Oxy-Combustion Integration for Direct Fired sCO2 Cycles

Aaron McClung, Ph.D.
Southwest Research Institute
San Antonio, Texas, USA

Contact:
Aaron.McClung@swri.org
210-522-2677
Outline

• sCO2 Cycles
• Oxy-combustion
• Direct Fired Cycles Evaluation
• Wrap-up
DIRECT FIRED SCO2 POWER CYCLES
sCO2 Power Cycles

- Offer +3 to +5 percentage points over supercritical steam for indirect coal fired applications
- High fluid densities lead to compact turbomachinery
- Efficient cycles require significant recuperation
- Compatible with dry cooling techniques
Fossil Based sCO2 Power Cycles

• Competition
  – Indirect: Supercritical Steam with CCS
  – Direct: Natural Gas Combined Cycle

• Advantages
  – High power efficiencies at “Moderate” temperatures
  – Oxy-combustion facilitates integrated carbon capture
  – Compact turbomachinery lead to compact power blocks
Challenges

• Challenges
  – 250 C thermal input temperature widow (recompression cycle) is not ideal for combustion based systems
    • 400 C Combustor inlet for 650 C Turbine Inlet
    • 950 C Combustor inlet for 1200 C Turbine inlet
  – Flue gas cleanup for direct fired systems
  – Non-trivial efficiency losses for indirect cycles
  – Compact power block offset by recuperation requirements
OXY-COMBUSTION
Oxy-combustion

- Combustion in an oxygen rich environment
  - Used for industrial applications for achieving high combustion temperatures
  - Commonly used in metal, glass, and cement industries

- Atmospheric Nitrogen is replaced by the combustion flue gas which is primarily Carbon Dioxide
  - Provides CO2 rich stream for capture and sequestration
  - Minimizes NOx formation
Flavors of Oxy-Combustion

• Flue Gas Recirculation
  – Combustion at near ambient pressures
  – Recycled flue gas is mixed with incoming air
  – Increases flame temperatures
  – Increases CO2 concentration for CCS

• Pressurized Oxy-combustion
  – Combustion at elevated pressure (~ 10 bar)
  – Latent heat is recoverable and heat transfer rates are increased
  – Minimizes air in-leakage

• Supercritical Oxy-combustion
  – Combustion occurs at supercritical pressures (>74 bar)
  – Required for direct fired sCO2 cycles, compatible with indirect cycles
  – CO2 acts as a solvent in dense phase, accelerating certain reactions
  – Compression requirements drive closed combustion solutions
  – Flue gas cleanup and de-watering at pressure may be challenging
Challenges

• Oxygen generation is not cheap
  – Cryogenic oxygen separation is current state of the art for commercial Air Separation Units
  – 250 to 360 kWh/ton of O2

• Higher power block efficiencies required to offset ASU power usage
Supercritical Natural Gas Oxy-combustion

• Natural gas simplifies fuel feed system, enables higher operating pressures
  – Requires Oxygen compression
• Simplifies flue gas cleanup
  – No solids removal
  – Fewer impurities to consider than coal
• Combustion system must operate at cycle conditions between 200 and 300 bar
• To achieve plant efficiencies approaching 55%
  – Drives cycles to turbine inlet temperatures near 1200 C to achieve power block efficiencies near 65%
  – ASU is still a significant power sink at 250 to 360 kWh/ton
• Oxy-combustor operating at 200+ bar is a significant technical risk
  – Oxy-combustor inlet temperatures enable an auto-ignition style combustor
  – Reaction rates and mechanism are well outside current literature
  – Radiant effects uncertain
Kinetics Knowledge Base

- **Pressure**
  - Sparse data at high pressure, low CO₂
  - Well-Developed Mechanisms
    - P up to 20 bar
    - $x_{CO₂} < 0.10$ (mostly as product)
  - Knowledge front
  - Sparse data at low pressure, high CO₂
  - No data at high pressure, high CO₂

- **Current Application**
  - P up to 290 bar
  - $x_{CO₂}$ up to 0.96 (mostly as diluent)

- **CO₂ concentration**

No data available at conditions relevant to this application.
Development Path

• System Design and Thermodynamic Analysis
  – Evaluate cycles to determine combustor design parameters

• System level Technology Gap Assessment

• Kinetics Models
  – Evaluate kinetic models to determine applicability
  – Initial kinetic evaluation at combustor inlet conditions

• Combustor Concept
  – Material constraints at 1000 C 200 bar inlet, 1200 C 200 bar outlet conditions

• Combustor demonstration
SYSTEM ENGINEERING DESIGN AND THERMODYNAMIC ANALYSIS
Thermodynamic Analysis

• Establish combustor operating parameters
  – Inlet Temperature, Pressure, mass flow
  – Thermal duty

• Plant models were developed and evaluated using ASPEN Plus
  – Incorporated secondary systems
    • ASU, Cooling, Fuel Compression
  – Incorporated equilibrium combustion model
Direct Fired Supercritical Oxy-Combustion

- Plant optimization focused on thermal efficiency
  - Target 52% plant efficiency to compete with NGCC
  - Drives 64% power cycle thermal efficiency
  - Turbine inlet near 1200°C
Metrics for Cycle Evaluation

• Combustor inlet temperature
• Overall cycle efficiency
• Overall heat exchanger area
• Volume flowrate per power out (turbine size)
• Power per mass flowrate
• Amount of high temperature piping/components needed
Recompression Cycle

- Leverages recent SunShot and DOE-NE cycles development
- High efficiencies possible for the power block, 60% at 1100°C, 65% at 1300°C
- High degree of recuperation drives a narrow thermal input window (~250°C) and high mass flow requirements
- Combustor inlet ~ 950°C for 1220°C Firing Temperature
Partial Condensation Cycle

- Trans-critical cycle
- Optimization schedules the vapor phase compression, cooling for liquefaction, and liquid pumping to reduce compression power requirements
Oxy-Combustion Plant Model
Cycle Analysis Results

• Recompression cycle has highest efficiency by 1.8% at 200 bar, 2.7% at 300 bar

• Condensation cycle is superior in all other metrics
  – Reduced recuperation (~ 50%)
  – Lower combustor inlet temperature
  – Higher power density (power output / flow rate)

• Both cycle configurations are compatible with an *auto-ignition* style combustor for 1200 C Turbine inlet temperatures.
## Cycle Comparison

<table>
<thead>
<tr>
<th></th>
<th>Single Recuperator Condensation</th>
<th>Single Recuperator Condensation</th>
<th>Recompression</th>
<th>Recompression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net fuel to bus bar plant efficiency</td>
<td>54.03%</td>
<td>51.60%</td>
<td>56.73%</td>
<td>53.44%</td>
</tr>
<tr>
<td>Total Recouperation (kW)</td>
<td>989.91</td>
<td>1078.16</td>
<td>1163.44</td>
<td>1205.34</td>
</tr>
<tr>
<td>HE Duty per Net Power Ratio (kW/kW)</td>
<td>2.48</td>
<td>3.21</td>
<td>4.34</td>
<td>6.55</td>
</tr>
<tr>
<td>Power per Mass Flow Ratio (kJ/kg)</td>
<td>399.06</td>
<td>335.38</td>
<td>268.08</td>
<td>183.92</td>
</tr>
<tr>
<td>Combustor Inlet Temp. (°C)</td>
<td>755.18</td>
<td>808.60</td>
<td>918.16</td>
<td>994.37</td>
</tr>
<tr>
<td>Combustor Inlet Pres. (bar)</td>
<td>300.00</td>
<td>200.00</td>
<td>300.00</td>
<td>200.00</td>
</tr>
</tbody>
</table>

**Cycles evaluated at 1200°C Turbine Inlet Temperature and unit 1 kg/s mass flow**
Modeling Considerations

- Combustion Models
- Equation of State
- Component Assumptions
- Dewatering and Cleanup
- Off design
- Transients
Takeaway

• Supercritical oxy-combustion has specific challenges that must be addressed through component development
• ASU power requirements drive the cycle conditions
• Supercritical natural gas oxy-combustion is feasible, has significant development requirements
  – Uncertainties related to the dense phase oxy-combustor
  – Fundamental combustion properties
  – Design for high temperature and high pressure
• Impact of water and flue gas impurities must be considered for material selection and corrosion
• High operating temperatures required to compete with NGCC
  – Requires material development, characterization, and certification
  – Impact of corrosion in hot CO2 environment not well understood
  – Requires advanced turbine cooling technologies for blades and seals
• Intermediate temperature combustor demonstration is a stepping stone
THANK YOU FOR YOUR ATTENTION