Technical Paper
BR-1825

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Presented to:
The 34th International Technical Conference on Clean Coal & Fuel Systems

Date:
May 31 - June 4, 2009

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Abstract

Pilot-scale emissions performance results are reported for the combustion of a western sub-bituminous Black Thunder Powder River Basin coal with air and oxygen-enriched air in a cyclone furnace. Unstaged firing of the high-moisture and low-nitrogen content Black Thunder coal at 17% excess air (1.17 stoichiometry) produced 759 ppmv NO_X (1.04 lb/million Btu) and 27 ppmv CO. Without oxygen enrichment, the lowest cyclone stoichiometry for continuous slag tapping was 0.70. Under this condition and 1.17 overall stoichiometry, the NO_X concentration was 108 ppmv (0.148 lb/million Btu), and the CO level was 24 ppmv. Partial substitution of secondary air flow to the cyclone combustor with oxygen was tested under staged operation using up to 10% O_2 enrichment and at an overall stoichiometry of 1.17. Oxygen enrichment of the cyclone combustor extended the lower stoichiometry limit while maintaining good slag tapping. At 1.17 overall combustion stoichiometry, the average NO_X concentration was 95 ppmv (0.126 lb/million Btu), and the average CO was 17 ppmv when the cyclone was staged to 0.66 stoichiometry and enriched with pure oxygen. The optimum emissions results represent 88% NO_X reduction from the uncontrolled operation.

Introduction

According to the Coal Power Plant database released in 2007 by the Energy Information Administration of the U.S. Department of Energy [1], coal-fired cyclone boilers in the U.S. have a generation capacity of 25,226 MWe. Over 60% of the power generated by cyclone boilers comes from units that burn low-sulfur, sub-bituminous, Powder River Basin (PRB) coals. Cyclone-equipped furnaces can burn a wide range of crushed coals with low flyash handling expenses and fuel preparation costs. But due to the intense turbulent mixing of coal and air, and the high-temperature combustion, NO_X ($NO+NO_2$) emissions from cyclone furnaces typically exceed 1.0 lb/10^6 Btu, requiring staging, fuel reburning, and/or backend pollutant control technologies for compliance with environmental regulations.

Current commercial performance for air-staged, PRB coal-burning cyclone units has been around 0.30 to 0.40 lb NO_X/106 Btu. Lower NO_X levels are achievable in exchange for higher flyash loading and unburned carbon content, and lower furnace slag tapping efficiency. Under the joint sponsorship of the U.S. Department of Energy - National Energy Technology Laboratory (DOE-NETL), Babcock & Wilcox (B&W) Power Generation Group, and Air Liquide, a program was undertaken for minimizing the NO_X emissions in coal-burning units including those equipped with cyclone furnaces. In a previous paper [2], we described an effective NO_X control method for cyclone boilers that included selective use of oxygen in the sub-stoichiometric combustion zone and fuel reburning with an eastern bituminous coal. In this paper, we report exemplary NO_X reduction performance from sub-stoichiometric and oxygen-enriched combustion of a PRB coal in a pilot-scale cyclone furnace.

Modeling simulations

Supportive computer simulations involved the application of B&W's COMO[SM] combustion model to examine the parametric effects of cyclone stoichiometry and oxygen enrichment variations on flow patterns, temperature profiles, and species concentrations. COMO is a multi-dimensional computational fluid dynamics code with advanced capabilities for simulating turbulent flow, particle trajectories, heat transfer, radiation, and heterogeneous and gas-phase reactions. It uses an unstructured mesh with a mixture of element shapes, and adaptive mesh refinement for higher resolution in regions of high temperature, velocity, or concentration gradients. COMO simulated the furnace, cyclone combustor, overfire air ports, and oxygen injection lances with sufficient control volumes. Figure 1 shows the computer model of the cyclone combustor and the pilot-scale boiler.

Modeling simulations included sub-stoichiometric combustion of the Black Thunder PRB coal with and without oxygen enrichment of the staged cyclone furnace. A slagging boundary condition was assumed within the cyclone combustor and boiler walls. At low heat fluxes, thick ash deposits could form as the boundary acted like an insulated wall with constant thermal resistance. At high heat fluxes, a constant temperature boundary at the ash melting point was applied and the run-off of molten slag regulated the thermal resistance.

Figure 2 compares the mid-plane contour plots of predicted temperature, and O_2 and CO concentrations in the cyclone combustor for unstaged and staged operations. As expected, decreasing the combustion stoichiometric ratio (SR) from 1.17 to 0.70 resulted in reducing conditions with rising CO formation. Without oxygen enrichment, the cyclone furnace became progressively cooler by decreasing the combustion stoichiometry as seen in Figure 2. Oxygen enrichment in the deeply staged (SR = 0.70) cyclone furnace at the 5% and 10% levels enlarged the high-temperature combustion zone in comparison with no enrichment cases and produced hotter conditions, especially near the walls. Here, oxygen enrichment is defined as the equivalent percentage of pure O_2 flow divided by the total oxygen that flows into the boiler by various oxidant streams (i.e., air and pure O_2). Point sources of locally high O_2 concentrations are also evident at the secondary air inlet to the cyclone where oxygen was injected via a multi-hole lance. Similar to the earlier modeling work [2], O_2 profiles indicate rapid consumption of the pure oxygen stream under sub-stoichiometric cyclone conditions. Since hot and oxygen-deficient combustion zones are conducive to nitric oxide destruction, the oxygen injector design selection for testing was based on these attributes and no attempt was made to predict NO_X.

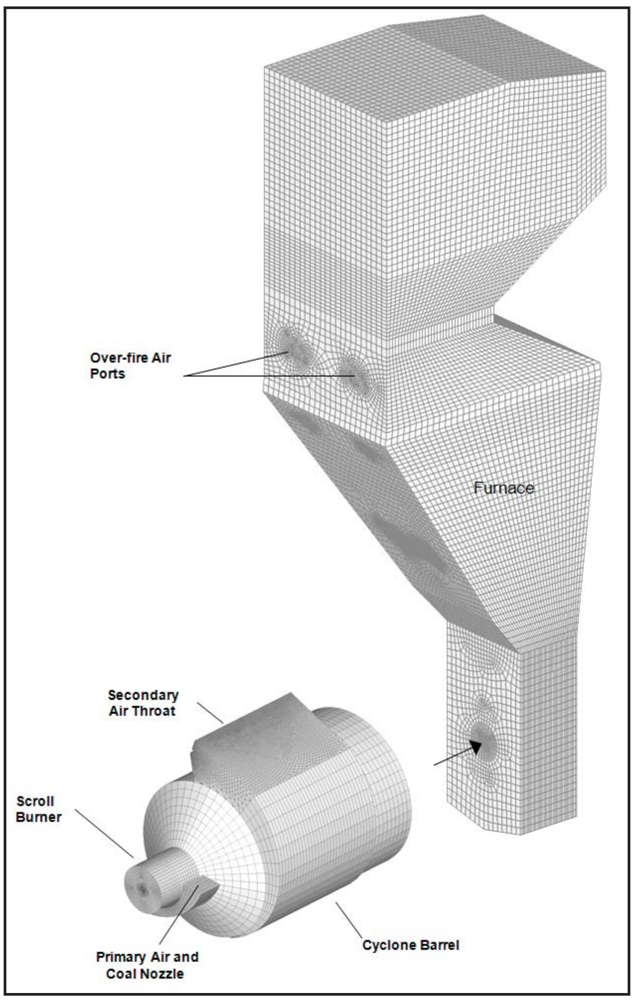

Fig. 1 Computer model of the cyclone combustor and furnace.

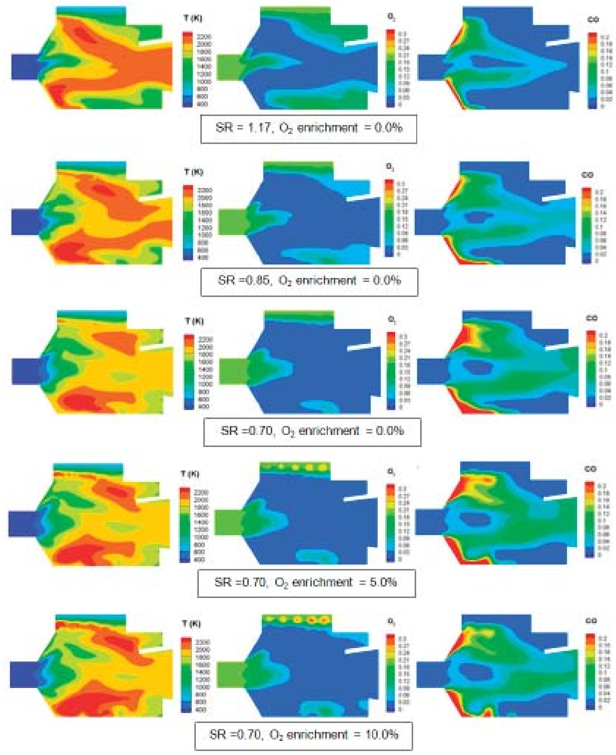

Fig. 2 Computed mid-plane contour plots of temperature (°K), and O_2 and CO mole fractions for Black Thunder PRB coal combustion in a pilot-scale cyclone furnace.

Pilot-scale facility description

Pilot-scale tests were performed in B&W's Small Boiler Simulator (SBS) facility. Figure 3 illustrates the cyclone firing configuration of the SBS. A calibrated gravimetric feeder controls the coal flow to the cyclone. For aerodynamic

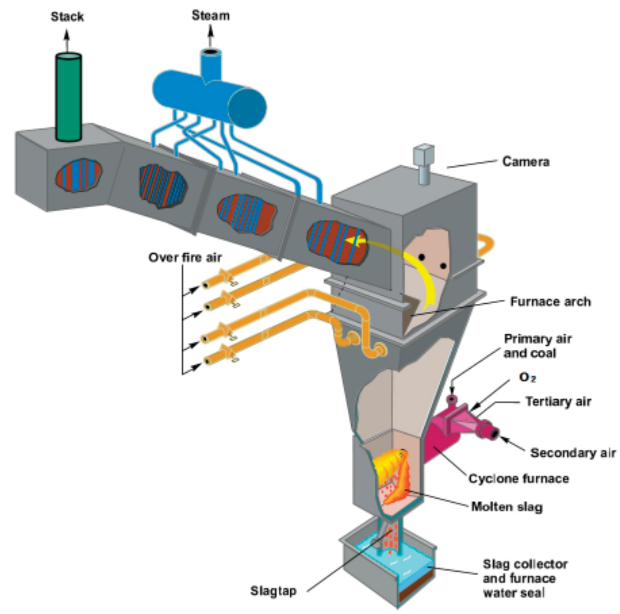

Fig. 3 Cyclone-fired configuration of B&W's SBS.

similarity, coarse pulverized coal instead of crushed coal (which is typical in commercial units) is carried by heated primary air in the transport pipeline and into a scroll burner on one end of the cyclone. Tertiary air is introduced from the center of the scroll burner to control the position of the main flame in the cyclone. As the coal/air mixture enters the cyclone barrel, it encounters a high-speed vortex from the 800°F secondary oxidant. Both the primary and secondary air streams swirl in the same direction. Fine coal particles burn in suspension and exit the center cone with hot gases. Due to the centrifugal action, large particles are captured and burned in a molten layer of slag that forms on the inner walls of the cyclone. The molten mineral matter exits the cyclone furnace from a tap below the cyclone throat and drops into a water-filled slag tank. About 80% of the coal ash leaves the cyclone as slag.

For staged combustion, the cyclone furnace was operated sub-stoichiometrically to minimize the NO_x formation. Staging air was introduced at two elevations each equipped with 2 overfire air (OFA) ports. Dampers in conjunction with pressure drop metering devices were used to balance the air flow to each OFA port. Combustion products exited the furnace and entered a convection tube bank. Stack gases were sampled continuously from the convection pass section outlet through a heated sample line. Gas sampling was done

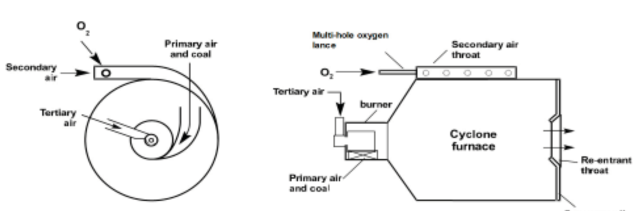

Fig. 4 Oxygen enrichment in the cyclone furnace.

at about 700°F. After filtering and drying, CO, CO_2, O_2, SO_2, and NO_x concentrations were measured by calibrated analyzers. Flyash was sampled across the convection pass section exit via an isokinetic probe and analyzed for loss on ignition (LOI) which closely approximates the flyash unburned carbon level. Non-intrusive flame imaging and temperature mapping were done with a two-color optical pyrometry system mounted on the SBS roof.

Liquid oxygen from a 9,000-gallon storage tank was vaporized in an ambient vaporizer and delivered safely from a central valve skid to the cyclone furnace. Figure 4 shows a multi-hole lance design that emerged from computer modeling as the best candidate for injecting oxygen into the secondary air inlet of the cyclone furnace.

Test results

Coal analysis

Table 1 lists the proximate, ultimate, and heating value analyses of the as-received coal sample. Coal ash composition is listed in Table 2.

Baseline performance results

Secondary air damper position at the cyclone furnace inlet was optimized at full load (5 million Btu/hr) and 3.1% boiler exit O_2 (corresponding to 1.17 overall stoichiometry, or 17% excess air in the air-blown case) for steady slag tapping and minimum pollutant emissions (NO_x and CO). NO_x emissions were lower when the staging air was split equally between the rear (lower) and front (upper) OFA ports. Bi-level addition of overfire air was previously proven [2] to be more advantageous than single-level operation since it provides a more gradual increase in the local stoichiometry and slows down the oxidation of nitrogenous species that form upstream in the main combustion zone.

Table 1
Coal Analysis

Proximate	**Value**
Fixed Carbon (%)	37.43
Volatile Matter (%)	30.84
Moisture (%)	25.92
Ash (%)	5.81
Ultimate	
Carbon (%)	50.57
Hydrogen (%)	3.66
Nitrogen (%)	0.56
Sulfur (%)	0.30
Oxygen (%)	13.18
Heating Value (Btu/lb)	8,718

Table 2 Ash Composition	
Constituents	**Weight %**
SiO_2	38.23
Al_2O_3	17.76
Fe_2O_3	6.46
CaO	16.19
MgO	4.09
Na_2O	1.03
K_2O	0.67
P_2O_5	1.52
TiO_2	1.01
BaO	0.57
SrO	0.30
SO_3	9.84

Firing the high-moisture and low-nitrogen content Black Thunder coal produced a cooler flame with lower NO_X emissions relative to a previously tested eastern bituminous coal [2]. Without oxygen enrichment, the lowest cyclone stoichiometry for continuous slag tapping was 0.7. Under this condition and 1.17 overall stoichiometry, the NO_X concentration was 108 ppmv (0.148 lb/million Btu), and the CO level was 24 ppmv. Unstaged NO_X and CO emissions levels were 759 ppmv (1.04 lb/million Btu) and 27 ppmv, respectively. Increasing the cyclone stoichiometry improved the fuel-N oxidation and resulted in higher NO_X emissions as seen in Figure 5. LOI levels were lowest around the cyclone stoichiometry of 1.0 where peak combustion temperatures are expected.

Birdseye view flame images and 2-D temperature maps of the cyclone combustor exit are shown in Figure 6. Exit gas luminosity and combustion temperature peaked at stoichiometric operation (SR=1.0) but decreased at 1.17 and 0.85 stoichiometries. Lowering the cyclone combustor stoichiometry from 1.0 to 0.70 cooled the flame from a peak value of around 2950°F (1621°C) to about 2700°F (1482°C).

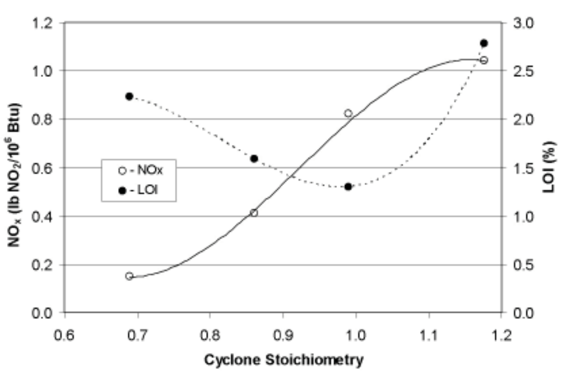

Fig. 5 Cyclone combustor stoichiometry effects on NO_X and LOI. Nominal operating conditions: 5 million Btu/hr firing of Black Thunder coal at 17% overall excess air with bi-level OFA ports.

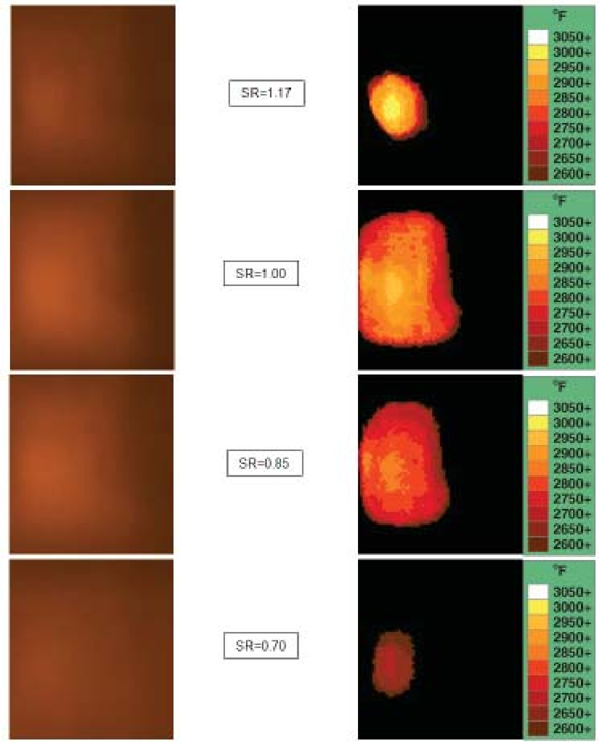

Fig. 6 Combustion stoichiometry effects on the cyclone combustor exit gas luminosity and temperature while burning Black Thunder coal with air at 5 million Btu/hr. Flow direction is from left to right.

Oxygen enrichment results

Partial substitution of secondary air flow to the cyclone combustor with oxygen was tested at a constant combustion stoichiometry of 0.70 using up to 10% O_2 enrichment and an overall stoichiometry of 1.17. Figure 7 shows the oxygen enrichment effects on NO_X, CO, and LOI values during staged operation. CO and LOI levels decreased with increasing oxygen enrichment. Within the 0-10% oxygen enrichment range, the lowest NO_X concentration of 109

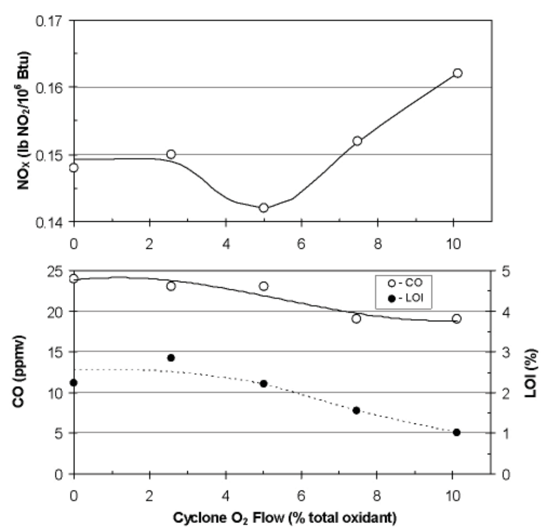

Fig. 7 O_2-enrichment effects on NO_X and LOI. Nominal operating conditions: 5 million Btu/hr firing of Black Thunder coal at 0.70 cyclone stoichiometry, bi-level OFA ports, and 1.17 overall combustion stoichiometry.

ppmv (0.142 lb/10^6 Btu) and the corresponding 23 ppmv CO and 2.2% LOI were measured at the 5% enrichment level. At this enrichment level, the sub-stoichiometric combustion zone may have reached the optimum temperature for NO_X destruction. Increasing NO_X emissions at higher oxygen (greater than 5%) enrichment levels is most likely linked to enhanced "fuel-bound nitrogen" oxidation.

As seen in Figure 8, the cyclone furnace exit gas luminosity and temperature increased progressively with rising oxygen enrichment. With 10% oxygen enrichment, the peak cyclone exit gas temperature rose by about 200°F (111°C) to 2900°F (1593°C), approaching the non-enriched stoichiometric operation value.

Oxygen enrichment of the cyclone combustor extended the lower stoichiometry limit to 0.61 while maintaining good slag tapping. At 0.61 cyclone furnace stoichiometry, 5% oxygen enrichment, and 1.11 overall boiler stoichiometry, the NO_X and CO emission levels were 96 ppmv (0.120 lb/million Btu) and 66 ppmv, respectively. At 1.17 overall combustion stoichiometry, the average NO_X concentration was 95 ppmv (0.126 lb/million Btu), and the average CO was 17 ppmv when the cyclone was staged to 0.66 stoichiometry and the pure oxygen flow to the cyclone was equivalent to 5% of the total oxidizer flowing into the furnace. Figure 9 provides a graphical summary of the results. For reference, burning an eastern bituminous Pittsburgh #8 coal in the pilot-scale furnace [2] at 5% oxygen enrichment level, 0.70 cyclone stoichiometry, and 1.17 overall stoichiometry emitted 132 ppmv NO_X (0.182 lb/million Btu). Commercial offering potential of this NO_X control technology is being assessed through economic evaluations.

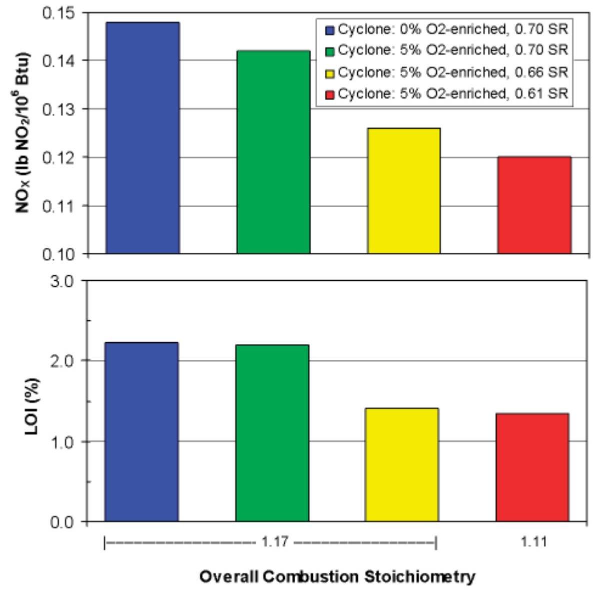

Fig. 9 Cyclone firing configurations and operating conditions effects on NO_X and LOI. Nominal operating conditions: 5 million Btu/hr firing of Black Thunder coal.

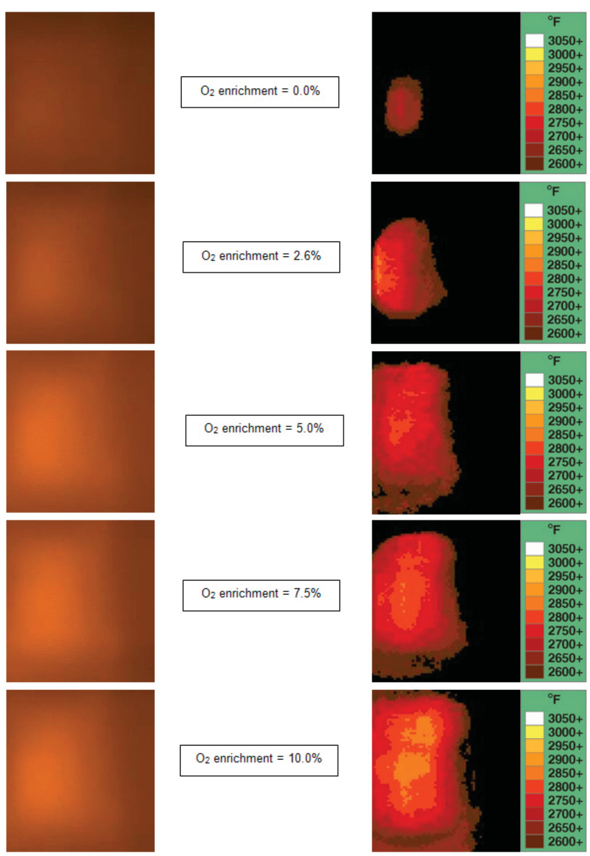

Fig. 8 O_2 enrichment effects on the cyclone combustor exit gas luminosity and temperature while burning Black Thunder coal at 0.70 stoichiometry. Flow direction is from left to right.

Acknowledgements

This paper is based upon work supported by the US Department of Energy under Award Number DE-FC26-05NT42301. The project was funded by the US Department of Energy - National Energy Technology Laboratory's (DOE-NETL) Innovations for Existing Plants Program. The authors would like to thank the DOE Project Officer, Bruce Lani for providing insightful advice during the course of the program. Assistance of Terry Wilson, Larry Mohr, Jeff Dudley, and Vern Burch in the pilot facility operation and instrument calibration is also greatly appreciated.

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2. Sarv, H., Sayre, A.N., Maringo, G.J., Varagani, R., and Levesque, S., "Selective Use of Oxygen and In-Furnace Combustion Techniques for NO_X Reduction in Coal Burning Cyclone Furnaces," Presented at the 33rd International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, FL, June 2008. (B&W Reference: BR-1809.)

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