Oxy-Fuel Coal Combustion

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Options for Clean Coal

Three front runners:

- **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)

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

"**Some current studies show oxygen combustion as the least costly while others lean toward IGCC, indicating that the jury is still out.**" (Williams et al., BR-1779, 2006)
What is oxyfuel combustion?

- **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
Progress of Project

- Literature Reviewed
- Radiation analysis in a pilot scale oxy-fuel boiler firing natural gas and coal in Jupiter’s pilot scale burner
- Construction of particle burner
- Initial combustion results
Radiation Measurements - Motivation

- Radiative Heat Transfer
  - 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

- 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
Experimental Methods

- **The Pilot Scale Boiler**
  - Doosan Backcock 80 MBtu/hr boiler
  - Four Maxson 10 MBtu/hr
  - Total heating rate during tests: < 30 MBtu/hr

- **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

- **Fast Infrared Array Spectrometer (FIAS)**
  - Portable
  - Staggered PbSe linear array sensor cooled by TEC
  - 160 wavelengths from 1.4 to 4.8 $\mu$m
  - Scan frequency: 6,250 Hz
  - Acquisition frequency: 1,320 Hz
From Jupiter Oxygen
Arrangement of spectral radiation intensity measurements
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
Results and Discussion

Comparisons of measured and predicted $I_\lambda$

- Test 23: HT oxy-fuel without FGR
- Test 24: HT oxy-fuel with FGR (CO$_2$ blanket)
Results and Discussion

Comparisons of measured and predicted $I_\lambda$

- Test 30: air firing
- Test 34: LT oxy-fuel with FGR (synthetic air)
Results and Discussion

Comparison of $I_\lambda$ of oxy-coal and oxy-NG flames

Measured $I_\lambda$ of oxy-coal flame
- Continuum radiation from particles
- Much smaller dips at 2.3, 2.7 and 4.0 $\mu$m
- Big dip at 4.2 $\mu$m

- Same measurement location
- Slightly different heat rate
- Maybe different flame length
- Maybe different flame temperature
Combustion Studies at Purdue

- Constant volume or pressure ignition and combustion
  - Flame and ignition characterization studies
  - Pollutant concentrations
  - RFG/O₂% optimization
  - Comparisons with Jupiter pilot reactor
  - Indiana coals considered

Can we stabilize O₂/CO₂/Coal flame with lower O₂ concentration?
Measurements:

- Flame Speed Measurements
- Radiation measurements
  - Temperature Profile of Flame using Inverse Flame Measurement Technique

While Varying:

- Initial Gasses (Oxygen, Nitrogen, Carbon Dioxide)
- Fuel/Oxidizer Ratio (Amount of Coal)
- Coal Particle Size
- Coal Type
Recent Milestones

- Repeatable combustible dust cloud combustion
- Compared with literature results
- Classification of Particle Size (Malvern Testing)
- Collected a few of coal types
- Developed Control System to run dust Cloud experiments
## Types of Coal to be Tested

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Indonesian Coal</th>
<th>Illinois Basin #6</th>
<th>Indiana Coal (Billings Mine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Classification</td>
<td>Bituminous (low sulfur)</td>
<td>Bituminous</td>
<td>*Bituminous (medium Volatile)</td>
</tr>
<tr>
<td>Ultimate Analysis (%)</td>
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<td></td>
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</tr>
<tr>
<td>Carbon</td>
<td>73.70%</td>
<td>68.30%</td>
<td>81.40%</td>
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<tr>
<td>Hydrogen</td>
<td>5.20%</td>
<td>5.00%</td>
<td>4.80%</td>
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<tr>
<td>Oxygen</td>
<td>18.80%</td>
<td>13.80%</td>
<td>4.60%</td>
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<tr>
<td>Nitrogen</td>
<td>1%</td>
<td>1.30%</td>
<td>1.60%</td>
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<tr>
<td>Sulfur</td>
<td>0.10%</td>
<td>3.50%</td>
<td>0.70%</td>
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<tr>
<td>Ash</td>
<td>1.30%</td>
<td>8.10%</td>
<td>6.90%</td>
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<tr>
<td>Typical Proximate Analysis (%)</td>
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<tr>
<td>Moisture</td>
<td>16.12%</td>
<td>10.10%</td>
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</tr>
<tr>
<td>Ash</td>
<td>1.06%</td>
<td>7.30%</td>
<td>6.90%</td>
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<tr>
<td>Volatile</td>
<td>42.59%</td>
<td>35.90%</td>
<td>29.20%</td>
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<tr>
<td>Fixed Carbon</td>
<td>40.23%</td>
<td>46.70%</td>
<td>63.90%</td>
</tr>
</tbody>
</table>

*Analysis of Indiana Coal Billings Mine is estimated on normal composition of coal from that area*
Classification of Particle Sizing

Measured Size Distribution of Coal Particle Diameter Using Malvern Mastersizer 2000
Using Sieves we will further classify the Coal into bins of:

- $>106 \ \mu m$
- $106 \ \mu m - 75 \ \mu m$
- $75 \ \mu m - 53 \ \mu m$
- $53 \ \mu m - 25 \ \mu m$
- $< 25 \ \mu m$
Cloud Burner Experiments

Experiment A
Indonesian coal:
50% O₂
50% CO₂
.539 kg/m³

Experiment B
Indonesian coal:
50% O₂
50% CO₂
.539 kg/m³
Particle size < 25μm
Cloud Burner Experiments

50% Oxygen and 50% CO₂, 0.539 kg/m³ amounts of a similar Bituminous coal

Suda reports ~1.3 m/s
Purdue Study ~1.7 m/s
Size, O₂ conc. Differences, etc.

Fig. 10. Effect of CO₂ on flame propagation velocity Coal A, 50 μm.
Bunsen Particle Burner (PSU)

Using a low-flow natural gas pilot flame we can stabilize the coal/oxygen Bunsen burner.

Also trying hot-wire Stabilization.
- Radiation measurements in pilot burner
- New particle cloud combustor built
  - Initial laboratory measurements made
- Obtained pulverized coal for studies and characterized
- Bunsen particle burner
  - Being adapting to coal combustion
  - Complements particle cloud experiment
Future Work

- Conduct parametric studies of laboratory scale oxy-coal flames
  - Various oxy-coal configurations
  - Spectral radiation intensity measurements from NIR to IR
  - Inverse estimates of temperature and species concentrations
  - Compare to pilot scale
Acknowledgements

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The radiation data were acquired by Jupiter Engineers, Steven Neid, Cassidy Jax, and Brian Patrick
Appendix: Temperature Estimate

We estimated the temperature profile using the following major assumptions,

1. Turbulent effects are not considered as a first approximation
2. Negligible radiation from the wall
3. Constant species (CO\(_2\), H\(_2\)O, O\(_2\), etc.) concentrations. The species concentrations were obtained by thermodynamics calculations using HYSYS (Jupiter’s calculation)
4. The temperature profile was described as the following,

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

where the normalized position, \( r \), is zero at the center and unity at the water wall boundary. The four parameters (\( T_b, T_p, c \), and \( r_p \)) are related to the gas temperature at the boundary (\( T_b \)), the normalized location of the flame front (\( r_p \)), the flame front temperature (\( T_p + T_b \)), and the gas temperature at the flame center. These parameters were first guessed and then determined when the calculated \( I_\lambda \) based upon these parameters were optimized to yield the best fit to the measured \( I_\lambda \) at four (at least) specifically chosen wavelengths.
Test Arrangement

Boiler Plan View

Three traversing type K, grounded junction TC's maximum insertion length 5 ft located on 36° vertical centers HVT radiant shielded type TC with gas sampling port.
