Oxy-Fuel Combustion: Laboratory and Pilot Scale Experiments

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Abstract

Our focus is on coal combustion and its associated heat transfer properties, especially radiative transport. Spectral intensity measurements and inferred temperature profile are being obtained in a laboratory setting as well as on a pilot scale boiler. The pilot-scale experiments utilize a boiler retrofitted for oxy-fuel that operates at a temperature ranging to over 3000K. Due to such high temperatures, temperature measurements of the flame are not possible with probes and are inferred by a process called inverse radiation interpretation instead. Laboratory-scale studies are also being performed to characterize the radiative properties and flame speed while varying the coal type, particle size and oxygen content. A dust cloud configuration is considered. We report spherical flame speeds, spectroscopic measurements and inferred temperature profiles in different flame configurations and conditions.

Introduction

With the public focused on environment-friendly abundant energy sources, clean coal power generation is thought by some to hold much promise. Oxy-fuel combustion produces a more concentrated carbon dioxide product stream that could be more easily sequestered and is an option for retrofitting current systems. While coal remains an abundant cheap fuel source, global warming has caused this power source to be re-examined. With an air fired fossil fuel furnace the gaseous products include CO_2, NO_x and SO_2. While much research has been focused on the reduction of NO_x and SO_2 gasses, a method to remove CO_2 from the products that is cost effective and does not compromise the overall efficiency of the furnace does not commonly exist in practice [3]. Since CO_2 is a primary combustion product this poses a daunting challenge.

When using an air-fired furnace, sequestration becomes expensive due to effort needed to separate the CO_2, NO_x and SO_2. However, if pure oxygen is used instead of the conventional air, NO_x gasses are greatly reduced and separating the CO_2 from mostly water products becomes a more financially reasonable approach.

One common method for studying oxy-coal combustion is in a dust cloud configuration, as explored in this study. Suda et al. studied oxy-coal combustion in a dust cloud configuration and reported flame propagation speeds for various conditions [2]. Specifically, different coal samples were explored at high oxygen concentration with N_2, CO_2 and Ar as diluents.

Several works have also discussed CO_2 recirculation and high temperature effects in pilot scale scenarios [5, 6]. Wall characterized the differences between oxy-fuel heat transfer and air fired coal combustion [4]. Other works have furthered the study of radiation in specific parts of industrial boilers, as well as providing numerical analysis of possible CO_2 recirculation effects [7-9].

Our study is an attempt to tie a link between well-controlled laboratory experiments and a pilot scale oxy-fuel combustion scenario. We will document laminar flame speeds, spectroscopic measurements and inferred temperature profiles in different flame configurations and conditions.

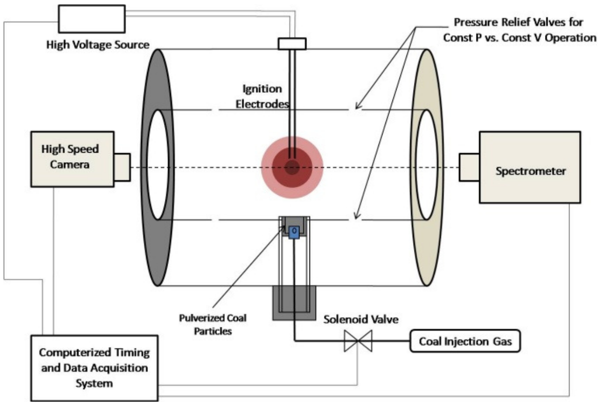


Figure 1 - Schematic of Dust Cloud Apparatus

Experimental Configuration and Specific Objectives

Figure 1 shows the first laboratory apparatus for the oxy-fuel experiments. We are beginning to use this apparatus to study coal cloud combustion and document flame speed and spectral radiation while varying particle size and O_2/CO_2 amounts. This cylindrical combustion chamber consists of a six-inch diameter cylindrical inner chamber that contains the combustion event and a twelve-inch diameter outer chamber equipped with pressure release valves to the inner chamber so product gasses can vent to during the combustion event. This yields a nearly constant pressure as configured. Six-inch diameter quartz

*Corresponding author: emiklasz@purdue.edu windows on either side allow viewing of the combustion event. This setup allows experiments to be performed while documenting flame speed and spectral radiation via a high-speed camera and a spectrometer. The spectral absorption of the quartz windows is accounted for. The overall design of the chamber is similar to that used by Qin and Ju that has been used for gaseous combustion studies [11]. The particle injection is similar to that used by Suda et al. [2], who used a constant volume vessel.

The same coal is used in the laboratory and pilot scale tests. The molecular analysis of the coal can be seen in Table 1. The coal was tested with a Malvern particle sizing apparatus and Fig. 2 shows the particle diameter distribution. The particle sizes for this sample ranged from approximately 1-100 µm. This distribution was further divided into subgroups shown below via sieving:

- < 25 µm, using sieve #500
- 25-53 µm, using sieves #500 and #270
- 53-75 µm, using sieves #270 and #200
- 75-106 µm, using sieves #200 and #150

Table 1- Coal Composition

Coal Type - Indonesian Coal	
Coal Classification - Bituminous (low sulfur)	
Ultimate Analysis (%)	
Carbon - 73.70% **Hydrogen - 5.20%** **Oxygen - 18.80%**	**Nitrogen - 1%** **Sulfur - 0.10%** **Ash - 1.30%**
Typical Proximate Analysis (%)	
Moisture - 16.12% **Ash - 1.06%**	**Volatile - 42.59%** **Fixed Carbon - 40.23%**

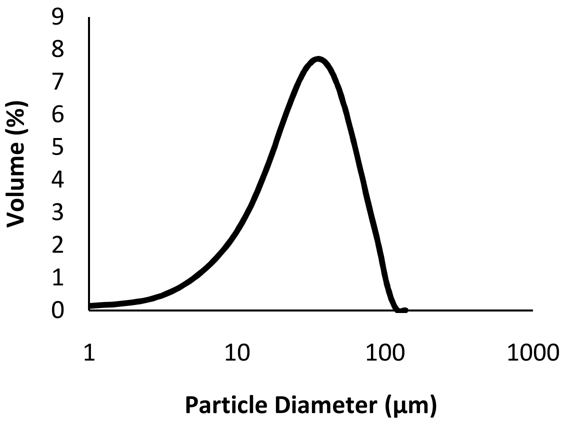


Figure 2 - Coal Particle Size Distribution

In the pilot scale experiments we quantify the radiation from a 30 MBtu/hr oxy-fuel boiler powered by natural gas and coal. Figure 3 shows the cross section of the furnace that was measured by the spectrometer. Heat flux and spectral intensity data was collected at different optical ports that allows for our analysis. The objectives of this work was to examine the spectral contribution from different products (e.g. H_2O, CO_2, particulates, etc.) at different locations along the flame to estimate flame temperature profiles. This method of estimating temperature profiles from spectral data has been done before with success for simpler flames [12]. Four different tests were run on the retrofitted oxy-fuel boiler. The test matrix that was analyzed includes:

- High-temperature (HT) oxy-natural gas combustion without flue gas (mainly CO_2) recirculation (FGR)
- High-Temperature (HT) oxy-natural gas combustion with FGR. CO_2 was in a surrounding co-flow (blanket)
- Low-temperature (LT) oxy-natural gas combustion with FGR. CO_2 was mixed with oxygen to get a synthetic air flow
- Air firing with natural gas

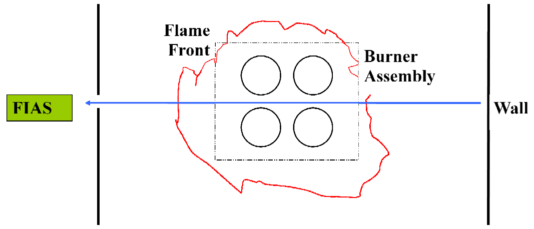


Figure 3 - Pilot Scale Experiment Configuration

Figure 4 shows the second laboratory apparatus to be used. It is a two-phase Bunsen burner that has the capability of burning coal with different oxidizers/diluents in a configuration similar to that seen in an industrial boiler. A camera as well as a spectrometer will be used to report flame speed as well as spectral intensity. This apparatus will allow us to determine the accuracy of the inverse temperature profile estimate that is used in the pilot scale experiments. Verification is needed because high temperatures (>3000K) do not allow for conventional probe measurement of flame profiles. Only initial experiments have been performed using this burner and the results will not be reported here.

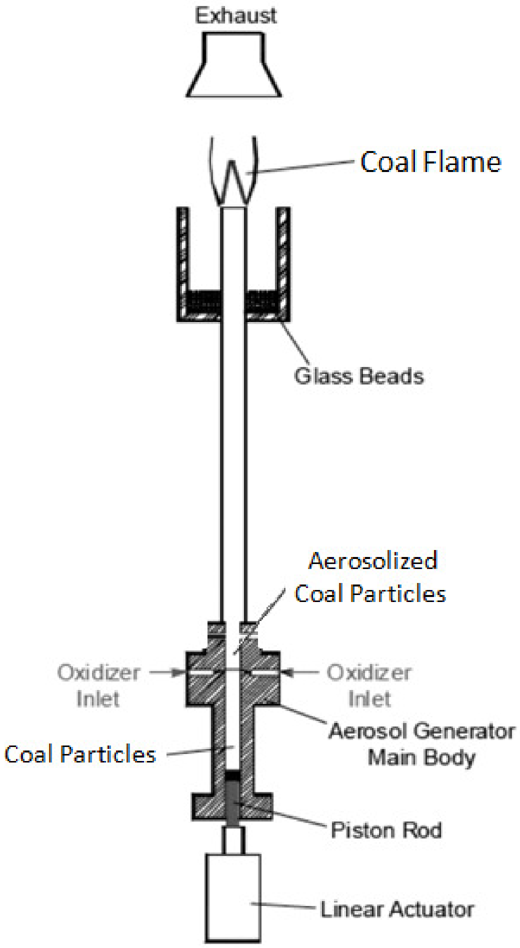
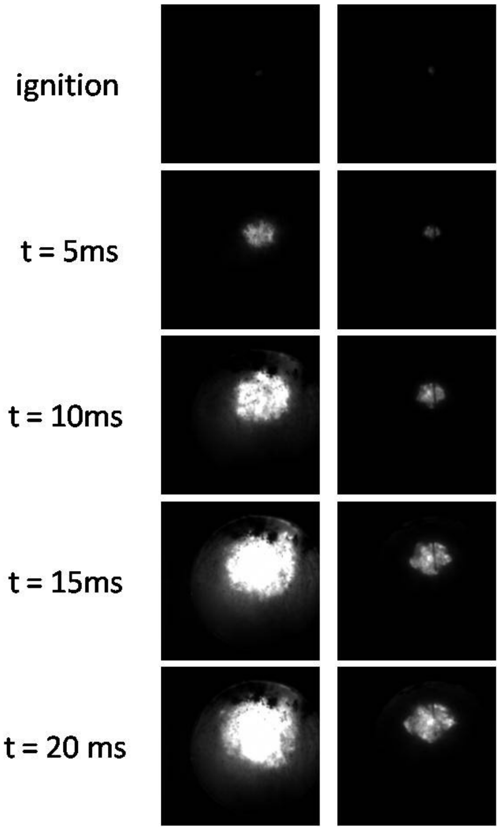


Figure 4 - Schematic of Two-Phase Bunsen Burner Apparatus

Results and Discussion

Figure 5 shows a spherical propagating flame ball over the span over 20 ms in two different cases. A MatLab code was developed to analyze the video and find the position as a function of time and ultimately the flame velocity. The area of the flame was determined over time using this code and then an effective diameter was calculated. This made the flame speed less sensitive to small inconsistencies in the flame front and distortions due to buoyancy or initial flow. The flame velocity was calculated as the slope of the mean diameter vs time after an initial ignition period of at least 10 ms after which the slope became fairly linear. Figure 6 contrasts the flame development between coal particles ranging from 25-53 µm and particles <25 µm. All cases have a dust cloud density of 0.539 kg/m^3, with 40% O_2 and 60% CO_2. In Fig. 5 case A, the coal was sieved to be only less than 25 µm while in case B the coal size was constrained between 53 and 75µm.



a) **Dia. <25 µm** **b) Dia. 53-75 µm**

Figure 5 - Flame Propagation in Coal Dust Cloud

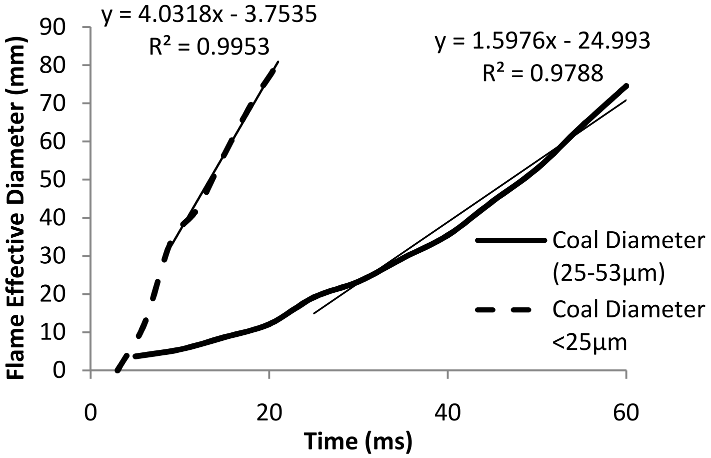


Figure 6 - Flame Position

Figures 7 & 8 show how flame speed is affected by particle diameter and oxygen concentration. As the average particle decreases, the flame speed increases. This is intuitive and numerically predicted elsewhere [2]. It is also expected that the burning rate increases with oxygen concentration since this effectively increases the overall reaction rate. The test parameters were: coal cloud density of 0.539 kg/m^3, with 60% CO_2 and 40% O_2.

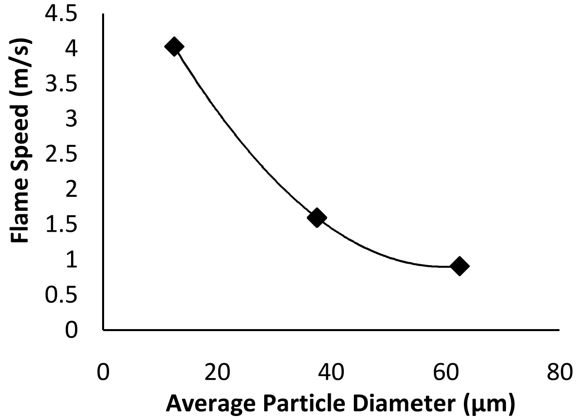


Figure 7 - Flame Propagation dependence on Particle Size

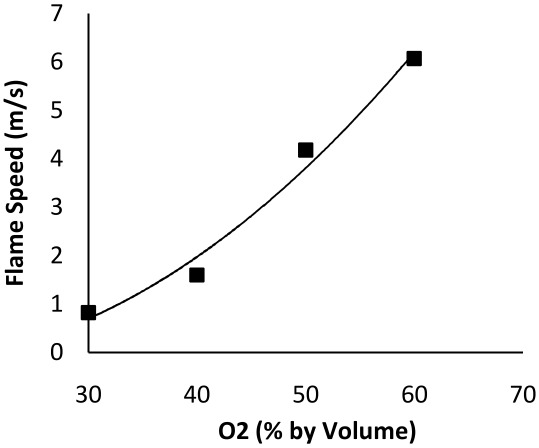


Figure 8 - Flame Propagation dependence on Oxygen

Figure 9 shows an initial relationship of how spectral radiation develops over time with a coal dust flame. Further tests will analyze the how spectral radiation changes while varying oxygen concentration and coal diameter. The spectral intensity (vertical axis) has units of W/m2-sr- µm while the wavelength (horizontal axis) has units of µm. This test had a dust cloud density of 0.539 kg/m^3, with 40% O_2 and 60% CO_2.

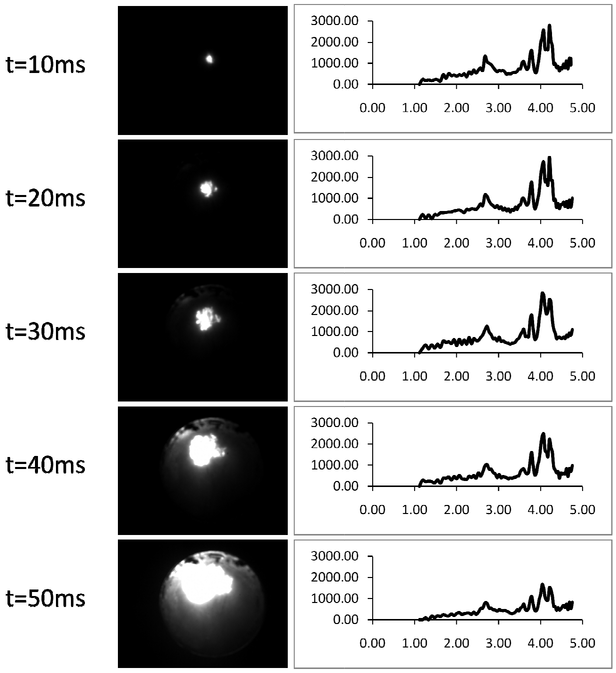


Figure 9 - Coal Flame Spectral Progression

The main objective of the pilot scale testing was to inversely estimate a temperature profile from spectral radiation. We estimated the temperature profile using the following major assumptions:

- Turbulent effects are neglected
- Negligible radiation from the walls
- Constant species (CO_2, H_2O, O_2, etc.) concentrations. The species concentrations were obtained by thermodynamics calculations using HYSYS [10]
- 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 $(T_p \exp\left(-r_p^2/c^2\right) + T_b)$. These parameters were first guessed and then determined when the calculated I_λ, based upon these parameters were optimized to yield the best fit to the measured I_λ at four (at least) specifically chosen wavelengths.

Figures 10-13 show the spectral radiation data obtained by Jupiter engineers plotted with spectral estimates calculated based on the assumptions previously mentioned.

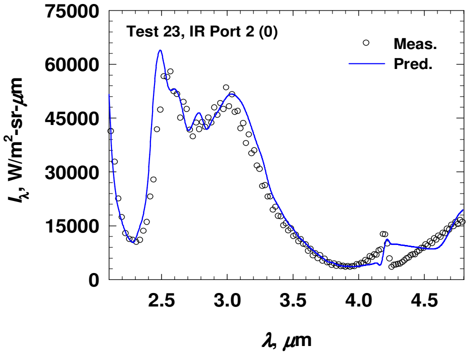


Figure 10 – Spectral Emissions of HT oxy-fuel w/o CO_2 recirculation

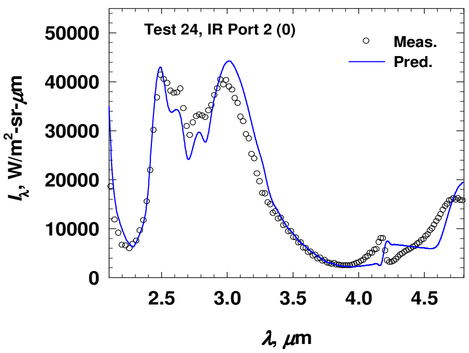


Figure 11 - Spectral Emissions of HT oxy-fuel w/ CO_2 recirculation

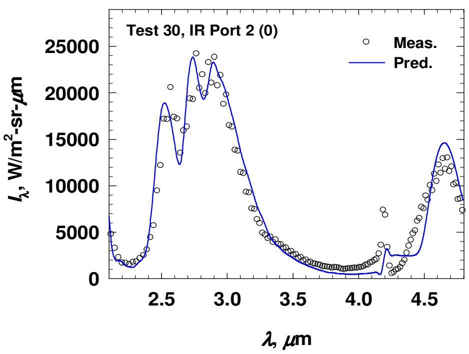


Figure 12 - Air-Fired Spectral Emissions

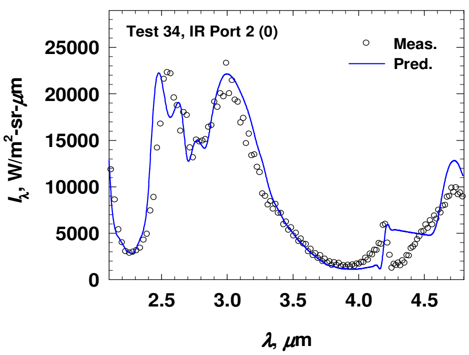


Figure 13 - LT oxy-fuel Spectral Emissions

Based upon calculation, there is a peak at 2.0 μm due to a water band emission. This peak was observed in the measurement but at much lower magnitude. This may be due to the use of neutral density filter, which works in the range from 2 μm to 12 μm. In the present study, we used data beyond 2.1 μm that should be reliable for temperature profile estimates.

Based upon prediction, there is a plateau between 4.2 μm and 4.5 μm. This was not observed in the measurements. This may be caused by calibration errors at the 4.3 μm band due to the existing of room CO_2 during the blackbody calibration process or by the uncertainties in the radiation property model. The peak at 4.2 μm observed in measurements had much higher magnitude then the prediction. Further investigation is desired.

Further analyses indicated that I_λ at the 2.3 μm dip and the 3.0-4.0 continuum region are good for initial temperature and water vapor concentration guesses, I_λ at the 2.5 μm and the 4.3 μm peaks are good for determining near wall temperature, and I_λ at the 2.7 μm dip and the 3.0 μm peaks are good for determining the peak temperature. Guided by the above, the estimated temperature profiles were optimized so that the predicted and measured I_λ are matched well. The estimated peak flame temperature for oxy-fuel without CO_2 recirculation is 3275 K (5435^{o}F). The estimated peak flame temperature for oxy-fuel with CO_2 recirculation is 3200 K (5300^{o}F) with a spatial resolution of 37 mm. It is also found that the water vapor concentration is about 15% lower in the with FGR case than that of without FGR case. FGR also makes the flame narrower and the near wall temperature lower.

The estimated peak flame temperature for air-firing is 2343 K (3758^{o}F) and the estimated peak flame temperature for LT oxy-fuel with FGR (synthetic air) is 2395 K (3851^{o}F). The estimated temperature profiles for all the four cases (HT oxy-fuel without FGR, HT oxy-fuel with FGR, air-firing, LT oxy-fuel) are summarized and compared in Fig. 14.

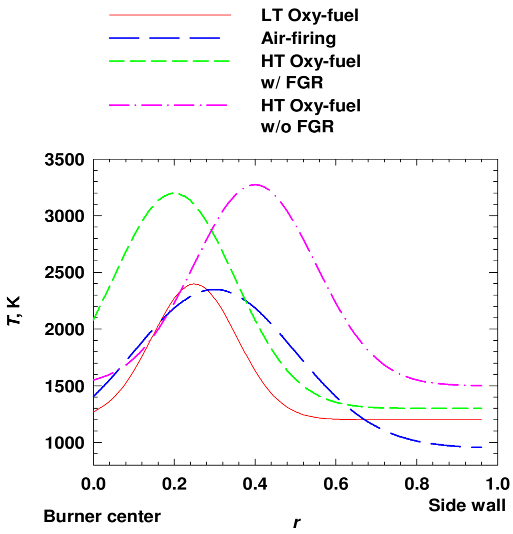


Figure 14 - Estimated Temperature Profiles

Conclusions/Future Work

Laboratory results showed that a decrease in particle size causes the flame speed to increase. It was also documented that increasing amounts of oxygen will also cause the flame speed to increase. This data will be used to compare to modeling.

Radiation data from a pilot scale oxy-fuel boiler have been analyzed as well as initial experiments in a laboratory setting. Temperature profiles, for the first time, have been inferred under conditions where probes cannot be used. Continuing laboratory experiments will allow us to determine the accuracy of the inverse temperature profile estimate that is used in the pilot scale experiments. Further testing will also allow for further documentation of spectral progression of a spherical oxy-coal flame. We plan to compare the laboratory measurements to calculations.

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