Coal Particle Flow Patterns for O₂ Enriched, Low NO_x Burners

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1) Introduction

Over the past year, the hot flow studies have focused on the validation of a novel 2M near-flame combustion furnace. The 2M furnace was specifically designed to investigate burner aerodynamics and flame stability phenomena. Key accomplishments include completion of coal & oxygen mass balance calculations and derivation of emission conversion equations, upgrade of furnace equipment and flame safety systems, shakedown testing and partial completion of a parametric flame stability study. These activities are described in detail below along with a description of the 2M furnace and support systems.

2) 2M Furnace

A novel 2 meter furnace is being used for the hot-flow experimental activities of this project. The 2M furnace complements two existing furnaces at the University of Arizona Combustion Research Group (CRG): a 6 meter, 15 cm ID down-fired unit mainly utilized for kinetic studies under post-flame conditions, and a medium (3 m) sized 15 cm ID unit also utilized for post-flame work. The 2M unit was specifically built to evaluate combustion characteristics in the near-flame region. It is designed to burn a wide variety of fuels including pulverized coal, liquid fuels and natural gas. The 2M furnace is integrated into the facility's compressed air, emission sampling and safety systems to allow great flexibility in experimental design and operation.

The furnace is constructed in the shape of an octagon with an internal diameter of 18" (0.5 m). The furnace walls are built from lightweight rigid refractory insulation and covered with 4" of Kaowool blanket. The furnace consists of a 3' upper section containing 3 zones of ceramic heaters that can reach 1100°C followed by a 3' cool section. Particulates in the exhaust stream are collected in a cyclonic collector. A process flow diagram for the 2M furnace is presented in Figure 1. The furnace can fire natural gas, pulverized coal fed via a loss in weight feeder (LWF) system as well as liquid fuels. The furnace is equipped with an optical quartz window running the full length of the hot section. The window is used for flow visualization studies. A second full-length port directly opposite the window can be fitted with a translating sampling stage or act as an explosion port.

The furnace is equipped with a novel axial jet burner that produces type 0 turbulent diffusion flames. The burner consists of a fuel injection tube surrounded by the secondary air annulus. The dual flow arrangement produces recirculation zones downstream of the burner which depend on velocity of the primary and secondary air flows. The burner design includes variable sleeves for both the primary (transport) and secondary (combustion) air streams. Thus one can adjust the velocity of the combustion air by selecting a wider or narrower combustion air sleeve without affecting the primary jet conditions. The velocity of the primary air-coal jet can be controlled in a similar fashion. Another method of adjusting the flow conditions of the secondary combustion air is to preheat the combustion air stream. Air preheat is provided by a 6 kW circulation

heater specifically designed for the CRG. The heater is sized to provide combustion air at temperatures up to 1000°F

3) Sampling & Data Analysis

The 2M sampling system includes both gas and temperature sampling devices. A water cooled quench probe is utilized for extractive gas sampling. The probe is constructed from ½" and 3/8" cooling sheaths welded to a ¼" sample tube. A 1/16" quench needle is inserted into the sample tube to wash soot from the tube. The quench needle is supported by triangular braces along its length to minimize blockage. The quench probe is depicted in Figure 4. Quench water is controlled by means of a rotameter and can flow at up to 120 ml/min.

The gas sample exiting the probe flows into a water knockout pot connected to a 20 foot hydrostatic drain leg where the bulk of the quench water is removed. The knockout pot is fitted with a float valve that seals the sample line outlet to prevent water from flowing into the sample system. The gas sample then flows through a sample conditioner consisting of a second knockout pot, refrigerated condensation coil and dual 0.5 micron coalescing filters to remove any remaining water and particulates. The sample then passes through a diaphragm pump and a series of gas used to direct sample, calibration or zero gases to the analyzers. Fairchild Model 10 low pressure regulators prevent analyzer over-pressurization, and rotameters (Matheson 603) control flow rates to the analyzers. Each analyzer is also fitted with a 2 micron metal frit filter.

Continuous gas analysis includes CO and CO₂, oxygen and NO_x. All analyses are conducted on California Analytical instruments. CO and CO₂ emissions are analyzed via infrared spectroscopy (Model ZRH). Oxygen is measured paramagnetically (Model 100P) and NO_x is measured as NO by chemiluminescent techniques (Model 300 CLD).

Gas temperatures in the furnace are measured by means of a water cooled R-type thermocouple probe. The probe is constructed from ½", 3/8" and ¼" stainless sheaths welded together. The bare thermocouple wire is threaded into ceramic insulators inserted into the probe. Temperature data is transmitted directly into the data acquisition system. K-type thermocouples measure the temperature at the furnace exhaust downstream of the cooling jackets and downstream of the dilution air system. The furnace top is also equipped with a K-type thermocouple for safety monitoring.

The zoned wall temperatures, furnace temperature and gas emissions data are collected and displayed at the control panel by means of a computer data acquisition (DAQ) system (Labtech v. 12). The DAQ includes sample averaging and data-logging features for monitoring and evaluation of experimental data. Additional data streams include flow rates of combustion air, dilution nitrogen and other gas streams that may be injected into the furnace.

4) Calculations Spreadsheet

An Excel spreadsheet ('98) originally developed to determine combustion air requirements and predict emission rates and concentrations for a given coal flow rate and overall air-to-fuel stoichiometric ratio (SR) has been updated for use when operating the 2M furnace. Combustion calculations are based on complete combustion approximations and do not predict formation of NO_x or CO. The spreadsheet includes input parameters for coal composition, combustion air composition, optional staged air combustion, ratio of transport to combustion air as well as air preheat.

Given these inputs, calculations are performed to determine the combustion and transport air flow rates and corresponding flow meter set-points. The spreadsheet also calculates gas velocities, Reynolds and Froude numbers as well as momentum fluxes for the combustion and transport air streams given the burner configuration. Burner input variables include the diameter of the primary jet and secondary annulus.

The spreadsheet has been revised to include a carbon and oxygen mass balance that will allow one to estimate the extent of carbon burnout and air inleakage into the furnace. Details of the derivation of the equations for estimating the carbon burnout and oxygen inleakage are described below.

5) Carbon & Oxygen Balance

The following derivation for determining the extent of carbon burnout and oxygen inleakage is based on assuming the following conditions were accurate:

- Dry basis CO_2 , CO, and O_2 concentrations
- Coal Feed rate and composition
- Flow rates for transport and combustion air streams (air, diluent nitrogen and enriched oxygen streams)
- All inleakage was assumed to be room air containing 21% oxygen

A mole balance on carbon in the system yields:

$$C_{\text{in}} = C_u + \text{CO}_2 + \text{CO} \quad 1$$

Where C_u represents unburned carbon.

A similar mole balance on oxygen yields:

$$\text{O}_{2, \text{ total in}} = \text{O}_{2, \text{ o}} + \text{CO}_2 + \frac{1}{2} \text{CO} + \text{SO}_2 + \frac{1}{2} \text{H}_2\text{O} \quad 2$$

Where H_2O is based on the hydrogen in the coal, not coal moisture. Equation 2 can be simplified to:

$$\text{O}_{2, \text{ total in}} = \text{O}_{2, \text{ o}} + \text{CO}_2 + \frac{1}{2} \text{CO} + \text{S} + \frac{1}{4} \text{H} \quad 3$$

Realizing that oxygen entering the system includes oxygen in the fuel, in the combustion air and inleakage, equation 3 can be rearranged to solve for inleakage oxygen, $O_{2,l}$:

$$O_{2,l} = O_{2,o} + CO_2 + \frac{1}{2} CO + S + \frac{1}{4} H - O_{2,f} \quad 4$$

Where $O_{2,f}$ includes both the oxygen in the coal, transport air and combustion air streams.

Similarly, the unburned carbon can be found by rearranging equation 1:

$$C_u = C_{in} - CO_2 - CO \quad 5$$

Equations 4 and 5 form the basis for the linked derivation of the carbon and oxygen balances. While they represent 2 equations and 7 unknowns, the oxygen, carbon dioxide and carbon monoxide concentrations from the furnace exhaust are known on a dry basis. Therefore, if these concentrations can be used to determine molar flow rates, the two equations can be solved simultaneously.

$$\% CO_2 = [CO_2] = \frac{\text{Moles } CO_2}{\text{Moles Dry Gas}} * 100\% \quad 6$$

$$\text{ppm } CO = [CO] = \frac{\text{Moles } CO}{\text{Moles Dry Gas}} * 10^6 \quad 7$$

$$\% O_2 = [O_2] = \frac{\text{Moles } O_2}{\text{Moles Dry Gas}} * 100\% \quad 8$$

Equations 6-8 can be arranged to solve for moles of CO_2 , CO and O_2 using T_m for moles of dry gas defined by:

$$T_m = N_2 + O_{2,o} + CO + CO_2 + SO_2 \quad 9$$

And N_2 includes the nitrogen in the feed streams and the nitrogen in the air inleakage. Thus, equation 9 can be rearranged as

$$T_m = N_{2,f} + 3.76O_{2,l} + CO + CO_2 + S + O_{2,o} \quad 10$$

It is important to realize at this point that all the terms in equation 10 are known or measured except for the second term on the right hand side. This equation can be rearranged to solve for oxygen inleakage:

$$O_{2,l} = \frac{T_m - (N_{2,f} + CO + CO_2 + S + O_{2,o})}{3.76} \quad 11$$

Thus, equations 4, 5 and 11 represent 3 equations and 3 unknowns that can be simultaneously solved for T_m , C_u and $O_{2,i}$. A solution for T_m , the total moles of dry gas can be found by combining equations 4 and 11 and rearranging:

$$T_m = \frac{A}{B} \quad 12$$

where the coefficients A and B can be determined given the emission concentrations and the feed rates:

$$A = \frac{1 - [CO] \times 10^{-6} - 0.01[CO] - 0.01[O_{2,o}]}{3.76} - 0.01([CO_2] + [O_2]) - \frac{1}{2}[CO] \times 10^{-6} \quad 13$$

$$B = \frac{N_{2,f} + S}{3.76} + S + \frac{1}{4}H - O_{2,f} \quad 14$$

The unburned carbon, C_u , can be found by plugging the value of T_m found in equation 12 into equation 5:

$$C_u = C_i - [0.01[CO_2] + [CO] \times 10^{-6}] * T_m \quad 15$$

Finally, the inleakage oxygen, $O_{2,i}$ can be determined by plugging in the value of T_m into equation 11:

$$O_{2,i} = \frac{T_m (1 - 0.01\{[CO_2] + [O_{2,o}]\} - [CO] \times 10^{-6}) - (N_{2,f} + S)}{3.76} \quad 16$$

The resulting coupled equations (12 through 16) were inserted into the excel spreadsheet and used to estimate the percentage of unburned carbon and oxygen inleakage based on fuel and air input flows and emissions data collected by the DAQ.

Example results are presented in Table 1. The data are based on a 2 kg/hr flow of coal, SR = 1.2 and air for both the combustion and transport air streams. Note that the estimated concentration data assume complete combustion and are presented on a dry basis.

Table 1. Emission Concentration Conversions

Pollutant	Actual Concentration	Estimated. Concentration*	Results
CO (ppm)	59	0	17% Unburned Carbon
CO ₂ (%)	11.81	14.83	4% Oxygen Inleakage
O ₂ (%)	6.84	3.73	

6) Emission Basis Conversion

Due to the extreme variability in operating conditions, pollutant emissions data are usually reported as an equivalent concentration at a given oxygen concentration, typically 3% or stoichiometric (0% excess air). Other methods of reporting emissions data are on a pounds per million BTU's basis. Both methods eliminate concentration reductions due to dilution, and the latter method allows for emissions rate comparison between different fuel types and/or combustion methodologies.

When converting emissions data to a specific oxygen content (i.e. 0% or 3%) for combustion processes utilizing air, the pollutant concentration at the desired oxygen level can be found from:

$$[\text{pollutant}]_{\text{desired O}_2} = [\text{pollutant}]_{\text{meas}} \frac{21 - \% \text{O}_{2, \text{desired}}}{21 - \% \text{O}_{2, \text{meas}}} \quad 17$$

For example, a 300 ppm reading for CO at 6% oxygen would increase to 360 ppm when corrected to 3% oxygen. Equation 17 can be derived from a simple mole balance assuming that any excess oxygen (measured oxygen) is from inleakage of room air (21% oxygen).

Unfortunately, equation 17 is not suitable when conducting combustion experiments with oxygen enriched or diluted gas streams due to the diluent effects of inert. Under these circumstances, pollutant concentrations would be artificially increased for oxygen enriched cases due to the reduced amount of nitrogen injected into the system with the combustion air.

Therefore, additional calculations must be performed to adjust the emission data to stoichiometric conditions based on air (21% oxygen, no enrichment or dilution). The equations necessary to perform these calculations are derived below. These calculations are based on the following assumptions:

- Room Air contains 21% oxygen
- Combustion Air is split into Transport Air (TA) and Secondary Air (SA)
- Overall Air to Fuel Stoichiometric Ratio (SR) is 1.2 (1.17 for the 100% dilution case)

Only the transport air stream (TA) is affected by oxygen enrichment or nitrogen dilution. The percent oxygen in the transport air stream can be found by:

$$\% \text{O}_{2, \text{TA}} = \frac{1}{1 + 3.76(1 - R)} \quad 18$$

where R is the percent dilution or enrichment. Note that when the air stream is diluted with nitrogen, R is negative.

Four scenarios were evaluated: the base case, 15% enrichment, and 30% and 100% dilution. For these four cases, the oxygen concentration in the transport air stream was calculated to be 21%, 23.8%, 17% and 11.7%, respectively using equation 18. The average oxygen concentration of the combined combustion air (transport and secondary air) is assumed to be a weighted average of the moles of oxygen in the two streams:

$$O_{2, \text{average}} = \frac{\%O_{2,TA} * m_{TA} + \%O_{2,SA} * m_{SA}}{m_{TA} + m_{SA}} \quad 19$$

Where m represents the total moles.

From equation 19, the overall combustion air concentration can be determined for each case as shown in Table 2:

Table 2. Average Oxygen Concentration in Combustion & Transport Air

Case	-100%	-30%	Base	+15%
% O ₂	20.47	20.68	21.00	21.32

Assuming that any excess air is only from combustion air (no inleakage), then the NO conversion from the measured value to stoichiometric (at the %oxygen for the scenario) is:

$$NO_{SR} = NO_{\text{meas}} \left(\frac{\%O_{2,CA}}{\%O_{2,CA} - \%O_{2,\text{measured}}} \right) \quad 20$$

Where %O_{2,CA} is the average oxygen concentration from Table 2. This allows the NO emissions data to be reported at the stoichiometric ratio of the inlet combustion air. However, to report the emissions data at stoichiometric **air** conditions, additional calculations must be performed. These additional calculations assume that the pollutant emissions are measured on a dry basis and that the emissions include nitrogen, carbon dioxide and trace contaminants. Due to the relatively small amount of NO and CO, mole balances on CO₂ and exhaust N₂ ignore these trace quantities. Thus, the concentration of CO₂, can be represented by:

$$\% CO_2 = \frac{CO_2}{N_2 + CO_2} 100\% \quad 21$$

which can be rearranged to yield

$$N_{2,\text{dilute}} = [1 - \%CO_2] T_m \quad 22$$

Where T_m is the total dry moles (carbon dioxide and nitrogen) of exhaust gases.

Note that the nitrogen found by equation 22 is the amount of nitrogen in the dilute (or enriched) combustion air listed in Table 2. Converting to an equivalent air basis (21% O₂) is accomplished by multiplying by a factor **Y**:

$$N_{2,air} = \mathbf{Y} * N_{2,dilute} \quad 23$$

The factor **Y** is the ratio of moles of nitrogen in the room air to dilute air basis which can be determined from:

$$\mathbf{Y} = \frac{N_{2,air}}{N_{2,SR}} = 3.76 * \frac{\%O_{2,CA}}{1 - \%O_{2,CA}} \quad 24$$

The moles of carbon dioxide and NO based on a dilute combustion air are found from:

$$CO_2 = \% CO_{2,SR} * T_m \quad 25$$

$$NO = \text{ppm } NO_{SR} * T_m \quad 26$$

Where NO_{SR} is the stoichiometric NO value calculated from equation 20.

The equivalent NO concentration based on room air can now be determined as the moles of CO₂ and NO do not change between these bases and the moles of N_{2,air} can be found from equation 23:

$$NO_{air} \text{ (ppm)} = \frac{NO}{N_{2,air} + CO_2 + NO} * 10^6 \quad 27$$

Insertion of equations 23 through 26 into equation 27 and upon rearrangement, the NO_{air} concentration is found from:

$$NO_{air} \text{ (ppm)} = \frac{NO_{SR}}{Y(1 - \%CO_{2,SR}) + \%CO_{2,SR} + NO_{SR}} \quad 28$$

The %CO_{2,SR} can be determined by solving equation 20 for carbon dioxide.

Equations 20, 24 and 28 were used to analyze the emissions data and convert the emissions concentrations to an air basis. Example results for NO are presented in Table 3.

Table 3. Corrected NO Emissions Data

Enrichment/ Dilution	Measured NO Concentration	Measured O ₂ Concentration	Y	Corrected NO Concentration
Base	107 ppm	6.33 %	1.00	153 ppm
+ 15%	102	6.6	1.019	145
-30%	114	6.39	0.98	168
-100%	232	6.16	.968	341

Note that the corrected data represents an equivalent NO concentration (ppm) based on 21% oxygen in the transport air stream and overall stoichiometric flow rates of air and coal.

7) Equipment Upgrades

The flame safety system controlling operations of the 2M, 6M and 3M furnaces in the CRG have been improved over the past year with the installation of 12V interlocks. The 12V DC relays replaced existing 120V controls installed in series within the system. Converting to 12V DC controls increases laboratory safety and improves system reliability. To date, the 6M exhaust fan, facility ventilation vacuum limits and coal feeder over-pressurization limit has been converted.

During initial shakedown tests on the 2M furnace, the coal conveyance lines repeatedly clogged between the K-tron loss-in-weight feeder (LWF) and the furnace. This problem was alleviated by constructing a platform off of the upper-bay which allows the LWF to be placed directly above the 2M furnace, thereby eliminating bends in the coal transport line. The stability of the coal flames during these tests also appeared to be greatly affected by perturbations in coal delivery. While the LWF system accurately meters out coal at flows as low as 1kg/Hr, the powdered fuel appeared to form clumps as it exited the feed screws due to their slow rotational speed. A set of smaller pitched screws were installed in the feeder that doubled the screw's rate of rotation. This has greatly increased feed uniformity, however, the fuel still appears to enter the furnace in pulses as noted by sporadic increases and decreases in the flame length. Work continues to further eliminate such disturbances as they likely greatly affect overall flame stability.

Additional equipment upgrades include installation of an electronic mass flow meter and two mass flow control valves for supplemental natural gas, transport air and nitrogen streams, respectively. These will greatly increase system accuracy and repeatability.

8) Partial Pressure Parametric Study

A parametric study was conducted to investigate the effect of oxygen partial pressure of the transport air on combustion stability and resultant NO_x emissions.

During the study a series of experiments were conducted (with replicates) to determine what effect oxygen partial pressure of the transport air has on coal combustion. The

partial pressure of oxygen in the transport air stream was varied via oxygen enrichment and nitrogen dilution while maintaining all other experimental variables constant. The targeted oxygen levels for the experiment are base case, 15% enrichment, and 30% and 100% dilution. Enrichment/dilution concentrations were determined as follows: 15% enrichment consists of 15% of the oxygen in the transport air provided by pure oxygen and the remaining oxygen provided by air according to the following equation:

$$\text{Mole Fraction } O_2 = \frac{1}{1 + 3.76(1 - R)} \quad 29$$

where R is the fraction of oxygen in the gas stream provided by pure oxygen. For the 30% dilution case, additional nitrogen is added to produce the desired oxygen concentration as if the 30% of the oxygen were removed (i.e. R = -30%).

During the experiments, the fuel feed rate, overall stoichiometric ratio, air preheat, combustion air and transport air velocities remained constant. The experimental parameters that were varied are the diameter of the transport air jet, oxygen content in the transport air and wall temperature. The resultant flame stability, standoff distance and CO, CO₂, O₂ and NO_x (as NO) concentrations in the furnace exhaust gases will be recorded. Note that the split between the primary (transport) air and secondary (combustion) air varied slightly to maintain constant transport air velocities during the runs. The experiments were conducted at 2 wall temperatures. The experimental parameters are presented in Table 4.

Table 4. Parametric Partial Pressure Experiment Conditions

Parameter	Value			
Coal Firing Rate	2 kg/hr			
Wall Temperature	750°C	900°C		
Combustion Air Preheat	450°C inlet			
Annular Jet diameter	1.69" ID			
Experiments	Base	+ 15%	-30%	-100%
Primary Air Oxygen, %	21	23.8	17	11.7
Primary Velocity 1/2" tube, fps	19.4	19.6	19.4	19.3
Primary Velocity 5/8" tube, fps	11.6	11.8	11.6	11.6
Primary/Second Air split, %	10	11.5	8.1	5.7
Secondary Air velocity, fps	31.8	31.2	32.5	32.5
Overall SR	1.2	1.2	1.2	1.17
SRp	.12	.138	.0972	.0667
Partial Pressure at 700mmHg	147.3	167.1	119.1	82.3

a) Procedure

The experiments conducted during the partial pressure parametric study were very similar in nature. Initially, the 2M furnace walls were preheated to the desired initial temperature (750° or 900°C) over a 1 to 3 hour period. As the wall temperature was ramped up, the combustion air flow was adjusted to the desired setpoint (based on a coal firing rate of 2 kg/hr and 1.2 SR). The air preheater was turned on and ramped up to a burner inlet temperature of 450°C. Once the wall temperature had stabilized and the combustion air preheat was at least 375°C, the 2M furnace was fired on natural gas. Natural gas firing rates were approximately 0.3 to 0.5 SCFM (5 to 9 kW). After a stable natural gas flame was established, the transport air was introduced into the furnace. Typically, setting the transport air flow consisted of adjusting the air flow followed by adjustment of the pure oxygen (enrichment) or nitrogen (dilution) streams. Once the furnace stabilized under these conditions, the loss in weight feeder was energized and coal was introduced into the furnace. The coal feed rate was increased from 0.75 to 1.25 kg/hr to 2 kg/Hr as the natural gas flows were reduced to 0.03 SCFM (0.5kW). Furnace operations, including furnace emissions were monitored for several minutes before the natural gas was turned off.

After the stabilizing natural gas was turned off, flame stability was evaluated by observing the location of the flame front and pollutant emissions concentrations were recorded every 1 to 3 minutes. Stable attached flames were considered to have flame fronts approximately ¼ to ½” below the nozzle. Flame detachment was determined by measuring the standoff distance from the burner to the flame front by means of a meter stick mounted beside the quartz window. A stable flame experiment lasted approximately 15 to 20 minutes.

In the event of flame blowout, the transport air stream was immediately turned off. The air preheater also turns off automatically with the loss of a flame signal. The furnace is then purged until the exhaust oxygen concentration returned to 20 to 21% and the CO/CO₂ concentrations reduce to negligible concentrations. The air preheater was then turned on and allowed to reach 450°C burner inlet temperatures before the furnace is relit. The experimental conditions described in Table 4 were performed in duplicate and in random order.

b) Experimental Results

The parametric study evaluated the effects of partial pressure of oxygen in the transport air stream on flame stability and NO_x emissions. The study included both visual observation of flame detachment and emissions analyses.

Both attached and detached stable coal flames exhibited fluctuations in flame luminosity and total flame length. These fluctuations were not apparent when co-firing natural gas. Initial runs at coal feed rates of 1.5 kg/hr using large-pitched LWF screws produced highly fluctuating flames and appeared to be caused by coal clumping in the feeder nozzle. Switching to finer pitched screws and increasing the feed rate to 2 kg/Hr has

reduced, but not eliminated these fluctuations. The observed reduction in the flame variability indicates that the fluctuations result from unsteady feeding of coal.

The NO_x emission data from the parametric stability study are presented in Figures 5 through 7. These figures present corrected NO emissions data as a function of average wall temperature for several transport air oxygen partial pressures. As noted in Table 4, all experiments were conducted at a 2 kg/hr firing rate, overall air to fuel stoichiometry of 1.17 to 1.2 and 450°C air preheat. Secondary combustion air velocities varied slightly due to changes in the ratio of combustion to transport air.

Figure 5 presents emissions data when operating at high transport air velocities (~19.6 fps), while figure 6 is for the lower velocity scenarios (approx. 11.6 fps). The data for both velocities are compared in Figure 7.

In figure 5a, NO_x data (corrected to 0% Oxygen and air feed) is presented for an 750°C initial wall setpoint temperature. At this low temperature, the dilute oxygen cases (12 and 17% oxygen) were unstable and the base case and oxygen enriched case (24%) became detached and unstable within 5 to 15 minutes. Data presented in Figure 5a are for attached flame conditions. This data shows a strong NO_x dependence on wall temperature, and appears to have little dependence on transport air oxygen concentration.

In figure 5b, the emissions data are presented for both attached and stable detached flames (denoted by a “D”) for initial wall setpoint of 900°C. Again, there appears to be some NO_x dependence on wall temperature for the attached flames, and we see a marked increase in NO_x emissions for the detached cases. The detached oxygen enriched flame (24%) exhibits higher NO_x emissions as compared to the detached 12% flame. This was expected due to the increased mixing and availability of oxygen to produce NO_x in the detached flames. Note that the 24% detached flame data point is from a series of runs where the flame was attached then detached then attached again.

The two runs (750° vs. 900° walls) are compared in Figure 5c. In this figure the overall temperature dependence for NO_x is clearly seen. Increasing the wall temperature by approximately 100° nearly doubles the NO_x emissions. The impact of detached vs. attached flames is also clearly seen. The stabilization effect of wall temperature can also be inferred as the lower wall temperatures could not support stable combustion for the dilute transport air cases and the base and enriched cases quickly detached and became unstable as compared to the stable attached or detached flames for the 900° runs.

As previously stated figure 6 presents NO_x emission data for the larger fuel jet. Increasing the jet reduces the fuel velocity by approximately 50% (19.6 to 11.6 fps). Reducing the fuel velocity increases flame stability as shown by the 17% oxygen run in Figure 6a. This figure shows the strong dependence of NO_x emissions on wall temperature. The data presented here do not indicate a strong dependence on oxygen concentration. Note that the 12% case was not run due to equipment failure.

Raising the initial wall temperature to 900°C greatly increases the NO_x emissions as shown in Figure 6b. Here both attached and stable detached flames were observed. It is somewhat difficult to determine any correlation between NO_x emissions and oxygen concentration, however it does appear that increasing the oxygen concentration might reduce the overall NO_x emissions. For example, at 925°C, the base case emissions (21%) were approximately 25 to 50 ppm lower than the 17% case. Also, the higher oxygen concentration cases produced similar NO_x emissions at a higher wall temperature as seen by the comparison between the 21% and 24% cases. This graph again clearly depicts the emissions increase between attached and detached flames. Note that there were no attached flames measured for the 12% case. The concentration dependence on NO_x emissions for the detached flames for the hot-wall runs is somewhat more intuitive, increasing the oxygen concentration increases the overall NO_x emissions; however, we did not observe any detached flames for the 21 or 24% cases.

In summary, we have shown that increasing the wall temperature increases flame stability-unstable flames become stable (attached or detached) and detached flames become attached flames. Reducing the jet velocity increases flame stability. However, as noted in Figure 7 (or comparing data from figures 5c and 6c), reducing the flame speed increases NO_x emissions. Note that in Figure 7, “-F” and “-S” represent the fast (1/2”) and slow (5/8”) fuel jets. The increase in NO_x emissions due to a reduction in jet velocity is most likely due to increased mixing between the two jets-the greater the difference between their velocities, the greater the shear and subsequent interactions.

The data presented in Figures 5 through 7 indicate that oxygen enrichment may reduce overall NO_x emissions. The reductions are not through modifications in NO_x reaction pathways, but by enhancement of overall combustion chemistry. The increased oxygen cases exhibited better flame stability which promotes carbon burnout near the burner. This reduces the total amount of oxygen available for NO_x formation, thereby reducing overall pollutant emissions.

9) Future Work

Additional experiments are planned to further investigate what effect oxygen partial pressure in the transport air stream has on flame stability and overall NO_x emissions. These experiments will be aimed at additional wall temperature set points and replicates.

Additional efforts are also underway to increase the fuel feed stability that should reduce perturbations in the flame that could artificially produce instabilities in the flame and/or cause an attached flame to detach.

And finally, the role of particle size on flame stability and pollutant emissions will be investigated.

Figure 1. Process Flow Diagram

Figure 2. Axial Burner

Schematic of Water Cooled and Water Quench Sampling Probe

Figure 3. Gas Sampling Probe

Figure 4. NO_x Emission data as a function of Wall Temperature for 19.6 fps Fuel Jet

Figure 5. NO_x Emissions as a function of Wall Temperature for 11.6 fps Fuel Jet

Figure 6. Combined NO_x Emissions Data