Co-Firing of Coal and Feedlot Manure Blends in Boiler Burners for Power Generation

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Abstract. Feedlots in the panhandle area of Texas produce millions of tons of manure, alternately termed as feedlot biomass (FB) that must be safely disposed of each year. One possible alternative to stockpiling and land application is using the manure for power generation by mixing it with coal and co-firing it in existing boiler burners. The high temperatures produced by the coal will allow for the complete combustion of the manure. A research program was undertaken at Texas A&M to fully investigate the use of animal manure as a co-firing fuel. First the fuel properties were examined with an ultimate and proximate analysis which revealed higher ash, higher nitrogen, higher sulfur, a lower heating value, and more reactive volatile matter. A laboratory scale boiler burner (30 kW or 100,000
BTU/hr) was then constructed and used to evaluate coal, and a 90:10 blend by mass of coal and manure. The results showed similar levels of NO, and CO despite the decrease in fuel properties. Finally, the results were compared to combustion results from a larger scale DOE boiler burner (150 kW or 500,000 BTU/hr). The DOE results confirmed similar levels of NO emissions, and also evaluated the fouling behavior of the fuels. Fouling is found to be more severe in high ash FB compared to low ash coal. An economic analysis was performed and results reveal fuel cost savings of about $9 million for a 2000 MW plant when 90:10 Coal:FB blend is used.

Keywords. Feedlot Manure, Co-firing, Biomass, Coal, Fouling, Boiler Burner
Introduction

The average production of animal waste has increased by 56% for cattle by 176% for Chicken since 1978. The Texas Panhandle region covering adjacent parts of Oklahoma and New Mexico is the largest cattle feeding region in the nation, producing about 7.2 million fed cattle annually, (32% of the fed cattle produced and slaughtered in the U.S.) and contributing $14 billion per year to the regional economy. The cattle feeding industry in the Texas Panhandle area is growing at the rate of approximately 100,000 head per year. It is also a major industry in several other major farming areas of the United States. Each animal fed leaves approximately one ton of collectable manure containing 35% moisture and 65% solids (combustibles + ash). Since the production of manure is in excess of what can safely be applied to farmland, the stock piled waste poses economic and environmental liabilities. The bio-waste, sometimes known as “bio-mess” can lead to ground water contamination and air pollution problems with the release of CH₄ (a greenhouse gas), NH₃, H₂S, amides, volatile organic acids, mercaptans, esters, and others. The development of alternative uses for feedlot manure may become more attractive in some cattle feeding areas in the future. Since the waste contains combustibles, it could be disposed off as an energy source and the land, air, and water pollution from stockpiled manure can be reduced. Various technologies, which utilize feedlot biomass as a sole energy source, are summarized in Sweeten et al (1986) and Annamalai et al. (1987). Previous attempts to use feedlot manure as a fuel source have met with only limited success due to the high moisture, high ash, and low heating value which lead to flame stability problems and combustor fouling.

One innovative method for disposing of feedlot manure is co-firing. In co-firing, the manure is mixed with coal and fired in existing boiler burners. The high temperatures produced by the combustion of coal allow the biomass fuel to be completely burned. The fuels are mixed in a 90:10 ratio by mass to minimize the change in the fuel properties. The coal-manure cofiring technology can provide an environmentally sound method of disposing of animal waste for useful power or steam and at the same time it can address groundwater contamination, and greenhouse gas concerns since it is renewable biomass. In farm belt areas, the use of manure in cofiring could provide additional financial return to feedlot operators through manure sales. Since feedlot manure has uses as both a fuel source and as a fertilizer it is properly referred to as feedlot biomass (FB) to emphasize its economic utility. A detailed research program was undertaken at Texas A&M to study the performance of combustors when fired with Coal:FB blends. The research program included the following activities: 1) a review of literature on coal:biomass cofiring (Sami et al 2001), 2) FB fuel characteristics (Sweeten et al.2002, Annamalai et al 1987a), 3) combustion characteristics when fired along with coal in a small scale (100,000 Btu/hr) Texas A&M (TAMU) boiler burner facility (Annamalai et al.2002, Frazitta et al. 1999), and 4) combustion and fouling characteristics when fired along with coal in a large pilot scale (500,000 Btu/hr) at the Department of Energy- National Energy Technology Laboratory facility or DOE-NETL, Pittsburgh under a Cooperative Research and Development Agreement CRADA) established between NETL and Texas A&M (Annamalai et al. 2002). This paper presents a brief overview of the results obtained under the current research program.

Materials and Methods

Fuel Properties

The fuels used were blends consisting of 90% pulverized Wyoming Powder River Basin (PRB) coal (Black Thunder Mine) as used by SPS and 10% (weight basis) pulverized partially composted feedlot manure from Hereford Feedyards and North Plains Compost. Detailed
ultimate and proximate analyses were conducted for raw, partially composed and finished composted FB to determine the basic fuel properties [Sweeten et al, 2002]. The results for partially composted FB are shown in Table 1. The decrease in heat value of dry manure with increase in ash content (e.g. during composting) of manure (collected elsewhere) is shown in figure 1. The maximum possible flame temperature that could be obtained by burning FB for various moisture and ash contents are shown in figure 2.

**TAMU Experimental apparatus**

The experiments were conducted in the downward fired 30 kW (100,000 BTU/hr) Texas A&M boiler burner facility as shown in figure 3. The interior is a 6 in cast ceramic shell backed up by a fibrous ceramic blanket, and contained by a steel shell. The chemical composition of green cast is presented in Table 2. Its relevance to SO$_2$ measurements will be discussed later. The air for combustion is supplied by a blower, and the fuel is premixed, fed into a hopper, dispensed by a commercial feeding system, and injected into the primary air line with a venturi valve. At the top of the furnace a set of swirler vanes imparted a tangential component to the velocity of the secondary air to create a recirculation zone to stabilize the flame and to ensure complete mixing. The flame is kept lit through the use of 2 propane torches at the top of the furnace. Gas readings are taken from the second to last sampling port with a commercial gas analyzer. After the sampling ports, a water spray quenches the hot gases and removes particulates. To conduct the experiments, the furnace was run for 1 hour or until it reached approximately steady state. Then 10 readings were taken at an interval of one minute from the final sampling port. After the experiment was over the furnace was allowed to cool, and ash samples were taken from bottom to conduct an ash analysis. A more complete description of the furnace and the experimental apparatus is found in Thien (2002). There are two versions of the burner: a) shorter (height: 51.6 or 1.31 m) and b) longer (height: 87.7" or 2.23 m) and hence residence time will be higher for the longer version. The facility can also be operated as a reburner for NO$_x$ reduction studies (Ben et al, 2001). Reburning is a process where the NO$_x$ emitted by main burners is reduced by injecting additional fuel and air but slightly rich in mixture downstream of the main burners.

**Diagnostics**

The diagnostic system consists of an orifice plate for measuring the secondary air flow rate, sheathed "type K" (Chromel/Alumel, 90% Nickel 10% Chromium / 95% Nickel, 2% Aluminum, 1% Silicon, and 2% Manganese) and "type S" (Pt/Pt-Rh 100%/90%-10%) thermocouples, in the boiler and the secondary air stream. A rotometer was employed to measure the primary air flow rate. The commercial gas analyzer uses electrochemical cells as sensors and is capable of measuring CO, O$_2$, NO, NO$_2$, CO$_2$, combustibles, and SO$_2$ at a stated accuracy of 3% percent of the measured gas reading. Additionally, it has a heated sample probe, and an air dryer in the probe to remove any water vapor in the combustion samples to prevent it from condensing, and reacting with SO$_2$ or NO$_2$. Calibration gases for CO, NO, NO$_2$, and SO$_2$ were used to periodically check the accuracy of the gas analyzer and measurements.

**DOE-NETL 150 kW (500,000 BTU/hr) Burner**

The DOE-NETL facility is well described in Smouse et al (1988), Robinson et al (1998), Freeman et al (1997, 2000) and is briefly explained in Annamalai et al 2002. The DOE-NETL facility known as CERF (Combustion Environmental Research Facility, not shown) consists of a vertical down-fired combustion furnace, with personal computer-based data acquisition and process control. It also has provisions to measure CO, NO$_x$, SO$_x$, and ash fouling characteristics. The soot-blowing is performed to remove the ash deposits from metal surfaces. The higher the fouling potential, the higher the peak pressure required to remove the ash deposited. A relative scale (1/2, 1, 2, 3) is reported based on the soot-blower supply pressure,
where ‘1’ represents an easily removed deposit, while ‘3’ indicates a deposit that is much more difficult to remove, requiring higher sootblowing pressures. After each soot-blower supply pressure increment, the percent heat flux recovery (relative to the clean surface value) is recorded as a means of gauging the extent of the deposit removal during soot-blowing.

Results and Discussion

**Fuel Properties**

Utilities are concerned with quality of fuel fired in the boilers. The results shown in Table 1 indicate that FB is a lower quality fuel than coal due to its high ash, low heating value, high nitrogen, and high sulfur. FB has approximately half the BTU content of coal, twice the volatile matter of coal, and four times the N content of coal on a heat basis. An increase in the homogeneity of properties but a decrease in the heat value occurs during composting. Over 50% of the ash in conventional FB is attributable to contamination from rocks and soil during the collection in unpaved feedlots. The ash content of FB is almost 9-10 times that of low ash (5 %) coal. The high ash and low heating value of the FB can lead to poor combustion when using biomass fuels, specifically flame stability problems and incomplete combustion. With a higher the heating value and a higher the flame temperature a more stable flame forms. A THERMOLAB spreadsheet based combustion program was run for many agricultural and animal based biomass fuels with varying, moisture and ash (Annimalai and Puri, 2001) in order to determine the adiabatic flame temperatures under stoichiometric air:fuel conditions. The curve fit shown in figure 2 for many different biomass fuels with moisture ranging from 0% to 45% and ash percentages ranging from 0% to 40% yields the following correlations:

\[
T(C) = 2012 - 1.8864*H_2O + 5.0571*Ash - 0.3089*H_2O*Ash - 0.1802*H_2O^2 - 0.1076*ASH^2 \quad (4)
\]

\[
T(F) = 3653 - 3.3955*H_2O + 9.1027*Ash - 0.5560*H_2O*Ash - 0.3244*H_2O^2 - 0.1937*ASH^2 \quad (5)
\]

where H_2O and ash are given on a mass % basis.

The fuel N per unit heat value is also considerably high as compared to coal, which may result in increased NO_x emissions. The higher sulfur in FB on heat basis can lead to greater production of the air pollutants NO_x and SO_x. Also the additional ash in FB can lead to combustion fouling and boiler tube corrosion problems. It is also important to note that the FB will have a higher percentage of its combustible content in volatile matter as compared to coal. The volatile matter will burn more readily, and might make up for the high ash and low heating value of the FB. It was found that the FB will also release its volatiles at a lower temperature and at a faster rate than coal Thien (2001). The coal could be easily ground and 90 % pass through 40 microns sieve but only 60-75 % pass through 40 microns for FB.

**Combustion Test Results from 30 kW (100,000 BTU/hr) TAMU Burner**

The CO emissions for the boiler burner facility and from a shortened version of the boiler burner are shown in figure 4. The short boiler burner was used initially, but unacceptably high levels of CO were produced due to the low residence time. The length of the furnace was doubled to double the residence time. In the elongated furnace lower levels of CO were found, with similar levels for 90:10 blend and coal. It is believed that the higher VM percentages on a dry ash free basis and the faster release of VM from the FB allowed for similar levels of combustion efficiency despite the high ash and low heating value and larger sized FB particles.

The NO_x emissions for coal and 90:10 blend are shown in figure 5. The results show that similar levels of NO emissions will be obtained for coal and 90:10 blend despite the higher level of nitrogen in the 90:10 blend fuel. Less of the N in the FB is converted to NO_x as shown in fuel conversion factor as shown in figure 6. The fuel N conversion factor assumes that all of the NO
formed from the fuel nitrogen, and none is formed from atmospheric nitrogen. The lower level of N conversion is attributed to the release of fuel nitrogen from FB in the form of ammonia which participates in more favorable nitrogen kinetics which proceed faster and form less NO than those that involve HCN. The high volatile matter of FB on dry ash free basis also adds to lower than expected NO emissions. More volatile matter is released more rapidly from the FB which creates localized fuel rich zones to minimize the creation of NO.

Finally the SO₂ emissions are shown in figure 7 for coal and a 90:10 blend of coal and FB. The emissions are relatively low and results show no clear trend, and a large variability in the measurements. The high variability is attributed to absorption of SO₂ by the ceramic shell, which is high in CaO (Table 2) which is a known sulfur absorbing agent.

**Combustion Test Results from 150 kW (500,000 BTU/hr) DOE-NETL Burner**

Although the bench scale tests at TAMU were not under optimally controlled conditions, including furnace temperatures that were below typical pulverized coal combustor operations, the preliminary results established the technical feasibility for FB cofiring and illustrated the need for further testing and scale-up. The tests were repeated with pilot plant experiments on FB blends under typical conditions for boiler operation. These tests were conducted at DOE/NETL under a Cooperative Research and Development Agreement (CRADA) with Texas A&M University. Flame stability, combustibility, emission, and slagging/fouling evaluations of Wyoming PRB coal and coal:FB blend were obtained for various firing rates at typical conditions of 10-20% total excess air, 500°F secondary air (SA) preheat, 0.6-0.7 secondary air swirl number (SN), and primary air/secondary air (PA/SA) ratio of about 0.24.

The Wyoming PRB coal was observed to burn extremely well, with residual carbon or loss-on-ignition (LOI) in the fly ash of less than 1%, which corresponds to combustion efficiencies well above 99%. Similarly, the coal:FB blend also exhibited excellent combustion, with very little unburned carbon, and fly ash LOI under all conditions.

**NOₓ and SOₓ emissions**

There was a very slight increase in NOₓ emissions from about 220 g/GJ (0.51 lb/MMBtu) to 236 g/GJ (0.55 lb/MMBtu) when cofiring FB at similar burner conditions. Such an increase (<10%) would not be considered significant, particularly given the fact that simple burner adjustments could be made to alter the performance with a 90:10 blend relative to Wyoming PRB coal. In general, burner operation at reduced excess air can be used to reduce NOₓ emissions. However, there was an increase of about 14% in SO₂ emissions (g/GJ basis) when cofiring FB that is consistent with the higher sulfur content (about 9% energy-basis) as compared to the Wyoming PRB coal. The absolute values of observed SO₂ emissions were lower than expectations on a g/GJ basis, although the high calcium nature of the PRB coal and 90:10 blend leads to some sulfur capture.

**Ash Fouling**

At 370 kBtu/hr and 1925-1943°F FEGT (furnace exhaust gas temperature), after just 1-hr, fouling deposits over 1-inch thick formed (due to high ash) and resisted soot-blowing, with only marginal recovery of heat flux (from 35 % to 65 % of clean surface value) at 80-350 psig soot-blowing.
Economics

A proposed scheme for utilizing FB as a fuel in the blend is shown in figure 8. An economic analysis has been performed on the use of feedlot biomass as a fuel in a power plant. The analysis is conducted for feedlot biomass collected from both the unpaved feedlot (UFB) and paved feedlot (PFB). Calculations for CO$_2$ and SO$_2$ emission are also performed to check whether a blended fuel is an environmentally friendlier fuel.

It is concluded that it is economically better to blend the coal with feedlot biomass than to use coal alone. Assuming that coal costs $25 per ton and $2.25 per ton for FB collection + $0.12/ton/mile with transportation distance of 30 miles, one can save up to $9.3 million per year in fuel cost for 90% coal and 10% FB blends when used in a 2000 MW power plant (Harahap, 2000).

The utilization of paved feedlots that incorporate coal-combustion by-products (CCB), such as concrete that utilizes boiler and fly ash, provides a more stable surface that minimizes the ash content (due to contamination from rocks and soil), while providing other benefits, such as reduced groundwater run-off. CCB-paved feedlots are expected to allow for enhanced FB with ash contents near 20% that would represent a significant (about 3-fold energy basis) reduction in ash loading as compared to conventional FB. Such a reduction would reduce delivered transportation costs (figure 8) while significantly improving FB fuel quality to reduce slagging/fouling impacts, biomass handling/processing requirements, and ash disposal considerations for cofiring or reburning applications.

Conclusion

- FB is a lower quality fuel as compared to coal due to its high ash, low heating value, high nitrogen, and high sulfur.

- In the elongated furnace, both coal and a 90:10 blend produced lower levels of CO as compared to the short furnace.

- Switching to a 90:10 blend did not result in greater NO$_x$ emissions as verified by the DOE results.

- Less of the nitrogen in FB is converted to NO$_x$ as illustrated by its lower fuel N conversion factor as compared to coal.

- Accurate SO$_2$ readings could not be obtained due to absorption by the CaO in the wall of the furnace.

- Tests revealed better combustion for 10% FB blends than for coal alone and NO$_x$ emissions were slightly less with blend than with coal even though FB had a much higher fuel nitrogen content of 2 wt% as compared to the baseline coal value of 0.7 wt%.

- The ash fouling problems associated with FB could be minimized with the use of advanced feedlot manure (i.e., low ash manure collected from paved feedlots) handling operations to achieve much lower FB ash contents that would be closer to the intrinsic mineral matter associated with the animal digestion process.

- Economic analysis reveals that the use of FB as a fuel in 90:10 coal:FB blend can result in savings up to 9 million dollars for a 2000 MW coal fired plants.
Acknowledgements

The Texas Higher Education Coordinating Board (THECB) under the 1997-1999 Advanced Technology Program (ATP) provided primary funding for the project, "Biosolid Fuel Blends for Power Generation and Reduction of Pollutants". The services of personnel and equipment provided by DOE/FETC as in-kind contribution to the ATP project on coal/feedlot manure blends was very significant, as was a research grant from TCFA, and the in-kind contribution of laboratory analysis by Southwestern Public Company. Appreciation is extended to Dr. Mehandra Mathur, Federal Energy Technology Center, for their leadership in organizing and conducting pilot plant tests at Pittsburgh. The work is also partially supported by DOE-NETL DE-FG26-00NT40810 (2000-2002) and DOE-Nebraska WRBEP 55026 (1999-2001).

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Table 1: FB-B and coal B properties

<table>
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<tr>
<th></th>
<th>Coal</th>
<th>Feedlot</th>
<th>Feedlot 90-10</th>
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<tr>
<td>C</td>
<td>60.3</td>
<td>23.6</td>
<td>56.6</td>
</tr>
<tr>
<td>H</td>
<td>3.62</td>
<td>2.9</td>
<td>3.55</td>
</tr>
<tr>
<td>O</td>
<td>14.5</td>
<td>19.1</td>
<td>15.0</td>
</tr>
<tr>
<td>N</td>
<td>0.96</td>
<td>1.78</td>
<td>1.04</td>
</tr>
<tr>
<td>S</td>
<td>0.23</td>
<td>0.5</td>
<td>0.26</td>
</tr>
<tr>
<td>Cl</td>
<td>&lt;0.1</td>
<td>1.85</td>
<td>NA</td>
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<tr>
<td>DL</td>
<td>15.12</td>
<td>7.7</td>
<td>14.4</td>
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<tr>
<td>FC</td>
<td>42.38</td>
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<tr>
<td>VM</td>
<td>37.17</td>
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<tr>
<td>Ash</td>
<td>5.33</td>
<td>44.2</td>
<td>9.21</td>
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<tr>
<td>HHV (kJ/kg)</td>
<td>23709.8</td>
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<td>22281</td>
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Table 2. Greencast 94 composition

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<tr>
<th>Ingredient</th>
<th>Formula</th>
<th>Percent</th>
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<tbody>
<tr>
<td>Silica</td>
<td>(SiO₂)</td>
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<tr>
<td>Alumina</td>
<td>(Al₂O₃)</td>
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<tr>
<td>Titanium</td>
<td>(TiO₂)</td>
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<tr>
<td>Iron Oxide</td>
<td>(Fe₂O₃)</td>
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<tr>
<td>Lime*</td>
<td>(CaO)</td>
<td>5.1</td>
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<tr>
<td>Magnesia*</td>
<td>(MgO)</td>
<td>0.1</td>
</tr>
<tr>
<td>Alkalies*</td>
<td>(Na₂O+K₂O)</td>
<td>0.2</td>
</tr>
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*These alkaline oxides may react with SO₂
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Primary air</td>
<td>0.118 m$^3$/min (250 SCFH)</td>
</tr>
<tr>
<td>Fuel flow rate</td>
<td>85 g/min</td>
</tr>
<tr>
<td>Primary air Loading ratio (air/fuel)</td>
<td>1.65</td>
</tr>
<tr>
<td>Secondary air</td>
<td>0.3823 to 0.4573 m$^3$/min</td>
</tr>
<tr>
<td></td>
<td>(810 to 969 SCFH)</td>
</tr>
<tr>
<td>Primary Air as a percent of total air</td>
<td>~ 22%</td>
</tr>
<tr>
<td>Secondary air Temp</td>
<td>380 K</td>
</tr>
<tr>
<td>Residence time</td>
<td>~2 sec cold, ~0.5 sec hot</td>
</tr>
<tr>
<td>Heat throughput</td>
<td>Coal: 30.3 kW (103,000 Btu/hr)</td>
</tr>
<tr>
<td></td>
<td>Blend: 28.6 kW (97,583 Btu/hr)</td>
</tr>
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</table>
Figure 1. Variation of Dry Heating Values of Manures with Ash contents

HHV-dry (BTU/lb) = -98.807* ash % + 9380

\( R^2 = 0.8734 \)
Figure 2. Correlation of Adiabatic Flame Temperature with Moisture and Ash contents;

\[ T(K) = 2285 - 1.8864 \times H_2O + 5.0571 \times Ash - 0.3089 \times H_2O \times Ash - 0.1802 \times H_2O^2 - 0.1076 \times Ash^2, \quad H_2O \text{ and Ash on mass } \% \]
Figure 3: A 30 kW or 100,000 BTU/hr TAMU boiler burner facility

Figure 4. CO emissions for short and long reactors
Figure 5. NO emissions for TAMU and DOE reactors

Figure 6. Fuel N conversion fraction
Figure 7. SO$_2$ emissions vs excess air percentage
Figure 8. A Proposed Scheme for Using Feedlot Manure/biomass (FB) as a fuel in power plants