Oxy-Fuel Combustion: Laboratory and Pilot Scale Experiments

Plus some initial calculations (Qiao)!

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Presentation Outline

- Oxy-fuel motivation
- Laboratory Experiments
- Initial Numerical Simulations
- Pilot Scale Experiments
- Continuing Work
Clean Coal Options:

- **Oxygen combustion (Oxyfuel)**
  - Concentrated CO$_2$ in products

- **Amine (or others) scrubbing** for new or existing plants
  - Extracts the CO$_2$ from the flue gas using a regenerable sorbent-catalyst such as momoethanolamine (or MEA)
  - More expensive by some estimates

- **Integrated Gasification Combined Cycle (IGCC)**
  - Also concentrates CO$_2$
  - Attractive approach, but challenges include complexity of operation
Oxy-fuel Motivation

- Oxyfuel
  - Pure oxygen as oxidizer (often diluted with flue gas)
  - Reduces or eliminates NOx (no Nitrogen in oxidizer flow)

- Increases CO$_2$ concentration
  - Easier to recover

Could be used in retrofit coal plants

From R Gupta
Oxy-coal is gaining momentum internationally

- Oxy-combustion boilers have been studied in laboratory scale and small pilot units of up to 3 MW
- Two larger pilot units at 30 MW are operating
  - Babcock & Wilcox (B&W), and Swedish power company Vattenfall.
- An Australian-Japanese project team is pursuing a 30 MW repowering project at the CS Energy’s Callide A station in Queensland, Australia
  - “stands to benefit from developments in oxygen separation such as membrane-based air separation technology, which could replace energy-intensive cryogenic process air separation technology”
- More work needed in this area!

“Advanced Coal Power Systems with CO₂ Capture: EPRI’s CoalFleet for Tomorrow Vision”, *A Summary of Technology Status and Research, Development, and Demonstrations, 1016877, Interim Report, Electric Power Research Institute, September 2008*
Some key areas

- Radiative Heat Transfer
  - More dominant heat transfer mode in boiler furnace
  - Non-gray body behavior (spectral dependence)

- Temperature Measurements in Oxy-Fuel Boilers
  - Pilot scale
  - Above 3,000 K in Jupiter burner
  - Challenging to measure
Objectives

Document
- Flame Speed
- Spectral Radiation
- Data for Models

Vary
- Coal type
- Particle size
- Oxygen content
- Diluent
### Coal Analysis

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Indonesian Coal</th>
<th>Illinois Basin #6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Classification</td>
<td>Bituminous (low sulfur, low ash)</td>
<td>Bituminous</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Ultimate Analysis (%)</th>
<th>Typical Proximate Analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>73.70%</td>
<td>68.30%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>5.20%</td>
<td>5.00%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>18.80%</td>
<td>13.80%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1%</td>
<td>1.30%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.10%</td>
<td>3.50%</td>
</tr>
<tr>
<td>Ash</td>
<td>1.30%</td>
<td>8.10%</td>
</tr>
</tbody>
</table>

- **Further Classify Coal using Sieves:**
  - >106 µm
  - 106 µm - 75 µm
  - 75 µm - 53 µm
  - 53 µm - 25 µm
  - < 25 µm
How Flame Speed was Obtained

Both cases:
Cloud density - 0.539 kg/m$^3$
40% O$_2$ and 60% CO$_2$
Indonesian Coal

• Less Sensitive to Human Error in choosing effective diameter
Laboratory Experiments – Results (Flame Speed)

Effect of Oxygen On Flame Speed

All cases:
Cloud density - 0.539 kg/m³
Particle Dia. – 25-53 μm
Carbon Dioxide Diluent

O₂ (% by Volume)

Flame Speed (m/s)

- Indonesian Coal
- Illinois Coal #6

60% O₂  40% O₂

ignition

$t = 5\text{ms}$

$t = 10\text{ms}$

$t = 15\text{ms}$

$t = 20\text{ms}$
Decrease in flame speed with smallest particle size can be attributed to:

• Material Sticking to windows (leaner mixture)
• Agglomerations (can be seen in videos)

All cases:
Cloud density - 0.539 kg/m³
40% O₂ and 60% CO₂
Effect of Diluent On Flame Speed

Due to property differences between CO$_2$ and N$_2$.

All cases:
- Particle Dia – 25-53 microns
- Indonesian Coal
- Cloud density - 0.539 kg/m$^3$
Fast Infrared Array Spectrometer (FIAS)
  • Portable
  • Staggered PbSe linear array sensor cooled by TEC
  • 160 wavelengths from 1.4 to 4.8 \text{um}
  • Scan frequency: 6,250 Hz
  • Acquisition frequency: 1,320 Hz
Laboratory Experiments – Results (Spectral)

Test Specs:
40% CO₂, 60% O₂
Particle Dia – 25-53 microns
Cloud density - 0.539 kg/m³
Trends

- Same General Shape
- Carbon Dioxide
  - Combating factors of increase in temperature vs. increased radiative potential
- Nitrogen
  - Increase in Intensity for increase $O_2$, decrease in Diameter
- Peak at 2.7 microns for Water and $CO_2$
Laboratory Experiments – Results (Spectral)

Test Specs:
Fire Ball Diameter ~ 48mm
CO₂ Diluent
Particle Dia – 25-53 microns
Cloud density - 0.539 kg/m³

Similar features in pilot scale measurements
Laboratory Results – Experimental (Spectral)

Test Specs:
40% O$_2$, 60% CO$_2$
Particle Dia – 25-53 microns
Cloud density - 0.539 kg/m$^3$
Simulations (Qiao)

- We investigated the transient combustion characteristics of a spherically symmetric cloud containing coal particles, as shown in Fig. 1.
- The cloud has a radius of $R_0$. Coal particles, with diameter $d_p$ and number density $n_p$, are uniformly distributed in the cloud.
- The cloud is numerically ignited using a hot spot.
  - The Three-Level Fully Implicit (TLFI) scheme of second-order accuracy was applied to transient terms of the gas phase equations.
  - The convective and diffusive terms are discretized using QUICK scheme and second order central difference, respectively.
  - The time dependent equations of particle phase were solved using a standard ODE solver for stiff system, DVODE.
The transient combustion is modeled by conservation equations for mass, species and energy with detailed consideration of devolatilization, homogeneous gas phase reaction, heterogeneous char surface reaction, and radiative heat transfer.

Assumptions:

(1) Gas phase and particles are uniformly mixed in space;
(2) The particles remain quiescent;
(3) Coal particles are spherical of various sizes;
(4) Each particle has uniform temperature because of its small size.
Note:
1. The above figure shows the transient gas-phase temperature as a function of radius.
2. The initial coal particle temperature is assumed to be room temperature.
3. This is for $O_2/CO_2=30/70$ case.
Note:

1. The above figure shows the species concentration profiles at 6 ms.
2. This is for $O_2/CO_2=30/70$ case.
Experimental vs Theoretical Flame Speed

All cases:
Cloud density - 0.539 kg/m³
Particle Dia. – 25-53 µm
Carbon Dioxide Diluent
Indonesian Coal
Pilot Scale Experiments

From Jupiter Oxygen in Hammond Indiana

Some funding from Jupiter Oxygen
Pilot Scale Experiments - Objectives

- Measure spectral radiation intensities of a pilot-scale oxy-fuel boiler at various locations (by Jupiter engineers)

- Analyze measured radiation data

- Estimate temperate profile at one cross-section of the boiler furnace using inverse radiation interpretation
Pilot Scale Experiments - Objectives

- The Pilot Scale Boiler
  - Doosan Backcock 23.4 MW boiler
  - Four Maxson 2.93 MW
  - Total heating rate during tests: < 8.79 MW

- Test Matrix
  - HT oxy-natural gas without CO$_2$ recycling
  - HT oxy-natural gas with CO$_2$ recycling (blanket)*
  - LT oxy-natural gas with CO$_2$ recycling (synthetic air)
  - Air firing natural gas
  - HT oxy-coal without CO$_2$ recycling

* http://www.jupiteroxygen.com
Pilot Scale Experiments – Pilot Scale Apparatus

Spectral Measurement Configuration

- Flame Front
- Burner Assembly
- FIAS
- Wall
Pilot Scale Experiments – Inverse Flame Temperature Technique

The temperature profile was described as the following:

\[ T(r) = T_p \exp \left[ -\left( \frac{r - r_p}{c} \right)^2 \right] + T_b \]

- Assumed Temperature Profile and best fit to boundary conditions and spectral data
- First time this technique applied to coal and pilot scale experiments
Pilot Scale Experiments – Results

Spectral Emissions of HT oxy-fuel w/o CO₂ recirculation

Air-Fire Spectral Emissions

Spectral Emissions of HT oxy-fuel w/ CO₂ recirculation

LT oxy-fuel Spectral Emissions (Synthetic Air with FGR)
Pilot Scale Experiments – Results

Jupiter Oxy-Coal Spectral Results
More analysis needed
NETL is using this data with modeling efforts there
Comparison of estimated temperature profiles

- Peak temperatures of HT oxy-fuel flames are MUCH higher
- Temperatures of LT oxy-fuel air-firing flames are comparable
- Gas temperature near the wall of the HT oxy-fuel without FGR configuration is the highest
Continuing Work

- Modify inverse temperature estimate code for dust clouds
  - Also, can take simulation results and calculate radiant emission
- More comparisons with calculations
  - About an hour for each simulation
- More spectral radiation analysis
- Repeat some nitrogen tests
- Do some tests with visible spectrometer
- Prepare final report
Future work?

- Would continue oxy-coal experiments with significant modeling effort (Qiao)

Fig. 3. Sketch of the flat dust coal flame burner and the fluidized bed feeder.
Future work?

- Diffusion HT burner

Fig. 4. Sketch of the Bunsen particle burner.
Future work?

- Benchscale 150 kW burner

Fig. 5. Jupiter Oxygen’s 150 KW furnace.

Also submitted white paper to DOE ARPA-E call
We’d like to thank Prof. Timothee Pourpoint for use of his Matlab Code for analyzing the high-speed images.

We thank Jupiter Oxygen engineers for gathering the data and providing pilot scale apparatus. In particular, we thank Brian Patrick and Steve Nied.

We thank the Center for Coal Technology Research for funding under contract number 7-PSC-CTR-002. In particular, we thank Marty Irwin and Brian Bowen for their support of this work.