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

Design, Fabrication and Testing of Novel Compact Recuperators for the Supercritical Carbon Dioxide Brayton Power Cycle

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Work supported by US DOE NETL: DE-FE0026273

Paper #175

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Outline

- Introduction to Thar Energy
- Stacked-Sheet Heat Exchanger (SSHX)
  - Concept & Design Criteria
  - 3D printed SSHX (3D-SSHX)
  - Laser cut SSHX (Laser-SSHX)
- sCO_2 Heat Exchanger Test Facility
- SSHX Test Data
- Summary

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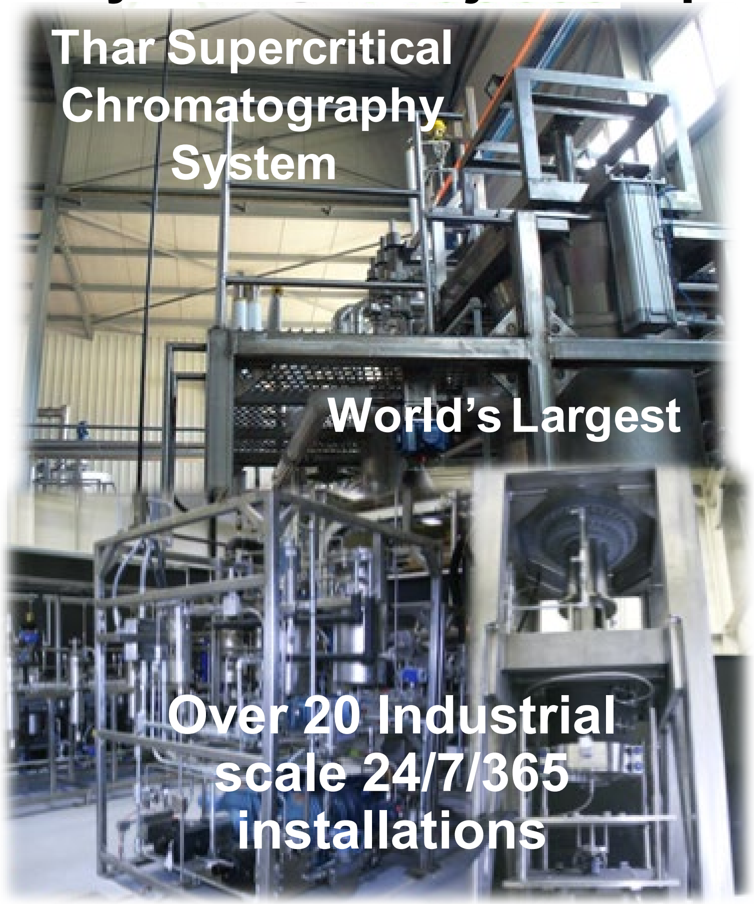
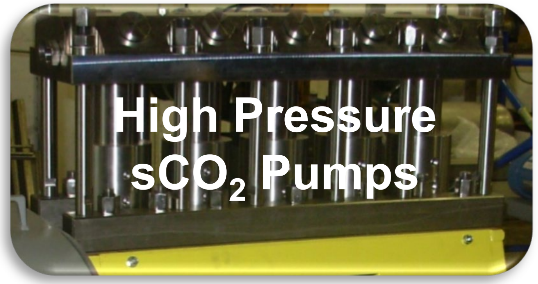
The Thar Brand - Over 30 years of Innovation with "Green" Supercritical Fluid Technologies

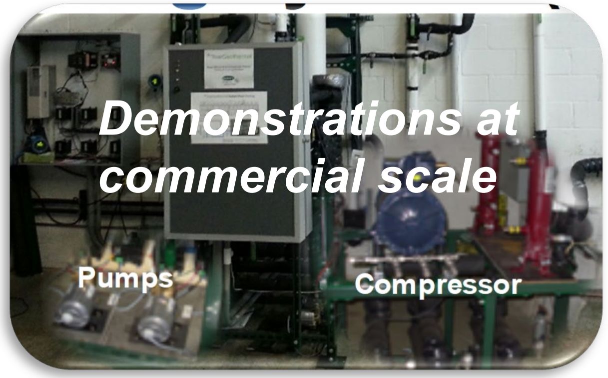
Design and commercialization of supercritical systems & major components

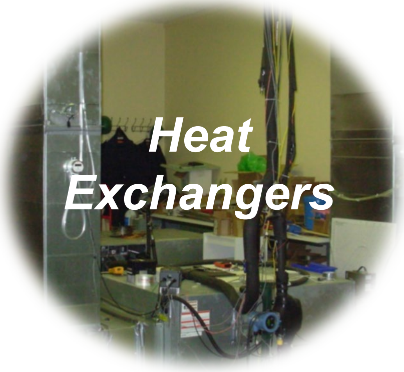




Over 5,000 scientific instruments installed

Direct Exchange, R744 (CO_2) Geothermal Heating & Cooling





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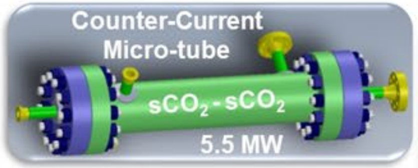
Timeline (recent past)

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

Gas Cooler
Air-sCO_2

2014 **2015** **2016** **2017**

TharProcess

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

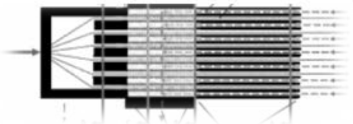
Expands into Liquid Chromatography

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

Thar Pharmaceuticals sold to GRUNENTHAL

UNITED STATES PATENT AND TRADEMARK OFFICE

Patent - Notice of Allowance
Counter Current Heat Exchanger/Reactor



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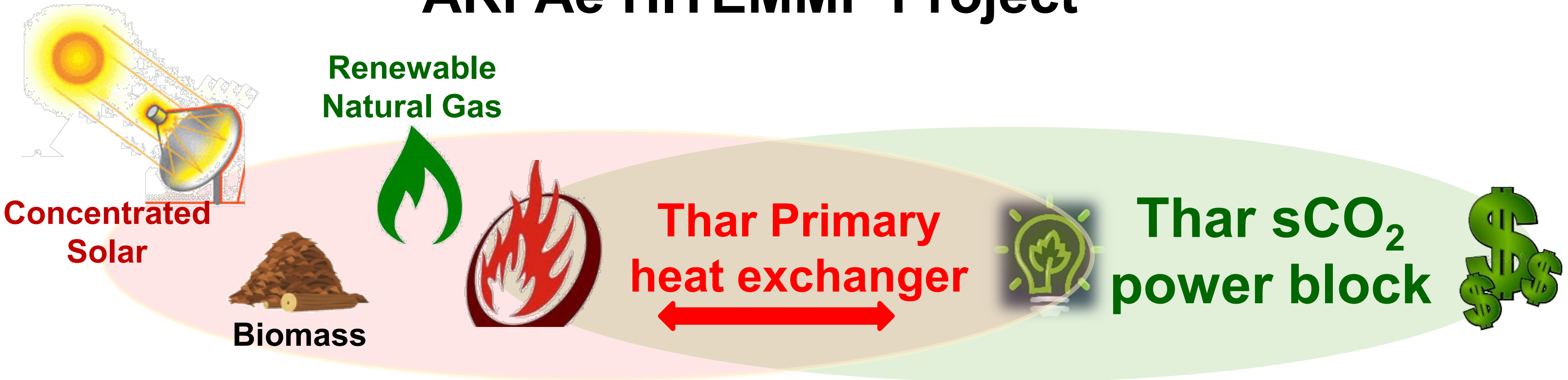
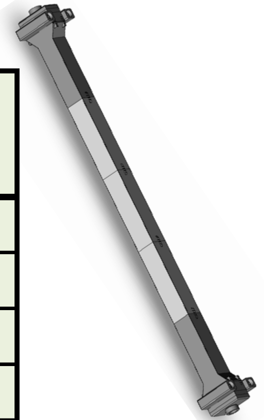
ARPAe HITEMMP Project



You bring the heat! We provide the power!

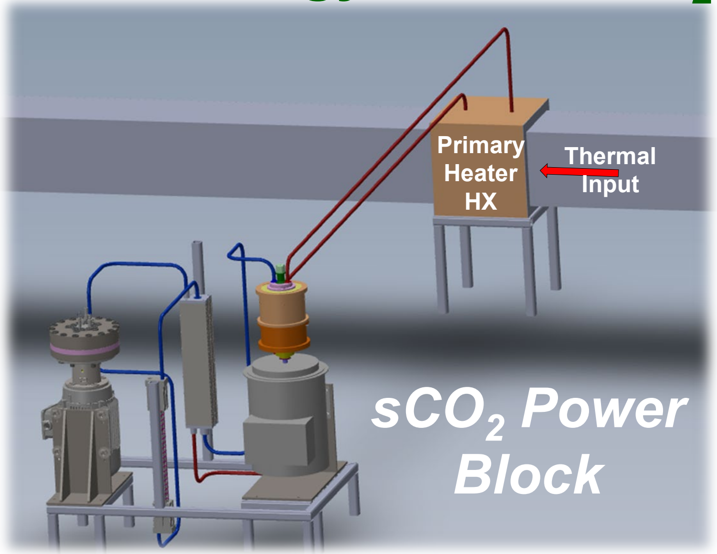
> 800°C Recuperator

Criteria	ARPA-E Category A Target	Thar Project Goals
Thermal Effectiveness	≥ 80%	**> 90%**
Temperature Limit	≥ 800°C	**> 800°C**
Low Pressure	≥ 80 bar	**≥ 80 bar**
High Pressure	≥ 250 bar	**≥ 300 bar**
Pressure Loss	$\Delta P_h < 2\%$	**$\Delta P_h < 2\%$**
	$\Delta P_c < 2\%$	**$\Delta P_c < 2\%$**
Cost	$2000/UA	**< $100/UA**



Haynes 282
γ' strengthened Nickel Super-alloys

Thar Energy's CHP sCO_2 Power Block



- ***Efficient***
  - Elec Efficiency: >45%
  - CHP Efficiency: >70%
- ***Modular & compact***
- ***Low cost of ownership***
- ***Reduced environmental impact***

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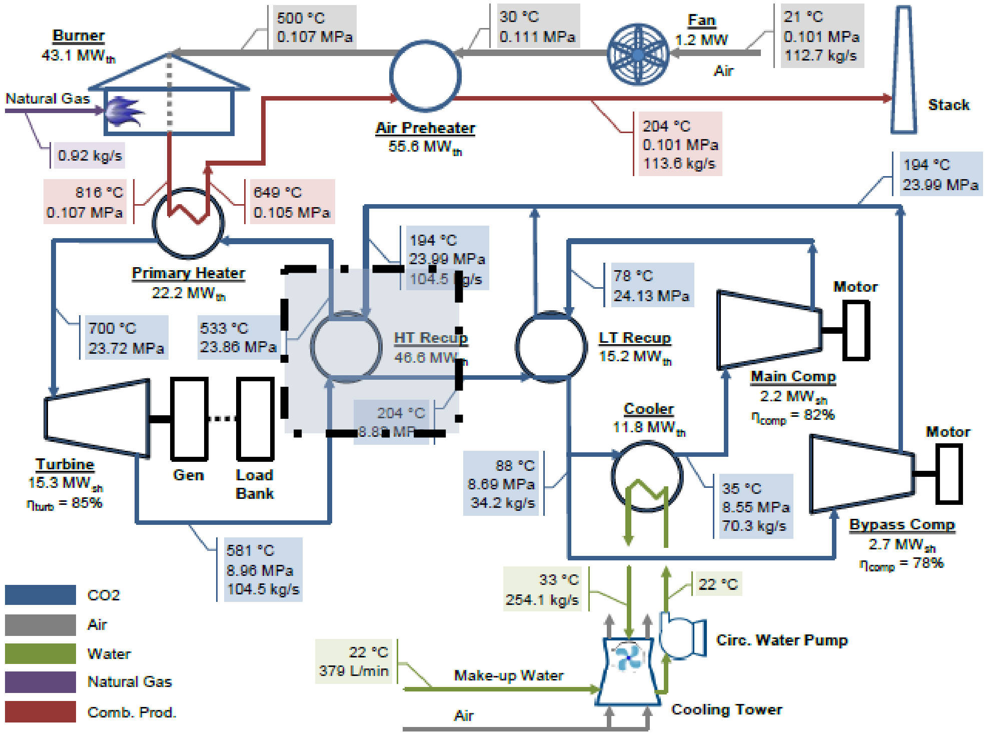
High Temperature Recuperator Design Criteria



STEP Conditions (2016)*

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

* Weiland, N, Updated Supercritical Transformational Electric Power (STEP) Cycle Conditions, NETL project communications, August 2016

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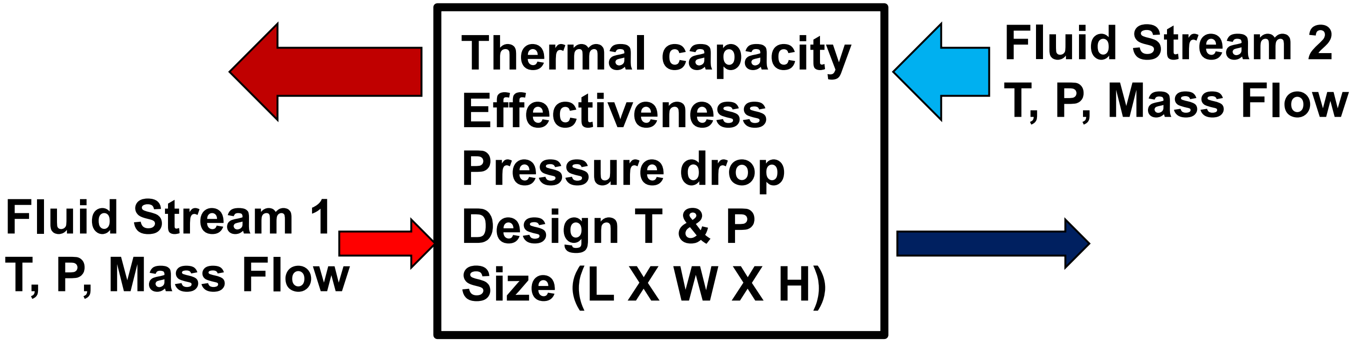
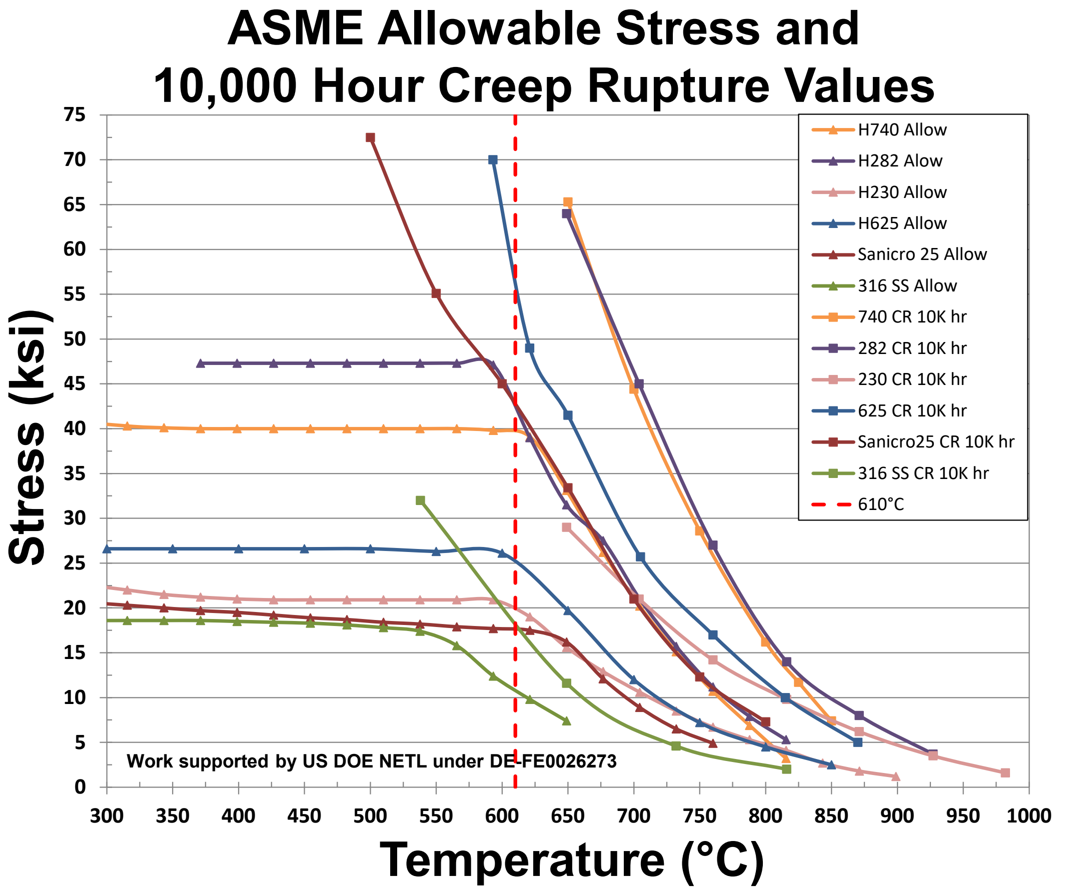
Recuperator Design





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

Design T ↑ $ ↑

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

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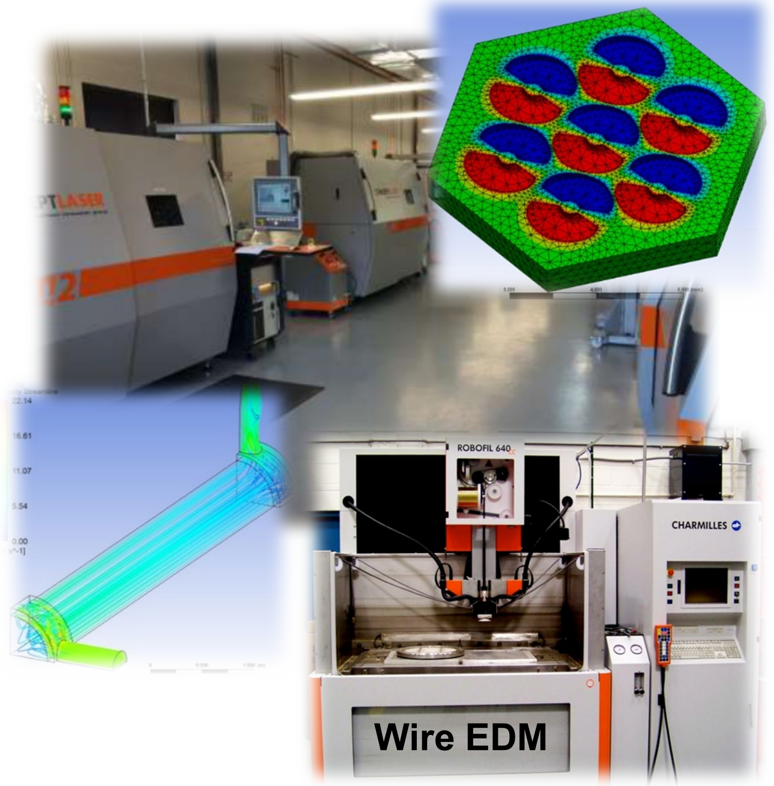
HTR Recuperator Concepts

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



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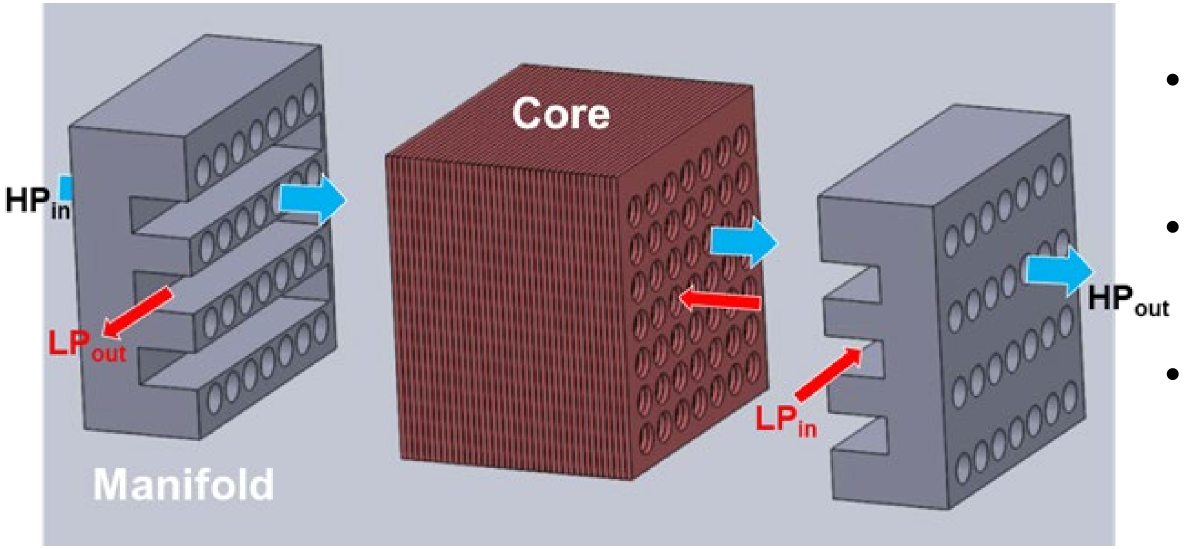
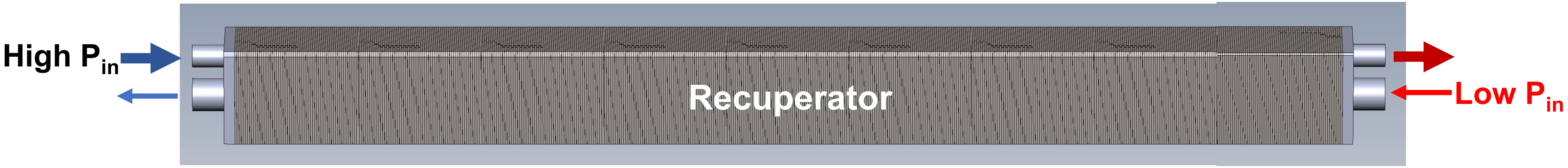
Thar's Stacked Sheet Heat Exchanger (SSHX) Recuperator Concept



- 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

<u>Accommodates advances in Subtractive and/or Additive Manufacturing</u>



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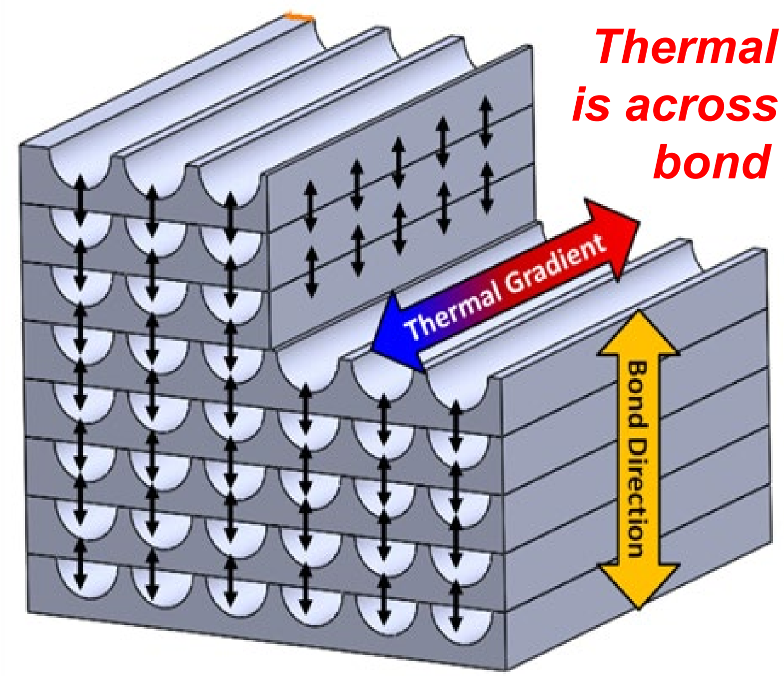
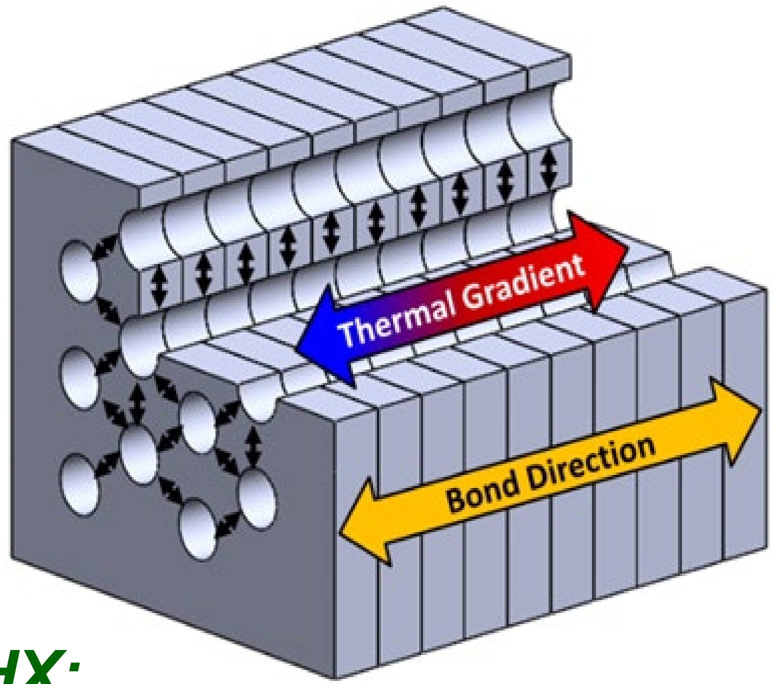
Mechanical & Thermal Stress Analysis - Printed-Circuit HX vs. SSHX



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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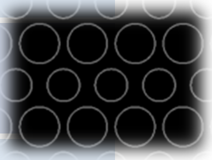
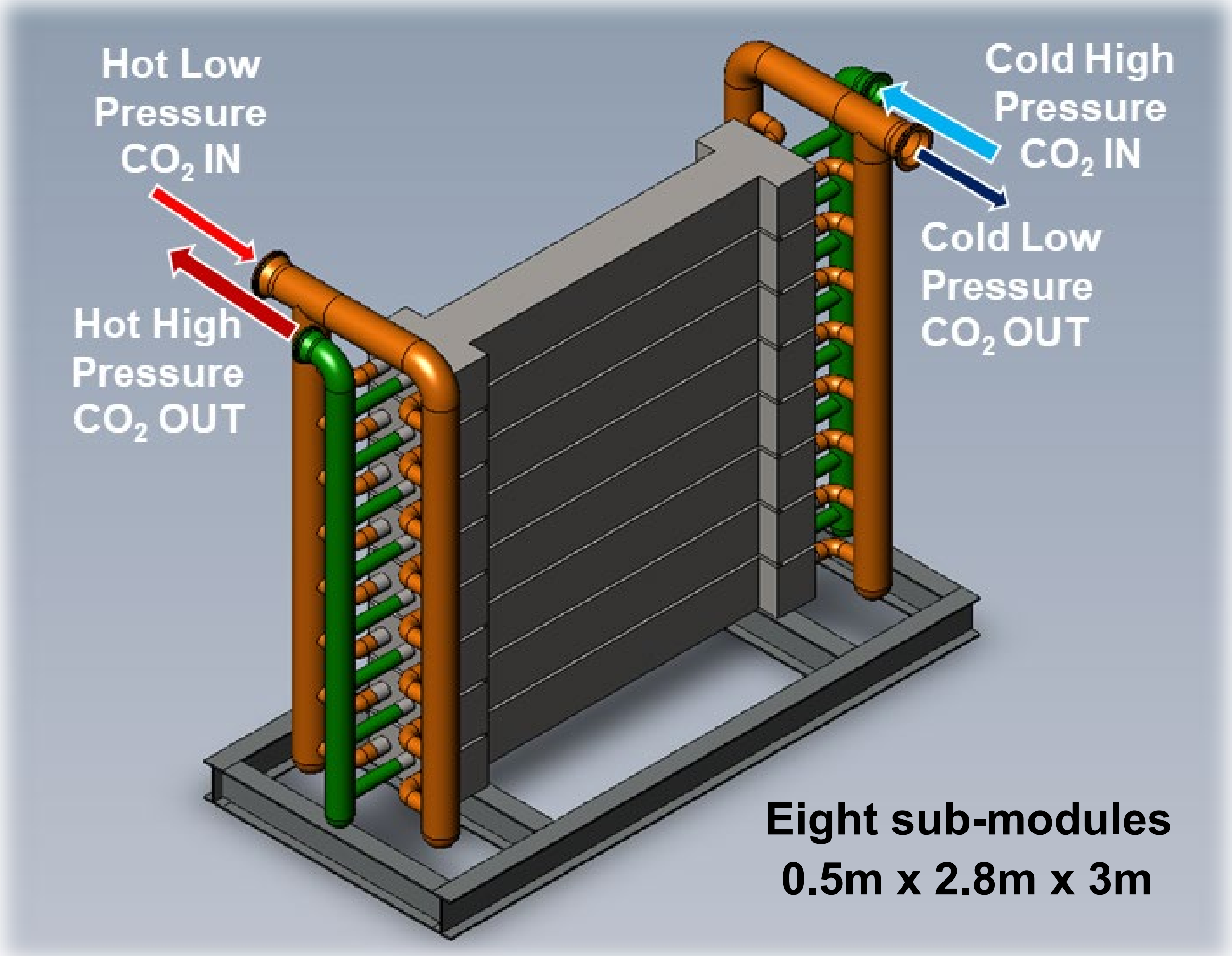
Prototype Recuperators

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%

Both methods passed hydro-tests

46 MWt Laser-SSHX Recuperator

Parallel Modular Design, Factory Fabricated



3D-SSHX 57% volume decrease

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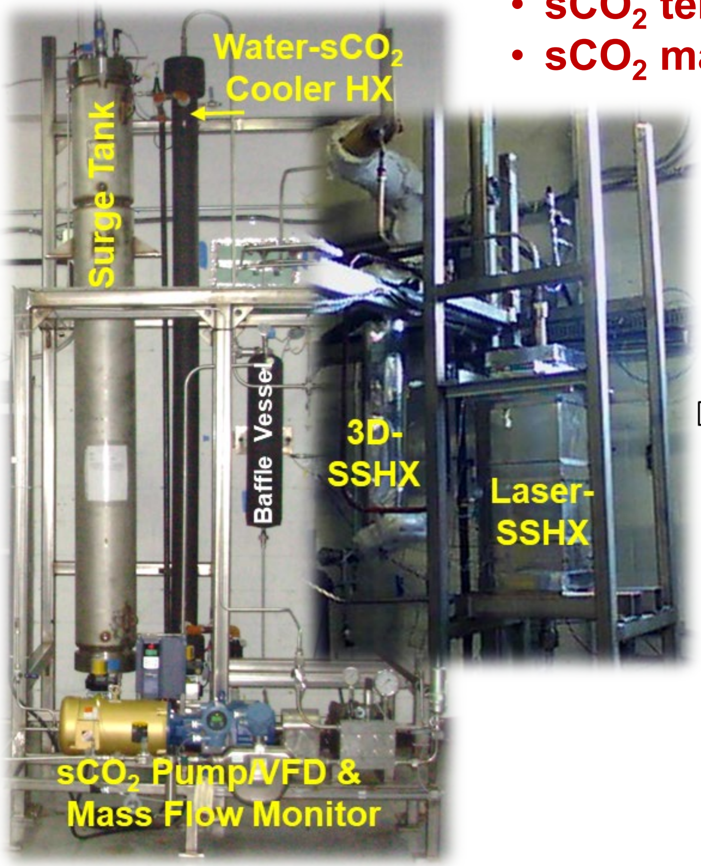
sCO_2 Brayton Power Cycle Heat Exchanger Test Facility

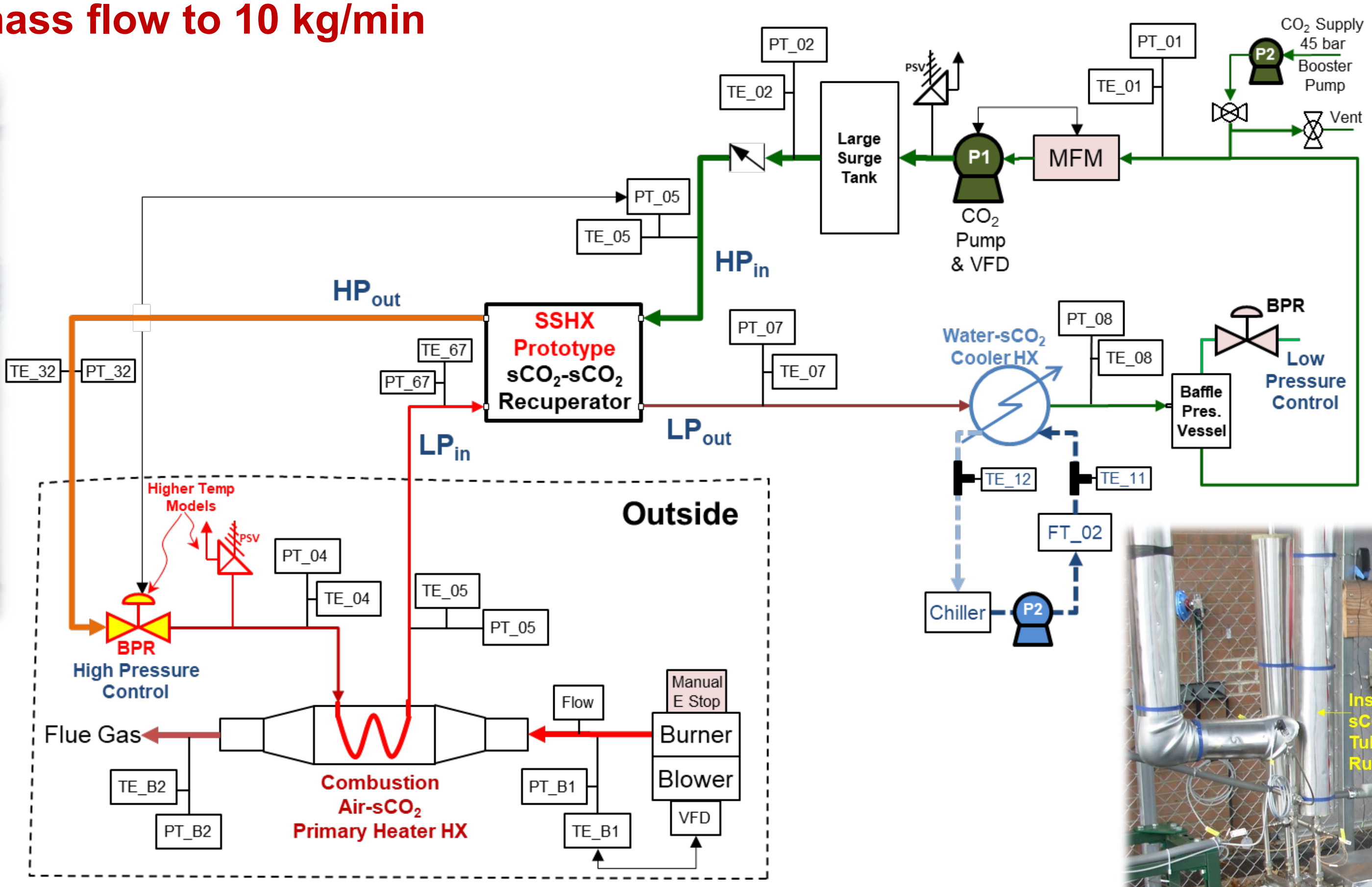
Reconfigurable Test Loop

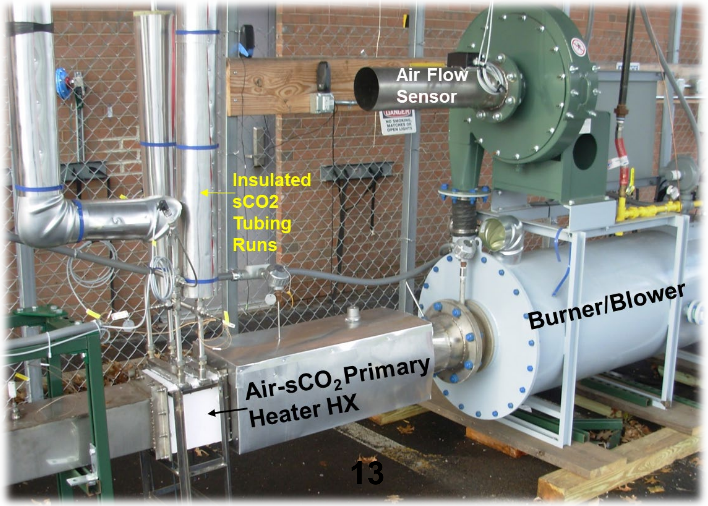
- sCO_2 pressures to 275 bar
- sCO_2 temperature to 700°C
- sCO_2 mass flow to 10 kg/min

Simple Recuperated Cycle

High temperature valve in place of expander







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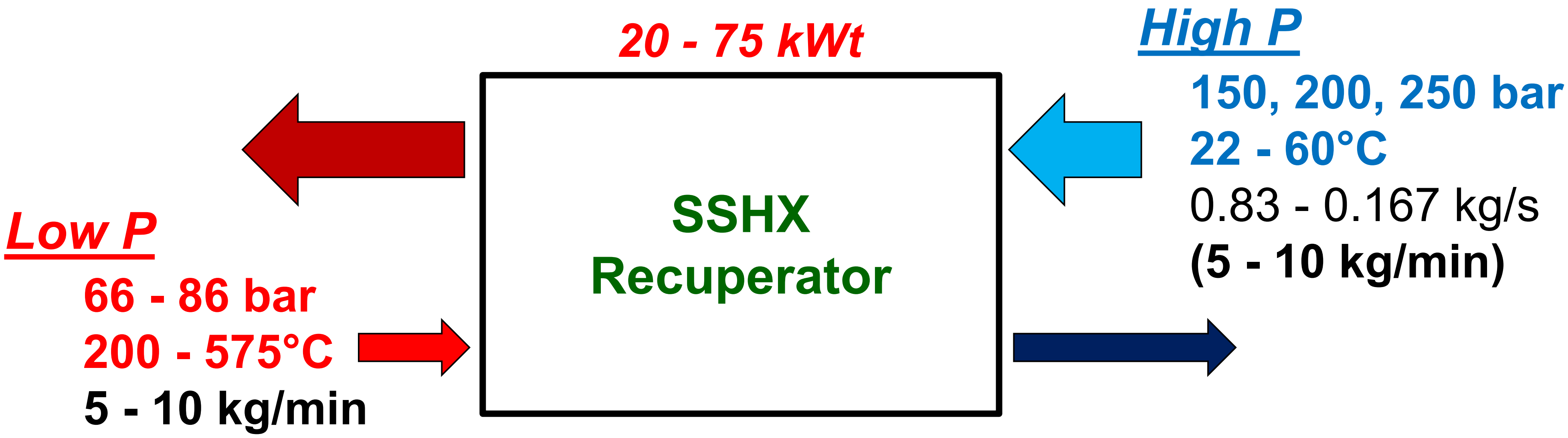
Test Conditions - SSHX Recuperator Prototypes



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

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)

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

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)

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

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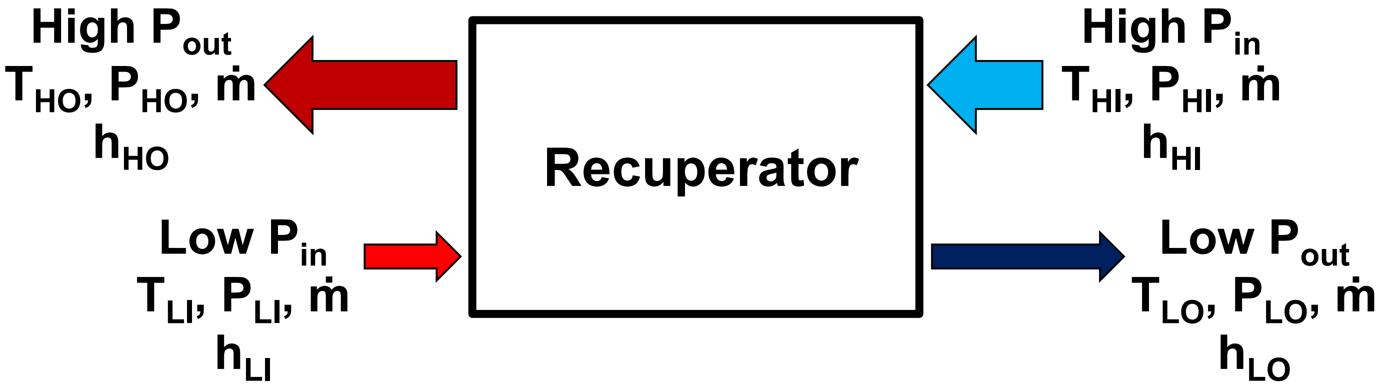
HX Performance Heat Transfer Equations



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

Q_{act} = 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} = 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 = $T_{LO} - T_{HI}$

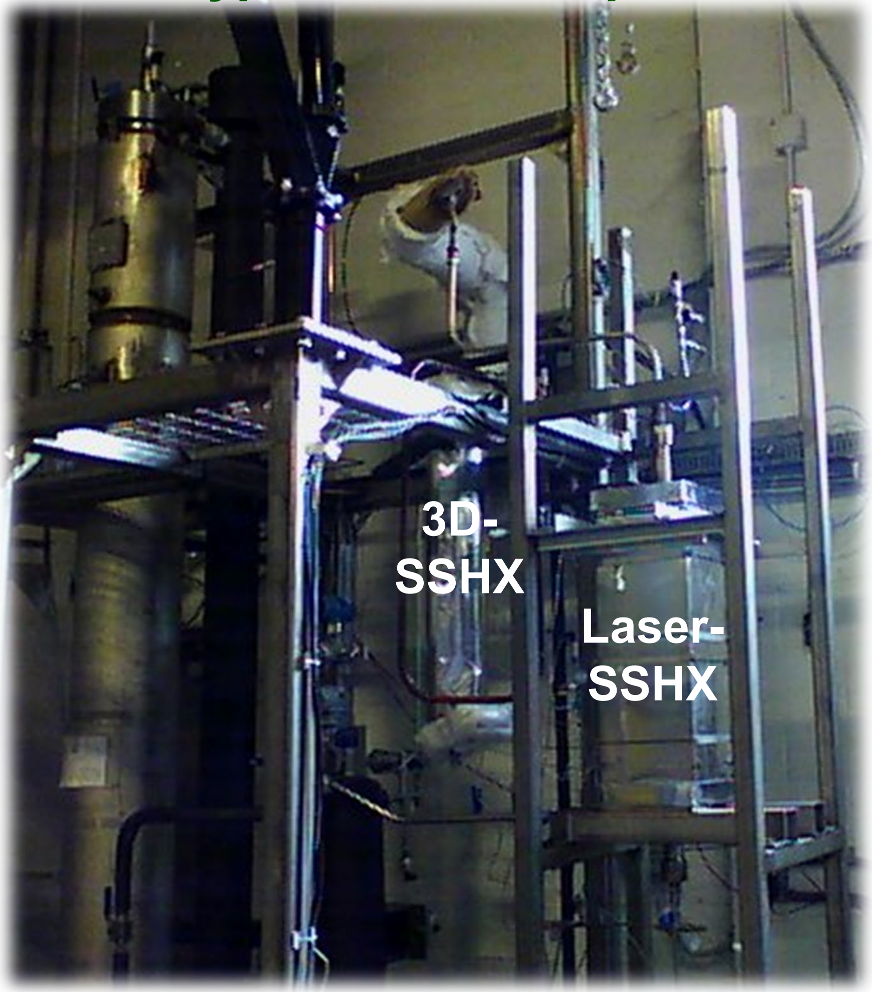
% Pressure Drop

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

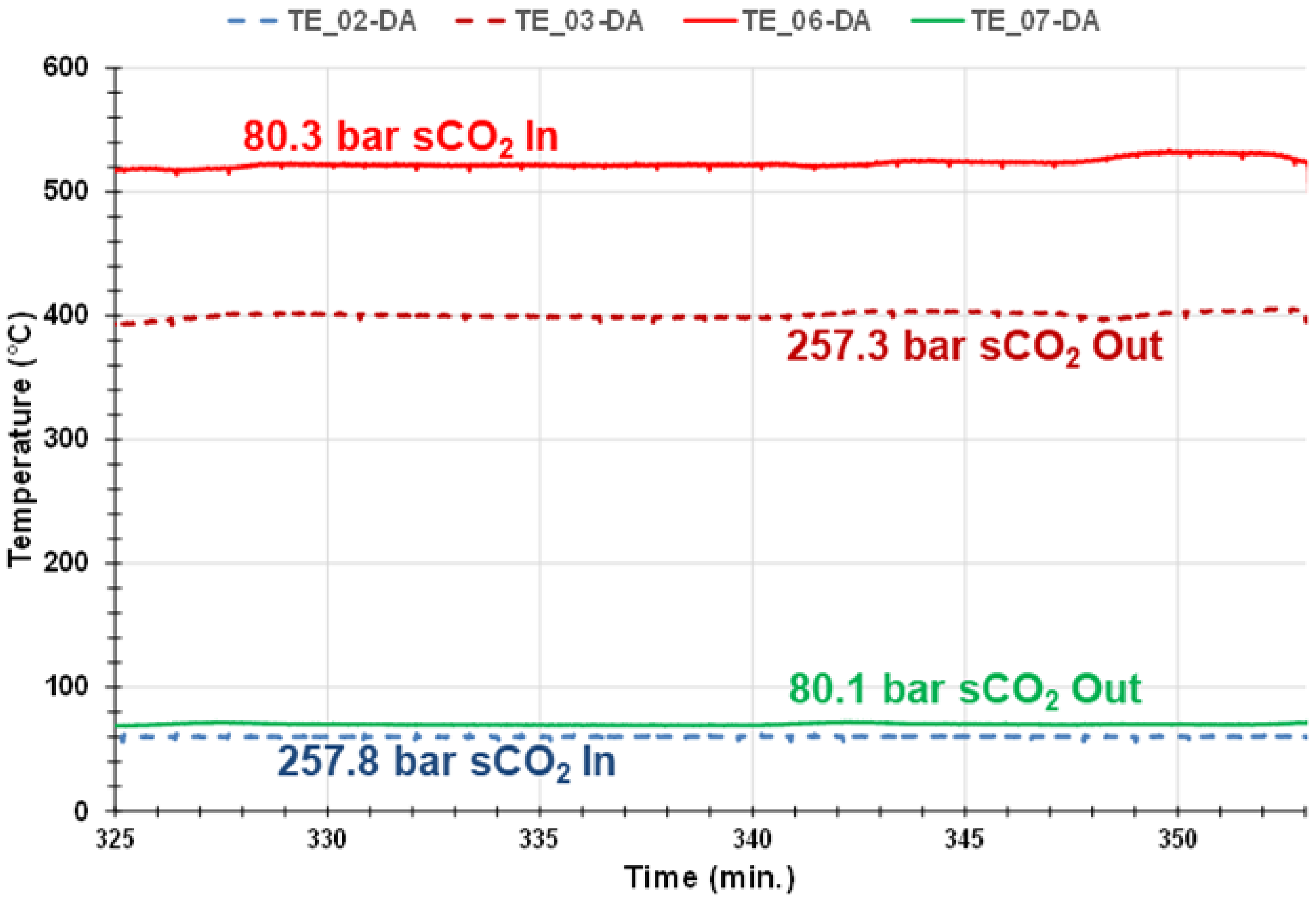
R. K. Shah and D. P. Sekulic, Fundamentals of Heat Exchanger Design, John Wiley & Sons, Inc., 2003

Steady State Time vs. Temperature Plot

Prototype SSHX Recuperators

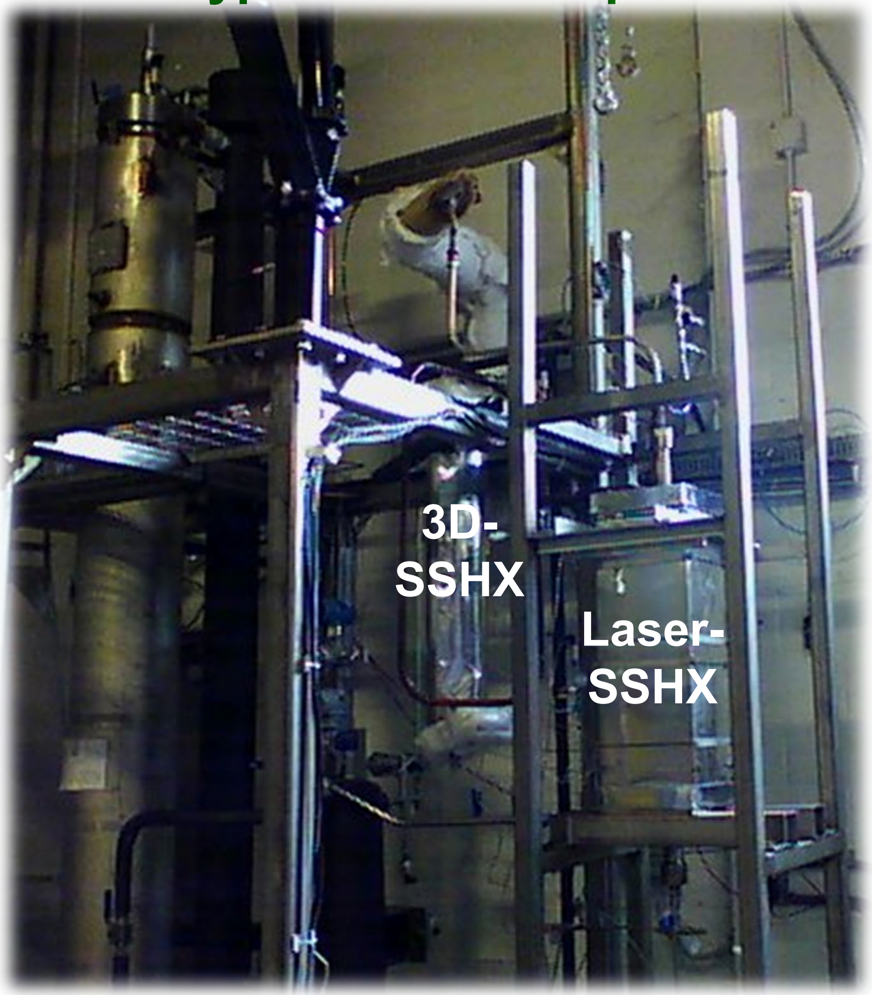


3D-SSHX – Steady State Plot

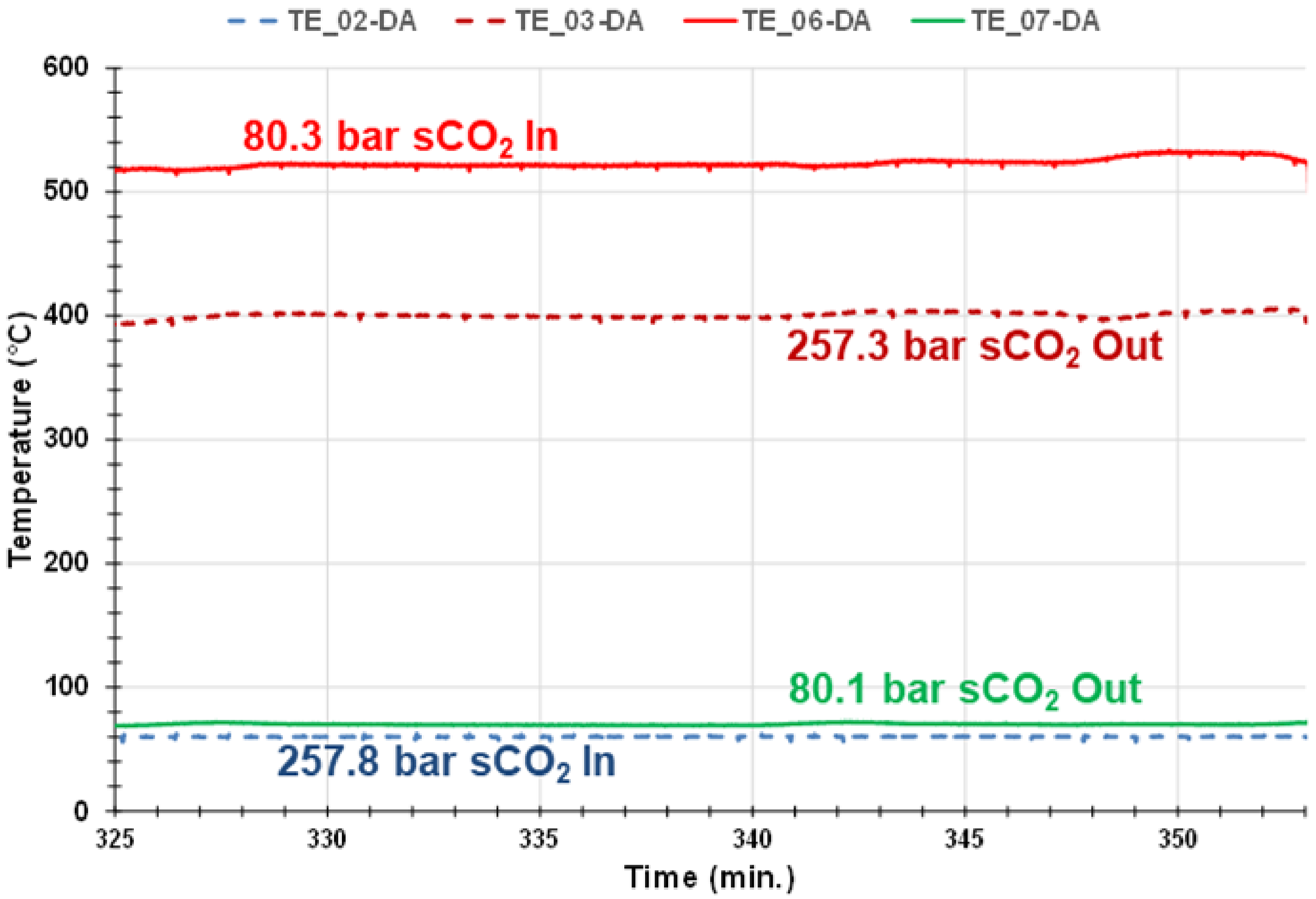


Steady State Time vs. Temperature Plot

Prototype SSHX Recuperators



3D-SSHX – Steady State Plot



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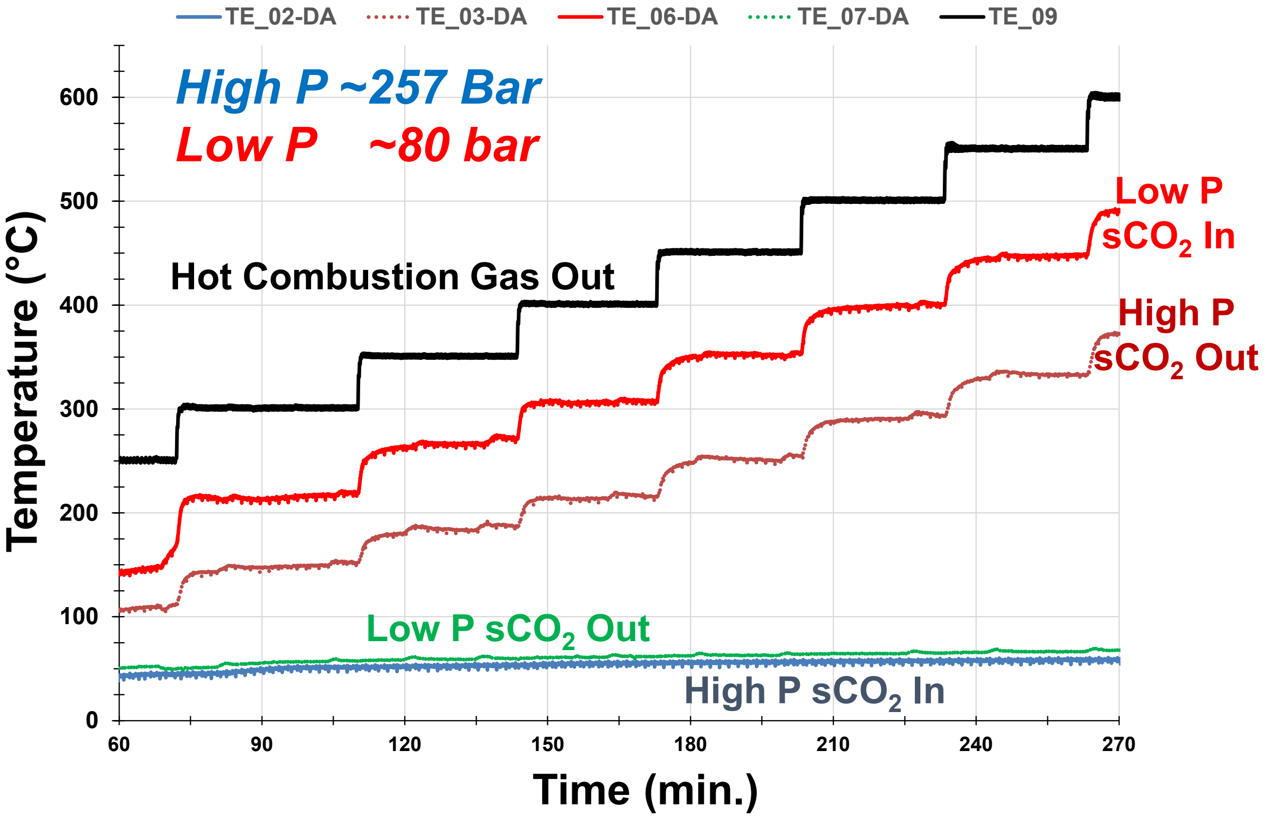
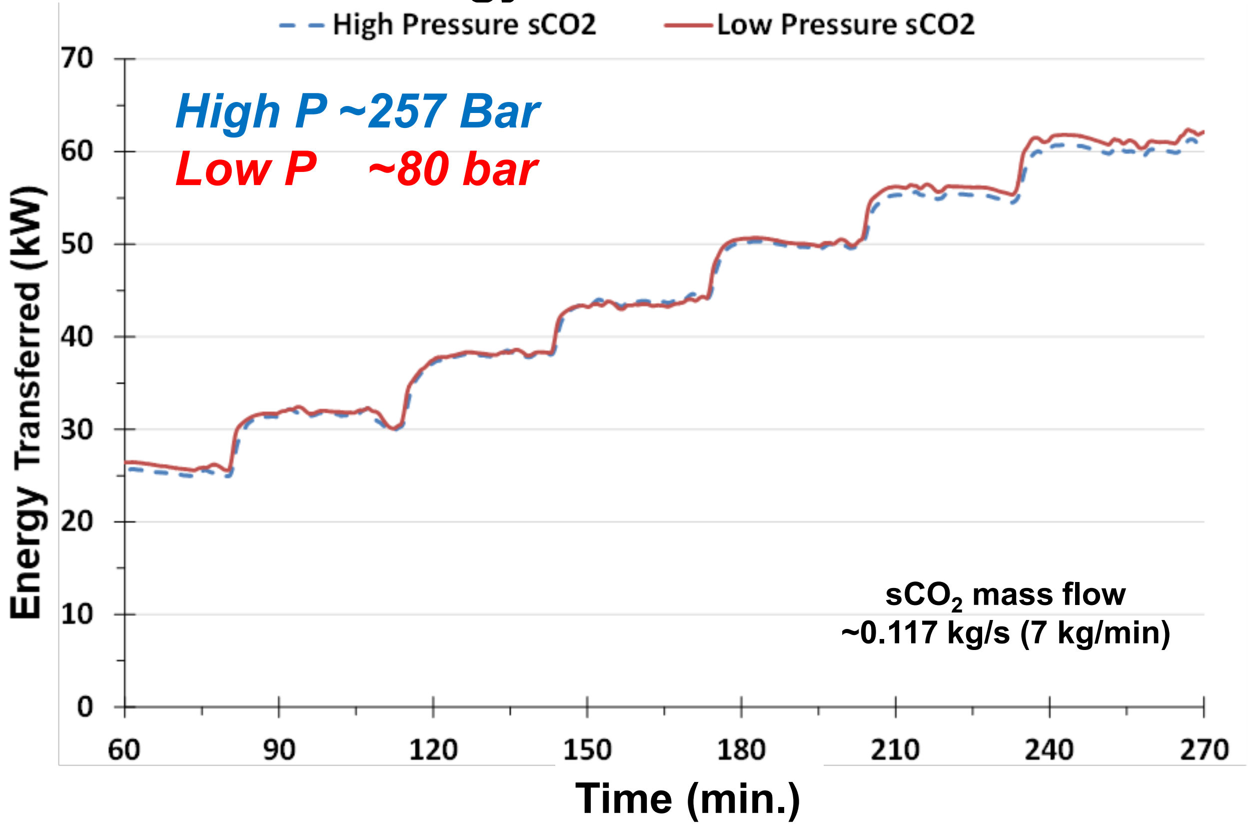
Test & Energy Balance Plots

Prototype 3D-SSHX Recuperator

Time vs. Temperature Plot



Energy Balance Plot



Approach T, < 10°C

Good Energy Balance, < 2% error

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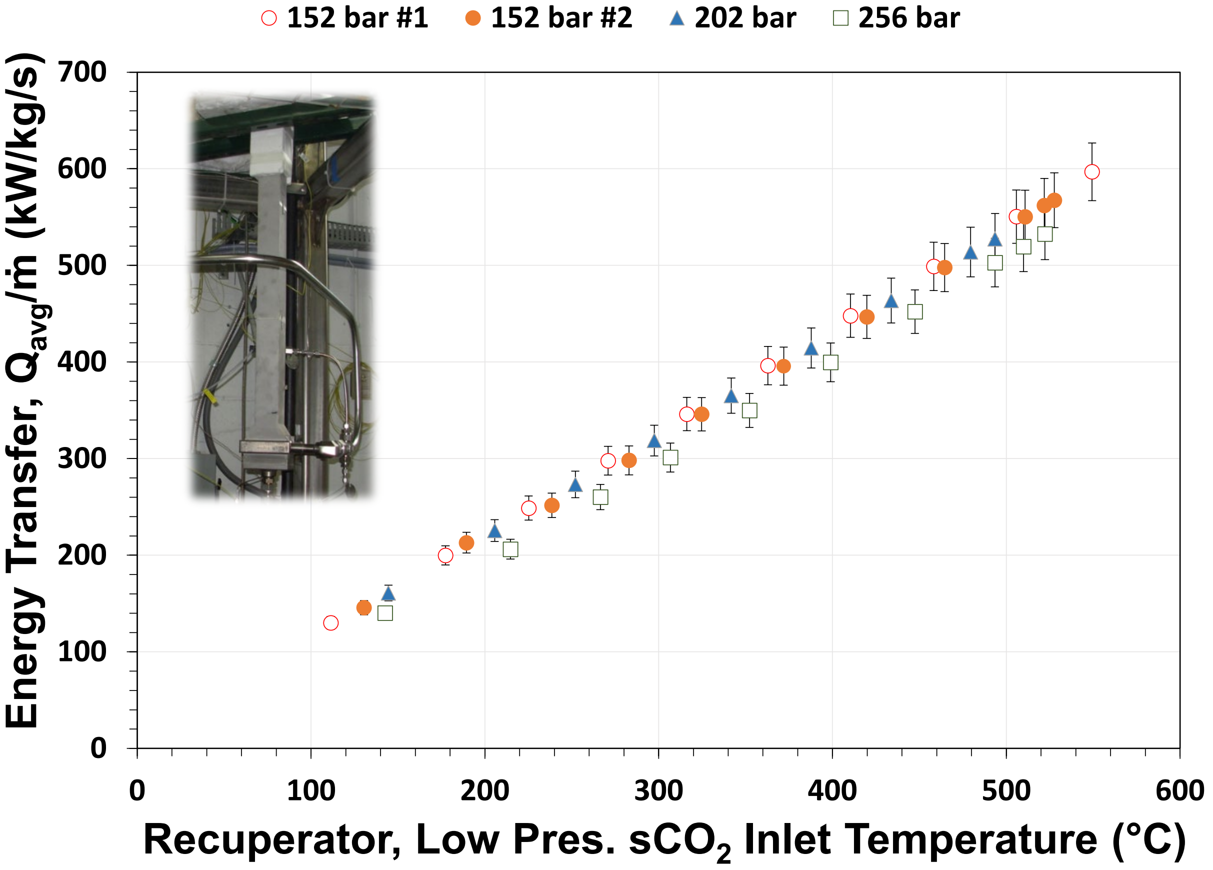
Energy Transfer Plots

SSHX Recuperator Prototypes

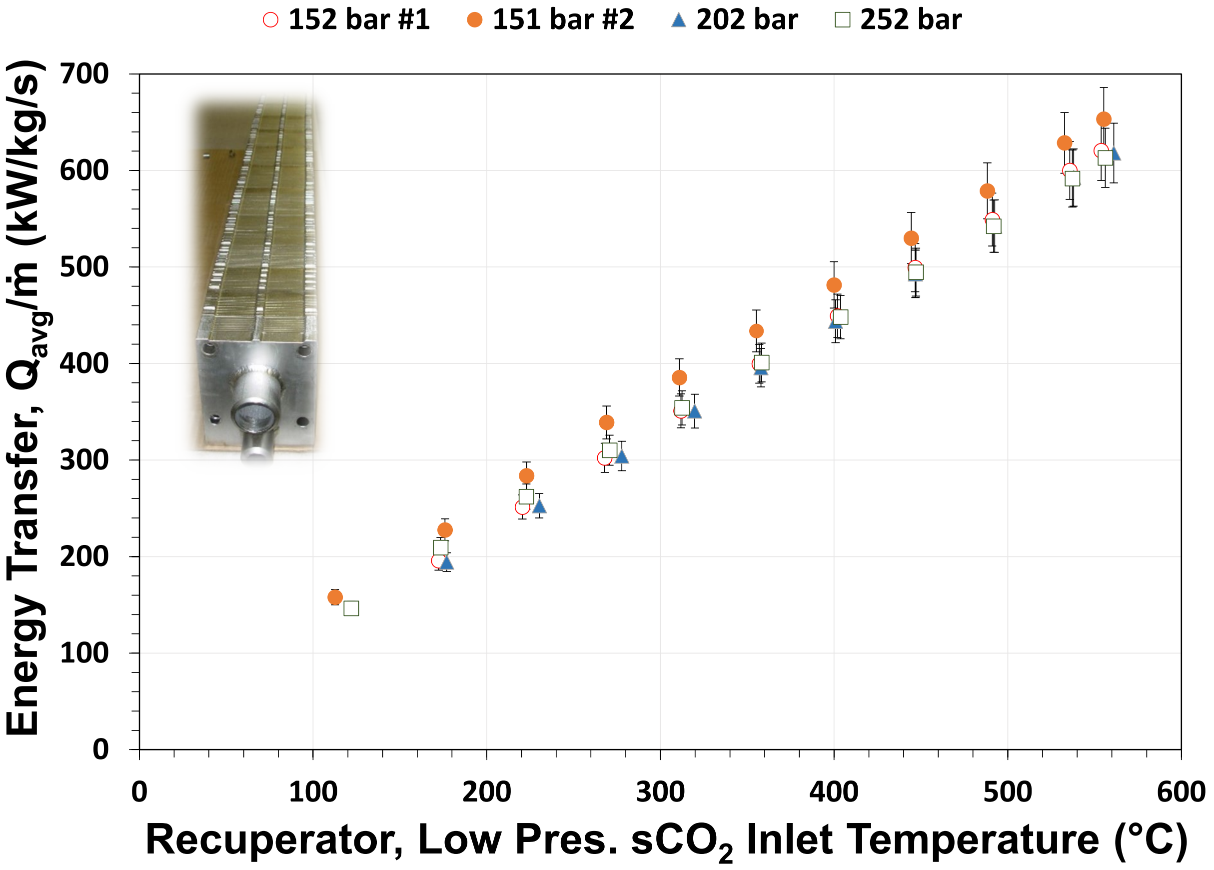
3D-SSHX

Inconel 625



Laser-SSHX

347H Stainless Steel



Linear Response

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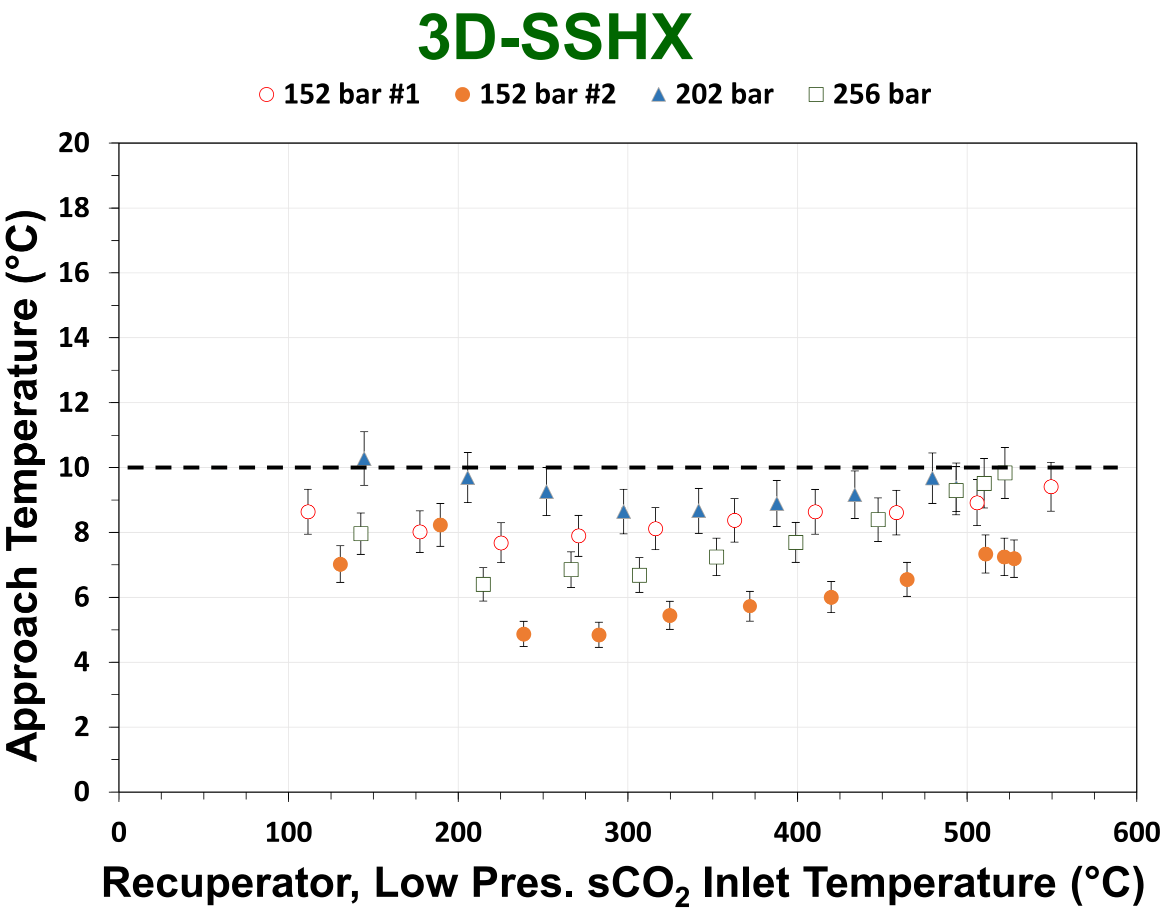
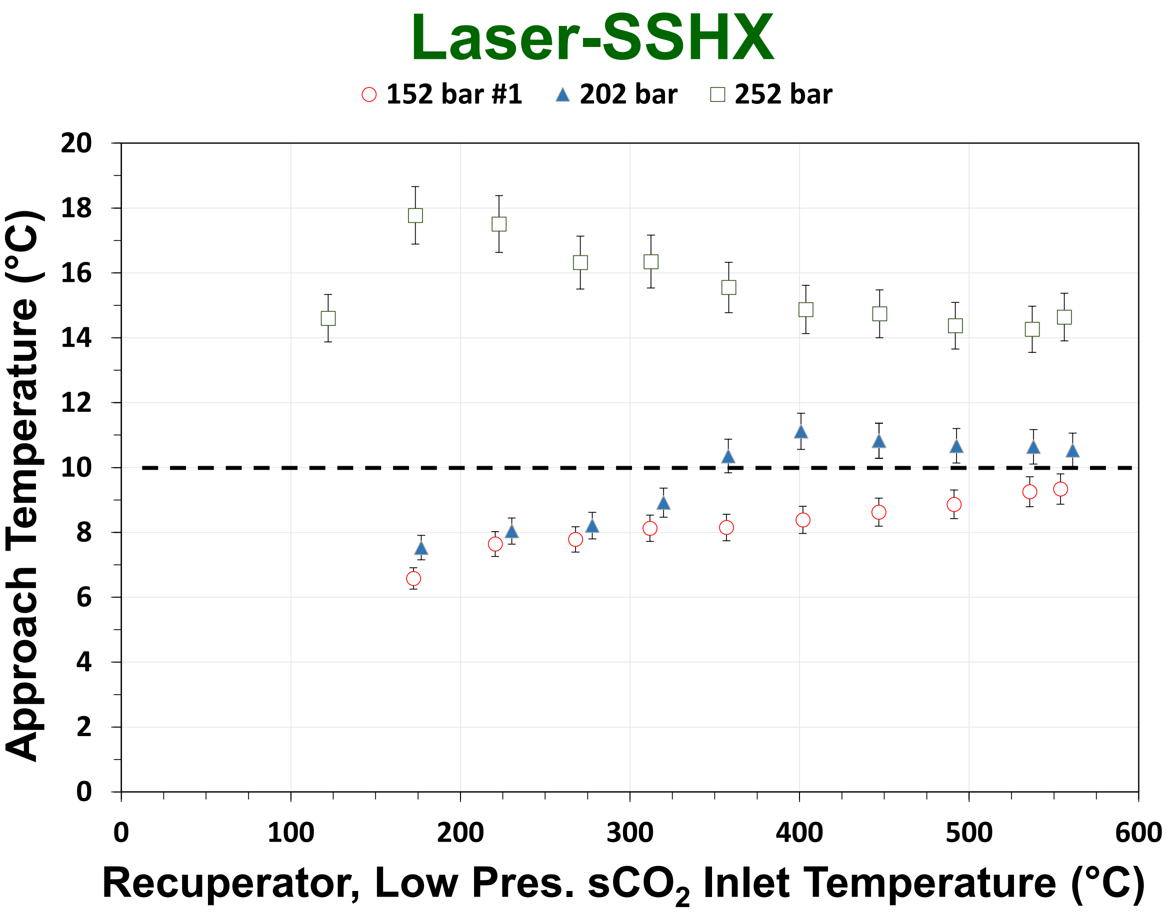
Approach Temperature Plots

SSHX Recuperator Prototypes



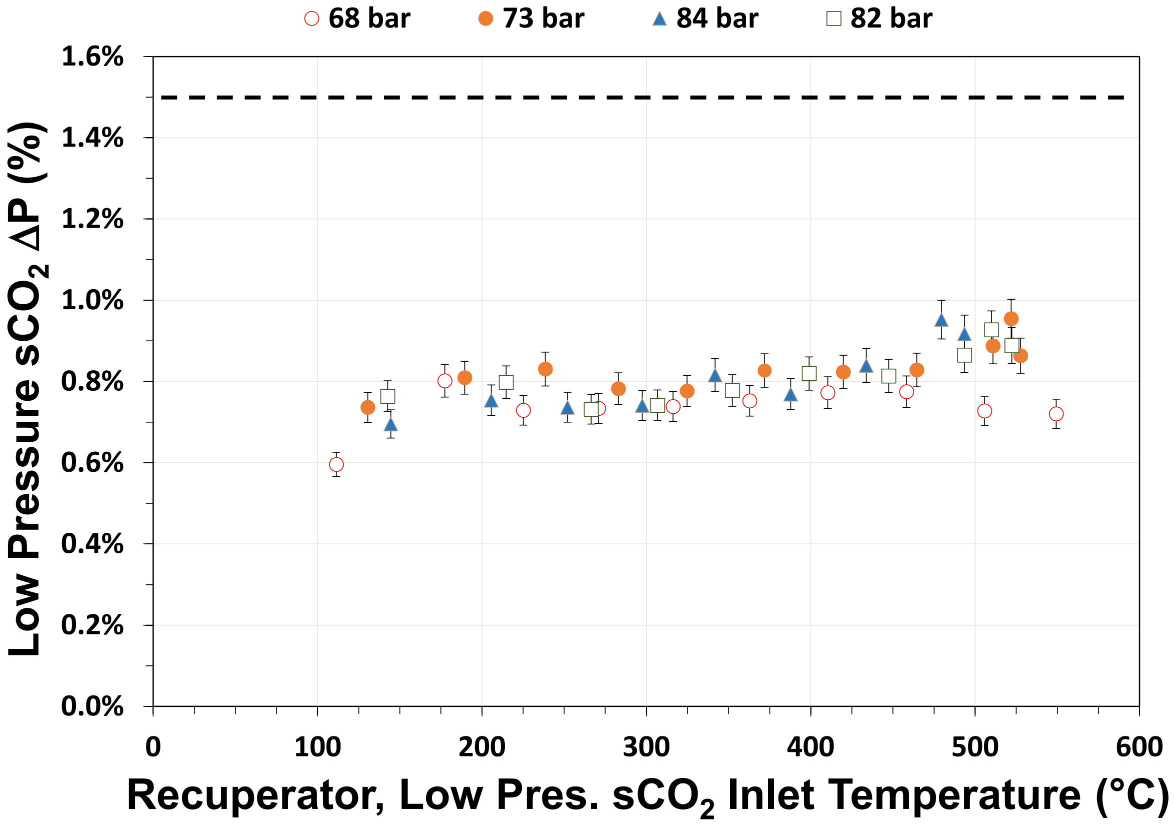


Meets design specifications

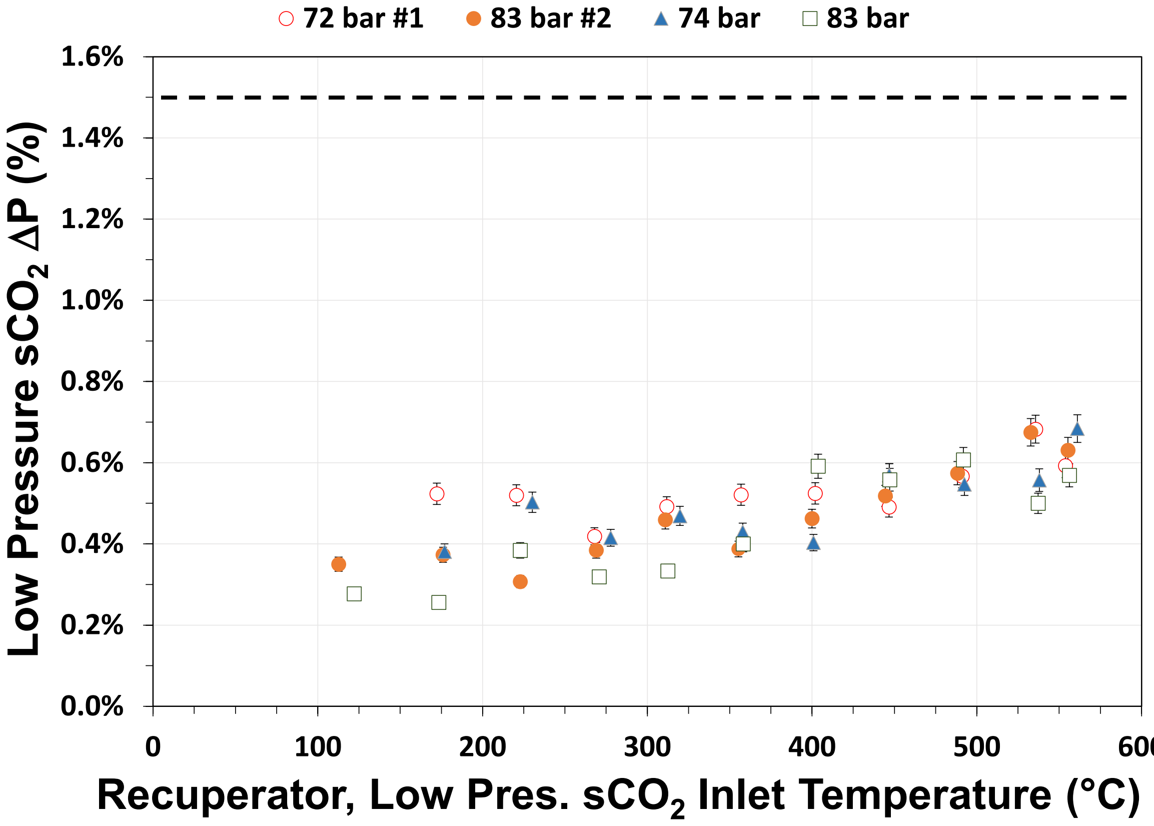
Lower Pressure sCO_2 ΔP Plots

SSHX Recuperator Prototypes

3D-SSHX



Laser-SSHX



Meets design specifications

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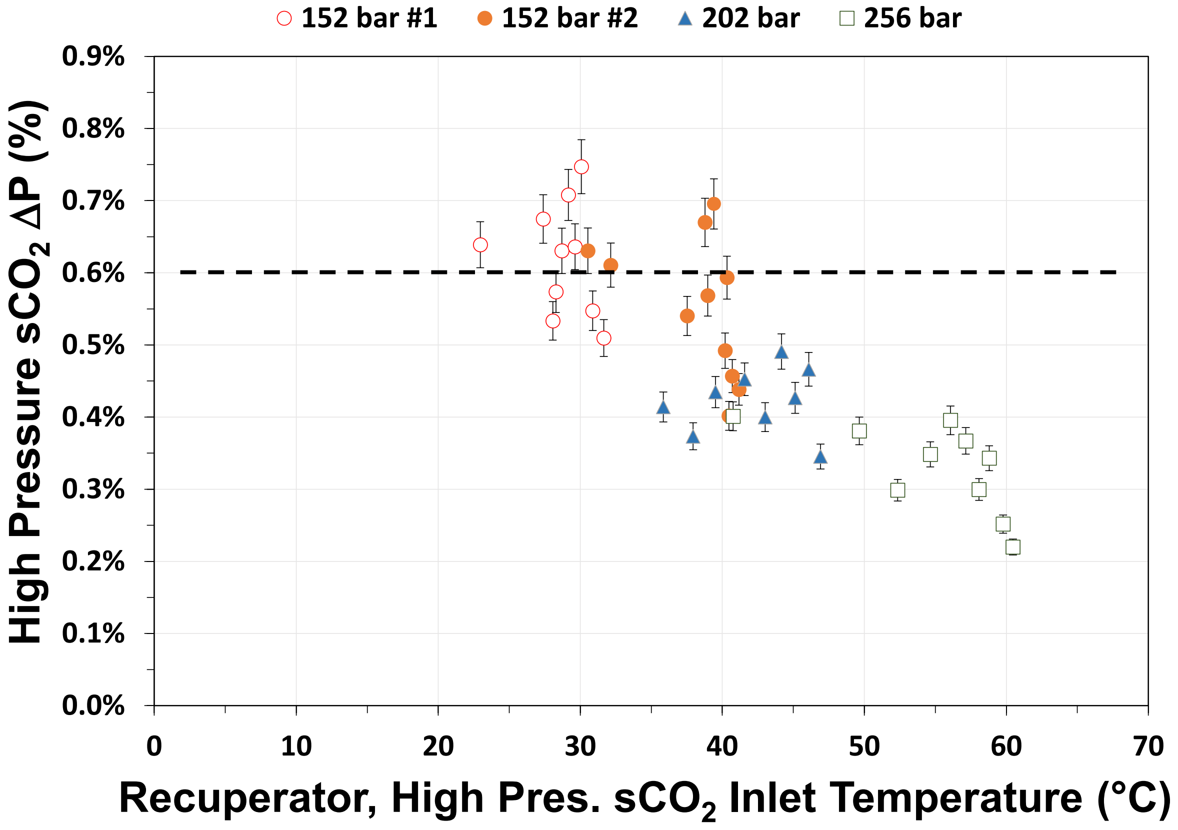
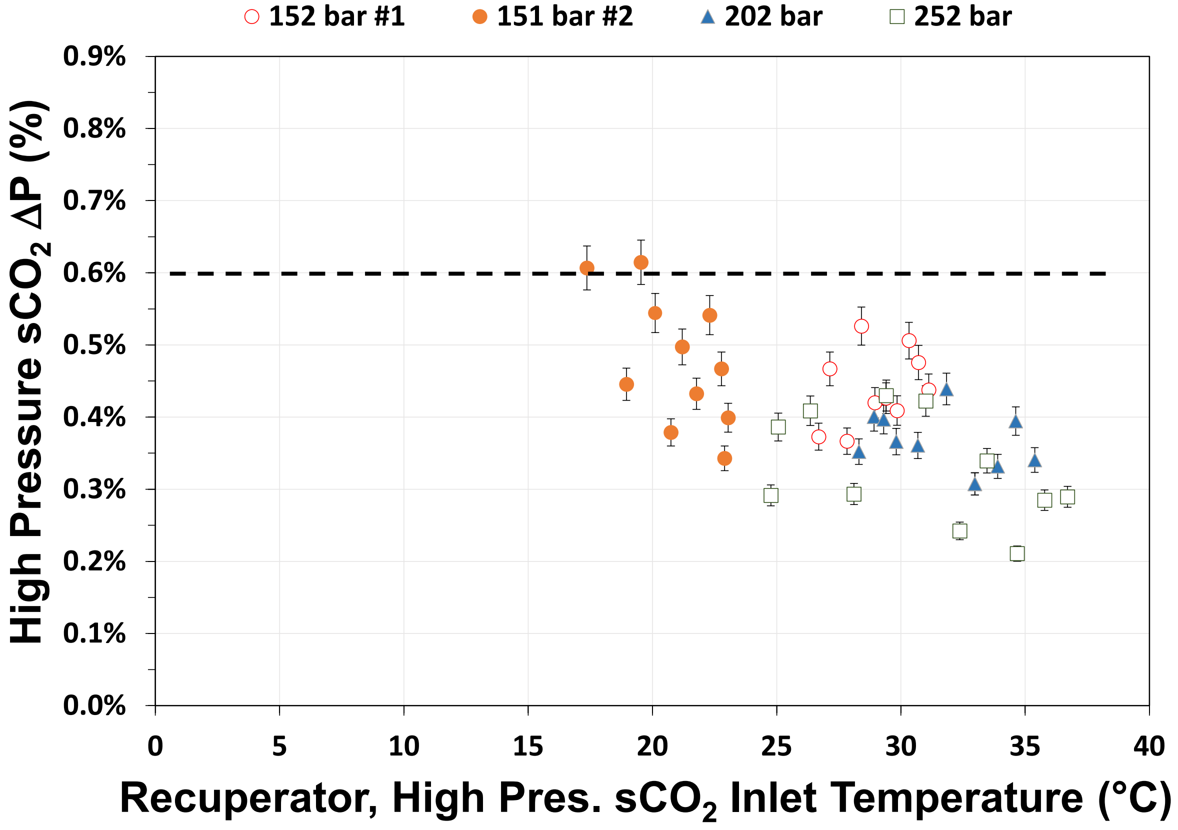
Higher Pressure sCO_2 ΔP Plots

SSHX Recuperator Prototypes

3D-SSHX



Laser-SSHX



Meets design specifications

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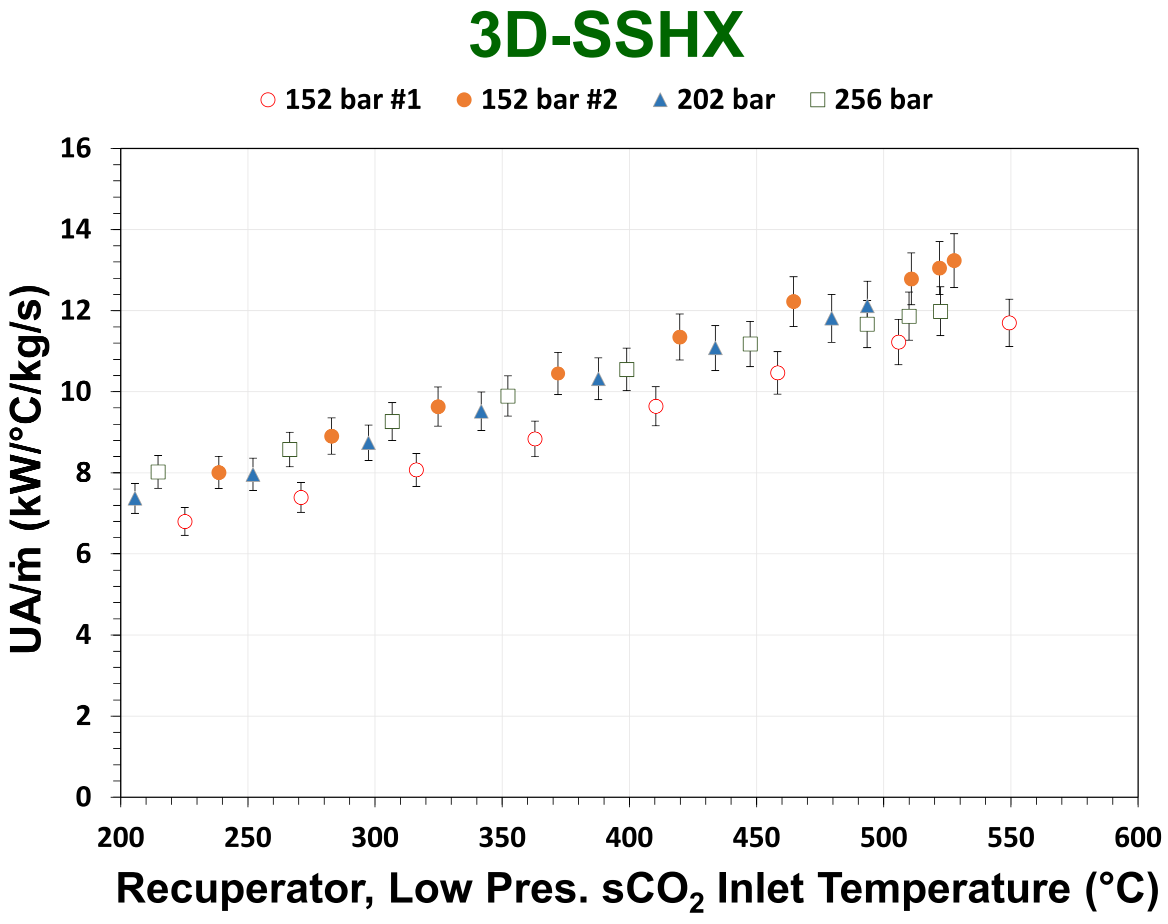
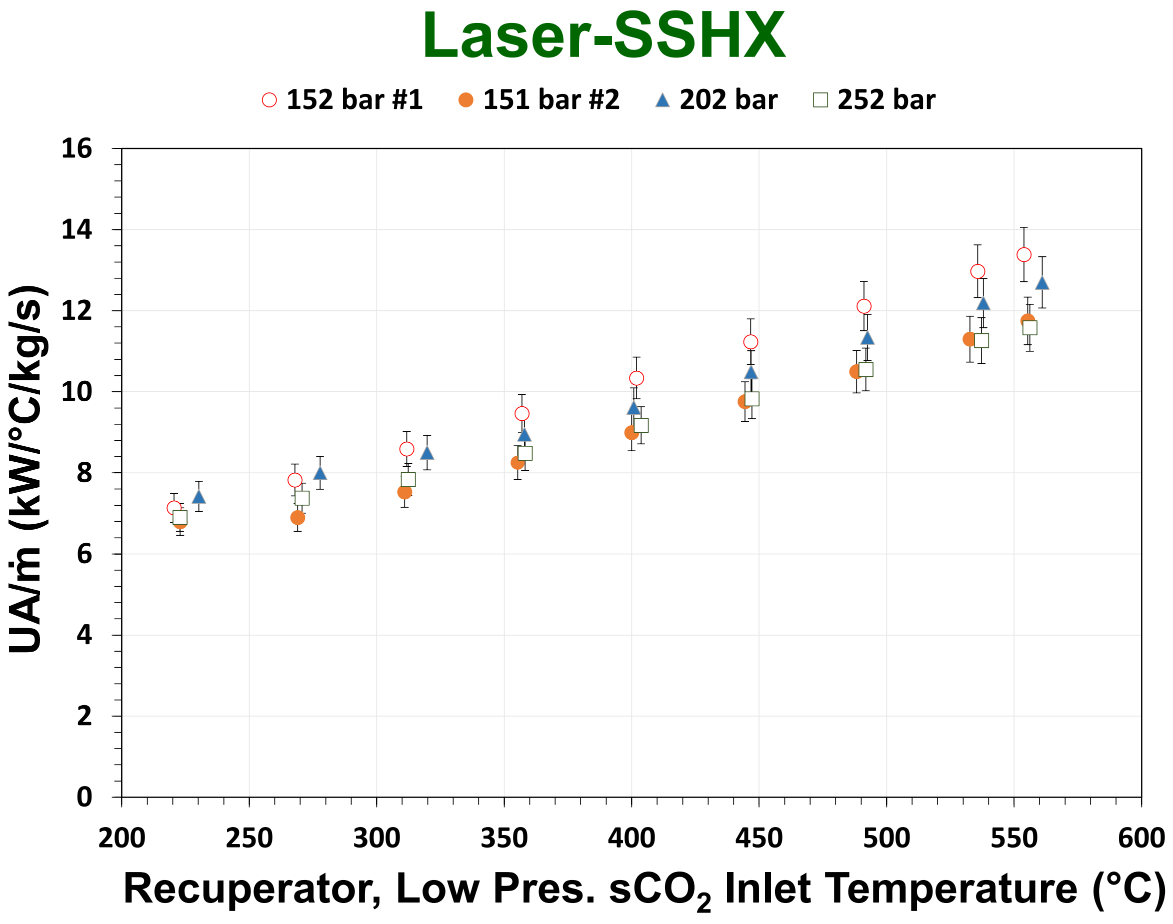
Heat Transfer (UA) Plots

SSHX Recuperator Prototypes





Linear Response

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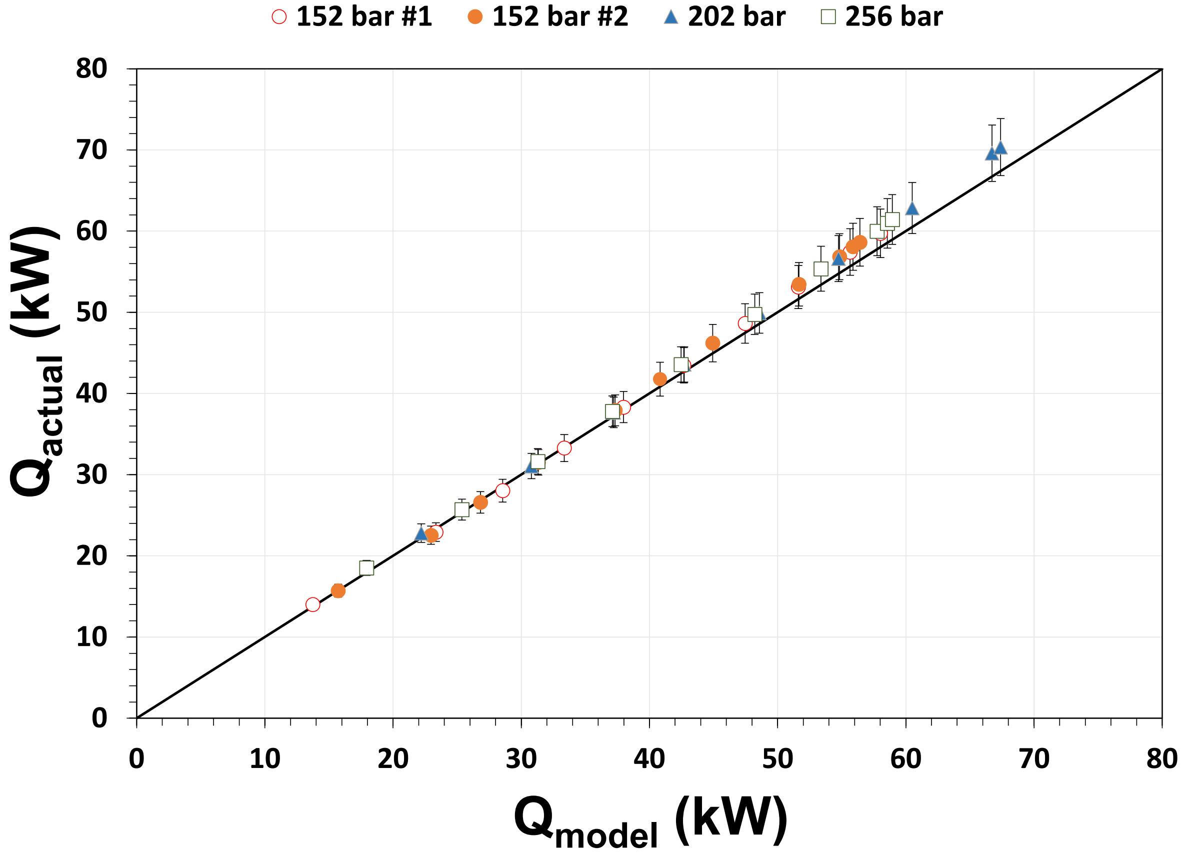
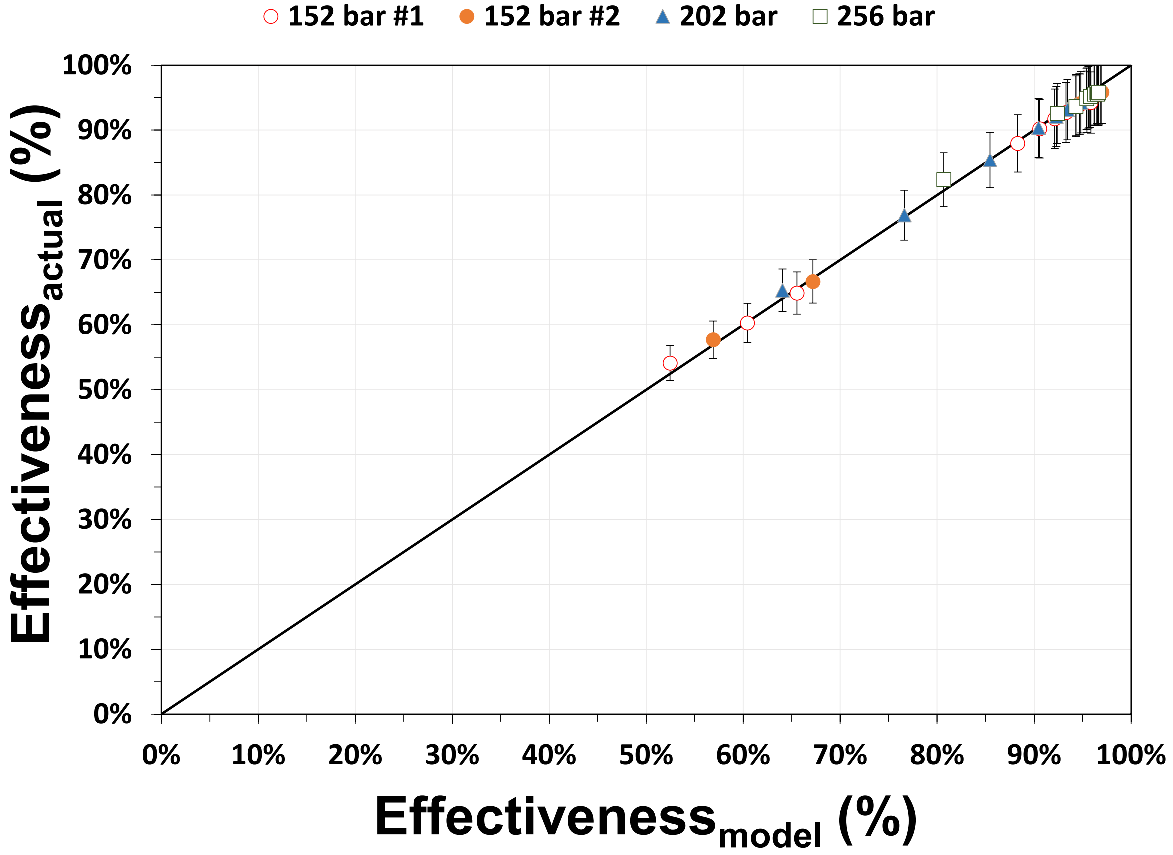
Good correlation between Design & Actual HX performance data

3D-SSHX

Transferred Energy, Q

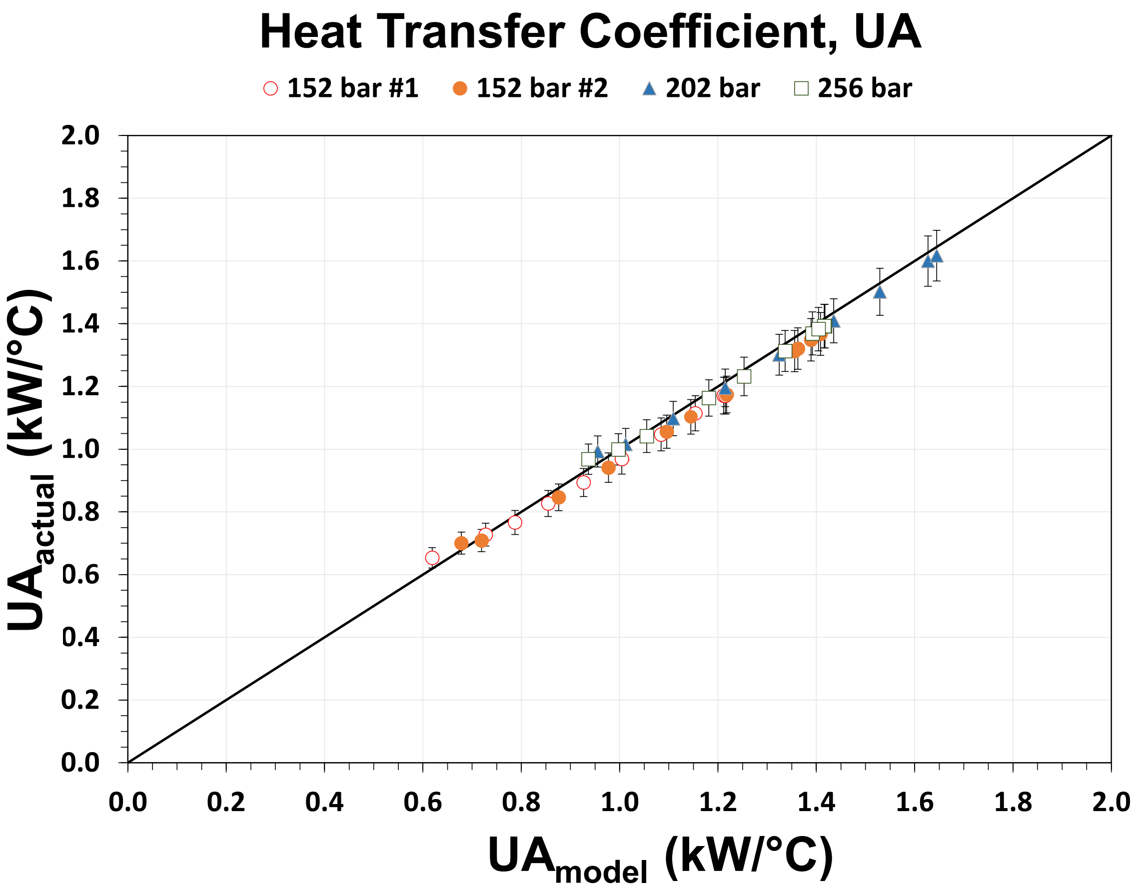


Effectiveness, ϵ



Data confirms SSHX Recuperator Performance

3D-SSHX



SSHX Recuperator meets or exceeds program requirements

Criteria	Updated - 8/16/16	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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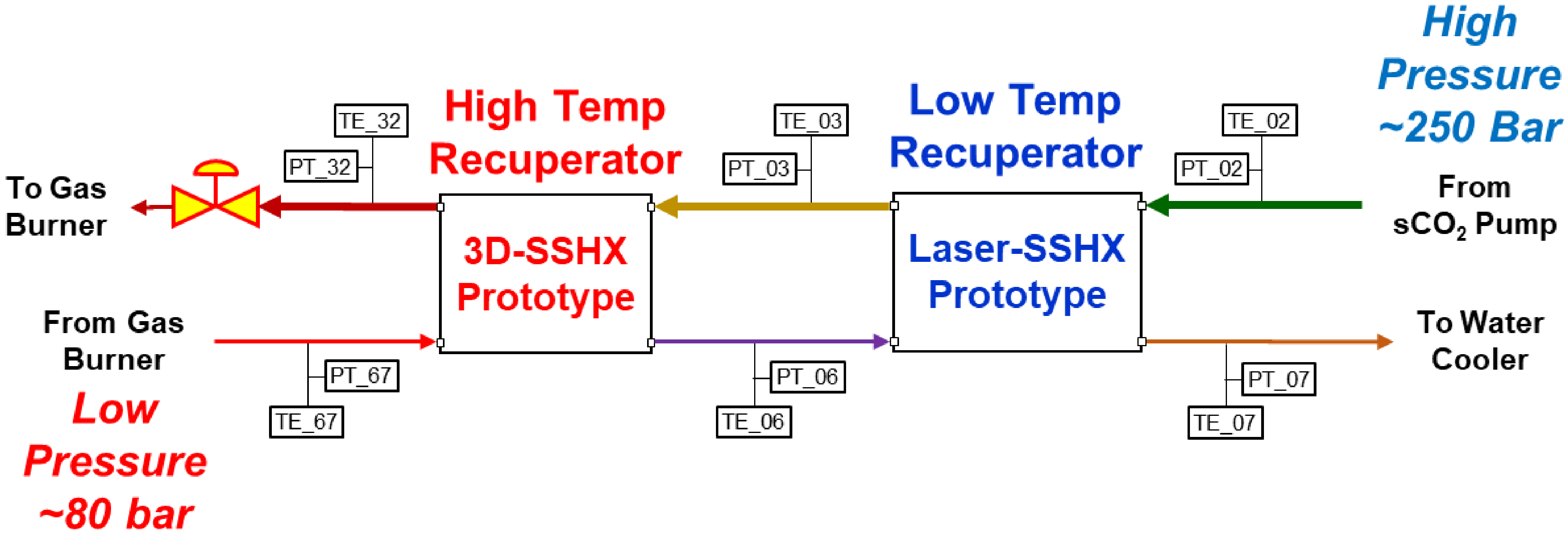
Reconfigured

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



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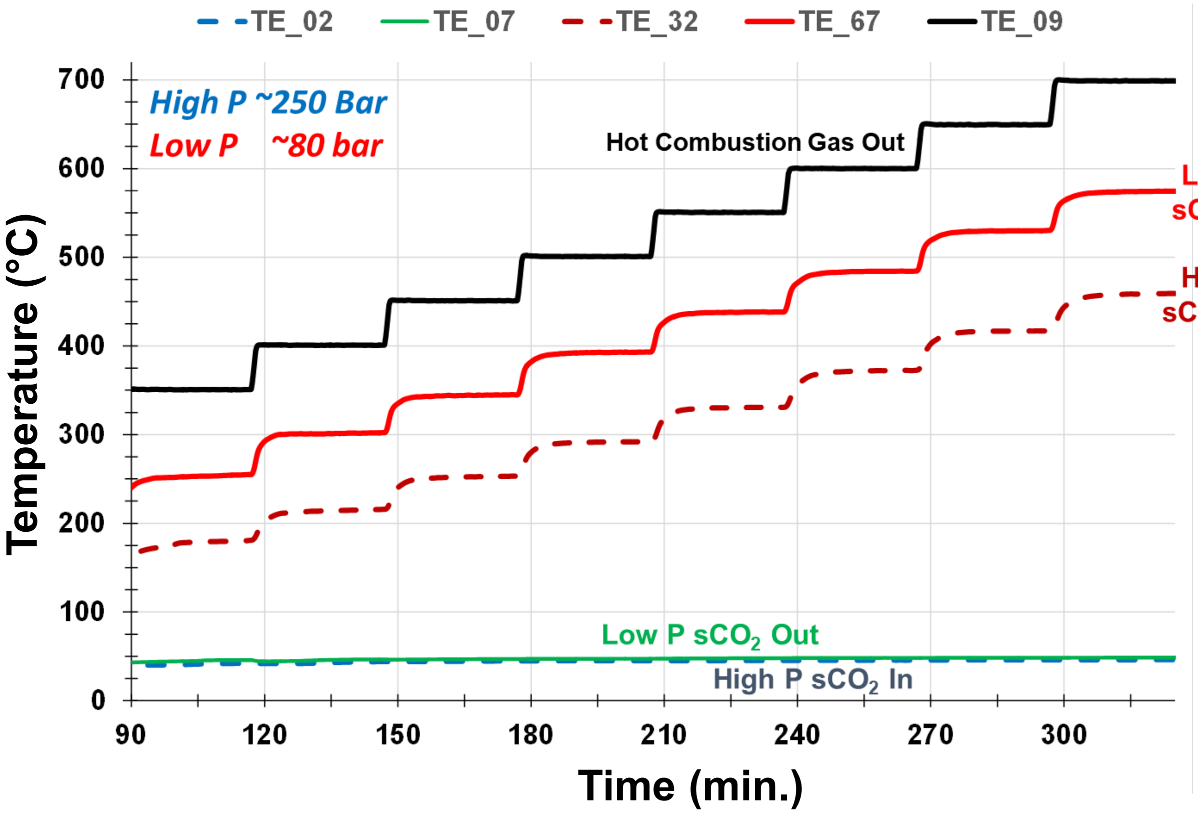
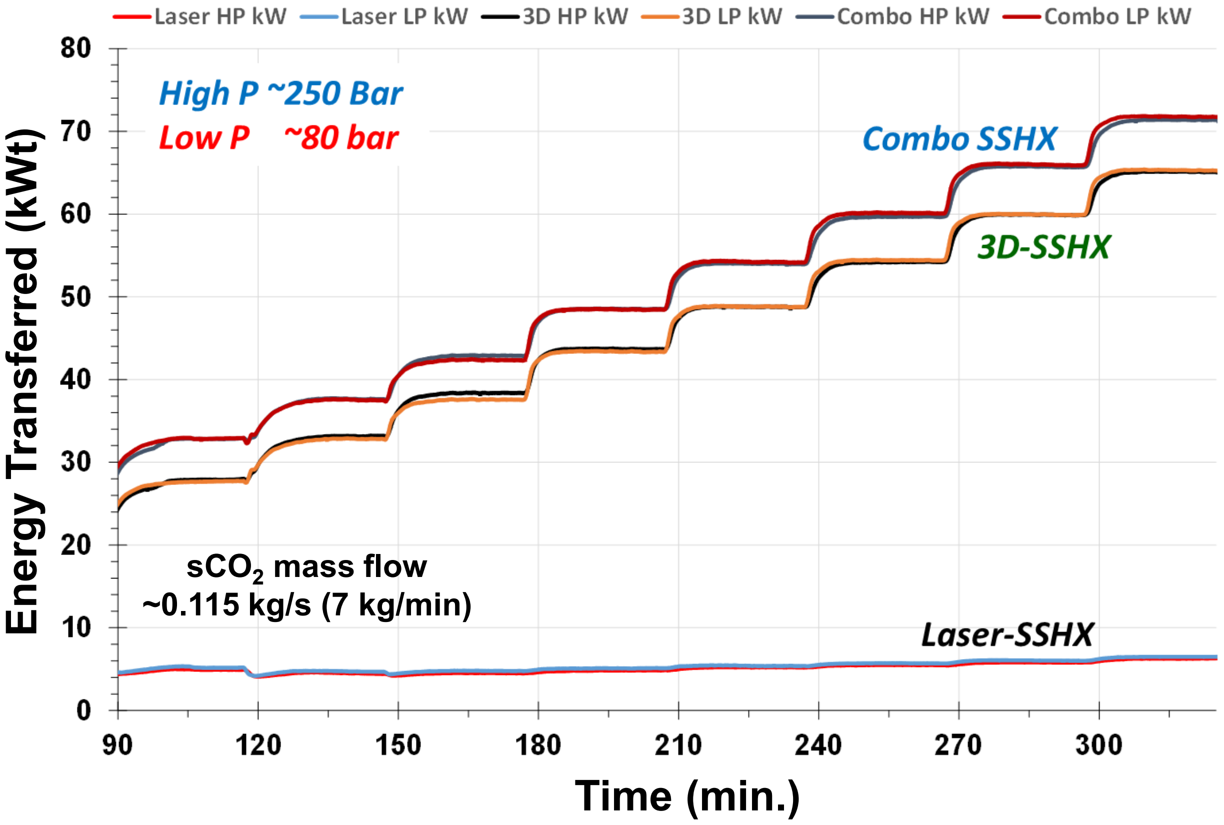
Test & Energy Balance Plots
COMBO-SSHX Recuperator
(Laser-SSHX & 3D-SSHX connected in series)

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***

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Thank you for your kind attention

Questions?

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