Development of Modular, Low-Cost, High Temperature Recuperators for the sCO₂ Power Cycles – Prototype Performance Update

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Outline

• Introduction to Thar Energy

• Project Recap
  o STEP Recuperator Criteria
  o Recuperator Concept Down Select
  o Scaling Considerations

• Project Update
  o Prototype Design & Fabrication
  o Prototype Performance Testing

• Project Summary
The Thar Brand
Over 25 years of Innovation with “Green” Supercritical Fluid Technologies

Timeline (recent past)

- **2014**: sCO₂ Brayton Power Cycle Development
  - COMPACT Heat Exchangers for sCO₂ Power Cycles
  - 3D Printed, Inconel 718, sCO₂-sCO₂ Recuperator
  - Tested at KAPL

- **2015**: Design – Construct – Install
  - Primary Heater for Sunshot
  - One MWe sCO₂ Test Loop

- **2016**: Design – Construct – Operate
  - sCO₂ Heat Exchanger Test Loop
  - 1st HX made using Inconel 740H

- **2017**: Design – Construct – Operate
  - Oxy Combustion Test Facility
  - Demonstrate auto-combustion
  - Patent - Notice of Allowance
  - Counter Current Heat Exchanger/Reactor
  - Pharmaceuticals sold to GRUNENTHAL

Expands into Liquid Chromatography
Heat Exchangers are key to improving \( s\text{CO}_2 \) power cycle efficiency and costs

Thar Energy - Manufacturer of

COMPACT Heat Exchangers for \( s\text{CO}_2 \) Power Cycles

- Recuperators
- Heaters
- Gas Coolers
- Water Coolers

Optimized Material Use
- Aluminum
- Carbon Steel
- Alloy Steel
- Stainless Steels
- Nickel Super Alloys

\( kWt \) to \( MWt \)

Typical \( s\text{CO}_2 \) Recuperated Recompression Brayton Cycle
Installed, Commissioned and Operated at SwRI

Thar Energy’s sCO₂ Primary Heater

Primary HX Design Conditions:
Gas Fired Burner/Blower Outlet Temperature: 870°C
sCO₂ Outlet Temperature: 715°C @ 255 bar
Project Recap

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

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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
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
Develop a Scalable, High Temperature Recuperator for STEP Conditions

High Temperature Recuperator

533°C
23.86 MPa

581°C
8.96 MPa

204°C
8.83 MPa

47 MWt

104.5 kg/s

DE-FE0026273
## Comparison of Recuperator Design Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Initial</th>
<th>Updated</th>
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<tbody>
<tr>
<td>Thermal Capacity</td>
<td>46.6 MWt</td>
<td>45.9 MWt</td>
</tr>
<tr>
<td>Thermal Effectiveness</td>
<td>96%</td>
<td>97%</td>
</tr>
<tr>
<td>Pressure Loss</td>
<td>$\Delta P_h &lt; 1.5%$ (1.3 bar)</td>
<td>$\Delta P_c &lt; 0.6%$ (1.3 bar)</td>
</tr>
<tr>
<td>Temperature Limit</td>
<td>581°C</td>
<td>577°C</td>
</tr>
<tr>
<td>Differential Pressure</td>
<td>152 bar</td>
<td></td>
</tr>
<tr>
<td>Life</td>
<td>30,000 hr</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>&lt; $100 / kWt</td>
<td></td>
</tr>
<tr>
<td>Package Dimensions</td>
<td>8.8 x 3.6 x 2.6 m</td>
<td></td>
</tr>
</tbody>
</table>
Heat Exchanger Design

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

Cost ↔ HTC
Effectiveness ↔ Approach Temperature
Area Density ↔ Pressure Drop

Alternating Rows
Checkerboard

- Alternating Rows
- Checkerboard
**Recuperator specifications influence cost**
Relatively independent for the heat exchanger concepts evaluated

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

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

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

---

**Graph Details:**
- **x-axis:** Heat Exchanger Effectiveness [%]
- **y-axis:** Relative Change in Cost
- **Legend:**
  - Helical
  - Plate Fin
  - Microtube
  - Corrugated
  - Stacked Sheet
  - HEATRIC (Shiferaw 2016)
  - Counterflow (NTU Ratio)
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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

As Design T increases, the material strength drops & corrosion rates increase
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, $\Delta P < 1.3$ bar, <$\$100$\$/kWt

- **Microtube**
  - 46 $\$/kW
  - Does not include header/manifold

- **Corrugated**
  - 52 $\$/kW
  - Does not include header/manifold

- **Helical**
  - 85-112 $\$/kW

- **Plate-Fin**
  - 63-212 $\$/kW etch
  - 130 $\$/kW fin
  - 1600 $\$/kW foam

- **Stacked-Sheet**
  - 29 $\$/kW
  - Does not include header/manifold

- **Liquid Metal Bath**
  - 136 $\$/kW

- **Plate-crossflow**
  - Relative to the microtube, it increases complexity & tube count

- **Spiral-Wound**
  - 507 $\$/kW

- **Double-pipe**
  - Increased frictional loss without increasing heat transfer.
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, \( \Delta P < 1.3 \) bar, \(<$100/\text{kWt}\)

- **Microtube**: $51/\text{kWt}
- **Stacked-Sheet**: $47/\text{kWt}
- **Corrugated**: \( >$107-380 \) /\text{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
CASE STUDY

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

Printed-Circuit HX:
The bond between sheets is: **perpendicular** to the mechanical stresses & **parallel** to the thermal stresses

**Thermal Gradient**
is across the entire bond length

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

**Improves structural integrity and thermal compliance**
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%)
Prototype SSHX Recuperators

<table>
<thead>
<tr>
<th>Criteria</th>
<th>3D-SSHX Prototype</th>
<th>Laser-SSHX Prototype</th>
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</thead>
<tbody>
<tr>
<td>Manufacturing Method</td>
<td>3D Printed</td>
<td>Laser Cut Sheets</td>
</tr>
<tr>
<td>Materials</td>
<td>Inconel 625</td>
<td>Stainless 347H</td>
</tr>
<tr>
<td>Channel Pattern</td>
<td>Circle-Star</td>
<td>Circle-Circle</td>
</tr>
<tr>
<td>Manifold Design</td>
<td>3D Printed</td>
<td>Laser Cut Sheets</td>
</tr>
<tr>
<td>Joining Method</td>
<td>Diffusion Braze</td>
<td>Diffusion Braze</td>
</tr>
<tr>
<td>Opacity</td>
<td>~46%</td>
<td>~73%</td>
</tr>
</tbody>
</table>
46 MWt Laser-SSHX Recuperator
Parallel Modular Design, Factory Fabricated

3D-SSHX
57% volume decrease

Example: Eight stacked Laser-SSHX sub-modules

0.5m x 2.8m x 3m
Test Conditions - SSHX Recuperator Prototypes

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

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

- Test thermal/hydraulic performance over a range of operating conditions
- Compare actual to predicted performance
- Rank prototypes by performance
sCO₂ Brayton Power Cycle Heat Exchanger Test Facility

Reconfigurable Test Loop
- Pressures to 275 bar
- Temperature to 700°C
- sCO₂ 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
HX Model Heat Transfer Equations

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

1. CO₂ Side Nusselt Number

Petukhov (1970)

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

2. Air Side Nusselt Number

Martin (2002)

\[ L_q = \begin{cases} 0.92H_g \times Pr_{air}^{(L)} \times \left(\frac{4X_T - 1}{X_T}\right) & X_L \geq 1 \\ 0.92H_g \times Pr_{air}^{(L)} \times \left(\frac{4X_TX_L - 1}{X_LX_D}\right) & X_L < 1 \end{cases} \]

\[ Nu_{air}^{(L)} = 0.404 \times L_q^{\frac{1}{3}} \]

3. CO₂ Side Pressure Drop

Bhatti and Shah (1987)

\[ f = 0.00128 + 0.1143Re^{-0.811} \]

\[ \Delta p_{CO_2} = f \frac{L \rho u^2}{d_o^2} \]

4. Air Side Pressure Drop

Zukauskas (1988)

\[ \Delta p_{air} = N_L X_p \left(\frac{P_{air}}{2}\right)^{\frac{1}{2}} f \]
**HX Performance Heat Transfer Equations**

**Effectiveness, ϵ = \( \frac{Q_{act}}{Q_{max}} \)**

\[
Q_{act} = \min(Q_{HI-HO}, Q_{LI-LO}) \\
Q_{HI-HO} = \dot{m} \times (h_{HO} - h_{HI}) \\
Q_{LI-LO} = \dot{m} \times (h_{LI} - h_{LO})
\]

\[
Q_{max} = \min(Q_{h_{max}}, Q_{c_{max}}) \\
Q_{h_{max}} = \dot{m} \times (h_{LI} - h_{(T_{HI}, P_{LO})}) \\
Q_{c_{max}} = \dot{m} \times (h_{(T_{LI}, P_{HO})} - h_{HI})
\]

**ΔT = \( T_{LI} - T_{HO} \)**

**% Pressure Drop**

\[
%\Delta P = \frac{(P_{in} - P_{out})}{P_{in}}
\]

**UA = \( \frac{Q_{act}}{T_{Ln}} \)**

\[
T_{Ln} = \frac{(\Delta T_{i} - \Delta T_{ii})}{\ln(\Delta T_{i} / \Delta T_{ii})} \\
\Delta T_{i} = T_{LI} - T_{HO} \\
\Delta T_{ii} = T_{LO} - T_{HI}
\]

Steady State Time vs. Temperature Plot

Prototype SSHX Recuperators

3D-SSHX – Steady State Plot

- 80.3 bar sCO₂ In
- 257.3 bar sCO₂ Out
- 80.1 bar sCO₂ Out
- 257.8 bar sCO₂ In
Test & Energy Balance Plots
Prototype 3D-SSHX Recuperator

Time vs. Temperature Plot

- **High P ~257 Bar**
- **Low P ~80 bar**

**Hot Combustion Gas Out**

- Low P sCO₂ In
- High P sCO₂ Out
- Low P sCO₂ Out
- High P sCO₂ In

Energy Balance Plot

- **High P ~257 Bar**
- **Low P ~80 bar**

sCO₂ mass flow
~0.117 kg/s (7 kg/min)

**Approach T, < 10°C**

**Good Energy Balance, < 2% error**
Energy Transfer Plots
SSHX Recuperator Prototypes

3D-SSHX
Inconel 625

Laser-SSHX
347H Stainless Steel

Recuperator, Low Pres. sCO$_2$ Inlet Temperature (°C)

Linear Response
Approach Temperature Plots
SSHX Recuperator Prototypes

3D-SSHX

- 152 bar #1
- 152 bar #2
- 202 bar
- 256 bar

Laser-SSHX

- 152 bar #1
- 202 bar
- 252 bar

Approach Temperature (°C)

Recuperator, Low Pres. sCO₂ Inlet Temperature (°C)

Meets design specifications
Lower Pressure $\text{sCO}_2$ $\Delta P$ Plots

**SSHX Recuperator Prototypes**

### 3D-SSHX

- 68 bar
- 73 bar
- 84 bar
- 82 bar

### Laser-SSHX

- 72 bar #1
- 83 bar #2
- 74 bar
- 83 bar

---

**Meets design specifications**
Higher Pressure sCO₂ ΔP Plots
SSHX Recuperator Prototypes

Meets design specifications
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**

- 152 bar #1
- 152 bar #2
- 202 bar
- 256 bar

**Effectiveness, $\epsilon$**

- 152 bar #1
- 152 bar #2
- 202 bar
- 256 bar

**Graphs:**
- Transferred Energy, $Q_{\text{actual}}$ (kW) vs $Q_{\text{model}}$ (kW)
- Effectiveness, $\epsilon_{\text{actual}}$ (%) vs $\epsilon_{\text{model}}$ (%)

**Observation:**

Good correlation between Design & Actual HX performance data.
Data confirms SSHX Recuperator Performance

3D-SSHX
Heat Transfer Coefficient, UA

Criteria | Updated - 8/16/16 | 3D-SSHX Prototype
---|---|---
Thermal Capacity | 45.9 MWt | ✓
Thermal Effectiveness | 97% | ✓
Pressure Loss | \(\Delta P_h < 1.5\% \text{ (1.3 bar)}\) | ✓
| \(\Delta P_c < 0.6\% \text{ (1.3 bar)}\) | ✓
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 | ✓
Reconfigured sCO₂ 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
Summary

• Prototype recuperators have been designed, fabricated, and tested
  ❖ 3D-SSHX
  ❖ Laser-SSHX
  ❖ Combo-SSHX: Laser-SSHX piped in series with the 3D-SSHX

• sCO₂ 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?

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Richard Dennis, Advanced Turbines Technology Manager
Seth Lawson, Program Officer, Advanced Energy Systems Division