IGNITION IN 40KW CO-AXIAL TURBULENT DIFFUSION OXY-COAL JET FLAMES

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Outline

• Introduction
• Objectives
• Experimental setup
• Methodology to quantify flame stability
• Results and discussion
• Conclusions
• Acknowledgements
Oxy-fuel Combustion Impacts upon Retrofit

(Flame Ignition (this work) Burnout SO\textsubscript{x}, NO\textsubscript{x}, Soot Heat transfer)

(Fouling, Slagging, Ash partitioning Ultra-fine particles)

(Adapted from: Stromberg, 2004)
Background: Coal Jet Ignition

- Standoff ignition distance depends on primary jet velocities, wall T, and $P_{O_2}$, which becomes an independent variable under oxy-coal combustion.
- Sub-model should capture observations that smaller particles preferentially migrate to jet edge. [Sinclair Curtis group Purdue University, 2003]. Implications on effects of secondary $P_{O_2}$, also an independent variable.
- Pyrolysis behavior. (Naredi and Pisupati, 2007, Penn State University)
- Particle ignition. (Shaddix and Molina, 2005, 2006, Sandia Labs) Influence of gas properties which vary heat transfer to coal particle.

- Ignition behavior
- Flame stability
- Flame length
Objectives

• To better understand, the effects of partial pressure of $O_2$ in a) the coal transport jet, and b) the secondary oxidant jet, and also the effects of other burner operation parameters on co-axial coal jet ignition and flame stability.

• To contribute to validated, turbulent diffusion coal flame simulations that predict the effects on flame stability of conversion from air fired to oxy-fired conditions in existing units.

• To develop techniques to quantify coal flame length and stand-off distance from photo-images to allow quantitative comparison with simulations, together with uncertainty quantification.
Experimental approach

• Tests on a 40kW (100kW max) down-flow combustor
  – Focus is on interactions between coal ignition chemistry and two phase turbulent co-axial jets, and neither on ignition chemistry nor on turbulent jets
• Well defined turbulent co-axial jet burner, no swirl.
• Small enough to allow targeted experiments and systematic variation of burner parameters
  – Momenta
  – Velocities
  – Wall temperatures, secondary oxidant preheat temperatures
  – Gas compositions of primary and secondary streams
• Large enough to contain essential physics of larger test rigs and field units
  – Tangentially fired units
  – Cement kilns
Experimental Details

- A 100 kW (max), down-fired, oxy-coal combustion furnace, once-through CO$_2$, secondary stream preheated to 640K
- Top section: 0.610 m I.D., 0.914 m O.D., 1.219 m in height; 2600 Fiberboard
- 24 × 840 W flanged ceramic plate heaters controlled by Type K T/C's
- 3 layers of insulation in radiant zone and 2 layers insulation in convection zone, with subsequent cooling by 8 heat exchangers.

Has heated walls and quartz windows for optical access that permit flame detachment / attachment studies and optical diagnostics.
Coal feeding

• Steady feeding was critical
  – K-tron twin screw feeder with modified eductor and mesh to break up clumps

• 5 methods used to confirm steady coal feeding behavior
  1) Visual inspection of coal jet and flame
  2) 500 photo image frames collected at 24 fps for 20s showed fluctuations about a relatively steady mean with no low frequency pulsations due to auger rotation (0.73Hz).
  3) Steady O₂, CO₂ and NOₓ consistent with mass balance
  4) LOI in ash always low (unsteady feeding causes high LOI).
  5) Photo images at 5000 fps w/o flame showed temporal variations with frequencies orders of magnitude greater than 0.73Hz (auger rotation).
Stand-off distance (and “flame envelope”) defined by photo image sampling method and device

Exposure time
- 8.3ms
- 0.25ms
- 5µs

Collection rate
- 30 fps
- 4 fps
- 5000fps

We chose $t_{\text{exp}} = 8.3\text{ms}$; collection rate 30 fps (far left) as being close to that observed by the human eye.
Methodology: 3rd Generation
(Sobel Method, Supercomputer Clusters)

(a) original image
(b) image converted to grayscale,
(c) edge detection using the Sobel method (max gradient pixel intensity)
(d) image converted to black and white using the threshold calculated from the Sobel method
(e) measurement of image statistics: standoff distance (if any), flame length, and intensity within flame envelope

Parallel computing on high performance clusters of University of Utah:
250 images’ processing: 7 sec vs. 20 min
Results

1. Qualitative effects of $P_{O_2}$ (primary)

2. Quantitative results
   1) PDF’s denoting stand-off distance of luminous zone, 6000 images, 3-5 replicate runs.
   2) Effects of $P_{O_2}$ (primary) and $T_{preheat,sec}$ on stand-off distance PDF’s
   3) Effects of $P_{O_2}$ (secondary) with 0% $O_2$ (primary) on stand-off distance PDF’s
   4) Special tests: replacement of $CO_2$ in primary by $N_2$. Secondary remains $O_2/CO_2$
Results 1. Qualitative effect of primary $P_{O_2}$
$t_{exp} = 0.25\text{ms}; \ O_2/CO_2; \ Overall \ P_{O_2} = 40\%, \ T_{preheat} = 489K; \ T_{wall} = 1283 \ K$
Example of PDF: $\text{O}_2/\text{CO}_2 + \text{Utah Bituminous}$, overall $P_{\text{O}_2} = 40\%$, secondary preheat $T = 489\ K$, $T_{\text{wall}} = 1283\ K$, primary $P_{\text{O}_2} = 0.144$
Example of PDF: $O_2/CO_2$ + Utah Bituminous, overall $P_{O_2} = 40\%$, secondary preheat $T = 489 \text{ K}$, $T_{wall} = 1283 \text{ K}$, primary $P_{O_2} = 0.207$
Results 2. Quantitative effect of primary $P_{O_2}$ & preheat

489 K preheat

544 K preheat

Primary $P_{O_2}$

0

0.054

0.099

0.144

0.207
Results 3: Effects of secondary $P_{O_2}$ with zero $O_2$ in primary jet:

- $sec P_{O_2}/overall P_{O_2}$:
  - 49/40
  - 51/42
  - 53/44

- Probability Density (1/cm) vs. Standoff Distance (cm):
  - Primary $P_{O_2}=0$, Overall $P_{O_2}=40%$
  - Secondary $P_{O_2}=49%$
  - $sec P_{O_2}/overall P_{O_2}$:
    - 50/41
  - Primary $P_{O_2}=0$, Overall $P_{O_2}=43%$
    - Secondary $P_{O_2}=44%$
    - $sec P_{O_2}/overall P_{O_2}$:
      - 52/43
  - Primary $P_{O_2}=0$, Overall $P_{O_2}=48%$
    - Secondary $P_{O_2}=57%$
    - $sec P_{O_2}/overall P_{O_2}$:
      - 57/48
Averaged data: Standoff distance vs. secondary $P_{O_2}$ for zero $O_2$ in primary

Primary $P_{O_2} = 0$, percentages on figure are vol% overall inlet $P_{O_2}$
Results 4: Special tests: N₂ as primary jet transport medium
Results 4: Special tests - primary CO\textsubscript{2} replacement
Measured average standoff distance v.s. primary P\textsubscript{O2}
Conclusions

• Systematic measurements (suitable for simulation validation) of stand-off distance versus primary, and secondary $O_2$ concentration ($P_{O2}$) have been obtained, for well defined oxy-coal coaxial turbulent diffusion flames, together with uncertainty quantification.

• A methodology of quantifying flame stability from photo-images has been developed.

• Flame stand-off distance is not a continuous variable and attachment/detachment passes through sudden transitions.
  - Flames close to stability limits depict multiple stationary states (multi-modes in PDF), but only at specific stand-off locations.

• Primary $P_{O2}$ has a quantifiable, first order effect on flame stability and coaxial coal jet ignition.
Conclusions (contd.)

• A small increase (489 K vs 544 K) in secondary stream preheat significantly increased flame stability.

• Secondary $P_{O_2}$ is also very important. Oxy-coal coaxial flames with 0% $O_2$ in the primary jet can be attached with secondary $P_{O_2}> 52\%$. This has practical significance.

• Co-axial coal jet ignition and flame stability is determined by both primary jet composition, and also secondary jet composition (and temperature).

    < Data are qualitatively consistent with an One Dimensional Turbulence (ODT) type process in which coal materials and surrounding carrier are transported radially into the secondary stream followed by molecular diffusion of oxygen (and/or heat) to the fuel. >
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Unimodal/bimodal flame stability observations in Test 4.1A and 4.1B. 0 to 20.7% are primary $P_{O_2}$ values. Blue, green and yellow represent flame detachment, bimodal attachment/detachment, and flame attachment, respectively. (U.D.: unimodal detached; B.D.: bimodal detached; B.A.: bimodal attached; U.A.: unimodal attached.)

<table>
<thead>
<tr>
<th>Test 4.1A</th>
<th>$P_{O_2} = 0$</th>
<th>$P_{O_2} = 5.4%$</th>
<th>$P_{O_2} = 9.9%$</th>
<th>$P_{O_2} = 14.4%$</th>
<th>$P_{O_2} = 20.7%$</th>
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<tr>
<th>Test 4.1B</th>
<th>$P_{O_2} = 0$</th>
<th>$P_{O_2} = 5.4%$</th>
<th>$P_{O_2} = 9.9%$</th>
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An Example of Multimodal Behavior