Technology Demonstration of a High-Pressure Swirl Oxy-Coal Combustor

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American Air Liquide
Grant No:  
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Project Title:  
Technology Demonstration of a High-Pressure Swirl Oxy-Coal Combustor

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The University of Texas at El Paso  
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Project Period:  
10/01/2016 (01/01/2017)-09/30/2019 (12/31/2019)

Project Manager:  
Mark Freeman
Agenda

- Introduction and Background
- Objective and Timeline
- Cycle Analysis
- Combustor Design
- Secondary Burner & Ignitor
- Injector Design
- Injector Water Test
- Exhaust System Concept
Introduction & Background
Pressurized Oxy-Coal Combustion

- **Pressurized oxy-coal combustion systems**
  - Improve efficiency by recovering latent heat of the steam in the flue gas
  - Achieve 90% CO2 capture [1]
  - Smaller system size and capital cost due to the reduction of flue gas at higher pressure

- **Swirl burners**[2]
  - Widely used combustion devices
  - Have superior flame holding
  - Higher conversion rate
  - Low pollutant emission characteristics


Proposed Cycles

ThermoEnergy Integrated Power System (TIPS) Cycle\textsuperscript{[1,2]}:
- Proposed and studied by CANMET and Babcock Power
- Contain:
  - Flue Gas Condenser (FGC)
  - Radiative and convective heat exchangers
- Suggested pressure with the benefit of latent heat recovery:
  - CANMET: 80 bar
  - Babcock Power: 20.7 bar

ENEL Cycle\textsuperscript{[1,2]}:
- Based on combustion process patented by ITEA and analyzed by MIT
- No use of radiant heat exchanger
- Most of the latent heat can be recovered at 11 bar

Objectives & Timeline
Objectives

Objective 1: Systems Configuration Analysis of a 1 MW_th Pressurized Oxy-Coal Swirl Combustor
- 550 MW_e TIPS and ENEL pressurized oxy-coal systems with CO2 recirculation modeled with ASPEN PLUS®

Objective 2: Design and Construction of a 1 MW_th Pressurized Oxy-Coal Swirl Combustor
- Detailed structural analysis
- Flow and combustion optimizations
- Manufacturing (conventional and advanced additive manufacturing)

Objective 3: Test of the Combustor Performance and Operability
- Flame stability analysis and flame temperature and heat flux measurements at range of pressure
- Swirl number (ratio of axial flux of the angular momentum to the axial flux of axial momentum)
- Flue gas analysis will be performed to produce fundamental combustion information
  - Effects of pressure
  - Swirl number
  - Stoichiometric ratio on burnout
  - Pollutant emissions
Timeline

- Kick off meeting: 12/01/2016
- Updated project management plan: 12/01/2016
- Determination of combustor operating conditions: 1/23/2017
- Analysis results of flue gas and CO₂ recirculation: 1/23/2017
- Technology gap analysis review: 10/17/2017
- Pintle injector design: 5/1/2018
- Preliminary design review: 7/18/2018
- Water test for the pintle injector: 9/1/2018
- Critical design review: 10/10/2018
- First article assembly: 4/10/2019
- Shake down test results: 5/20/2019

2016: OCT FEB JUN OCT FEB JUN OCT FEB

2019: OCT FEB
Cycle Analysis
ENEL

Main sections:
- Upstream
- Heat Exchanger
- Carbon Capture Unit

Has convective heat exchanger

Turbomachinery must operate up to 10 bar pressure

Increased efficiency
**TIPS**

- **Main sections:**
  - Upstream
  - Heat Exchanger
  - Carbon Capture Unit

- Has radiative heat exchanger in addition to convective heat exchanger

- Turbomachinery has to operate up to 80 bar pressure
**Cycle Analysis**

- **Cycle Simulation Parameters:**

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Flow Rate [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>18.87</td>
</tr>
<tr>
<td>Water</td>
<td>16.15</td>
</tr>
<tr>
<td>Oxygen</td>
<td>50</td>
</tr>
</tbody>
</table>

  **Equivalence Ratio: 0.95**

  **Total Thermal Input: 550 MW**

- **Simulations Completed:**

<table>
<thead>
<tr>
<th>Case</th>
<th>Recirculation Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20%</td>
</tr>
<tr>
<td>2</td>
<td>35%</td>
</tr>
<tr>
<td>3</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>65%</td>
</tr>
<tr>
<td>5</td>
<td>75%</td>
</tr>
</tbody>
</table>
Efficiency

- Efficiency Ranges
  - ENEL = 26-38%
  - TIPS = 32-35%

- ENEL increases the burning rate of char and the heat transfer rates in the convective sections of the heat transfer equipment[1]

- ENEL reduces the energy penalties
  - Turbomachinery

Combustor Design
Combustor Design
Power Head

- Reactants Direction
- Secondary Burner #1
- Igniter #1
- Igniter #2
- Secondary Burner #2

Combustor Design
Secondary Burner & Igniter
## Design Methodology (Igniter)

### Operational Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Pressure</td>
<td>5 - 20 bar</td>
</tr>
<tr>
<td>Total Mass Flow</td>
<td>4.5 - 9 g/s</td>
</tr>
<tr>
<td>Maximum burn time</td>
<td>5 s</td>
</tr>
<tr>
<td>Igniter Body Temperature</td>
<td>150 – 800 K</td>
</tr>
</tbody>
</table>

![Igniter Diagram](image-url)
Secondary Burner

- Two secondary burners
  - 125kW firing input each

- Co-axial shear injector
  - Fuel centered

<table>
<thead>
<tr>
<th>Mass Flow Rate</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>2.5 g/s</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>10 g/s</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>12.5 g/s</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Velocities</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>23.14 m/s</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>4.20 m/s</td>
<td></td>
</tr>
<tr>
<td>Velocity Ratio</td>
<td>5.51 N/A</td>
<td></td>
</tr>
<tr>
<td>Momentum Flux Ratio</td>
<td>15.38 N/A</td>
<td></td>
</tr>
</tbody>
</table>
Secondary Burner Test
Secondary Burner Test

Ignition

Pressurization

Operation

Depressurization
Secondary Burner Test

Ignition

Pressurization

Operation

Depressurization
Secondary Burner Test
Secondary Burner Test

Ignition → Operation → Pressurization → Depressurization
Secondary Burner Test

- Ignition
- Pressurization
- Operation
- Depressurization
Injector Design
Benefits
- Utilized for liquid injection
- Wide range of firing input
- 90% of burning efficiency

Pintle Injector History
- Developed in mid 1950s[1]
- Atomization and mixing propellants in rocket engines
- Performance in range of 96-99%[2]

Design Criteria
- Coal slurry as fuel (Radially)
- Gaseous oxygen as oxidizer (Axially)

Advantages
- Variety of firing input
- Range of spray angle
- Maintenance

Coal Slurry
- The coal powder mixed with water
- The percentage of solids concentration is $C_w = 75\%$ by weight $^{[1]}-^{[2]}$
- The maximum powder size is $200 \mu m$

Properties
- The density of slurry $\rho_{sl} = \frac{100}{\left(\frac{C_w}{\rho_{co}} + \frac{1-C_w}{\rho_{w}}\right)}$
- The oxygen density is obtained at 11 bar

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firing input</td>
<td>250</td>
<td>kW</td>
</tr>
<tr>
<td>Lower Heating Value</td>
<td>27.5</td>
<td>MJ/Kg</td>
</tr>
<tr>
<td>O/F stochiometric</td>
<td>2.56</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Density</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>14.3</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Coal</td>
<td>850</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Water</td>
<td>998.6</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Slurry</td>
<td>882.8</td>
<td>kg/m$^3$</td>
</tr>
</tbody>
</table>

Injector Design: Pintle

Flow rates

- Coal mass flowrate, \( m_{coal} = \frac{\text{Firing Input}}{\text{lower heating value}} \)
- Oxygen mass flowrate, \( m_{oxygen} = (m_{coal}) \times \left( \frac{0}{F} \right)_{st} \)
  - Slurry mass flow rate \( m_{slurry} = \frac{100 \times m_{coal}}{C_w} \)

<table>
<thead>
<tr>
<th>Mass Flow Rate</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>9.1</td>
<td>g/s</td>
</tr>
<tr>
<td>Oxygen</td>
<td>23.3</td>
<td>g/s</td>
</tr>
<tr>
<td>Slurry</td>
<td>12.1</td>
<td>g/s</td>
</tr>
<tr>
<td>Total</td>
<td>35.4</td>
<td>g/s</td>
</tr>
</tbody>
</table>
Injector Design: Pintle

Total momentum ratio \( TMR = \frac{m_{sl} v_{sl}}{m_o v_o} = \tan \alpha \)

\( \alpha \): Spray angle

The velocity of the slurry \( v_{sl} = \frac{m_{sl}'}{A_{sl} \rho_{sl}} \)

The area of slurry \( A_{sl} = N \frac{\pi}{4} D_{po}^2 \)

\( N \): The number of orifices on pintle tip
\( D_{po} \): The orifice diameter

\[ \text{Number of orifices} \]
The velocity of the oxygen \( v_o \) is given by:

\[
v_o = \frac{TMR m_{sl} v_{sl}}{m_o}
\]

The area of oxygen \( A_o \) is:

\[
A_o = \frac{m_o}{v_o \rho_o}
\]

The Closing Plate hole diameter \( D \) is:

\[
D = \sqrt{\frac{4A_o}{\pi}} + D_p^2
\]

\( D_p \): The pintle post outer diameter

The annulus gap \( Gap \) is:

\[
Gap = \frac{D - D_p}{2}
\]
Injector Water Test
An optical method based on:
- High resolution imaging
- High illumination

Used for visualizing:
- Particles, droplets, and structures

Advantages
- Better identification of droplets and flow patterns
- Ideal for water testing
- Measure droplets
- Monitor atomization

DynamicStudio controls camera settings and acquires images

Shadow sizing of droplets analyzed by same program
Water Set-Up
Water Set-Up

Pintle injector

Isolation device

Diffuser plate and LED light

Angle
# Water Set-Up Results

<table>
<thead>
<tr>
<th>Run</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Angle (Degree)</td>
<td>90</td>
<td>88</td>
<td>87</td>
<td>86</td>
<td>85</td>
</tr>
<tr>
<td>Water Flowrate (g/s)</td>
<td>37.6</td>
<td>37.6</td>
<td>37.6</td>
<td>37.6</td>
<td>37.6</td>
</tr>
<tr>
<td>Nitrogen Flowrate (g/s)</td>
<td>0</td>
<td>7.6</td>
<td>14.7</td>
<td>19.9</td>
<td>26.3</td>
</tr>
<tr>
<td>Experimental Angle (Degree)</td>
<td>90</td>
<td>89</td>
<td>85</td>
<td>73</td>
<td>80</td>
</tr>
<tr>
<td>error(%)</td>
<td>0.0</td>
<td>-1.1</td>
<td>2.4</td>
<td>17.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>
Exhaust Design Concept
Exhaust Design Concept

- A small pressure vessel is attached with flanges

- Ash removal
  - Water added with sprinklers
  - Ash drained and collected at the bottom

- Modular design for the ash collection
  - Maintenance

- Pressurized with chocked flow
  - Valve
Exhaust gas with water

Schematic of exhaust system

Gas

Water and Ash

Side View of the Exhaust

Top View of the Exhaust
Team Members

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Mechanical Engineering

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