Development of Modular, Low-Cost, High-Temperature Recuperators for the sCO$_2$ Power Cycles

Lalit Chordia, PhD, Ed Green, Danyang Li, Marc Portnoff

Grant Musgrove, Stefan Cich, C.J. Nolen, Anthony Costanzo, Klaus Brun
Outline

• Introduction to Thar Energy

• Project Overview
  • Objectives
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• Project Update
  o STEP Recuperator Criteria
  o sCO₂ Recuperator Concepts and Ranking
  o Preliminary Engineering Analysis
  o Recuperator Criteria - Updated
  o Preliminary Engineering Findings
  o Prototype Design, Fabrication & Testing
  o Closing Summary
The Thar Brand - Over 25 years of Innovation with “Green” Supercritical Fluid Technologies

Design and commercialization of supercritical systems & major components

Thar Supercritical Chromatography System

World’s Largest

Over 20 Industrial scale 24/7/365 installations

Direct Exchange, R744 (CO$_2$) Geothermal Heating & Cooling

Over 5,000 scientific instruments installed

High Pressure sCO$_2$ Pumps

Demonstrations at commercial scale

Heat Exchangers
Heat Exchangers are key to improving sCO₂ power cycle efficiency and costs

Thar Energy sCO₂ Recuperators, Primary Heater HXs & Gas Cooler HXs

Typical sCO₂ Recuperated Recompression Brayton Cycle
sCO₂ Gas Cooler HXs
35-500 kW

CO₂-Air Approach
Temperature as Low as 2°C

115 Tons

Test Facility
sCO₂ Counter-current Microtube Recuperator

Flanged Pressure Vessel similar to Shell & Tube:

- **Floating Head Design**
- Horizontal Separators vs. Vertical Baffles
- **Replaceable Tube Bundle**
- Design per ASME Sec VIII, Div 1
- Design Conditions: 575°C @ 280 bar (1053°F @ 4116 psi)
sCO₂ 5.5 MWt Recuperator Tube Bundle

> 20,000 microtubes

Tube Bundle
4,500 m²/m³
Recuperator Tube Bundle Cross Section
9” diameter, over 20,000 microtubes

Microchannel Printed Circuit HX

Entropy 2015, 17, 3438-3457; doi:10.3390/e17053438

Opacity: 74%
1st Generation Recuperator Pressure Vessel

ASME Stamped - Design Conditions:
575°C @ 280 bar (1053°F @ 4116 psi)
Sunshot Heater HX Design – 2.5 MW
Hot Gas to sCO₂ HX
Inconel 740H Construction

Design Conditions:
Gas Fired Burner/Blower Outlet Temperature: 870°C
sCO₂ Outlet Temperature: 715°C
Installed at SwRI

Thar Energy’s 2.5MW 740H Hot Air to sCO$_2$ HX
& 5.5 MW sCO$_2$ Recuperator Pressure Vessel
Project and Technology Overview
Objective:

- Advance high-temperature, high-differential-pressure recuperator technologies suitable for use in sCO$_2$ Recompression Brayton Cycle (RCBC)

- Evaluate, advance, and demonstrate recuperator concepts, materials, and fabrication methods that facilitate the commercial availability of compact and low cost recuperators for RCBC conditions (e.g. turbine inlet temperatures exceeding 700°C, and differential pressures on the order of 200 bar)

- Emphasis placed on scalable solutions able to accommodate plant sizes from 10 - 1,000 MWe.

Program will:

1. Address critical design, materials, and fabrication challenges

2. Significant impact on recuperator cost, performance, and scalability
Project Participants

Lalit Chordia, Ed Green, Danyang Li, Peter Shipe, Tom Koger, Marc Portnoff

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

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

Techno-Economic Analysis for selected recuperator concepts

Task 3.0  Preliminary design (detail design of 100 kWt prototype)
Task 4.0  100 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
## Project Schedule

<table>
<thead>
<tr>
<th>Task</th>
<th>Phase 1 (10/1/15 - 3/31/17)</th>
<th>Phase 2 (4/1/17 - 3/31/19)</th>
</tr>
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<tr>
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<td>Q1</td>
<td>Q2</td>
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<tr>
<td>Task 1.0 - Project management</td>
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<tr>
<td>Task 2.0 - Engineering Assessment</td>
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<tr>
<td>Task 3.0 - Preliminary design</td>
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<td></td>
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<td></td>
<td></td>
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DE-FE0026273
Develop a Scalable, High Temperature Recuperator for STEP Conditions

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Quantitative Evaluation Criteria  
47 MWt Recuperator Module  
Used for Concept Down-Select

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Metric</th>
<th>Target Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Effectiveness*</td>
<td>$\varepsilon = \frac{Q_{actual}}{Q_{max}}$</td>
<td>$\varepsilon \geq 96%$</td>
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<tr>
<td>Pressure Loss*</td>
<td>$\Delta P = \frac{(P_i - P_o)}{P_i}$</td>
<td>$\Delta P_c &lt; 1.5%$ (1.3 bar)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta P_h &lt; 0.6%$ (1.3 bar)</td>
</tr>
<tr>
<td>Temperature Limit*</td>
<td>Material operating temperature</td>
<td>581°C</td>
</tr>
<tr>
<td>Differential Pressure*</td>
<td>Pressure difference across high pressure (e.g. 240 bar) and low pressure (e.g. 88 bar) streams</td>
<td>152 bar</td>
</tr>
<tr>
<td>Life</td>
<td>One or more of: pressure code requirements, fatigue, creep, and corrosion</td>
<td>30,000 hr</td>
</tr>
<tr>
<td>Cost</td>
<td>$$/kWt</td>
<td>&lt; $100/kWt</td>
</tr>
<tr>
<td>Package Dimensions</td>
<td>Shipping size of the heat exchanger or modular section</td>
<td>8.8 x 3.6 x 2.6 m</td>
</tr>
</tbody>
</table>

* Target value estimated from STEP facility process schematic
Heat Exchanger Configuration

- 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

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State-of-the-art sCO₂ HX were reviewed in detail.

- **Brayton**: stacked plate brazed modular cells
- **Thar Energy**: brazed & diffusion-bonded
- **Comprex**: stacked sheets diffusion bonded PCHE, H2X, FPHE
- **Velocys**: diffusion-bonded stacked plate
- **Altex**: plate-frame configuration
- **Heatric**: stacked sheets diffusion bonded
Insufficient information in the literature, concerning state-of-the-art sCO₂ plate-type (brazed or diffusion-bonded) HXs, to meet project criteria:
47MWt, 240 bar, 581°C, 96% Effectiveness, ΔP < 1.3 bar, <$100kW
Recuperator Concepts Selected from Brain Storming

- Microtube
- Corrugated
- Helical
- Plate-Fin
- Stacked-Sheet
- Liquid Metal Bath
- Plate-crossflow
- Spiral-Wound
- Double-pipe
One-dimensional methods are used for conceptual sizing the heat exchanger cores at 47 MWt scale

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<td>$D_{P_c} &lt; 1.3 \text{ bar}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$D_{P_h} &lt; 1.3 \text{ bar}$</td>
</tr>
<tr>
<td>STEP Pressure &amp; Temperature</td>
<td>$24\text{MPa} - 194^\circ\text{C} &amp; 9\text{MPa} - 581^\circ\text{C}$</td>
<td></td>
</tr>
</tbody>
</table>

1) Assume constant thermal properties to find the required overall heat transfer coefficient ($UA$)

$$NTU = \frac{1}{C_{\text{min}}/C_{\text{max}} - 1} \ln \left( \frac{\varepsilon - 1}{\varepsilon C_{\text{min}}/C_{\text{max}} - 1} \right)$$

$$UA = NTU \times C_{\text{min}} = 1,597 \text{ kW/K}$$

2) If available, use a discretized model to achieve the required thermal duty (47 MWt)
Concept Evaluation using 1-D Thermal Fluid Modeling

Pros
- Computationally efficient
- Scalable
- Flexible
- System level performance information

Cons
- Reduced order fidelity
  - Does not provide details on the physics
- Relies on other sources for some information (i.e. HTC from CHT)
ANSYS thermal models are used to account for complex thermal circuits.
Heat exchanger cost is estimated from the size of the major material components

- Equivalent $/lb material costs are usually based on Thar & SwRI past experience:
  - Tubes
  - Casing
  - Flanges
  - Sheets

- Multiple vendor quotes are correlated for estimating cost of specific features:
  - $/Area for formed sheets
  - $/Hole – Conventional vs. EDM drilling
  - Hole punching
  - Chemical etching
  - Brazing
  - Diffusion Bonding
47 MWt Recuperator Concept Comparison

• Model each Recuperator Concept, at the 47 MWt scale, for performance:
  ❖ 96% Effectiveness, $\Delta P < 1.3$ bar, $581^\circ$C & 240 bar per ASME Code

• Determine Recuperator Size & Cost:
  ❖ Does it meet the cost criteria, <$100$/kWt?
The double-pipe increased frictional loss without increasing heat transfer
Relative to the microtube, the plate-crossflow increases complexity and tube count.
The liquid metal bath concept has a high cost due to the manifold arrangement and number of tubes.

**Liquid Metal Bath**: 136 $/kW

- Microtube
- Corrugated
- Helical
- Plate-Fin
- Stacked-Sheet
- Plate-crossflow
- Double-pipe

[Diagram showing different types of heat exchanger configurations]
The spiral-wound requires large tubes and long lengths, resulting in high material costs.

- Microtube
- Corrugated
- Helical
- Stacked-Sheet
- Plate-Fin
- Liquid Metal Bath
- Plate-crossflow
- Spiral-Wound
- Double-pipe

Costs:
- Microtube: 136 $/kW
- Corrugated: 507 $/kW
- Helical: 31 $/kW
- Stacked-Sheet: 507 $/kW
- Plate-crossflow: 136 $/kW
- Spiral-Wound: 507 $/kW
- Double-pipe: 136 $/kW
Plate-Fin, Plate-Foam, & Etched Plate-Fin concepts were too expensive

- Microtube
- Corrugated
- Helical
- Stacked-Sheet

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

Spiral-Wound:
- 507 $/kW

Liquid Metal Bath:
- 136 $/kW

Plate-crossflow

Double-pipe
The Helical concept had uncertainty in design and manufacturability in addition to a high cost.

- **Microtube**
- **Corrugated**
- **Stacked-Sheet**
- **Helical**
  - 63-212 $/kW etch
  - 130 $/kW fin
  - 1600 $/kW foam
- **Plate-Fin**
  - 63-212 $/kW etch
  - 130 $/kW fin
  - 1600 $/kW foam
- **Spiral-Wound**
  - 507 $/kW
- **Plate-crossflow**
- **Double-pipe**

The costs are as follows:
- **Liquid Metal Bath**: 136 $/kW
The Microtube, Corrugated & Stacked-Sheet Recuperator Concepts were down selected for low complexity and cost.

- **Microtube**: 46 $/kW
- **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**: Does not include header/manifold
- **Spiral-Wound**: 507 $/kW
- **Double-pipe**: Does not include header/manifold
Preliminary Engineering is performed on the three down-selected recuperator concepts

Includes:
- overall system performance
- cost
- flow path design
- detailed analysis of critical design features
- material selection
- design for manufacturing to ASME code
- design for operation and maintenance.

Using:
- Fluid-thermal network analysis or bulk properties finite element analysis (FEA) to evaluate recuperator performance, as well as to facilitate the optimization of recuperator modules.
- Computational fluid dynamics (CFD), FEA, and conjugate heat transfer (CHT) to establish heat transfer coefficient and pressure loss.
- Material properties such as yield strength, creep strength, and corrosion resistance.

Incorporate header & manifold designs in all concepts
Considerations for Updating Recuperator Criteria

• **Effectiveness Rating: 92-96%**
  - Effect on HX size and Cost

• **Rated Design Point**

• **Fouling Potential:**
  - Particle size vs. channel passage size
  - Cost of larger recuperator vs. use of filters
Recuperator Criteria Considerations

*Effectiveness rating requirements can have a dramatic impact on HX size and cost*

sCO2 Heat Exchangers - Cost optimization

Le Pierres, R., Heatric, Industry Panel Session, 5th International Supercritical CO2 Power Cycles Symposium
Selected Alloy Properties

ASME Allowable Stress and 10,000 Hour Creep Rupture Values

Higher Design T increases costs faster than Design P due to material strength reduction & increased corrosion rates
sCO$_2$ Power Cycle - Alloy Corrosion

ORNL’s guidance of corrosion at STEP conditions

Corrosion is not expected to be a problem for:

- Stainless Steel Alloys below 550°C
- Nickel Alloys below 650°C

30K hour corrosion allowance: 1 mil (25.4 μm)
### Recuperator Temperature & Pressure

#### Rated Design Points

<table>
<thead>
<tr>
<th>Condition</th>
<th>Temp. (°C)</th>
<th>Pres. (bar)</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Operating Point</td>
<td>581</td>
<td>240</td>
<td>from Step facility process schematic</td>
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<tr>
<td>Rated Design Pt. 1</td>
<td>591</td>
<td>264</td>
<td>T+10°C, P+10%</td>
</tr>
<tr>
<td>Rated Design Pt. 2</td>
<td>611</td>
<td>280</td>
<td>T+30°C (~5%), P+ 5% + PSV setting</td>
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<tr>
<td>Rated Design Pt. 3</td>
<td>640</td>
<td>293</td>
<td>T+10%, P+10% + PSV setting</td>
</tr>
</tbody>
</table>

Guidance provided by ASME and Industrial Standards (e.g. NORSOK)

**Team Recommendation: Rated Design Point 2**

*Provides a margin of safety with minimum over design.*
47MWt Microtube Recuperator Fabrication

Discussion with numerous vendors have been initiated

Advanced Manufacturing
- Laser cutting
- Laser welding
- Water jet cutting
- 3D metals printing
- Sheet bending/forming
- Metal plating
- Stamping
- EDM wire cutting
- Electro discharge machining (EDM)
- Electro-chemical etching
- Electro-chemical machining (ECM)
- Brazing
- Welding
- Diffusion Bonding
Updated STEP Cycle Conditions – 8/18/16

STEP sCO₂ Cycle Assumptions:

• Net electric power output = 10 MWe
• Turbine efficiency = 85%
• Generator efficiency = 98.5%
• Main Compressor efficiency = 82%
• Bypass Compressor efficiency = 78%
• Compressor Motor efficiency = 96.5%
• HX pressure drop/pass = 138 kPa
• Temperature approach = 10°C
• Mass flow = 101.5 kg/s
## Comparison of Recuperator Design Criteria

<table>
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<tr>
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<th>Initial</th>
<th>Updated</th>
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<td>96%</td>
<td>97%</td>
</tr>
<tr>
<td><strong>Pressure Loss</strong></td>
<td>(\Delta P_c &lt; 1.3) bar (\Delta P_h &lt; 1.3) bar</td>
<td></td>
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<td><strong>Temperature Limit</strong></td>
<td>581°C</td>
<td>577°C</td>
</tr>
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<td>152 bar</td>
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  o STEP Recuperator Criteria
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  o Down-Selection Process
  o Preliminary Engineering Analysis
  o Recuperator Criteria - Updated
  o Preliminary Engineering Findings
  o Prototype Design, Fabrication & Testing
  o Closing Summary
Microtube Recuperator – evaluate how relationships between design parameters allow for cost reduction while meeting performance goals

**Design Parameters**
- Number of tubes
- Tube diameter
- Tube length
- Tube spacing

**Effects on Size and Cost**
- Casing diameter and thickness
- Tube sheet thickness
- Tube sheet manufacturing cost

![Graph showing the relationship between Number of Tubes and Relative Tube Size](image)

![Graph showing the relationship between Number of Internal Bundles and Normalized Overall Cost](image)
Microtube Recuperator - updates are made to the thermal-hydraulic performance calculations

Improve fidelity for effects of separator sheets
- Pressure drop
- Heat transfer area

One-dimensional pressure drop calculations confirmed with reduced-order CFD model

Include ASME code calculations for tube sheet and casing

Discretized one-dimensional model to account for varying fluid properties
Microtube Recuperator

Modular tube bundle is preferred to single module design

- Removable tube bundles for maintenance and repair
- Each tube bundle has its own floating tube sheet
- Each tube bundle has its own pressure boundary
- Economies of scale lower the modular tube bundle costs
- 200 MWt unit meets shipping criteria

200 MWt
46 MWt
4.6 MWt
The Stacked-Sheet Recuperator Concept has similar design relationships to the Microtube Concept

Design Parameters
• Number of passages
• Passage diameter
• Passage length
• Passage spacing

Effects on Size and Cost
• Overall dimensions
• Sheet thickness
• Manufacturing limits
The critical components in the design are the manufacturability and pressure containment

Manufacturability effects:
• Surface roughness characteristics in the passages
• Alignment of sheets and manufacturing tolerances
• Diffusion bonding vs. brazing

Pressure containment:
• High pressure loading and thermal growth
• Thickness between passages for containment
Evaluation of thermal-mechanical stress to ASME Code
Stacked-Sheet Recuperator – Size Comparison

- 235 MWt
- 47 MWt
- 4.7 MWt
The Corrugated Recuperator concept is similar to a plate-type heat exchanger with brazed channels.
Corrugation size directly affects the overall sheet size and must provide pressure containment

**Design Parameters**
- Sheet width
- Corrugation size
- Sheet length
- Number of sheets
- Sheet thickness

**Effects on Size and Cost**
- Total height
- End plate thickness and cost

Required sheet thickness for pressure containment is determined for a large range of corrugation design parameters
CHT simulations were used to check the validity of passage size approximations for heat transfer.

Elliptical flow passages assumed for HTC

A modification factor \( \sim 0.75 \) should be used for the approximate UA value.
Additional analysis showed that the Corrugated Recuperator concept exceeds the cost criteria at the 47 MWt scale

• Manifolds had a higher than expected impact on the overall cost

• Cost of corrugated HX is above STEP target of $100/kW
  - Geometry for high risk manufacturing: $107/kW
  - Geometry for low risk manufacturing: $380/kW

• Since the concept does not meet the cost criteria, the recommendation is to discontinue further design or fabricate a prototype for testing.
Recuperator Concepts
Engineering Analysis

46 MWt, 280 bar, 610°C, 97% Effectiveness, $\Delta P < 1.3$ bar, <$100$ kW

- **Microtube**: $51$/kWt
- **Stacked-Sheet**: $47$/kWt
- **Corrugated**: $> 107-380$ /kWt
Prototype Design, Fabrication and Testing

- Prototypes sized for performance testing in the Thar sCO$_2$ test loop, ~100 kWt
- Prototypes to encompass critical features of the 46 MWt scale recuperator
  - Manufacturing methods
  - Heat transfer assumptions
Prototype HX Pressure and Performance Testing

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

Thar Energy Test Stand Flow Diagram

• Test thermal performance over a range of operating conditions
• Compare actual to predicted performance
• Rank prototypes by performance
HX Test Stand 3D Layout

Air-sCO2 Heater HX

sCO2-sCO2 Recuperator

sCO2 Pump

Burner/Blower
Closing Summary

• Stacked Sheet and Microtube 46 MWt Recuperator Concepts meet STEP Performance and Cost Criteria.

• Both concepts can be scaled to industrial thermal capacity requirements.
  - Stacked-Sheet Concept has advantages of lower cost, smaller package size, and potential for future enhancements.
  - Microtube Concept has advantages of using a floating tube sheet to accommodate thermal stresses, and a removable tube bundle that accommodates cleaning, maintenance and repair.

• Recommending to discontinue work on the Corrugated Recuperator Concept since it does not meet the cost criteria.
Thank you for your kind attention

Questions?

Work supported by US DOE under DE-FE0026273
Richard Dennis, Advanced Turbines Technology Manager
Seth Lawson, Program Officer, Advanced Energy Systems Division