Direct Fired Oxy-Fuel Combustor for sCO2 Power Cycles

Jacob Delimont, Ph.D.
Aaron McClung, Ph.D.
Southwest Research Institute

Marc Portnoff
Lalit Chordia, Ph.D.
Thar Energy L.L.C.

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Outline

• Phase I Overview
  – Background
  – Project Objectives
  – Phase I Progress
    • Cycle Modeling
    • Chemical Kinetics
    • Preliminary Combustor Design
    • Bench-top Combustor Test

• Phase II Project Plan
What is a sCO2 cycle?

- **Closed Cycle**
  - Working fluid is CO2
- **Cycle Type**
  - Vapor phase
  - Transcritical
  - Supercritical
- **Supercritical CO2 has:**
  - High fluid density
  - High heat capacity
  - Low viscosity
Why 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

Third Generation 300 MWe S-CO2 Layout from Gibba, Hejzlar, and Driscoll, MIT-GFR-037, 2006
Why Oxy-Fuel Combustion?

- Capture 99% of carbon dioxide
- Higher turbine inlet temperatures possible
Project Objectives

• Optimize the supercritical CO2 power cycle for direct fired oxy-combustion
  – Target plant conversion efficiency is 52% (LHV)

• Technology gap assessment for direct fired plant configurations

• Develop a high inlet temperature oxy-combustor suitable for the optimized cycle
  – Target fuels are Natural Gas and Syngas
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Oxy-Combustion Plant Model

De-watering and Cleanup

Fuel, Oxidizer, and Combustion

11/3/2015
2015 University Turbine Systems Research Workshop
Condensation and Recompression Cycles
Cycle Analysis Results

• Recompression cycle has highest efficiency
  – 53.4% at 200 bar, 56.7% at 300 bar
• Condensation cycle
  – 51.6% at 200 bar, 54.0% at 300 bar
  – 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.
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Kinetic Model: Motivation

- The fundamental size of the combustor is governed by the timescale of chemical reactions.
- The chemical reaction kinetics determine how fast fuel oxidation occurs.
  - A detailed chemical kinetic model is required to size the combustor.
  - A reduced chemical kinetic model is required for detailed flow-field design in CFD.
Kinetics Knowledge Base

Well-Developed Mechanisms
P up to 20 bar
$x_{CO_2}$ < 0.10 (mostly as product)

Pressure
Sparse data at high pressure, low CO$_2$

Current Application
P up to 200 bar
$x_{CO_2}$ up to 0.96 (mostly as diluent)

CO$_2$ concentration
Knowledge front
Sparse data at low pressure, high CO$_2$

No data available at conditions relevant to this application.
Mechanism Selection

• Primary selection criterion is accurate prediction of the overall reaction time scales
  – Drives the combustor design
  – More important than other details such as peak concentration values

• USC-II is the clear choice based on this criterion
  – Most accurate in highest pressure flamespeed and autoignition validation comparisons

• USC-II also had good to adequate performance in low pressure CO$_2$ studies

• USC-II predictions should carry +/- 50% uncertainty in this application
Reduced Order Model

- For incorporation into a CFD model a reduced order model was developed
- Equations based on Arrhenius rate equation were tuned to match USC-II model predictions
  - Match autoignition delay
  - Match residual CO levels
  - Overall time to complete reaction
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Mixing vs. Kinetics Time Scales

- Time scale of reaction kinetics is much smaller than physical mixing time scales
- Combustion size and length governed by physical mixing
- Use of CFD with finite rate chemistry to model this
Initial Combustor Concept

- Multiple 90° O₂ injection jets
- Multiple 90° fuel injection jets
- Pressure vessel
- 950°C CO₂ inlet
- Solid liner
- Oxidizer premixing zone (jet-in-crossflow)
- Cold CO₂ – regenerative cooling
- Distributed reaction zone (stabilized by autoignition)

Fuel vs. oxidizer jet clocking

O₂ injection plane

Fuel injection plane

Centerline

SwRI

11/10/2016

2016 University Turbine Systems Research Workshop
CFD Model Setup

• ANSYS CFX 16.2
• Unstructured mesh
  – Boundary layer and injection region refinement
  – 4 million elements
  – Mesh sizes from 2 to 17 million elements for independence study
• Finite rate chemistry
  – Extrapolated reduced order equations
Temperature in 45° Clocked Case

Temperature Streamline 2

Temperature Contour 5

Ave Temperature (K)

Max Temperature (K)

Temperature (K)

Axial Distance (m)
Change Injection Spacing

- Injection oxygen and fuel need not be at the same location
- Auto-ignition allows even small concentrations of fuel+oxidizer to react
Final Design: Fuel Injection 24in Upstream

- Fuel well mixed throughout combustor before oxygen
- Allows hydrocarbon “cracking” before oxygen injection
- Cooler max temperatures
- Very good mixing at outlet
- Very low unburnt fuel percentage
Preliminary Mechanical Design

• Thermal design
  – Thermal containment using refractory insulating layer
  – Cooling CO₂

• Mechanical design
  – Utilizes stainless steel ANSI pipe and flanges
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Bench-top Combustor Test

• Small bench top test to study proof of concept, autoignition delay, and chemical kinetics
• Once through type system
  – 200 bar pressure
• Electric heaters used to set inlet temperature
• Jet in cross flow type fuel and oxidizer injection
Test Stand Loop Design
Oxy-fuel Test Reactor

- Machined from Haynes 230 bar stock
- Instrumentation standoff tubes welded to main combustor
- Two stage pre-heater to achieve 925°C combustor inlet
- Water jacketed gas sampling
Fuel and Oxygen Injector Design

- Precise sapphire orifice set into stainless steel mount
- Orifice constriction placed close to the combustor
- Mounted inside welded in place standoff
Combustor Test Stand
Test Stand Assembly

- Testing at Thar’s facility in Pittsburg, PA
- Outdoors with remote operation
Instrumentation

- Thermocouples in combustion zone
- Dynamic pressure transducers
- Three gas sampling ports
  - Optical emission spectroscopy (OES) to analysis chemical makeup
Optical emission spectroscopy (OES)

- Utilizes a plasma generator to identify chemical species
- Requires rapid thermal quenching of sample to halt chemical reactions
- SwRI has experience using OES for gas species analysis
Test Stand Operation

• Shake down tests
  – Observed auto-ignition combustion during shakedowns at full pressure and 80% temperature

• Component failures
  – Backpressure control valve
  – Mass flow controllers
    • Viton rubber does not mix with sCO2
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Phase II

• Complete detailed design
• Fabricate combustor and test loop
• Shake down and commission
• Test combustor
• Phase II duration: 3.5 years
• Partnered with Thar Energy, Georgia Tech, UCF and GE Global Research
Detailed Combustor Design

• Develop more detailed and accurate combustion kinetic mechanisms
• Utilize CFD to study combustion flow field
• Detailed thermal and mechanical design
• Final design for manufacturing
Combustor Integration with Sunshot Test Hardware
Combustor Integration

- Utilize existing Sunshot hardware
- Install oxy-fuel combustor
  - Demonstrate a direct fired oxy-combustor in a closed Brayton cycle
  - Evaluate combustor performance
  - Evaluate flue gas cleanup
  - Indirect heater allows for various combustor inlet conditions to be studied

Oxy-Combustor added downstream of indirect heater

Add flue gas cleanup and water separation
Planned Test Measurements

• Multiple OES sample locations
• Temperature measurements
• High speed pressure measurement for acoustic phenomena
• Study water dropout and separation
• Possible measurements
  – Optical access for advanced diagnostics
  – Materials sample testing
QUESTIONS?