Reburning of Cattle Biomass with Coals for Emissions Control

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ABSTRACT

Reburn studies were performed at a 30 kW_t (100,000 Btu/h) down-fired boiler burner facility to evaluate the potential of cattle biomass (CB) as a reburn fuel and to investigate the effect on the NO_x emission. The NO_x emission decreased with a greater percentage of CB in the reburn fuels and with increased equivalence ratios (ϕ_{RBZ}), i.e. less combustion air. The NO_x reductions were greater when heat exchangers (HEXs) were present, because of the catalytic effect of ash deposited on the HEX's surfaces. The CB ash was stickier than the coal ash, and thus the CB ash on HEXs was more difficult to remove compared to the coal ash. The burnt fraction increased with increased percentages of CB in the reburn fuels. Both dairy biomass (DB) and feedlot biomass (FB) can be used as reburn fuels for effective NO_x reductions in coal-fired power plants.

Keywords: cattle biomass, reburn, co-firing, NO_x reductions

1 INTRODUCTION

The biomass fuels can be classified into animal waste/biomass (AnB) and agricultural biomass (AgB). The AnB includes cattle biomass/manure (CB), poultry biomass/litter (PB), hog biomass (HB), swan biomass (SB) etc. Since chemical compositions of AnB fuels are almost similar to the ration fed to animals, except for N and P, the quality of fuels is similar to those of AgB on a dry, ash-free basis. Thermo-chemical energy conversion technologies have been investigated during co-combustion of AnB and coal. Co-combustion of coal and AnB can potentially be an alternative way of disposing manure at large concentrated animal feeding operations and to control emissions both at feeding operations and power plants, especially NO_x and nonrenewable CO_2. In addition, CB has been proposed as a reburn fuel [1,2]. Reburning coal with CB has the potential to reduce NO_x and nonrenewable CO_2 emissions in coal-fired boilers as well as to lower fossil fuel consumption and costs. The classification of CB and the processes of the collection, storage, composting, and disposal of CB are described elsewhere [3,4]. The reburn process is a well known technology for reducing NO_x by burning natural gas (NG) or more coal in a secondary (or reburn) zone downstream from the main burn region. Instead of burning NG, CB can be co-fired with coals in the reburn zone to possibly reduce NO_x generated by the main coal burners. In typical power plants, the equivalence ratio (ϕ) in the reburn combustion zone (RBZ) is maintained at $\phi_{RBZ} > 1.0$ (fuel-rich or deficient amount of combustion air) for the most effective NO_x reduction while it is kept at $\phi_{PRZ} < 1.0$ (fuel-lean) in the primary combustion zone (PRZ).

The objectives of the current study are to (1) evaluate the potential of CB as a reburn fuel, (2) investigate the effect of reburning with blends of CB and coals on the power plant's NO_x emission in a small-scale boiler burner facility, and (3) investigate the effect of ash from CB combustion on heat exchangers (HEXs) and on the NO_x reduction. The authors of this article and previous papers [1-4] have hypothesized that most of the fuel-nitrogen in the CB exists in the form of NH_3 or urea, and thus the combustion of CB can result in higher NO_x reductions.

2 EXPERIMENTAL

2.1 Fuel Characterization

Primary Fuel	Natural gas (NG)		
Heating value	37,050 kJ/m^3		
Empirical Formula	$CH_{3.87}N_{0.0068}O_{0.033}$		
Compositions	94.3% CH_4, 2.4% C_2H_6, 1.7% CO_2, etc.		
Reburn Fuels	TXLC	DB	FB
Proximate analysis (%)			
Moisture	38.34	25.26	19.64
Ash	11.46	14.93	16.50
Volatile Matter (VM)	24.79	46.86	52.33
Fixed Carbon (FC)	25.41	12.95	11.54
Ultimate analysis (%)			
Carbon	37.18	35.20	33.79
Hydrogen	2.12	3.12	3.65
Nitrogen	0.68	1.93	1.97
Oxygen	9.61	19.15	23.94
Sulfur	0.61	0.43	0.51
HHV, kJ/kg	14,289	12,845	13,267
(BTU/lb)	(6145)	(5520)	(5705)
Empirical Formula	$CH_{0.68}N_{0.02}$ $O_{0.19}S_{0.006}$	$CH_{1.06}N_{0.05}$ $O_{0.41}S_{0.005}$	$CH_{1.28}N_{0.05}$ $O_{0.53}S_{0.006}$

Table 1: Properties of primary and reburn fuels.

The proximate and ultimate analyses of the reburn fuels and the properties of the primary fuel are listed in Table 1.

During experiments, NG was burned in the primary burn region along with NH_3 to simulate the NO_x emissions found in the main burn zone of a coal-fired plant. For the current study, pure CH_4 (36,340 kJ/m^3) was used to determine the operational conditions instead of the actual NG composition, which has a slightly different empirical chemical formula (See Table 1) indicating about 2% lower in heating value. The change, however, had a negligible effect on the operational conditions. Two types of CB contain low amounts of ash: dairy biomass (DB) collected on concrete surfaces and feedlot biomass (FB) collected from feedlots paved with fly ash. A solid separator was used for separating solid DB from the flushed liquid manure of a free-stall dairy. Both DB and FB were partially composted in windrows for about 55 days. Texas Lignite Coal (TXLC) was used as the base case reburn fuel. DB and FB were blended with TXLC on a mass basis as 90:10 and 80:20 coal to biomass ratios.
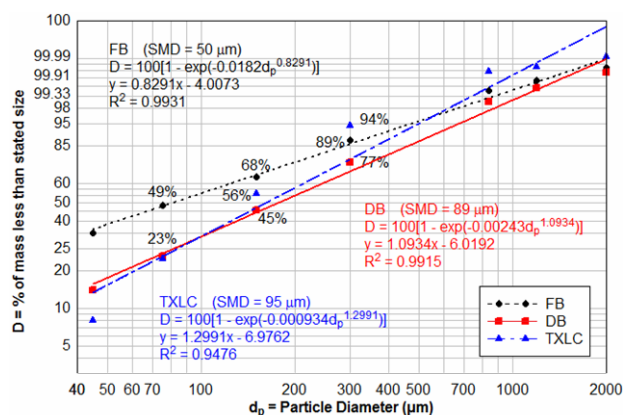

Figure 2: Particle size distributions for reburn fuels.

The size analysis of fuel particles is important since it has strong effects on the rate of the O_2 reduction due to oxidation and hence their effects on NO_x emissions. The Rosin Rammler relation and Sauter mean diameter (SMD) of reburn fuels are shown in Figure 2. Particles smaller than 75 μm (or 200-mesh screen) are 49% for FB, 23% for TXLC and DB by mass. More than 75% of particles for all fuels are smaller than 300 μm. The SMD was determined to be 50 μm for FB, 89 μm for DB and 95 μm for TXLC. Oxidation and pyrolysis of both DB and TXLC were characterized by Thermogravimetric Analysis (TGA). Fuel particles smaller than 840 μm were tested using 100 ml/min of air for oxidation and 100 ml/min of N_2 for pyrolysis. ASTM standard procedures were selected: ASTM E-872 and D-3175 for the estimation of VM % and E-1755 for the estimation of ash %. The heating rate was about 190ºC/min for the oxidation and 120ºC/min for the pyrolysis.

2.2 Operational Condition

A schematic of the 30 kW_t (100,000 Btu/h) down-fired boiler burner facility is shown in Figure 3, and the detailed information about the facility, operational procedures and equipment are described elsewhere [4,5]. The operating conditions of the PRZ and RBZ were determined by Equation (1) and are listed in Table 2. The PRZ was maintained in a slightly fuel-lean condition to burn NG completely. NH_3 was injected to form NO_x for simulating NO_x emissions from coal-fired power plants. For the cases using HEXs, three single-pass cylindrical shape HEXs were located below the reburn nozzle section. Air was used as the cold fluid, and the air flow was set to 9.44 SLPM (standard liters per minutes) based on standard ambient temperature and pressure (SATP).
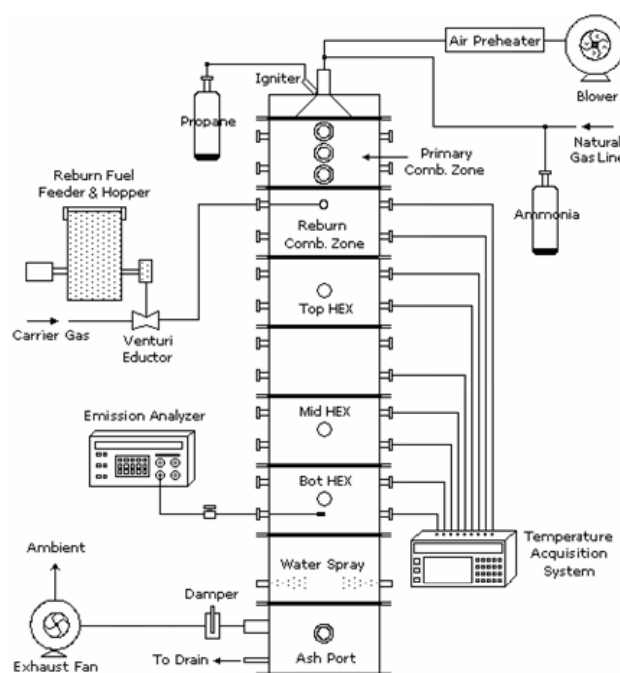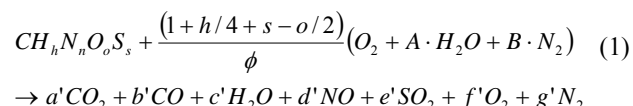
$$CH_hN_nO_oS_s + \frac{(1+h/4+s-o/2)}{\phi}(O_2 + A \cdot H_2O + B \cdot N_2) \quad (1)$$
$$\rightarrow a'CO_2 + b'CO + c'H_2O + d'NO + e'SO_2 + f'O_2 + g'N_2$$

Figure 3: A schematic of the small-scale (30 kW_t or 100,000 Btu/h) down-fired boiler burner facility.

Primary Combustion Zone (PRZ)	
Fuel flow (NG) / Air flow	30.1 SLPM / 320.3 SLPM
Heat input	70% (or 21 kW_t)
Equivalence ratio, ϕ_{PRZ}	0.95
NH_3 injection	0.12 SLPM
Baseline NO_x emission	420 – 440 ppm

Reburn Combustion Zone (RBZ)	
Fuel flow (TXLC)	36.9 g/min
Air flow	115 – 136 SLPM
Heat input	30% (or 9 kW_t)
Equivalence ratio, ϕ_{RBZ}	0.95 to 1.1
HEXs	No

Table 2: Operating conditions of the PRZ and RBZ.

3 ANAYSES FOR RESULTS

3.1 Dilution Effects

The dilution effect of the reburn air is significant on the measurement of NO_x emission in ppm. It resulted in the decrease of the NO_x emission in ppm by almost 30%. When NO_x emissions are measured on a heat basis, however, the dilution effect is removed. Thus all the results of reburn tests are reported on a heat basis to neutralize the dilution effect. It is described as below [6]:

$$NO_x(kg/GJ) = \frac{46.01 \times x_{NO_x} \times C \; fraction}{12.01 \times (x_{CO_2} + x_{CO}) \times HHV(GJ/kg)} \quad (2)$$

where *C fraction* is the mass fraction of carbon in the "as received" fuel, *HHV* is the higher heating value of the "as received" fuel, and *x* is the mole fraction. Note that (1) *C fraction* and *HHV* for the reburn study are the combination values of those in the primary and reburn fuels, and (2) a molecular weight of 46.01 is used for NO_x since all NO is eventually converted into NO_2 in the atmosphere.
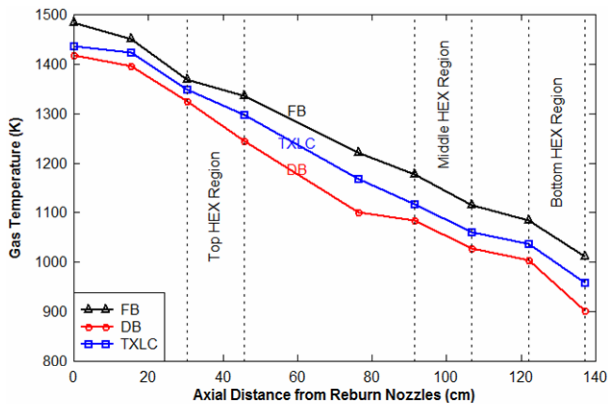

Figure 4: Temperature distribution of the flue gas.

3.2 Temperature Distribution

The temperature distribution of the flue gas is presented in Figure 4. Because the reactions of NO_x formation and reduction are sensitive to temperature, the gas temperature in the RBZ was maintained between 1400 and 1500 K. This relatively low and steady temperature was able to prevent the high production of thermal NO_x. The gas temperature linearly decreased along the reactor. In the presence of the HEXs, the local gas temperatures near the HEXs were about 100 K lower than those in the absence of the HEXs.

4 RESULTS AND DISCUSSION

4.1 Oxidation and Pyrolysis

A TGA trace is able to give a complete picture of thermal degradation or gasification of the fuels. Figure 5

presents the oxidation and pryolysis results of the fuels ($45 \leq D_p \leq 75$) on a dry basis. The temperatures increased and remained at 950ºC for oxidation and at 575ºC for pyrolysis. The oxidation result of DB shows that Region *I* (200 – 400°C) for a rapid release of volatiles, Region *II* (400 – 850°C) for a release of fixed carbon, and Region *III* (850 – 950°C) for ash. The moisture loss was about 10% of the total weight, and the amount of volatiles released in Region *I* was about 35 to 60% on a dry basis depending on the particle size. The trend of FB results was very similar to those of DB in that the smaller particles contained less volatiles and more ash than the larger particles because CB has more fiber. Compared to the ash particles, fibrous material is not easily pulverized, but instead mashed, thus more fiber remained in the larger particles indicating higher volatile contents. Unlike ash and volatiles, the amounts of fixed carbon released were relatively the same for all particle sizes. Though it is difficult to distinguish Regions *I* and *II* for TXLC, it can be seen that the amounts of volatiles released from TXLC were less than those from DB. The ignition temperature was found to be 250ºC for DB and 270ºC for TXLC elsewhere [7]. The presence of auto-gasification is another interesting phenomenon. The auto-gasification of wet fuels occurs in the absence of O_2 where the char, along with the rest of the organic matter in the fuels, is completely converted into gaseous fuel. The amounts of ash at the end of both pyrolysis and oxidation were very similar indicating the O_2 available in the fuel alone helped for converting fuel to ash.
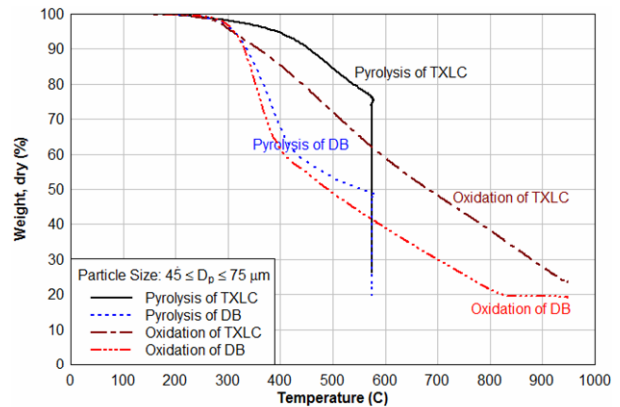

Figure 5: Oxidation and pyrolysis results of DB and TXLC.

4.2 NOx Reduction

The NO_x reduction on a heat basis is presented in Figure 6 (a) as a function of the ϕ_{RBZ}. The baseline NO_x level was about 180 g/GJ (or 430 ppm). The results show that higher percentages of DB in the reburn fuel generate higher NO_x reductions. The NO_x reduction also increased with an increase in ϕ_{RBZ} because the depletion of O_2 in the RBZ slows down the NO_x formation and allows the NO_x reduction to be dominant. At $\phi_{RBZ} = 1.1$ for DB and FB, higher than 90% NO_x reductions were achieved, and blending 10% DB with 90% TXLC increased the NO_x

reduction about 15% compared to the result of TXLC. However, the practical blending ratio in large coal-fired power plants may be limited to 95% coal and 5% CB due to the limited supply of low ash CB in feeding operations near the power plant.
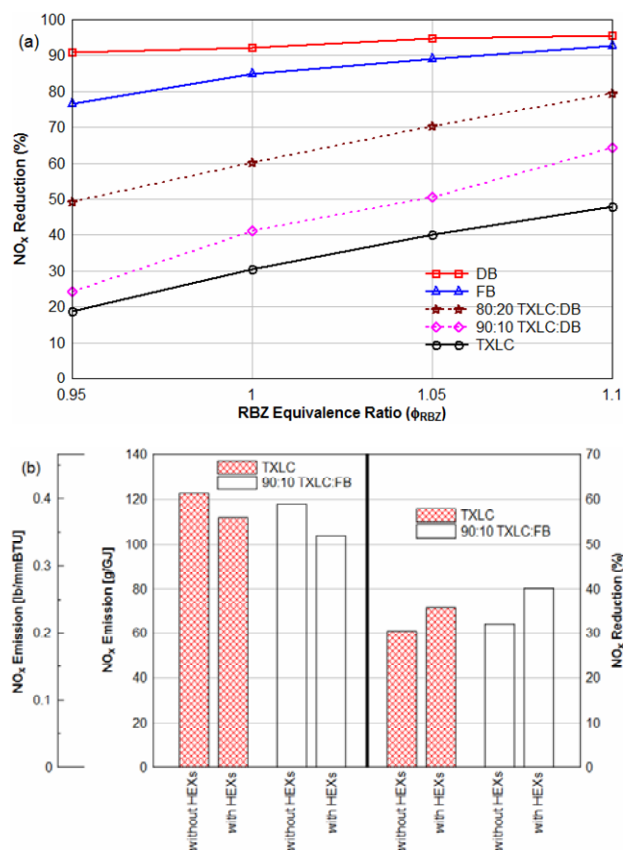

Figure 6: (a) NO$_x$ reductions on a heat basis and (b) NO$_x$ emissions and reductions at $\phi_{RBZ} = 1.0$.

The effects of the HEXs on the NO$_x$ reduction using air cooled HEXs are presented in Figure 6 (b). NO$_x$ emissions are lower and NO$_x$ reductions are higher for the cases with the HEXs than the cases without the HEXs: about 5% higher for TXLC and about 8% higher for 90:10 TXLC:FB. It seemed that the catalytic effects of metallic oxides in ash deposited on the HEX surfaces aided the NO$_x$ reduction. The amounts of metallic oxides (Fe_2O_3, Na_2O, K_2O, and CaO) were 43% in the FB ash and 20% in the TXLC ash; therefore, the ash from 90:10 TXLC:FB had a stronger catalytic effect than the ash from TXLC. The catalytic effects of metallic oxides were investigated elsewhere [8].

4.3 Ash Characteristic and CO Emission

The ash fusion temperatures (AFTs) of the fuels were analyzed, and the AFT of CB was lower than the AFT of TXLC, i.e. the hemispherical temperature was found to be about 1175°C for CB and 1245°C for TXLC in an oxidizing atmosphere. The AFT results indicate that the CB ash sticks

to the HEXs surface and tends to accumulate at lower temperatures than the coal ash. It was found that the CB ash on HEXs was more difficult to remove than the TXLC ash. The burnt fraction increased when the reburn fuels contained higher percentages of CB because more VM from the CB was released at lower temperatures and faster than the VM of TXLC.

During the tests, a fuel-rich environment was formed in the reactor causing high CO emissions, which were also measured. With an increase in ϕ_{RBZ}, the CO emissions increased while the NO$_x$ emissions decreased. The CB fuels emitted more CO than TXLC because their particles contained more oxygen compared to the coal particles.

5 SUMMARY AND CONCLUSIONS

The potential of cattle biomass (CB) to be a reburn fuel in coal-fired power plants was evaluated by investigating the effects of reburning with blends of coal and CB on the NO$_x$ reduction in a small-scale (30 kW$_t$ or 100,000 Btu/h) down-fired boiler burner facility.
(1) Both DB and FB can be used as reburn fuels for effective NO$_x$ reductions in coal-fired power plants.
(2) The ϕ_{RBZ} and CB percentage in the reburn fuel both have significant effects on the NO$_x$ reduction and burnt fraction.
(3) The catalytic effects of ash deposited on the HEXs slightly increase the NO$_x$ reduction.
(4) The CB ash deposited on the HEXs was more difficult to remove than the coal ash.

6 ACKNOWLEDGMENT

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