DOE Initiative on SCO2 Power Cycles (STEP)
- Heat Exchangers: A Performance and Cost Challenge -

EPRI-NETL Workshop on Heat Exchangers for SCO2 Power Cycles
San Diego, CA; October 15, 2015
Presentation Outline
DOE Initiative on SCO2 Power Cycles (STEP)
- Heat Exchangers: A Performance and Cost Challenge -

• Why SCO2 Power Cycles
• FE Applications of SCO2 Power Cycles
• Recuperators for SCO2 Power Cycles
• Overview of the DOE SCO2 Crosscut Initiative
• Summary
Why Use Supercritical CO$_2$ (SCO2) for Power Cycles?

- Applicable to multiple heat sources for indirect heating
- Potential for higher efficiency relative to traditional power cycles
  - Double recuperated with recycle compressor
  - Beneficial properties near the critical point
- Closed cycle (noncondensing)
- Reduced turbomachinery sizes
- CO$_2$ is generally stable, abundant, inexpensive, non-flammable, and less corrosive than H$_2$O

Source: NETL
## Common FE, NE, EERE Application Space

<table>
<thead>
<tr>
<th>Application</th>
<th>Size [MWe]</th>
<th>Temperature [°C]</th>
<th>Pressure [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear (NE)</td>
<td>10 – 300</td>
<td>350 – 700</td>
<td>20 – 35</td>
</tr>
<tr>
<td>Fossil Fuel (FE) (Indirect heating)</td>
<td>300 – 600</td>
<td>550 – 900</td>
<td>15 – 35</td>
</tr>
<tr>
<td>Fossil Fuel (FE) (Direct heating)</td>
<td>300 – 600</td>
<td>1100 – 1500</td>
<td>35</td>
</tr>
<tr>
<td>Concentrating Solar Power (EERE)</td>
<td>10 – 100</td>
<td>500 – 1000</td>
<td>35</td>
</tr>
<tr>
<td>Shipboard Propulsion</td>
<td>&lt;10 – 10</td>
<td>200 – 300</td>
<td>15 – 25</td>
</tr>
<tr>
<td>Geothermal (EERE)</td>
<td>1 – 50</td>
<td>100 – 300</td>
<td>15</td>
</tr>
</tbody>
</table>
FE Applications of the Indirect and Direct Supercritical CO₂ Power Cycle

### Indirect SCO₂ Cycle
- Main Compressor
- Recycle Compressor
- Heater
- Primary Heat Exchanger
- Low Temperature Recuperator
- High Temperature Recuperator
- sCO₂ Turbine

### Direct SCO₂ Cycle
- Pressurized Oxy-combustion
- Primary Heat Exchanger
- sCO₂ Turbine
- Generator

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<table>
<thead>
<tr>
<th>Cycle/Component</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (°C)</td>
<td>P (MPa)</td>
</tr>
<tr>
<td><strong>Indirect</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heater</td>
<td>450-535</td>
<td>1-10</td>
</tr>
<tr>
<td>Turbine</td>
<td>650-750</td>
<td>20-30</td>
</tr>
<tr>
<td>HX</td>
<td>550-650</td>
<td>8-10</td>
</tr>
<tr>
<td><strong>Direct</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustor</td>
<td>750</td>
<td>20-30</td>
</tr>
<tr>
<td>Turbine</td>
<td>1150</td>
<td>20-30</td>
</tr>
<tr>
<td>HX</td>
<td>800</td>
<td>3-8</td>
</tr>
</tbody>
</table>
Recuperator Discussion
Recompression Closed Brayton Cycle

~ 2/3 of the heat in the cycle is recuperated

\[ W_C = \text{Compression Work} \]

\[ Q_C = \text{Heat Loss to Cold Sink} \]

\[ Q_H = \text{Heat Addition} \]

Work Out = \( W_E + W_C \)

Pressure vs. Specific Enthalpy Diagram
Heat Transfer = Overall HX Coef. * Area * Temperature Difference
\[ Q = U \times A \times \Delta T \]

As \( \Delta T \) decreases, effectiveness increases, but the area must increase to make up for the decrease in \( \Delta T \)

- Increasing the contact area generally results in an increase in volume of material required
- Heat exchangers are often characterized by the ratio of contact area to volume:
  \[ \beta = \frac{A}{V} \]
Recuperators – Basic Heat Transfer

What about pressure drop?

• Heat transfer coefficient increases with an increase in turbulence, but so does pressure drop

• Increasing heat transfer coefficient, $U$, allows less contact area, $A$, and a smaller heat exchanger
  
  $Q = U \cdot A \cdot \Delta T$

• However for a given heat exchanger design, increasing $U$ comes with the penalty of increased pressure drop
Vendor Inquiries for Recuperators

Recuperators for a 550 MWe power plant

- **OF PFBC w/ SCO2 power cycle**
  - 550 MWe; 1280 MWth,
  - 50.5 cycle efficiency
  - 2993 MWth HTR / 750 MWth LTR

- **Recuperator development plans**
  - Development plan
  - Qualifications
  - +/- 30 % cost estimate
  - Compactness criteria 700 m²/m³

- **Vendors requested to provide**
  - conceptual design, development plan, commercial cost estimate

- **Limited vendor response**
Vendor Inquiries for Recuperators

Recuperators for a 550 MWe power plant

• **Suggested materials:** Inconel (HTR), 316H (LTR)

• **Allow delta P to double -> 10 to 20 psi**
  – Allows over all mass to be reduced by 2x
  – Core matrix volume can be reduced by 25% cuts price in half

• **Cost range for mature commercial product**
  – (~$120M - ~ $280M)
  – Savings ~ $160 M yields 7.2% reduction in COE (0.88 Cents/kwh)

• **Challenges**
  – Balancing cost, performance and cycle optimization
  – Optimizing design for the application
  – Facilities for the fabrication of commercial systems
Recompression Brayton Cycle
## Recompression Brayton Cycle

### Baseline Cycle Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working fluid</td>
<td>CO₂</td>
</tr>
<tr>
<td>Compressor pressure</td>
<td>Varied</td>
</tr>
<tr>
<td>Compressor efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Turbine inlet temperature</td>
<td>1300 °F</td>
</tr>
<tr>
<td>Turbine exit pressure</td>
<td>1320 psia</td>
</tr>
<tr>
<td>Turbine efficiency</td>
<td>0.927</td>
</tr>
<tr>
<td>Cooler pressure drop</td>
<td>20 psia</td>
</tr>
<tr>
<td>Cooler temperature</td>
<td>95 °F</td>
</tr>
<tr>
<td>Heater pressure drop</td>
<td>20 psia</td>
</tr>
<tr>
<td>Heater duty</td>
<td>100 MMBtu/hr</td>
</tr>
<tr>
<td>Minimum temperature approach</td>
<td>10 °F</td>
</tr>
<tr>
<td>High temp recuperator cold side pressure drop</td>
<td>20 psia</td>
</tr>
<tr>
<td>High temp recuperator hot side pressure drop</td>
<td>20 psia</td>
</tr>
<tr>
<td>Low temp recuperator cold side pressure drop</td>
<td>20 psia</td>
</tr>
<tr>
<td>Low temp recuperator hot side pressure drop</td>
<td>20 psia</td>
</tr>
<tr>
<td>Cooler bypass fraction</td>
<td>0.2853</td>
</tr>
</tbody>
</table>
Recompression Brayton Cycle

Sensitivity to Pressure Drop

![Graph showing the relationship between cycle efficiency and cycle pressure drop. The graph indicates a downward trend as the cycle pressure drop increases. The cycle efficiency decreases from 54% to 51% as the cycle pressure drop increases from 0 to 200 psia.](image-url)
Recompression Brayton Cycle

Sensitivity Analysis to Cooler Bypass Fraction

Cycle efficiency (%) vs. Cooler bypass fraction
Recompression Brayton Cycle

Sensitivity Analysis to Turbine Efficiency

Cycle efficiency (%) vs. Pressure ratio

- TrbEff = 1.00
- TrbEff = 0.95
- TrbEff = 0.927
- TrbEff = 0.90
- TrbEff = 0.85
- TrbEff = 0.80
- TrbEff = 0.75
Materials Considerations for Recuperators

- TIT = 700°C -> recuperator inlet temp. would be ~ 580°C (1080°F) – red line
- Stress levels < ~10 ksi for SS and higher for more expensive nickel-alloys
FE Project Activities in SCO2 Based Power Cycles

- **Turbo Machinery for Indirect and Direct SCO2 Power Cycles**
  - Low-Leakage Shaft End Seals for Utility-Scale SCO2 Turbo (GE)
  - Adv. Turbomachinery Comp. for SCO2 Cycles (Aerojet Rocketdyne)
- **Oxy-fuel Combustors for SCO2 Power Cycles**
  - Coal Syngas Comb. for HP Oxy-Fuel SCO2 Cycle (8 Rivers Capital)
  - HT Combustor for Direct Fired Supercritical Oxy-Combustion (SwRI)
  - Oxy Fuel Combustion (NETL)
  - Autoignition and Combustion Stability of High Pressure SCO2 Oxy-Combustion (GA Tech)
  - Chemical Kinetic Modeling and Experiments for Direct Fired sCO2 Combustor (UCF)
- **Recuperators / Heat Exchangers for SCO2 Power Cycles**
  - Low-Cost Recuperative HX for SCO2 Systems (Altex Tech. Corp)
  - Mfg. Process for Low-Cost HX Applications (Brayton Energy)
  - Design, Fab, and Char. Microchannel HX for FE SCO2 cycles (Oregon State U)
  - HT HX for Systems with Large Pressure Differentials (Thar Energy)
  - Thin Film Primary Surface HX for Advanced Power Cycles (SwRI)
  - HX for SCO2 Waste Heat Recovery (Echogen / PNNL, SBIR)
- **Materials, Fundamentals and Systems (AT)**
  - R&D materials & systems (NETL)
  - Materials Issues for Supercritical carbon Dioxide (ORNL)
  - Thermodynamic and Transport Properties of SCO2 (NIST)
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# Thar Energy Recuperator Development Projects

## High Temperature Heat Exchanger Design and Fabrication for Systems with Large Pressure Differentials

**Thar Energy**
- Prime contractor
- Technical gap assessment
- Prototype recuperator
  - Design
  - Fabrication
- Test stand design and assembly
- Recuperator testing and evaluation

**SwRI**
- FEA modeling

**Bechtel Propulsion**
- Technical Support
  - Materials science
  - Prototype testing

## Technology Development of Modular, Low-Cost, High-Temperature Recuperators for sCO₂ Power Cycles

**Thar Energy**
- Prime contractor
- Technical gap assessment
- Design for manufacturing
  - Focus manufacturability & cost
  - Multiple design analysis
- Design for operability, prototyping, & fabrication
  - Down select
- Final Design for manufacturability
- Recuperator fabrication

**SwRI**
- Combined system engineering design
- Thermodynamic analysis
- FEA modeling

**ORNL**
- Materials science
  - Long-term corrosion resistance
  - Creep resistance
  - New alloy and/or coating formulation

**Georgia Institute of Technology**
- CFD simulation & analysis of heat exchanger concepts
In Summary Recuperator Challenges for SCO2 Power Cycles

• **Objectives**
  – Maximize heat transfer efficiency
  – Minimize pressure drop
  – Ensure even flow distribution
  – Minimize Cost

• **Challenges**
  – Seals and pressure containment
  – Materials strength and stability
  – Oxidation resistance
  – Fouling effects
DOE SCO2 Crosscut Initiative

• One of a handful of recognized intra-office DOE crosscut teams
• Nuclear Energy (NE), Fossil Energy (FE) and Energy Efficiency & Renewable Energy (EERE) collaborate on SCO2 power cycles
• Based on advantages of SCO2 power cycles
  – Heat source neutral
  – Applicability to wide range of stakeholders
  – Potential higher efficiency and lower COE
• Mission
  – Realize a lower COE with SCO2 power cycles compared to SOTA steam cycles
  – Reduce technical barriers and risks to commercialization
• Request for Information
  – RFI 1 & RFI 2

• Workshops
  – SwRI/NETL/SNL/NREL; June 2014; September 2014

• Symposium and Conferences
  – ASME IGTI Turbo Expo & Int. Symp. on SCO2 PC

• Collecting information for an effective solicitation
  – Technical approach and cost for a 10 MWe facility

• On going SCO2 base programs with FE, EERE and NE
  – Focusing on respective technology application issues
SCO2 Crosscut Initiative
Next Steps / Path Forward

- DOE Offices of NE, FE & EERE collaborating on this initiative
- “...gather information and engage industry to develop an effective solicitation for a public-private cost-shared supercritical carbon dioxide demonstration program....” (1)
- “..10-megawatt supercritical CO2 technology electric power (STEP) demonstration project..” (2)

(1) http://docs.house.gov/billsthisweek/20141208/113-HR83sa-ES-D.pdf;
(2) http://energy.gov/news-blog/articles/secretary-monizs-written-testimony-house-committee-appropriations-subcommittee
Summary

• **SCO2 power cycles provide an attractive alternative to the incumbent H2O based Rankine cycles**
  – Efficiency
  – Broad application to heat sources
  – Characteristic benefits

• **Unique and ubiquitous market entry points**

• **Near term technology challenges**
  – Recuperators
  – Turbomachinery
  – Materials
  – Controls
  – COE

• **DOE sCO2 Crosscut Initiative**
  – Plan for an effective cost shared solicitation
Upcoming Events

EPRI INTERNATIONAL CONFERENCE ON CORROSION IN POWER PLANTS
October 13 – 15, 2015 • Hilton Mission Bay • San Diego, California USA
NETL-EPRI WORKSHOP ON HEAT EXCHANGERS FOR SUPERCRITICAL CO₂ POWER CYCLES
October 15, 2015 • Co-located with EPRI International Conference on Corrosion in Power Plants

2015 UNIVERSITY TURBINE SYSTEMS RESEARCH WORKSHOP
November 3-5, 2015
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