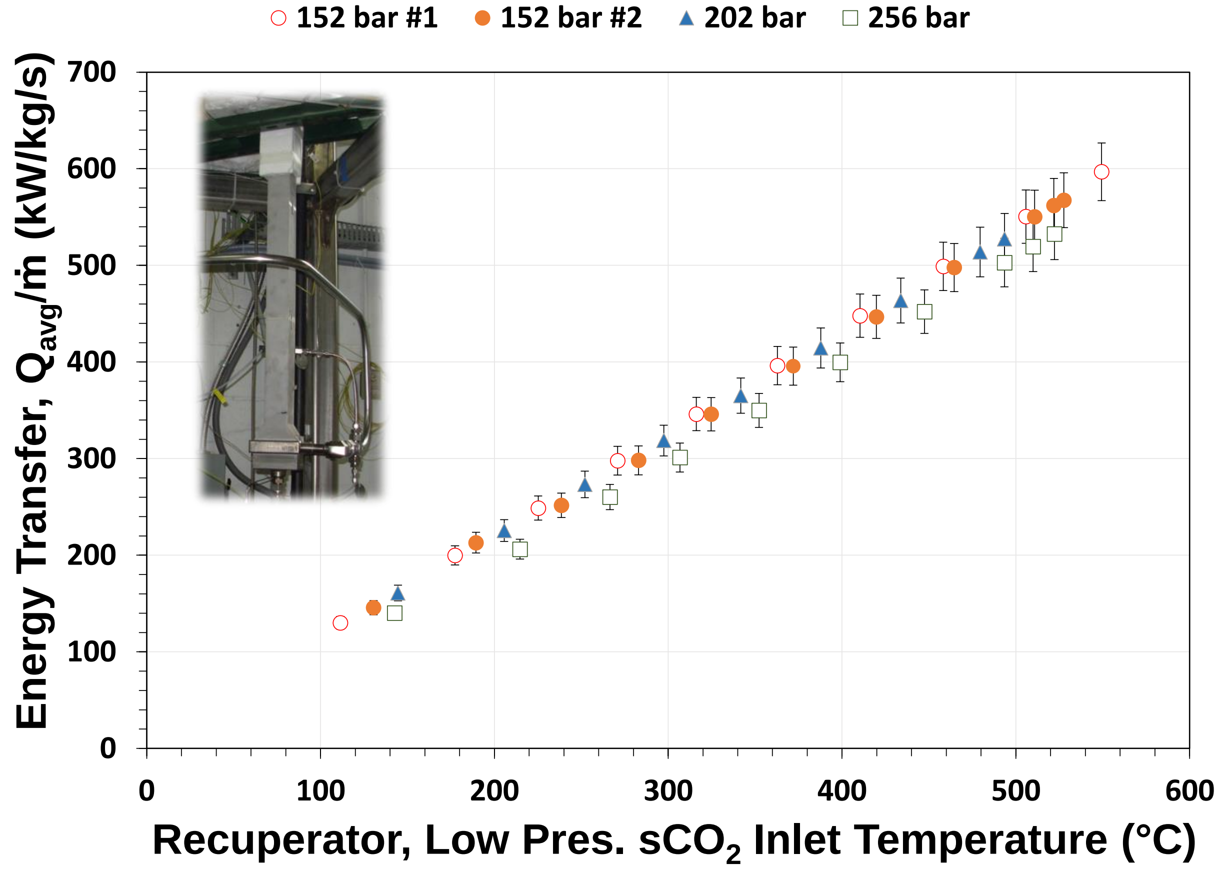
Energy Transfer Plots

SSHX Recuperator Prototypes

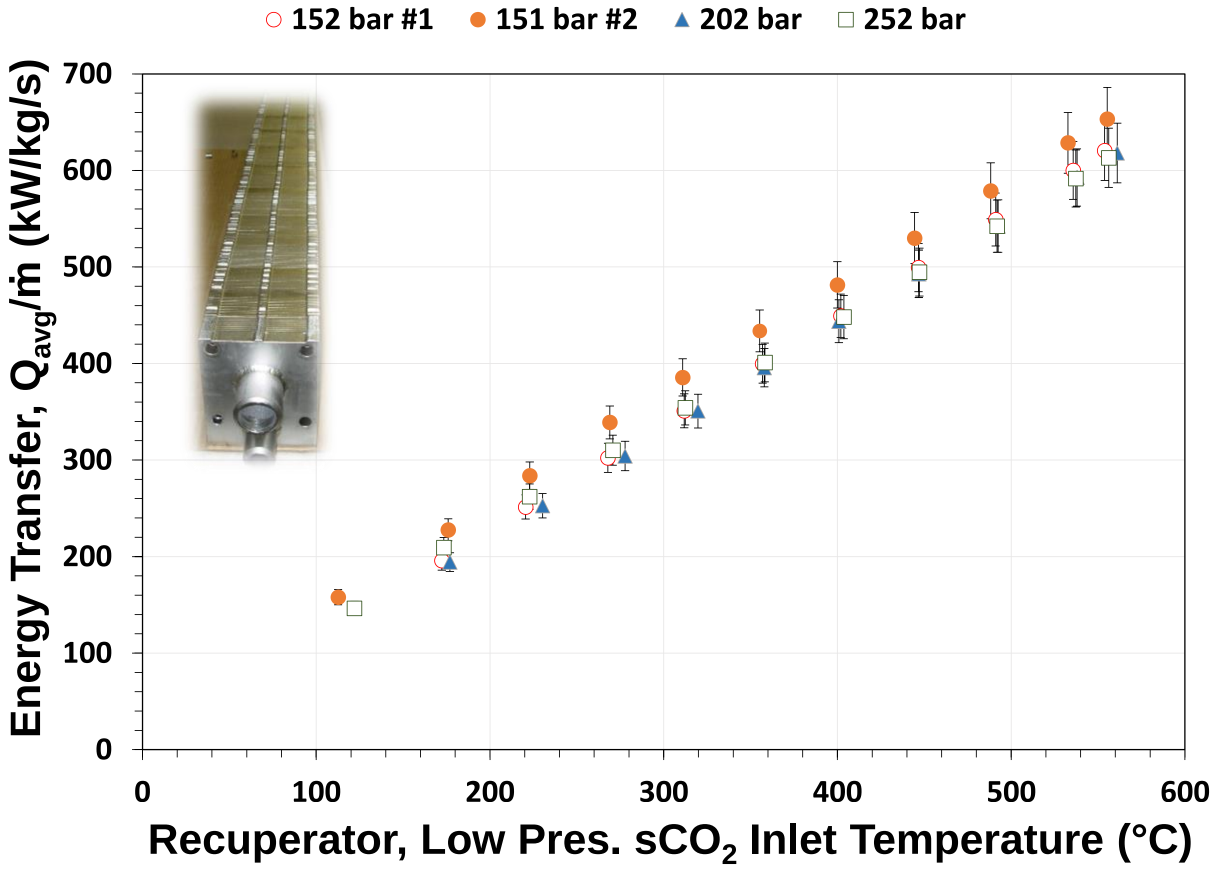
3D-SSHX

Inconel 625



Laser-SSHX

347H Stainless Steel

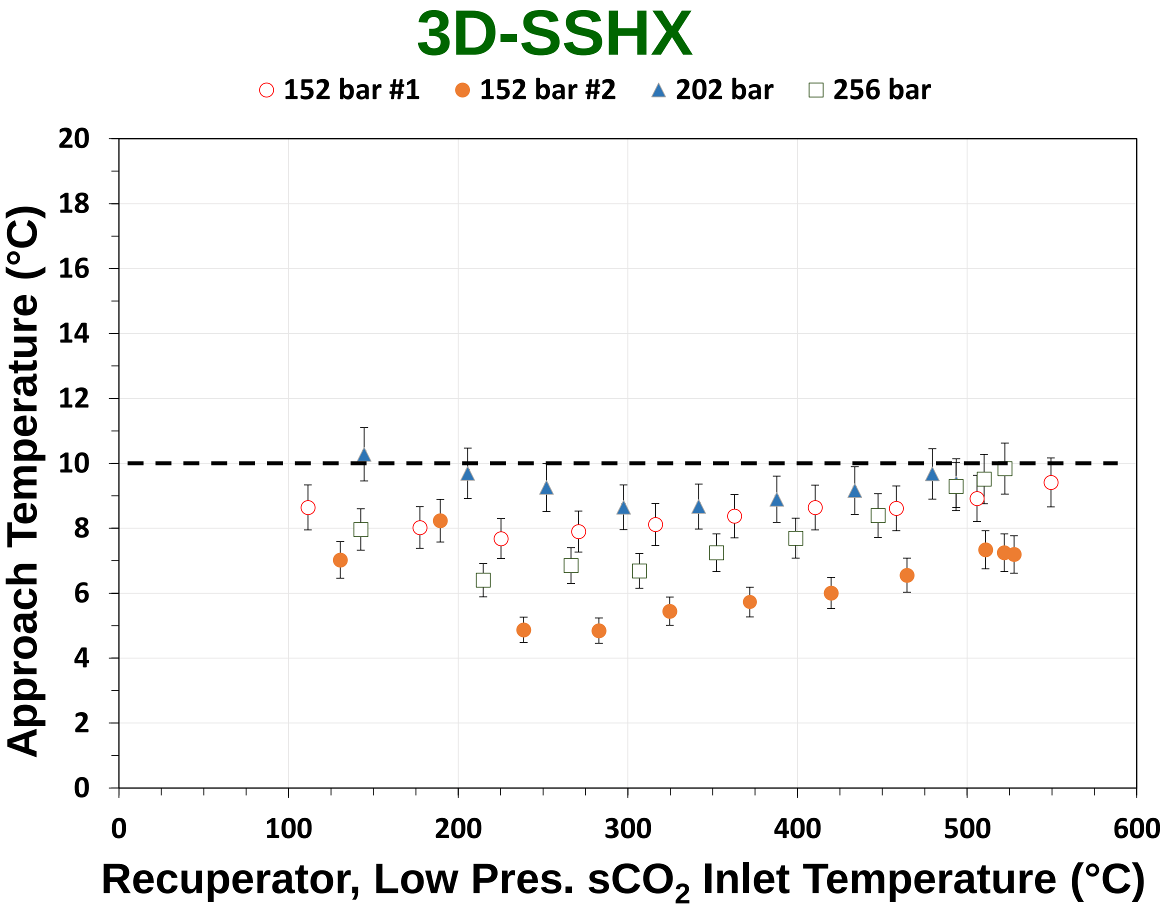


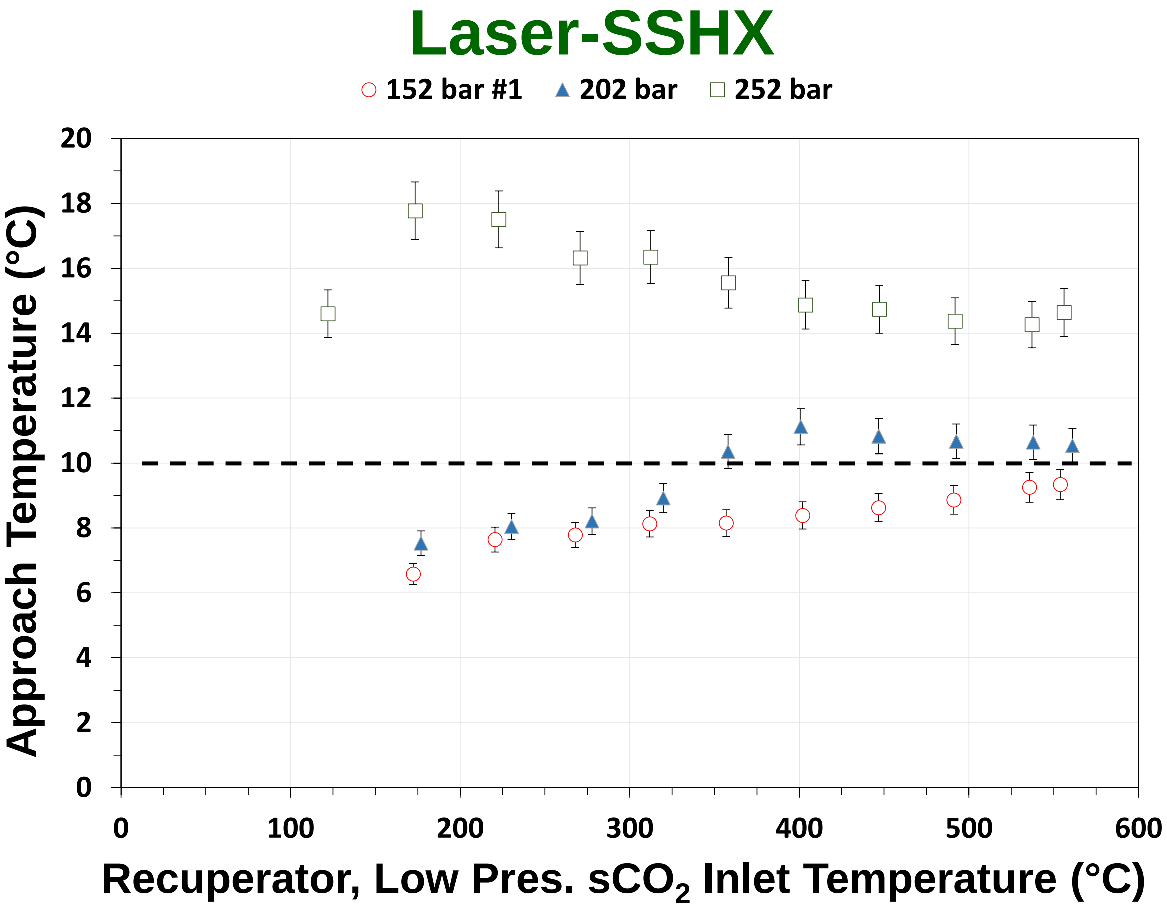
Linear Response

DE-FE0026273

Approach Temperature Plots

SSHX Recuperator Prototypes





Meets design specifications

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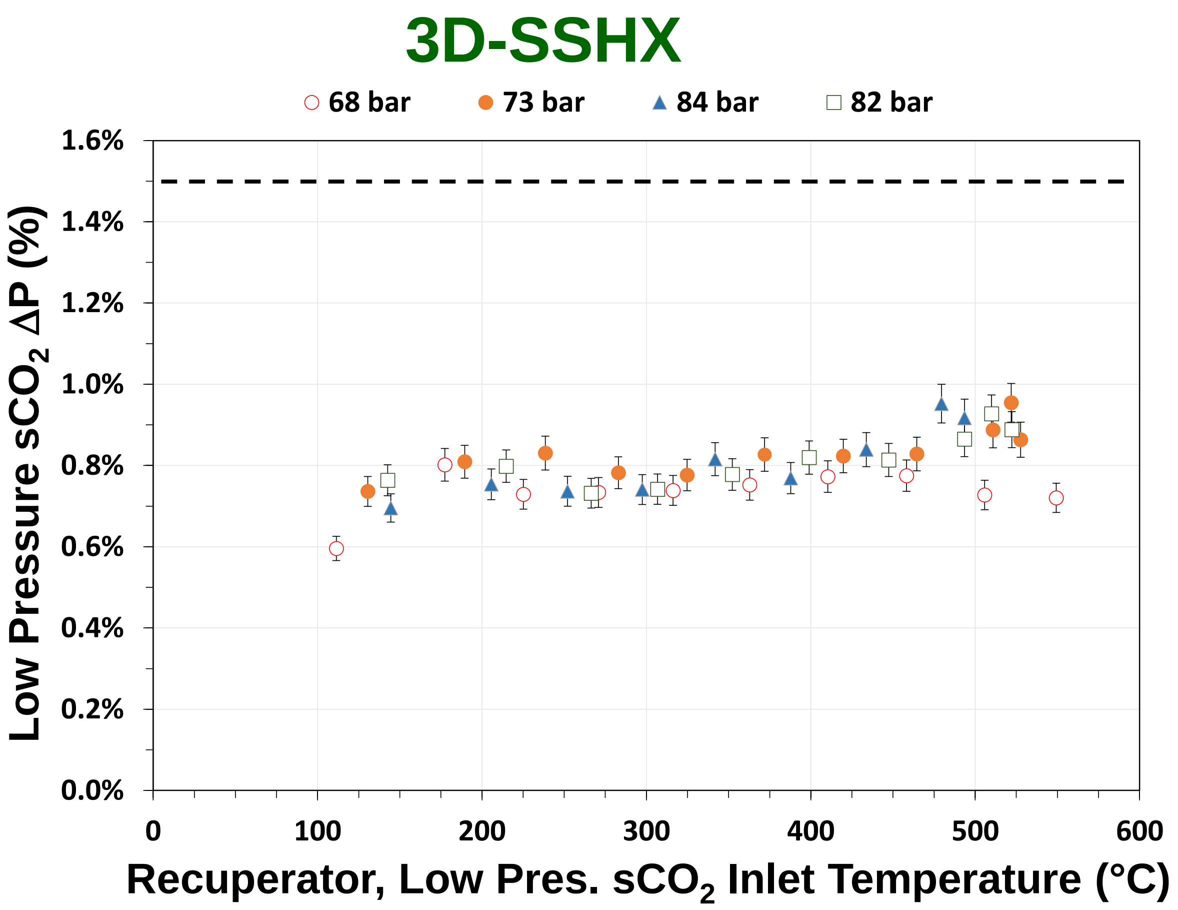
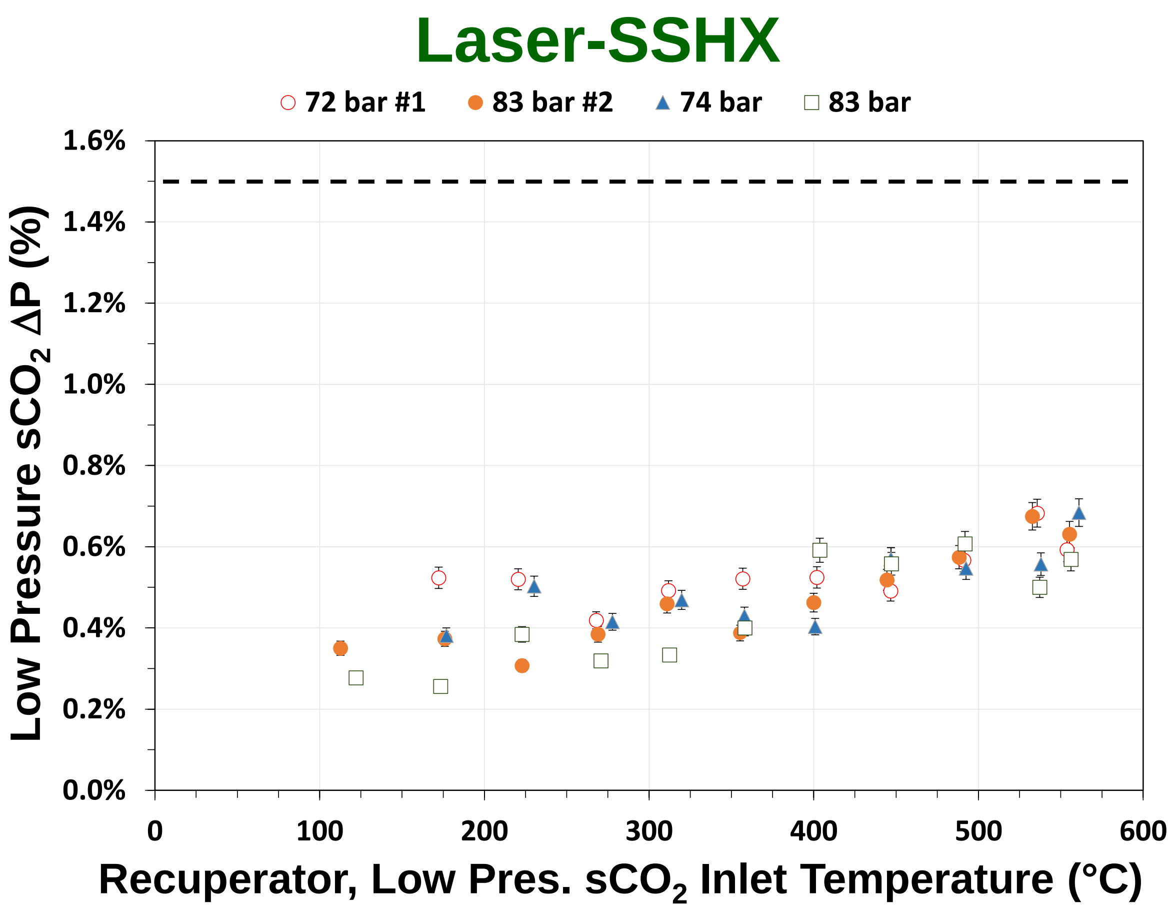
Lower Pressure sCO_2 ΔP Plots

SSHX Recuperator Prototypes





Meets design specifications

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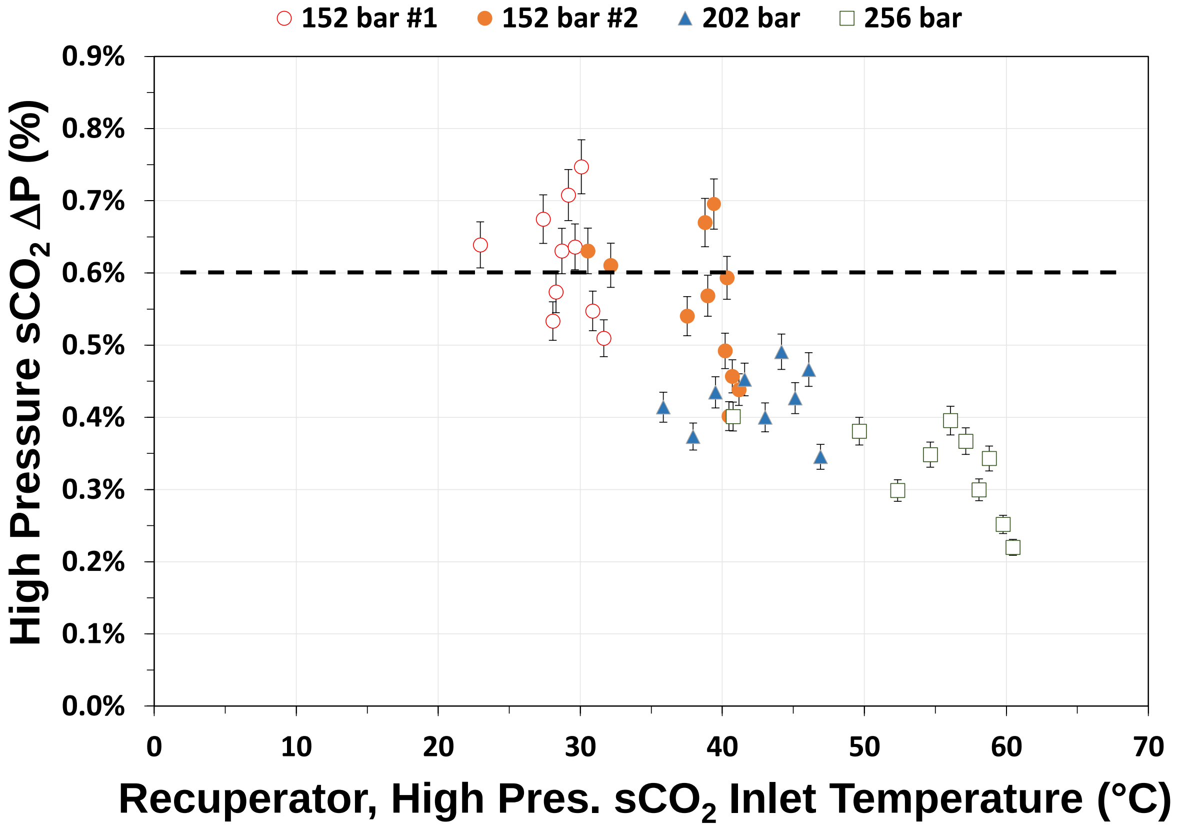
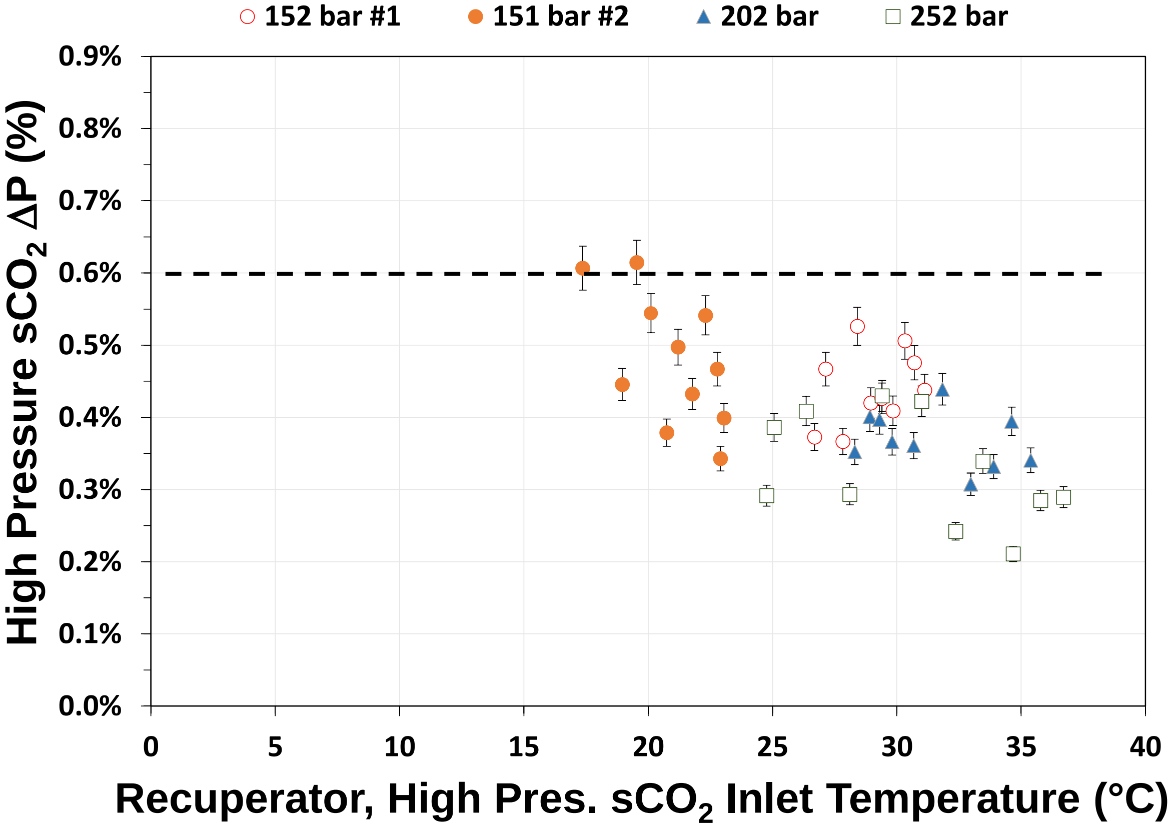
Higher Pressure sCO_2 ΔP Plots

SSHX Recuperator Prototypes

3D-SSHX



Laser-SSHX



Meets design specifications

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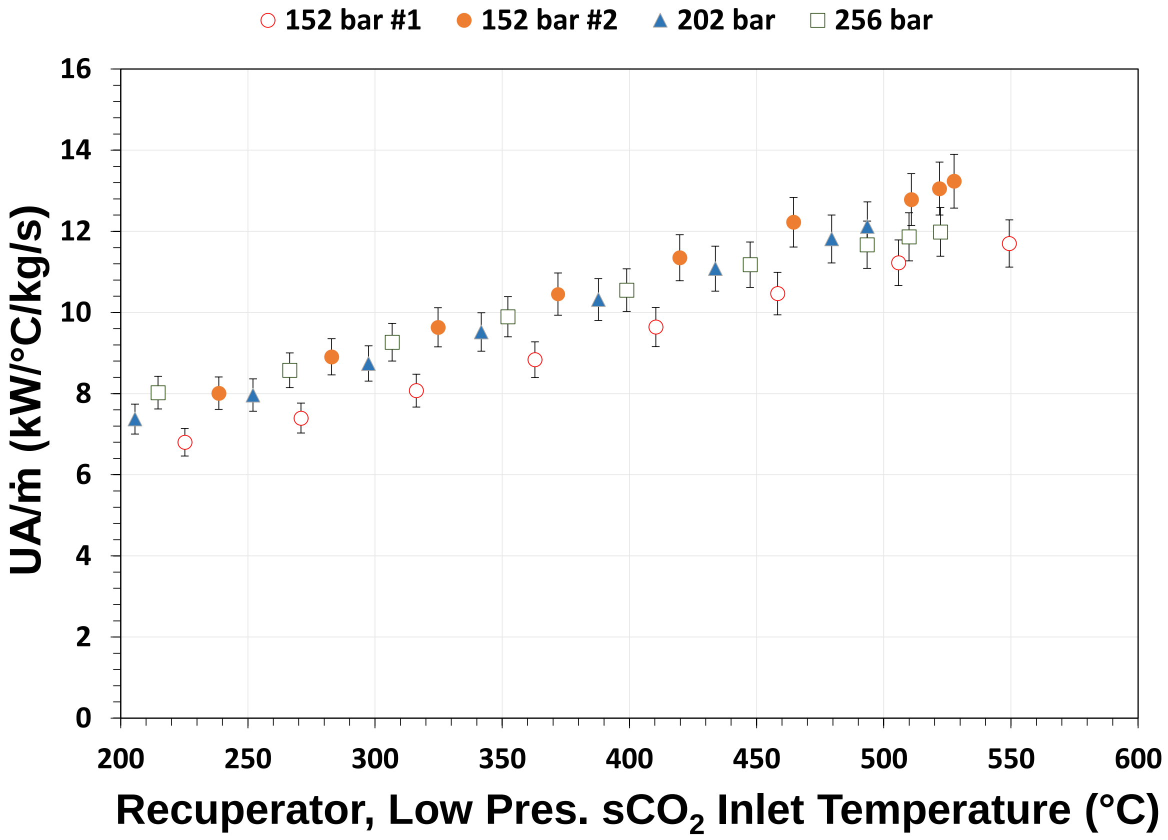
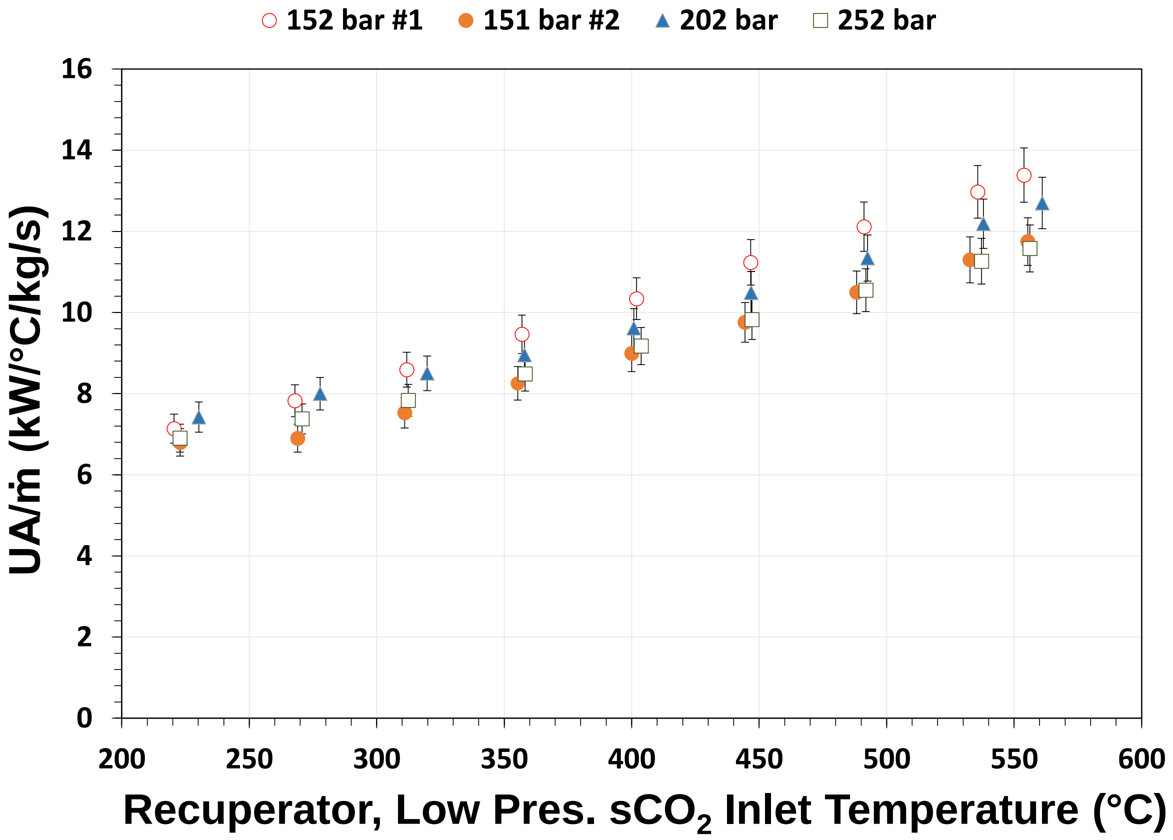
Heat Transfer (UA) Plots

SSHX Recuperator Prototypes

3D-SSHX



Laser-SSHX

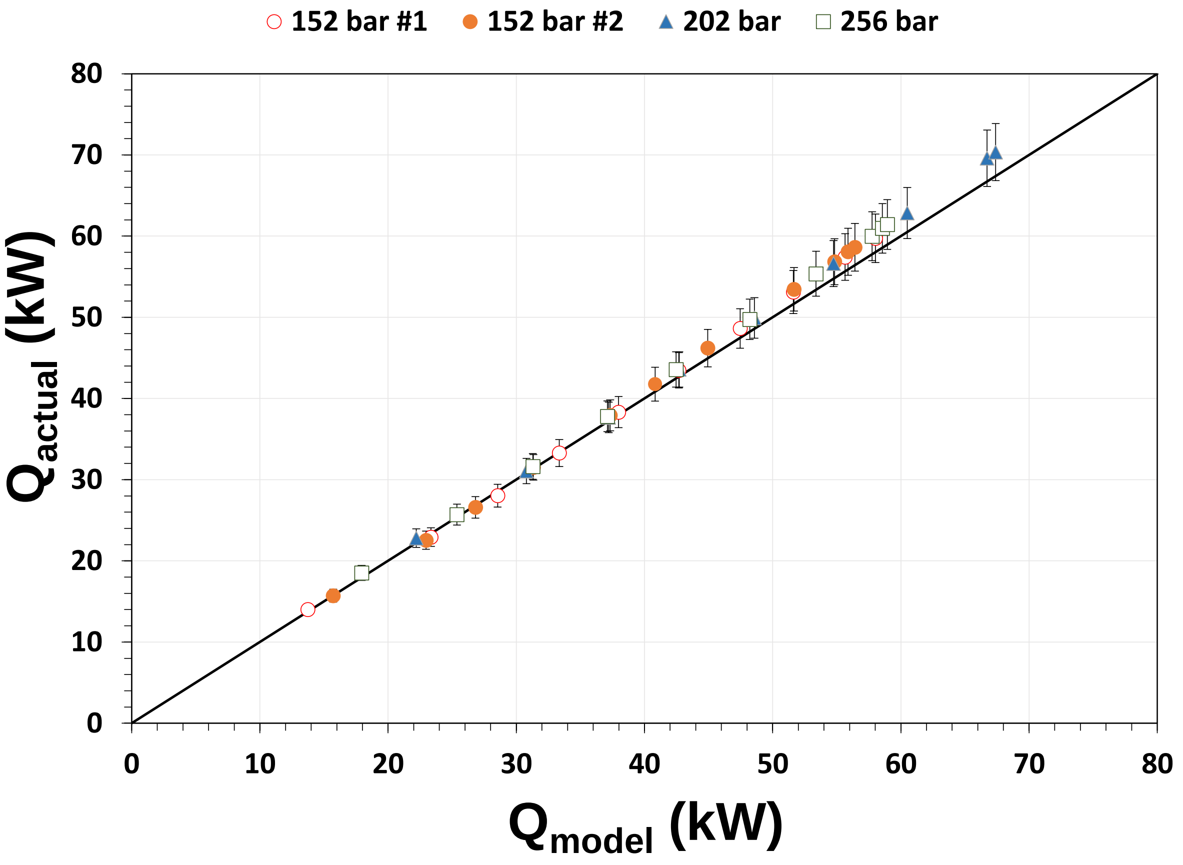


Linear Response

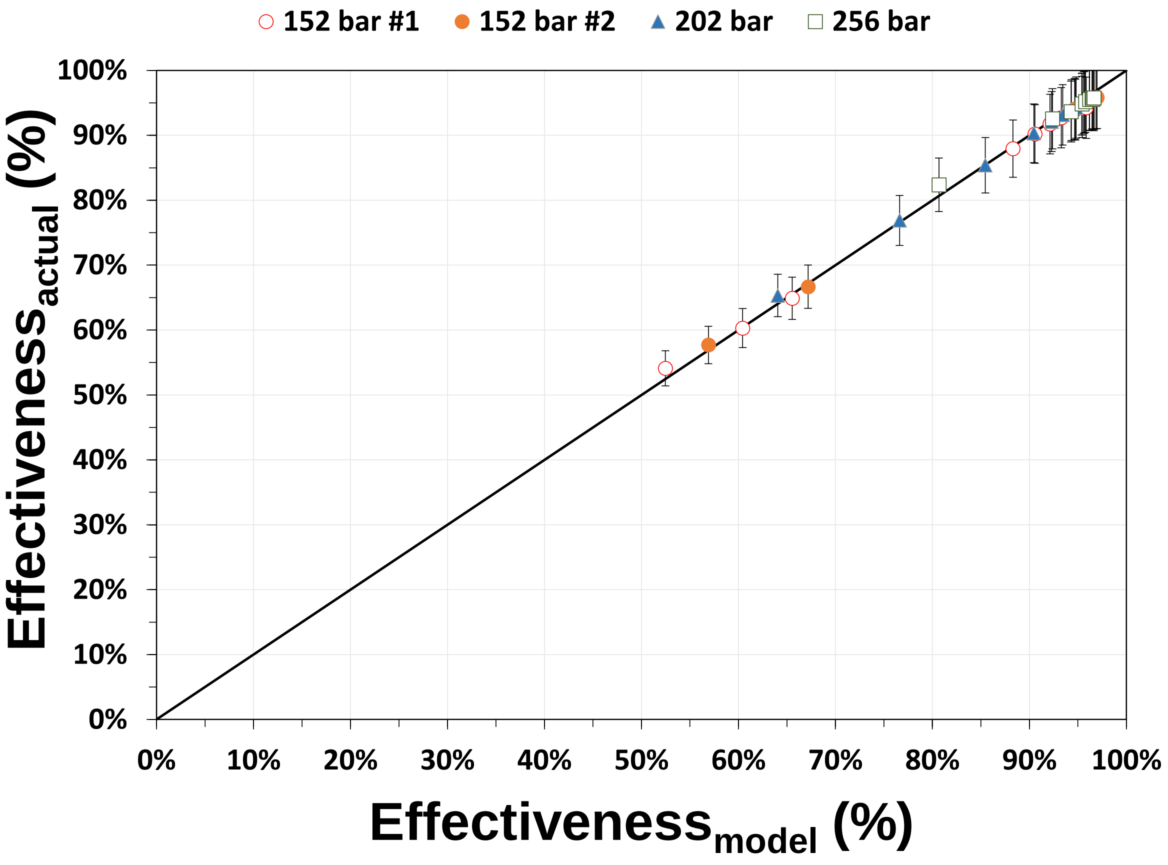
Good correlation between Design & Actual HX performance data

3D-SSHX

Transferred Energy, Q



Effectiveness, ϵ



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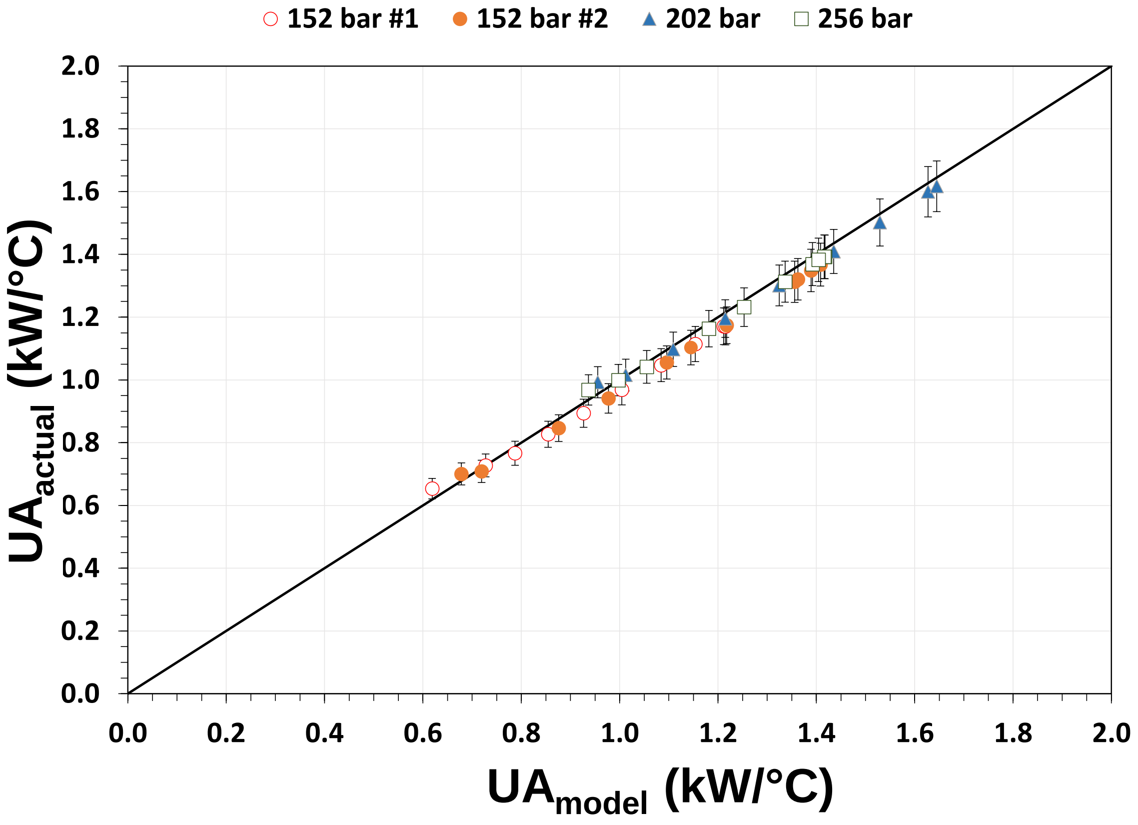
Data confirms SSHX Recuperator Performance

3D-SSHX

Heat Transfer Coefficient, UA



SSHX Recuperator meets or exceeds program requirements

Criteria	Updated - 8/16/16	3D-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	✓

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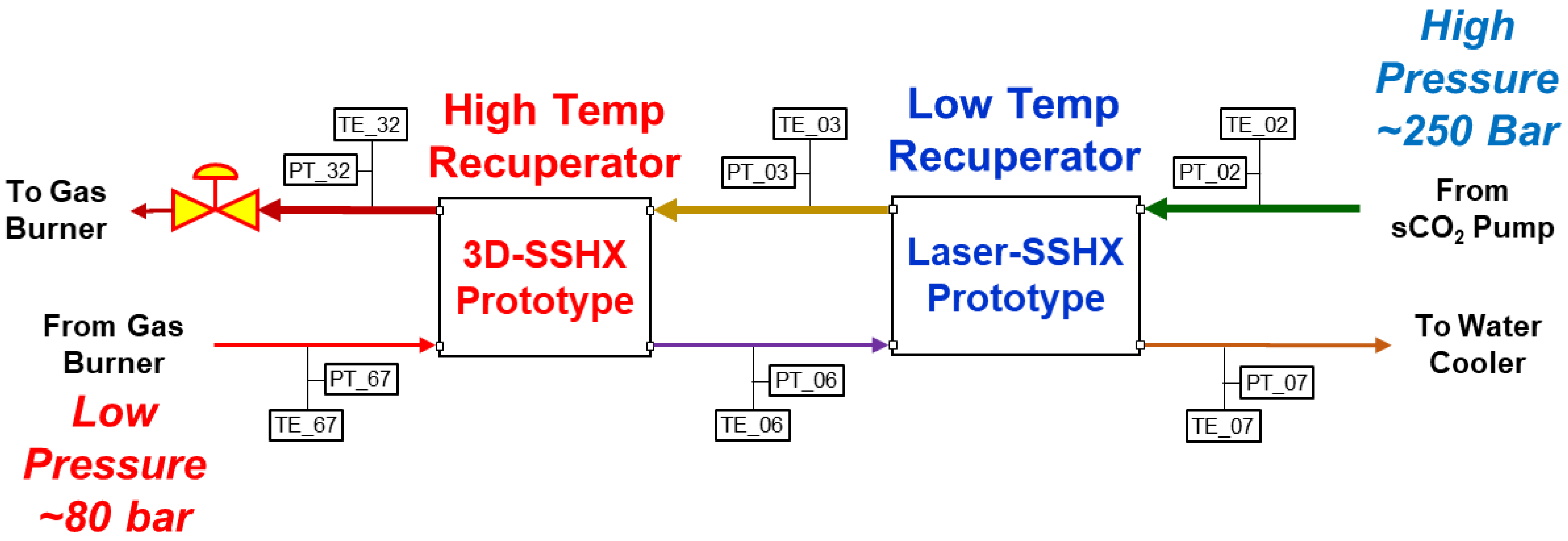
Reconfigured

sCO_2 Brayton Power Cycle Heat Exchanger Test Facility

- COMBO-SSHX: Laser-SSHX & 3D-SSHX piped in series
- Additional Temp. & Pres. sensors
- Higher Temperature BPR & PSV

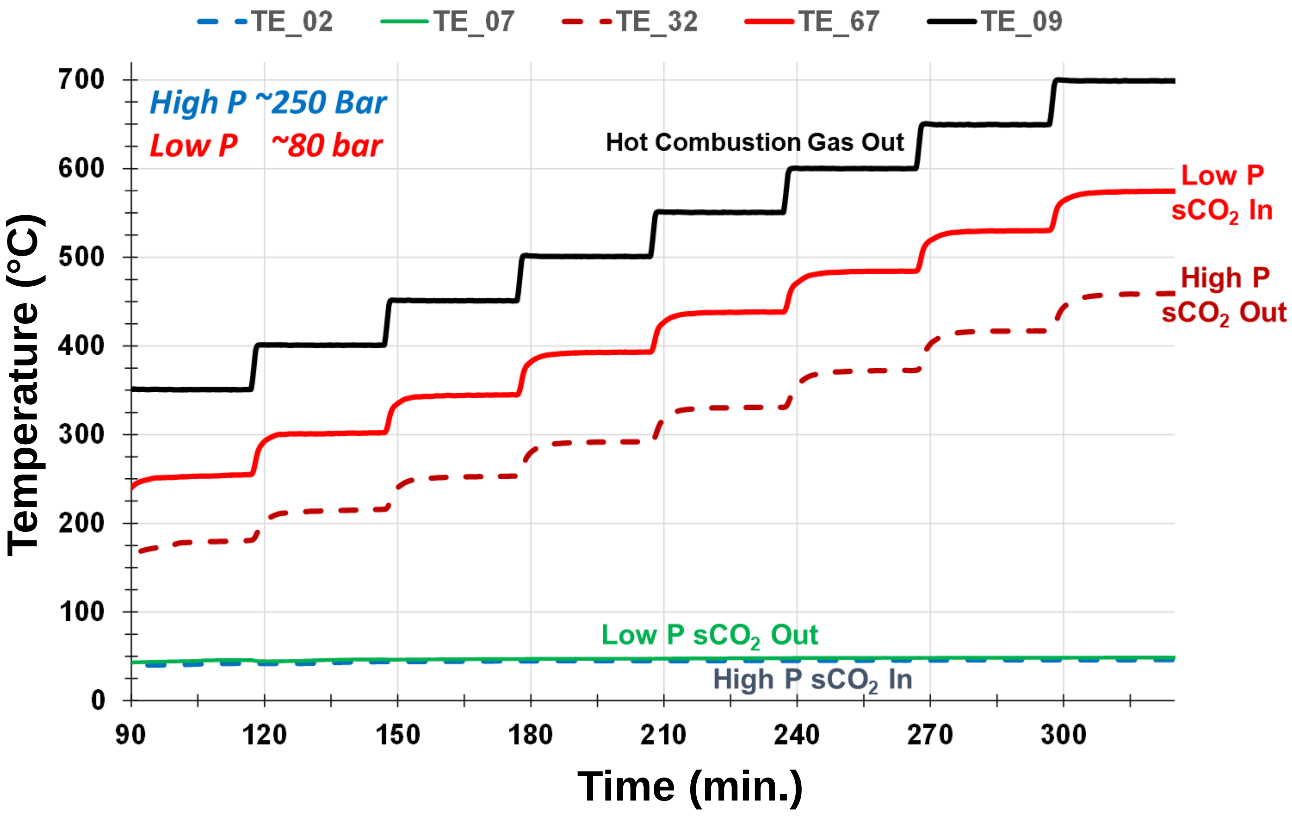


Test & Energy Balance Plots

COMBO-SSHX Recuperator

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

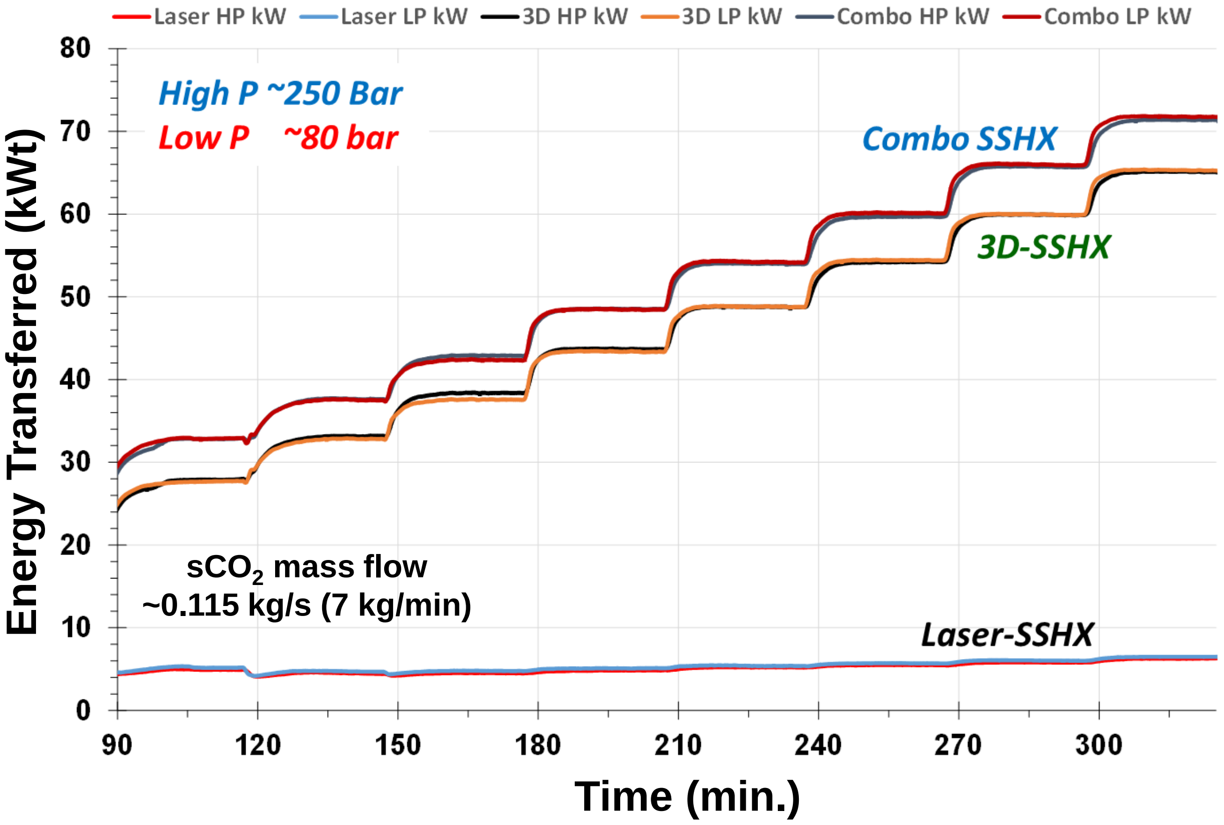
Combo-SSHX Time vs. Temperature Plot



Approach T: < 5°C

Effectiveness: > 98%

Energy Balance Plot



Good Energy Balance, < 2% error

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Summary

- Prototype recuperators have been designed, fabricated, and tested
  - 3D-SSHX
  - Laser-SSHX
  - Combo-SSHX: Laser-SSHX piped in series with the 3D-SSHX
- sCO_2 Heat Exchanger Test Loop has been *successfully operated* over range of operating conditions
- The SSHX recuperator concept *meets or exceeds* STEP cost and thermal/hydraulic performance criteria
  - Concept been scaled to 46 MWt thermal capacity, industrial scale
  - Modular/Factory Fabricated design incorporates compact size/cost
  - *Potential for future enhancements*
- Focus: Demonstrate robust SSHX manufacturing at the MWt scale

Thank you for your kind attention

Questions?

Work supported by US DOE under DE-FE0026273
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