Staged, High Pressure Oxy-Combustion Technology: Development and Scale-Up

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Project Overview

Project Objectives: Phase II

Design and build a laboratory-scale facility and conduct laboratory-scale experiments and complimentary modeling that address the technical gaps and uncertainties addressed in Phase I. Advance SPOC technology to TRL-5.

Funding

Total project (Phases I & II): $5,243,789

DOE share: $4,137,184
Cost share: $1,106,614

Project Performance Dates

10/01/2012 - 09/30/2017 (extended)

Project Participants

Washington University – Lead: SPOC development, experiments
EPRI – Technology evaluation, end-user insight, corrosion
ORNL – Corrosion study
Technology Background
Pressurized Oxy-Combustion

• The requirement of high pressure CO\(_2\) for sequestration enables pressurized combustion as a tool to increase efficiency and reduce costs.

• Benefits of Pressurized Combustion
  – Recover latent heat in flue gas
  – Latent heat recovery can be combined with integrated pollution removal
  – Reduce gas volume
  – Avoid air-ingress
  – Higher partial pressure of O\(_2\)
  – Optically dense atmosphere
Motivation for SPOC

Key Features:

Improve capital costs by:

- Optimizing use of radiation to minimizing heat transfer surface area
- Minimizing recycled flue gas (RFG)
- Minimizing equipment size
- Utilizing modular boiler construction

Improve operating costs by:

- Maximizing plant efficiency
  - Low FGR
  - Dry feed
  - Minimizing oxygen requirements
- Utilizing “lead chamber” process for SOx & NOx removal
- Increasing performance of wet, low BTU fuels
SPOC Process Flow Diagram

For a 550 MW_e power plant with > 90% CO_2 capture

courtesy of EPRI

Modeling parameters from DOE NETL Guidelines
SPOC Process Flow Diagram

For a 550 MW<sub>e</sub> power plant with > 90% CO<sub>2</sub> capture

Modeling parameters from DOE/NETL Guidelines
courtesy of EPRI
### Plant Efficiencies

**a) supercritical steam conditions, net power output = 550 MW**

<table>
<thead>
<tr>
<th></th>
<th>Air-fired</th>
<th>Atmos. P oxy-combustion</th>
<th>SPOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal type</td>
<td>Illinois #6</td>
<td>Illinois #6</td>
<td>Illinois #6</td>
</tr>
<tr>
<td>Net generating efficiency, HHV (%)</td>
<td>39.3</td>
<td>29.3</td>
<td>36.7</td>
</tr>
</tbody>
</table>

**b) independent study comparing two pressurized oxy-combustion processes**

<table>
<thead>
<tr>
<th></th>
<th>Air-fired</th>
<th>Atmos. P oxy-combustion (conservative)</th>
<th>Atmos. P oxy-combustion (optimized)</th>
<th>Pressurized oxy-combustion ISOTHERM</th>
<th>Pressurized oxy-combustion SPOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net generating efficiency, LHV (%)</td>
<td>46.1</td>
<td>36.1</td>
<td>39.1</td>
<td>38.4</td>
<td>42.3</td>
</tr>
</tbody>
</table>

- 25% improvement in plant efficiency over first-generation oxy-combustion

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Technical Approach/Project Scope
Work Plan

Tasks

1. Project management
2. Design, fabrication and installation of high pressure combustion furnace
3. High pressure combustion experiments (heat flux, temp, ash, deposition)
4. Materials corrosion studies (high O\textsubscript{2} and SO\textsubscript{2} environments)
5. Modeling direct contact cooler
6. Re-evaluation of burner/boiler design
7. Update process model and techno-economic analysis
Projected Phase 2 Outcomes

• Proof of concept demo of coal combustion under SPOC conditions.

• Improved understanding of radiation heat transfer in pressurized oxy-combustion conditions

• Improved understanding of ash formation/deposition mechanism in pressurized oxy-combustion conditions

• Knowledge of performance of boiler tube materials under SPOC conditions

• Improved estimate of SOx, NOx removal efficiency in direct contact cooler

• Reduced uncertainty and contingencies → improved COE
Progress and Current Status:
Key Considerations for Improved Low-Recycle Pressurized Oxy-Combustion Burner-Combustor

• High pressure
  o Pressure vessel – cylindrical: high aspect ratio.
  o Requires distribute heat release.
  o Requires control of soot formation.

• Low-recycle (high T flame)
  o Avoid flame impingement.
  o Avoid excessive heat flux
  o Control oxygen concentration near boiler tubes.
  o Control soot formation.

• Minimize ash deposition (fouling & slagging).
• Ensure resilience to variations in flow conditions.
• Obtain high turn-down operation.
Key Considerations for Improved Low-Recycle Pressurized Oxy-Combustion Burner-Combustor

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Reduce Buoyancy Effects

- Richardson number—buoyancy vs convection. $Ri_x = g \beta (T_{hot} - T_{surr}) \frac{x}{v^2}$

- Option 1. Shrink diameter to increase $v$—loose heat transfer surface area.

- $Q_{\text{gas}}$ increases due to 1) increase in $T$, & 2) gas generation via $C(s) \rightarrow CO_2 (g)$

- Option 2. Reduce inlet size of reactor—incase axial velocity.

- Tapered design-low $Ri$ everywhere.
Radiation in axial flow combustion

- Incoming radiation
- Absorbed
- Scattered
- Emitted
- Outgoing radiation

- Oxidizer
- Fuel
- Oxidizer

- Incident radiation

Adapted from Xia, et al. (2016)
Optically dense medium.

Wall heat flux only dependent on the temperature distribution in the radiation penetration layer ($\delta_{RP}$).

Very high core temperatures acceptable if temperature in $\delta_{RP}$ controlled.

At high pressure:

- Optically dense medium.
- Wall heat flux only dependent on the temperature distribution in the radiation penetration layer ($\delta_{RP}$).

Radon penetration layer

\[
\tau_w = 2.3
\]

\[
-x \ln \left( \frac{I}{I_0} \right) = \tau_w(x)
\]

\[
= \int_{x}^{x_w} [N_p(x)c_{ext}(d_p)]dx
\]

($\tau_w = 2.3$; transmissivity $\approx 10\%$)

$x$: Distance from the wall

$T$: Temperature

$\tau_w$: Optical thickness from the wall

Gopan et al. (2017a in review); Xia et al. (2016)
Burner/Boiler Design

10 m

45.3 m

$O_2 + CO_2$

Coal + CO$_2$

Coal + CO$_2$

$O_2$

Gopan et al. (2017a in review)
Burner/Boiler Design

Gopan et al. (2017a in review)
Central-Oxygen Burner – Flame Shapes

Three main flame shapes with an over-ventilated triaxial flame:

Unacceptable
Flame impingement – high heat flux

Acceptable
But low central oxygen => more recycle

Preferable solution

Gopan et al. (2017a in review)
SPOC Boiler Results

SO \([O_2]\) = 35 vol.%

High temperature in the core of the boiler
But, low temperature in the radiation penetration layer.

Refractory wall

Conical frustum

Gravity

Wall heat flux (kW/m²)

Distance from the burner outlet (m)
High temperature in the core of the boiler
But, low temperature in the radiation penetration layer.

SO$_2$ = 35 vol.%

Refractory wall

Conical frustum

Gravity
Effect of Mixing – Central Oxygen Flow

$SR_{\text{CentOx}} = \frac{\text{Central O}_2 \text{ Supplied}}{\text{Total O}_2 \text{ Required}}$

Radiative heat flux (kW/m$^2$)

Distance from the burner outlet (m)
Soot Comparison – Normal vs. Tri-axial

<table>
<thead>
<tr>
<th>Configuration</th>
<th>IO Flow (m³/h)ᵃ (pure oxygen)</th>
<th>Fuel stream flow (m³/h)ᵃ</th>
<th>Fuel stream [CH₄] (%v)</th>
<th>SO Flow (m³/h)ᵃ</th>
<th>SO Stream [O₂] (%v)</th>
<th>SR_IO</th>
<th>SR_Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0</td>
<td>3.1</td>
<td>62.7</td>
<td>19.7</td>
<td>45.5</td>
<td>0</td>
<td>2.3</td>
</tr>
<tr>
<td>Triaxial</td>
<td>2.7</td>
<td>3.1</td>
<td>62.7</td>
<td>17.0</td>
<td>36.8</td>
<td>0.7</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Total # concentration:
- Normal: $1 \times 10^6$ #/cm³
- Tri-axial: $1 \times 10^4$ #/cm³
Particle Deposition in Conventional and SPOC Boilers

High-mixing traditional systems

Wall-fired  T-fired

Inertial impaction is dominant

Low-mixing, axial flow SPOC

\[ \overline{u_n} > 0 \]

\[ \overline{u_n} = 0 \]

\[ \sqrt{u_n'^2} < \overline{u_n} \]

Eddy impaction & thermophoresis dominant
Deposition temp. in non-isothermal flows

- Non-dimensional deposition temperature
  \[ T_d^+ = \frac{\rho g c_p g u^* (T_d - T_w)}{\dot{q}} \]

- \( S^+ > 10 \quad S^+ < 1 \)
- Edge of viscous sublayer \( y^+ = 5 \)

- \( S^+ \) determines residence time
- \( S_T^+ \) determines cooling speed

\[ T_d^+ = f (S^+, S_T^+) \]

SPOC particle deposition

• CFD simulation results

The average particle impact rate in the SPOC boiler is an order of magnitude lower than that in conventional PC boilers.\(^1\)

The temperatures of all ash deposits are lower than 850 °C, which is much lower than the ash fusion temperature. Slagging is unlikely.\(^2\)


\(^2\) Yang et al. (2017 in prep); Gopan et al. (2017c in prep);
Pressurized Oxy-Combustion Facility

Objectives:
• ~100 kW test under SPOC conditions
• Wide operating range, pressure 1-15 bar, oxygen concentration 21~100%

Capabilities:
• Visual access of flame shape
• Laser diagnostics
• High-speed, high-resolution camera
• Heat flux sensors
• Pressurized sampling (gas & particle)
  o CEMS, FTIR, SMPS, ELPI

DOE
U.S.-China CERC
CCCU
Pressurized Oxy-Combustion Facility

- Oxygen
- Carbon dioxide
- SO₂, NO
- Water

Diagram showing components:
- Coal feeder
- Quartz viewport
- Refractory combustion zone
- Exhaust gas
- Quench water spray
- Sampling probe inlet
- Exhaust

Additional notes:
- ESP (future)
- DCC (Installed in 2017)
- Pressure control valve
- CEM Gas Analyzer
High-Speed Video
SPOC Status

Next steps:

- U.S.-China Clean Energy Research Center (CERC-ACTC)
  - Increasing scale of existing facility
  - Advancing technology to Pre-FEED for pilot scale facility

  - Will discuss in next talk

- Enabling Staged, Pressurized Oxycombustion: Improving Flexibility and Performance at Reduced Cost DE-FE0029087
  - EPRI (Lead), Doosan Babcock, Air Liquide and WUSTL
Development Roadmap

Full Scale
- Process & Techno-Econ Models
- CFD Boiler Design
- Dynamic Process Modeling
- LES Simulation

Pilot Scale
- Pre-FEED
- Commission Test Facility
- Pollutant Removal Demo

Lab Scale
- Materials Evaluation

>100 MW
- 2012
- 2014
- 2016
- 2018
- 2020
- 2022
- 2024
- 2026

10 MW

0.1-1 MW
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