Performance of a Co-Fired Boiler Burner with Water Injection

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ABSTRACT

A Co-firing technology with coal:biomass blends is expected to reduce land application requirements for manure based biomass wastes, and provide a renewable, low cost, and zero net fossil based CO₂ fuel. The choice of low BTU biomass fuels may include conventional agricultural or unconventional animal based biomass fuels depending upon local availability and transportation costs. For power plants located near feedlots where cattle are fattened for slaughter, the best choice of renewable biomass fuel is feedlot manure, properly referred to as feedlot biomass (FB). Coal can be mixed with FB in a 90:10 (coal:FB) ratio by mass and fired in existing boiler burners. A 30 KW (100,000 BTU/hr) boiler burner facility was built and tested for firing coal or coal-FB blends at Texas A&M University. FB has a moisture content ranging from 20% to 40% moisture, but most of the previous data have been generated using low moisture FB (<10% moisture) due to problems processing moist manure. The current work will investigate the effect of different moisture levels using external water injection. The boiler burner was modified with an air atomizing water injector. At a fixed equivalence ratio and swirl number for the secondary inlet air stream, the effect of different moisture levels and different biomass particles on boiler performance was investigated. NOₓ, O₂, and CO profiles along the axis of the furnace were obtained. The effect of atomizing air on the co-firing performance was also investigated. The results are summarized as follows: just with atomizing air is the wter injector, the NOₓ concentrations increased from 350 ppm to 650 ppm while CO decreased from 46,000 ppm to 18,000 ppm. External water injection decreased the NOₓ pollutant emissions from 570 ppm (zero external water) to 300 ppm (40% water in FB), but increased CO emissions from 2,500 ppm (zero external water) to 10,500 ppm (40% water in FB) due to incomplete combustion. Smaller sized particles of FB in the blended fuel produced less NOₓ but more CO.

INTRODUCTION AND OBJECTIVE

Coal has contributed more than 50% of total electric power generated over the past decade. Coal combustion generates pollutants in the form of NOₓ and SO₂, which causes smog, acid rain, depletes the ozone layer, and contributes to global warming with the release of CO₂. In 1994, coal power plants were responsible for 70% of all sulfur dioxide (SO₂), 33% of all nitrogen oxides (NOₓ), and 36% of all carbon dioxide (CO₂) released [1]. To reduce NOₓ, SO₂ emissions, the percentage of coal used in power generation could be reduced. Renewable biomass fuels could provide on such substitute. Biomass is organic matter such as wood, agricultural crops, or animal waste and 110 million dry tons of feedlot manure (alternatively called feedlot biomass, FB) and poultry litter (litter biomass, LB), are generated per year [2]. Not all of the animal waste produced can be used as fertilizer, and if improperly stored, or used as fertilizer, runoff or ground water pollution problems can occur.

Animal-based biomass fuels have a higher moisture and ash content than coal which result in lower heating values. The blending of low heat value FB with high heat value coal can reduce the ignition and flame stability problems caused by FB. Thus the overall focus of the research program is to develop a technology for co-firing coal with animal based biomass. A small scale 30 KW boiler burner facility (100,000 BTU/hr) has been constructed, to evaluate coal-biomass blends under a variety of conditions. Previously, the performance of a burner with coal and FB co-firing was determined under transient and steady state combustion conditions [3,4]. Their tests were performed in a 150 KW pilot scale (500,000 BTU/hr) facility at the National Energy Technology Laboratory (NETL),

Fibrous FB particles cannot be ground so finely as coal, which results in a larger FB particle size distribution. The primary objectives of the current research are to conduct a detailed set of experiments with external water injection to simulate different moisture contents and particle sizes of FB and to obtain the performance of the co-fired boiler burner.

LITERATURE REVIEW

A comprehensive review of cofiring literature has recently been compiled by Sami et al [6]. The effect of fuel moisture on combustion performance has also been investigated by Asay et al [7]. They report that NOx concentrations increase with the stoichiometric ratio (SR) and with swirl numbers (S) greater than five or less than one. At the lowest SR the system was predominately fuel-rich and NOx changed little with a change in swirl number. Slightly higher NOx was produced with wet coal under lean conditions due to an increased flame stand off distance. The increased flame stand off distance allowed more oxygen to be entrained in the flame, leading to increased NOx emissions. Hill et al. [8] simulated the effect of particle size on NOx formation in pulverized coal combustion. They report that smaller particles burn at a faster rate, approach a higher peak temperature more rapidly, and produce greater NOx concentrations. The gases devolatilized from small particles, mixed rapidly with oxygen containing gas and produced more NOx. Okazaki et al [9] analyzed the effect of different sizes on NOx formation in pulverized coal combustion. They reported that for large particles, the flame zone was established farther from the particle surface and volatile matter was selectively consumed. For the small particle, both volatile matters and fixed carbon burned on the particle surface or in the pores of particles during the combustion process. The NOx formation rate is greater in smaller particles since O2 can diffuse at a faster rate to char and hence O2 is readily available at the particle surface.

Abbas et al. [10] investigated the effect of coal particle size on NOx formation in a down-fired pulverized coal furnace. Low NOx concentration values were observed with smaller particles suggesting that the momentum of finer particles was strongly influenced by swirl forces, which anchored the flame near the exit to the burner exit. The larger particles penetrate the recirculation zone and root of the flame moves away from the burner. Hydrocarbon radicals, CO, NH3, and char favor NOx reduction in fuel-rich environment. Smaller particles release hydrocarbons and CO more rapidly, which can create a fuel rich zone and reduce NOx. This mechanism is different from the one proposed by Okazaki et al, and their results are in contrast to those of Hill et al.

FUEL PROPERTIES

FB was collected from the Hereford Feedyards and North Plains Compost, Amarillo Texas, and composted for 32 days to make partially composted FB. The moisture content of partially composted FB was still at about 31% (wet basis) after composting. Moisture levels above 10% lead to difficulties grinding the manure. The FB was dried to 10-12% moisture in a thin bed in a greenhouse, and then shipped for grinding. The final product was shipped to the Boiler Burner Laboratory, at Texas A&M University, for small-scale co-firing tests.

Wyoming PRB coal was supplied by New Centuries Energy, Amarillo Texas. The coal was ground to 70% passing through 75 μm (200 mesh), but the FB was not ground as fine. A blend of 90:10 by mass fraction of coal and FB was prepared for the co-firing experiments. Coal and FB particle sizes were classified according to the relevant ASTM standard. A sieve shaker was used to obtain the cumulative distribution that is shown in Figure 1. The FB size distribution was also fit to Rosin-Rammler distribution. It indicated that 70% of the FB was less than 150 μm, 17% was between 150 μm and 300 μm, and 13% was above 300 μm.

![Figure 1. Cumulative Distribution of Coal and Feedlot Biomass Particles, X = Size.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coal</th>
<th>FB</th>
<th>90:10 Coal-FB Blend</th>
</tr>
</thead>
<tbody>
<tr>
<td>C %</td>
<td>54.065</td>
<td>23.895</td>
<td>51.048</td>
</tr>
<tr>
<td>H %</td>
<td>3.435</td>
<td>3.565</td>
<td>3.448</td>
</tr>
<tr>
<td>N %</td>
<td>0.81</td>
<td>2.3</td>
<td>0.959</td>
</tr>
<tr>
<td>O %</td>
<td>13.075</td>
<td>20.26</td>
<td>13.7935</td>
</tr>
<tr>
<td>S %</td>
<td>0.385</td>
<td>0.9</td>
<td>0.4365</td>
</tr>
<tr>
<td>Moisture %</td>
<td>22.805</td>
<td>6.79</td>
<td>21.2035</td>
</tr>
<tr>
<td>Ash %</td>
<td>5.445</td>
<td>42.29</td>
<td>9.1295</td>
</tr>
<tr>
<td>FC %</td>
<td>37.25</td>
<td>40.4</td>
<td>34.577</td>
</tr>
<tr>
<td>VM %</td>
<td>9.67</td>
<td>11.37</td>
<td>35.09</td>
</tr>
<tr>
<td>HHV (as received)</td>
<td>21384 kJ/kg (9193.5 Btu/lb)</td>
<td>9561.5 kJ/kg (4111 Btu/lb)</td>
<td>20202 kJ/kg (8685 Btu/lb)</td>
</tr>
</tbody>
</table>

The coal particle size was kept fixed at 70% passing through 60 μm in co-firing. Table 1 shows the proximate and
ultimate analyses of Wyoming coal, FB, and 90:10 Coal-FB blend.

**EXPERIMENTAL SETUP**

Figure 2 shows a schematic of the boiler burner facility after the water injection modifications. The furnace (1) is 0.15 m (6 in) in diameter and 2 m (80 in) in height. Six sampling ports (2), spread apart by 0.15 m (6 in) are used to record data at 30 seconds intervals. The air supplied to the reactor includes the compressed primary air (3), which transports the fuel into the furnace and the atomizing nozzle air (4) used in atomizing the external water injection both are supplied by an air compressor. The secondary air (5), is preheated by circulation heater (6) and supplied by the rotary blower. The secondary air is given a swirl motion by swirler vanes in the burner to establish a recirculation zone (7). Primary air and atomizing nozzle air are kept constant at 155 SCFH and 32.25 SCFH. By adjusting the secondary air one can maintain the same excess air percentage at different fuel flow rates. The fuel flow rate is controlled by a variable speed DC motor (8). The fuel blend in the feed hopper (9) is transported to the furnace by the primary air via a venturi valve (10), which provides a small negative pressure to allow fuel entrainment. The water (11) along with atomizing air is injected into the furnace by two atomizing water injection nozzles (12). The blended fuel is injected into the reactor through an impeller plate to distribute the fuel uniformly across the reactor. The quarl (13) provides a radiant source of heat for the fuel suspension. A new quarl with four holes are made so that two propane torches for lighting the fuel suspensions and two atomizing water injection nozzles can be inserted. The nozzles and propane torches are mounted around the quarl so that the blended fuel can pass through the entire cross section of the propane flame and water spray. The temperature is measured by sheathed R type thermocouples (Pt, 13%Rh/Pt) (14), at every 0.15 m (6 in) along the reactor. The exhaust gas is quenched and cleaned by dual cooling water jets (15) and carried away by an exhaust ventilation system (16) and drainage system (17). The entire facility is operated from a central control panel (18). The gas composition is measured by a portable electrical-chemical cell based, flue gas analyzer (Lancom 6500). Three separate filters remove water and particulate to ensure a dry, clean sample. The analyzer can measure six gases O₂, NO, NO₂, CO (low), CO (high), and SO₂ and is periodically calibrated.

FB is typically dried prior to pulverization (to avoid grinding problem) in a boiler burner and it has been shown that the drying of high moisture FB has a negligible effect on the DAF heat value [11]. The different moisture content in FB is simulated in the current experiments by injecting water into the small-scale boiler burner (simulated feedlot biomass, SFB). Two sets of parametric studies were performed in the co-firing experiments. Case #1 maintained a 90:10 Coal-FB blend ratio as constant (90% coal, 10% FB by mass fraction with FB moisture at 6.79%) while external water was injected to simulate various moisture percentages in FB (20%, 30% and 40%). For Case 1, the effect of water injection resulted in (a) an increase in the moisture percentage in the SFB, (b) decreasing the coal-SFB blend ratio (SFB, simulated feedlot biomass, SFB = FB + external water) blend ratio from the parent 90:10 coal-FB blend, and (c) decreasing the higher heating value (HHV) of SFB and hence the HHV of the coal-SFB blend. The total thermal heat rate (heat throughput) was maintained at about 97,000 BTU/hr by increasing the total fuel rate. Case #2 maintained the Coal:SFB ratio at 90:10 and the heat throughput was again kept at 97,000 BTU/hr. Note that the coal:F blend ratio (fed through feeder for Case #2) is altered to maintain Coal:SFB at 90:10 and hence HHV decreases as the percent of moisture on SFB is increased. For the size effect experiments, the FB was sieved into three different size groups. Particle diameter (d) for parametric studies were (a) d <150μm (small), (b) 100μm<d<300μm (medium) and (c) 300μm<d<1,000μm (large), respectively. Apart from these tests, unsieved FB with size distribution (called combined) as shown in Figure 1 was also used.

![Schematic of Boiler Burner Facility](image)

**RESULTS AND DISCUSSION**

**Effect of Atomizing Air Injection**

The external injection of atomizing air may result in increased NOₓ formation. It is necessary to compare the
Experimental results with and without atomizing nozzle air under zero water injection. Figures 3 and 4 show the profiles of NOx (normalized to 3% O2), and CO concentrations along the burner axis with and without atomizing air injection (i.e. under zero water injection). The NOx concentration increased by 100% with atomizing air even though overall excess air percentage is the same. The large NOx increase could be caused by the direct turbulent mixing of the atomizing air with fuel blend to create an increased local O2 concentration. The higher O2 concentration resulted in the more rapid oxidation of the FB volatiles and the char particles in the flame, and produced higher NOx. Further, the secondary airflow was slightly reduced (in order to maintain overall equivalence ratio), the overall swirl number may have decreased due to injection of atomizing air, which can cause the flame to lift off from the burner. This could result in more air entrained into the recirculation zone, and cause more NOx formation. The O2 concentration increased (not shown) with the addition of atomizing air resulting in the strong oxidation of CO to CO2 and a decrease in the CO concentration (Fig. 4).

![Normalized NO Concentration Measured along Furnace with and without Atomizing Air Injection](image)

**Figure 3.** Normalized NO Concentration Measured along Furnace with and without Atomizing Air Injection

**Moisture Effect**

Water injected into the furnace can reduce the temperature and increase the moisture concentration in the recirculation zone. Figures 5 and 6 show the NOx concentration along the axis of the furnace and at 36" from the burner. The NOx concentration was closely related to the local stoichiometry. The NOx formation was higher near the burner where the oxygen was available (locally fuel lean). The NOx concentration kept decreasing due to reduction reactions proceeding under reduced oxygen conditions. The O2 percentage was higher for 6.79% moisture and the nitrogen containing volatiles such as HCN and NH3 reacted with O2 to produce more NOx.

![Normalized NO Measured along Furnace for Moisture Effect](image)

**Figure 5.** Normalized NO Measured along Furnace for Moisture Effect

The gas temperature was reduced with water injection, which lowered the devolatilization rate and hence N release rate near the burner inlet where O2 was readily available. The lowered temperature shows the CO oxidation rate. Profiles of CO concentration along the burner axis and at 36" for four different moisture levels are shown in Figures 7 and 8. CO was formed in flames by the rapid oxidation of HC by oxygen in the reaction zone (homogeneous reaction) or by the oxidation of char in the post-flame region (heterogeneous reaction) and then CO was subsequently slowly oxidized to CO2. Higher CO concentrations with the injection of water could be due to increased steam carbon reaction. Downstream the CO oxidation proceeded lowering O2 and CO concentrations.
Particle Size Effect

The concentrations of NOX, along the axis and at 36" are shown in Figures 9 and 10. Smaller particles resulted in lower NOX compared to the medium and larger sized particles near the burner. This effect can be explained by the variation in devolatilization rates caused by different particle heating rates. Close to the burner, higher NOX concentrations for medium and large particles resulted from the high availability of oxygen. The NOX concentration for the large FB particle size dropped rapidly near the 12" sampling port and had a second peak near the 24" sampling port. The first peak was due to NOX release from coal while the second peak was from the slower heating up of FB particles. The smaller sized FB particles on the order of 150 µm while the diameter of coal particles was much less (70% < 60 µm). Medium sized particles were an exception to this trend.

Small particles are believed to release volatiles faster due to large surface area per unit volume. More oxygen is available which leads to greater NOX formation. The lower NOX concentration compared to the medium and large particles indicates that the NOX reduction mechanism becomes more effective with volatiles from FB. The CO concentration was greater with small and combined size particles (Figure 11). This effect could result from the faster release of volatiles, such as hydrocarbons, which increased the oxidation rate to CO. The double peaks in NOX were confirmed by modeling results [12].
CONCLUSIONS

- O₂ concentration was significantly increased by atomizing air injection and NOₓ concentrations increased by 100%. CO concentrations decreased with the atomizing air injection.

- Parametric tests of moisture and particle size in FB have been conducted. The results are summarized as follows:
  a) Lower O₂ availability coupled with lower temperatures during water injection led to lower NOₓ concentrations than no water injection
  b) The CO concentration increased with water injection due to the steam carbon reaction and incomplete combustion of CO.
  c) The large particle size group had two peaks of NOₓ formation along the centerline of the boiler, which suggested two stages of the volatile release and was confirmed by modeling results. The first stage was due to NOₓ release from coal and the second one was due to delayed release of NOₓ from larger sized FB particles.

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REFERENCES
