Workshop on New Cross-cutting Technologies for Nuclear Power Plants

Session 2: Supercritical CO$_2$ cycle for advanced NPPs

MIT: Cambridge, MA : Jan 30-31, 2017

Steven A. Wright (PhD)
swright@supercritical.tech
505 452 7774

Mark Anderson (PhD)
manderson@engr.wisc.edu
608-263-2802

SuperCritical Technologies Inc.
Bremerton, Wa
Sandia National Laboratories (Retired)

University of Wisconsin
Madison, Wisconsin
Can we increase the efficiency/utilization? **YES**

The sCO$_2$ power cycle allows for high temperature heat and waste heat recovery, carbon capture. (Significant Market Potential)

Potential for Natural Gas/Coal with CO$_2$ Capture Oxy-Fuel Combustion Cycle (This is already being done by NetPower) 50MWth system

Advanced High Temperature CSP Energy Generation

Advanced High Temperature Nuclear Energy Generation

Increasing from 39% Eff to 50-55% Provides an LCOE = 6 – 7 ¢/kWh

Energy Generation from Waste Heat, NG-Compression, Industrial
T-S diagram for Split flow s-CO2 cycle

“Recompression” Cycle

- Higher operating temperature
- Higher thermal efficiency
- Single Phase
- Simplified Power Cycle

PC = 7.3 Mpa (1070psi), TC = 31°C (88F)
Larger Scale SCO2 Recompression Cycle

What is Supercritical Carbon Dioxide? Inert Abundant Gas

- Use of carbon dioxide (CO$_2$) above its critical point.
  - Critical temperature is 31.1°C (88°F).
  - Critical pressure is 7.39 MPa (1,072 psi).

  Low temperature acts like a liquid – High temp acts as a gas

- Currently used extensively as a solvent and occasionally as a refrigerant.
  - Dry cleaning, decaffeinating coffee, etc.

- Ideal for use in a power cycle---closer to the ideal Carnot Cycle ---
could displace the use of steam -> $10$’s of billions/year in potential technology.
  - With Condensation Efficiencies increase. “Transcritical Cycle”
  - Cascaded cycles are good for Sensible Heat (WHR, and Fossil)

Abundant – Inexpensive, Non-toxic, GWP=1
How is this cycle different from Rankine?

sCO$_2$ Turbine Region of Operation
What about capital costs?
The sCO₂ cycle is much smaller – less material

- sCO₂ cycle has potential for thermodynamic performance > steam Rankine
- Potential for improved capital cost saving
  - Turbine size: S-CO₂ < He << Rankine
  - Compressor size: S-CO₂ <<< He
  - Total pipe volumes: S-CO₂ << He
  - Cost of working fluid: S-CO₂ << He

sCO₂ has high power density


10MWe size comparison

50 kW (67 horsepower) compressor

Paul Pickard (SNL), 2004
Is it more complicated? No

The sCO2 cycle is also actually much simpler

\[ \eta_{\text{plant}} = 45\% \]

\[ \eta_{\text{plant}} = 39.8\% \]
There are Lots of $\text{SCO}_2$ Power Cycles

Cycles Appropriate for Heat Flux Based Heat Sources
Nuclear and Concentrated Solar Power (High Efficiency Cycles)

Simple closed recuperated Brayton cycle

Recompression cycle

Precompression cycle

Partial cooling cycle

Nuclear & CSP

SRBC

RCBC

Recompression Cycle has Highest Efficiency
Variations such as Condensing, Inter-Cooling, Reheating improve efficiency
Other Cycles available for Sensible Heat Power Systems

Source: Kulhanek M., Doshiertal V., Todynamic Analysis and Comparison of Supercritical Carbon Dioxide Cycles. Supercritical CO2 Power Cycle Symposium, May 24-25, 2011
Representative Cycle Efficiency

Recompression Brayton Cycle

(from McClung 2015)
sCO$_2$ Power Cycle: Advantages & Disadvantages

Advantages

1. 2-4 Percentage Points more Efficient than Steam Plants at same Turbine Inlet Temperature (Re-Compression Cycle is closer to the Ideal Carnot Cycle)
2. Small Turbomachinery (due to low pressure ratio => Lower Costs)
3. Operates well with Dry Cooling (Larger dT, Pinch Point is less Challenging, Benefits for CHP)
4. Operating Pressure is Same or Lower as in Steam
5. Integrates well with all Heat Sources + New Opportunities (Bulk Energy Storage)
6. Potential for Very High Temperature Operations (750-1200 C) (Eff 50-60%)
7. Oxy-Combustion Enables Fossil Fuels with Near Zero Emissions

Disadvantages

1. Added Capital Costs Due to Recuperation and High Temp. Heat Exchangers & High Nickel Steels
2. Very High Power Density in Turbine (Reliability needs Proving + New Design Req.)
3. Generally Needs Higher Mass Flow Rates than Steam (may limit size to 300-600 MWe)
4. Costly Materials at High Temperature
5. New Technology for Oxy-Combustion and High Power Density Turbines
CROSS CUTTING TECHNOLOGIES

Small Turbomachinery
Turbomachinery Support Hardware
Heat Exchangers
Materials

Supercritical Oxy-Combustion
sCO2 High Temperature Reactors
Turbomachinery is Small but High Risk
Heat Exchanger Costs Can Be Large (~50% depending on design)

SCO2 RCBC: 4 Heat Exchangers
Steam Rankine: 2 Heat Exchangers
Gas Turbine: 0 Heat Exchangers

Cost Break down

Tim Held Echogen
Example: 10 MWe Turbine Comparison

Turbomachinery Support Hardware
Seals (lower leakage, larger sizes)
Bearings (CO2 Hydro/static or dynamic)
High Speed Permanent Magnet Bearings and Generators
Hermetic Designs (Windage/Thrust)
High Turbine Power Density (Erosion)
Small Size complicates thermal management

Source: Persichilli et al. (2012)
Advanced Compact Heat Exchangers
Channel $D_h$ 1-2 mm : 1000-4000 $m^2/m^3$ High Pressure Capable

Micro Channel MCHE Diffusion Bonded Heat Exchanger

MICRO TUBE HX

U Stamp
Multiple Vendors
1-2 mm Width

Meets ASME Design Specs.
Tube and Shell Standard Welds Inspectable
Ustamp & Nstamp Capable
Less Material ...
Lower Cost
Robotic Assembly
Corrosion Resistance Issues?

Tubes & Headers
$\frac{1}{16}”$ to $\frac{1}{4}”$

Microtube HXs Lead to Cost Reductions
30%-100% for SS300 series steels
Factors of 2-4 for Advanced Alloys
sCO₂ Materials Research

Several groups, vendors and worldwide are looking at corrosion in CO₂ and there is a lot of collaboration in this area.

S-CO₂ Static autoclave testing

S-CO₂ Flow testing (corrosion/erosion)

Low speed HX test facility

Valve, seal, high speed flow test facility
Current Status of materials

Higher Creep Strength at Elevated Temperatures

Lower Corrosion at Elevated Temperatures
<table>
<thead>
<tr>
<th>Alloys</th>
<th>Oxide</th>
<th>Number Density</th>
<th>overall corrosion rate</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haynes 282</td>
<td>Elongated Nb-Ti rich oxide cluster (50um)</td>
<td>Low</td>
<td>(~1um-2um)/year@750C</td>
<td>Excellent corrosion resistance/good strength at temp</td>
</tr>
<tr>
<td></td>
<td>Cr rich oxide (&lt;1um)</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IN740</td>
<td>Elongated Nb-Ti rich oxide cluster (50um)</td>
<td>Low</td>
<td>(~1um-2um)/year@750C</td>
<td>Excellent corrosion resistance/good strength at temp</td>
</tr>
<tr>
<td></td>
<td>Cr rich oxide (&lt;1um)</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haynes 230</td>
<td>Elongated W rich oxide cluster (30um)</td>
<td>Medium</td>
<td>450C - &lt;1um/year</td>
<td>Good corrosion resistance. Needs to be looked at for higher temps.</td>
</tr>
<tr>
<td></td>
<td>Cr rich oxide (&lt;1um)</td>
<td>High</td>
<td>550C - &lt;1um/year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Octahedral Fe oxide cluster (30um)</td>
<td>Medium</td>
<td>650C - 5um/year</td>
<td></td>
</tr>
<tr>
<td>IN800H</td>
<td>Ti oxide cluster (20um)</td>
<td>Low</td>
<td>450C - 1-2um/year</td>
<td>Performed similar to 347 but cost is considerable higher</td>
</tr>
<tr>
<td></td>
<td>Cr-Mn rich oxide (&lt;1um)</td>
<td>High</td>
<td>550C - 5 um/year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Octahedral Fe oxide cluster (30um)</td>
<td>Medium</td>
<td>650C - 30 um/year</td>
<td></td>
</tr>
<tr>
<td>347SS</td>
<td>Nb oxide (&lt;1um)</td>
<td>Medium</td>
<td>450C - 5um/year</td>
<td>Alloy performed pretty well at most temps - started to fall off at 650 not suitable for higher temps</td>
</tr>
<tr>
<td></td>
<td>Needle Cr-Mn rich oxide scale</td>
<td>Whole surface with some spallation</td>
<td>550C- 5um/year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Octahedral Fe oxide cluster (20um)</td>
<td>High</td>
<td>650C - 35um/year</td>
<td></td>
</tr>
<tr>
<td>316L</td>
<td>Octahedral Fe oxide scale</td>
<td>70% of surface</td>
<td>450 C - 10um/year</td>
<td>Ok for lower temperatures 347 performed much better</td>
</tr>
<tr>
<td></td>
<td>Octahedral Cr-Mn rich oxide scale</td>
<td>30% of surface</td>
<td>550 C - 30-50um/year</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>650 C- 100 um/year</td>
<td></td>
</tr>
<tr>
<td>AFA-OC6</td>
<td>Nb oxide (&lt;10um)</td>
<td>High</td>
<td>450C - 1-2um/year</td>
<td>Ok for low temperatures/ alloy somewhat unstable</td>
</tr>
<tr>
<td></td>
<td>Cr-Mn rich oxide (&lt;1um)</td>
<td>Very high</td>
<td>550C- 5-10um/year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe oxide (&lt;10um)</td>
<td>Low</td>
<td>650C - 200um/year</td>
<td></td>
</tr>
<tr>
<td>P91/T122</td>
<td>Magnetite and spinel layers</td>
<td>100% coverage high corrosion rate</td>
<td>&gt;1000mu/year</td>
<td>not suitable for 450+</td>
</tr>
</tbody>
</table>

There is currently also work looking at impurities and coatings.
Dostal V., Driscoll MJ, Hejzlar P.,
Cross Cutting Technology Conclusions

- MIT Study on sCO₂ Power Conversion for Nuclear Reactors: Cross Cut Success
  - Fostered a New sCO₂ Power System Industry (Nuclear, CSP, WHR, Fossil) (see map)
  - Enables Burning of Fossil Fuels with Zero Emissions at Affordable Costs
  - Cross Cutting Support within DOE (EERE, FE, NE)

- Turbine is high risk component, but small and affordable
- Micro-tube Heat Exchangers offer low mass, small size and lower costs
- New Materials (Alloy 740 has high creep strength and low corrosion)
Current sCO2 work sites

- Echogen
- SwRI
- SNL
- Bechtel/NETL/Thar
- UW Madison/CompRex
- ANL/GTI
- UWM
- GE/KAPL
- EPRI

International:
Canada – Canmet/Uni
Australia - CSIRO
UK – universities
China - fossil/Uni
Korea – Uni/labs/industry
Japan – Uni/industry
India - Uni
sCO\textsubscript{2} Power and Reactors

Eff increase from 39% to 50% -55% Lowers Cap Cost and LCOE

Direct sCO\textsubscript{2} Reactors Lower Capital Costs and Lower LCOE Costs

No prim HX, No 2ndary HX, Smaller Reactor and Turbine Hall
Natural Circulation for Decay Heat Removal
Much higher efficiency (55%) at 850-900C

Indirect Cooled Reactors
Focus on Lower Cap. Costs
High Temp 700-750C and high 50% efficiency

Direct

\begin{center}
\begin{tabular}{c}
\textbf{sCO2 Gas} \\
\textbf{Cooled Reactor}
\end{tabular}
\end{center}

Indirect

\begin{center}
\begin{tabular}{c}
\textbf{Molten Salt} \\
Pb \\
\textbf{Sodium}
\end{tabular}
\end{center}

\begin{center}
\textbf{sCO2 Power Cycle}
\end{center}

LCOE = \left( \frac{\text{Project Cost} - \text{PV Tax Shield} + \text{PV Lifetime Operating Costs} + \cdots}{\text{Lifetime Electric Production}} \right)
sCO2 Power System Costs

SCT 5-10 MWe sCO2 WHR

- Plant Costs WHR 1.2-1.5 $/We n<sup>th</sup> of a kind

GE-(Dash et al. 2013) sCO2 Demo

- Net Power : 137.5 MW
- Efficiency : 49.31 %
- Plant Cost (10th unit) : 146.6 M$
- Plant Specific Cost: 1070 $/kWe
- No DM Water Plant, less O&M
- Suitable for remote operation & fast start

<table>
<thead>
<tr>
<th>Gas Turbine</th>
<th>15 MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>sCO2 Plant</td>
<td>5 MWe</td>
</tr>
<tr>
<td>Efficiency</td>
<td>47-48%</td>
</tr>
</tbody>
</table>
## Future: Advanced sCO2 Power System

### COST SUMMARY

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Cap Cost</th>
<th>LCOE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overnight Cost</td>
<td>Fuel Cost</td>
</tr>
<tr>
<td>Gen IV HT-Nuclear</td>
<td>tbd</td>
<td>tbd</td>
</tr>
<tr>
<td>[9] NuScale LWR-SMR</td>
<td>5078</td>
<td>10</td>
</tr>
<tr>
<td>sCO2 HTGCR eff-55% no HX *****</td>
<td>4000-5400</td>
<td>6.4 est</td>
</tr>
<tr>
<td>Nuclear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[8] NGCC (2016)</td>
<td>978</td>
<td>3 est</td>
</tr>
<tr>
<td>[7] NGCC CCS (2010)</td>
<td>1637</td>
<td>6.55</td>
</tr>
<tr>
<td>[7] Oxy-CES(Steam)</td>
<td>3146</td>
<td>6.55</td>
</tr>
<tr>
<td>NGCC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal Oxy-sCO2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[10] PC Coal-CO2 Indirect SWRI</td>
<td>5600</td>
<td></td>
</tr>
<tr>
<td>[12] PC Coal-CO2 Indirect BAH</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>[13] Coal-Gas CO2 Direct NetPwr</td>
<td></td>
<td>1.73</td>
</tr>
<tr>
<td>sCO2 System Estimates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Turbine or sCO2 Turbine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[11] NG-sCO2 GE Feasibility</td>
<td>1100</td>
<td>6.0 est</td>
</tr>
<tr>
<td>NG Direct Oxy-sCO2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[13] NG-NetPower Allam (2016)</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Oxy-CO2 Direct (2016) ***</td>
<td>1800-2800</td>
<td>3</td>
</tr>
</tbody>
</table>

1) Adv sCO2 Nuclear Competitive to NGCC
2) Existing Nuclear Competitive to NGCC – CCS
3) Oxy-Combustion Competitive to NGCC
sCO\textsubscript{2} Development Path

Next Step in sCO\textsubscript{2} Evolution

- Multiple 5-10 MWe or Greater Pilot Plant Systems (WHR or Biomass)
- Commercial (Echogen\& Affiliates, SuperCritical Technologies, Peregrine Turbines)

sCO\textsubscript{2} Systems High Temperature System

- Systems having: Zero Emissions using Fossil Fuels
  - Commercial Net Power, Toshiba, CBI, Exelon
- Systems having High Temp, High Efficiency for Reactors & CSP
  - US Government STEP Program + Other Nation States

Call for proposals for a 6 year $100M program (20% required cost share) to develop and test components of a 10MWe sCO\textsubscript{2} cycle that operates at 700C

Oct 17, 2016 DOE announced a $80M STEP initiative project award led by GTI with GE and SWRI as major team partners. Contract Negotiations are still in progress.

Caution: All early systems are Developmental
Conclusion: sCO₂ Reactor Business Model

• Proposal
  – US or International Corporation
  – Develop High Temperature, High Efficiency Reactor with sCO₂ Power Conversion (target 50-55% efficiency 50%)
    • Use known fuel cycle and fuel fabrication (oxide, coated particle)
    • Target Lower Specific Capital Costs to ~ $4000-5400/kW)
  – Investment Funding
    • Focus on Volume Sales, with preset PPAs, Contractual Sales Agreements if performance targets are met in a Pilot Plant
    • Operation of Pilot Plant Pays for the Demonstration Testing
  – Design Focus
    • Single loop, small foot print, natural circulation decay heat removal, 50-55% Efficiency, with known fuel processing capabilities
    • Factory Built SMR 100-250 MWe
    • Licensed via Nation State (US, Canada, UK, S. Korea, India, Indonesia, etc.)
    • Focus Markets on High Growth Regions (Africa, India, S.E. Asia, Pacific Nations)
  – Deal with Policy Issues
    • Fuel Fabricated in West, and Returned to West
    • Requires a Licensed Waste Repository