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# Performance of a Burner with Coal and Coal–Bio-Solid Fuel Blends

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**Powerplants spend nearly 50 billion dollars a year on fuel cost, and coal accounts for over 55% of the fuel used in the utility industries. The fuel cost could be reduced by supplementing coal fuels with alternative renewable fuels such as the byproducts of industries located in the vicinity of the powerplants. One of the byproducts of feedlots is manure, a biosolid fuel that is cheaper than coal, on a tonnage and heat-value basis. Coal–manure blend or, more simply, "blend" technology is proposed as a beneficial use of manure for powerplants located near feedlots. Experiments were performed in a small-scale boiler burner facility with coal only, and then for 80:20 blends on a wet-weight (as-received basis). Data were taken during the warm up, gasification, and combustion. Three types of feedlot manure were examined for blending: raw feedlot, partially composted feedlot, and finished composted feedlot. A summary of the findings is as follows: 1) Manure contained up to 80% volatile matter (VM) on a dry ash-free basis, which was twice the VM of conventional coal. 2) Combustion efficiency was slightly higher with the coal–manure blend than with coal. 3) $NO_x$ emission increased from 420 ppm at 80% burned fraction (BF) to 550 ppm at 95% BF for coal, whereas corresponding numbers for the blend were 620–550 ppm. 4) $SO_x$ increased from 30 to 180 ppm for coal, whereas for the blend it was nearly 0 ppm up to 90% BF, but increased to 10 ppm at 95% BF.**

## Introduction

UNITED STATES electric power utilities consume 80% of the one billion tons of coal produced annually, and coal constitutes about 55% of the fuel used in the utility industries. As such, the attendant air-pollutant emissions have also increased. Significant among these pollutants are oxides of sulfur ($SO_x$) and nitrogen ($NO_x$), which cause acid rain and ozone depletion. For the foreseeable future, coal will continue to be the dominant fuel used in the production of electricity. Therefore, new technologies must be developed in an effort to reduce gaseous emissions. Because of concerns over public health and the environment, federal regulations, regarding the emission of these pollutants, have become particularly demanding. Since 1970, a 37% reduction in $SO_2$ has been achieved. The cost to polluters associated with the reduction of pollutants has risen dramatically, by almost 35% of the investment in recent years. The Environmental Protection Agency (EPA) new source performance standards (NSPS), passed in 1990, require a 50% reduction of emissions that lead to acid rain. The NSPS stipulate that $NO_x$ and $SO_x$ emissions should not exceed 260 g/GJ (0.6 lb/million Btu). In Sweden and in some states in the United States, e.g., California, the standards are more severe, limiting the emissions to 50 g/GJ.

Costs associated with reducing emissions could be reduced if cheaper fuel sources are explored. One such alternate source exists in feedlot manure, a renewable fuel resource (112 million tons of cattle and poultry manure per year). The beef-cattle feedlot industry is a major industry in the southern Great Plains states, and faces environmental constraints with regards to waste disposal.[1] Most of the manure is sold as fertilizer for grain crops. These wastes, if stockpiled rather than utilized, pose economic and environmental liabilities.[2,3] Animal manure stored anaerobically releases $CH_4$, $NH_3$, $H_2S$, amides, volatile organic acids, mercaptans, esters, and other chemicals. Previous attempts to use feedlot manure as an energy source are summarized in Refs. 4 and 5. They include on-site gasification, fluidized beds,[5] and circulating fluidized beds.[4] A few of the technologies met with success, but the projects were complicated by the highly variable properties of manure. Anaerobic digestion is a slow process, resulting in emissions over a longer period of time; it requires liquefaction and the use of precious water, and does not result in complete conversion of the solids into gas. Finally, the ash content poses chronic mechanical problems.

Because feedlot manure has higher moisture (as high as 80%), nitrogen, chlorine, and ash, it has a lower heating value than coal. Thus, blending of manure with high-quality coal would reduce the flame stability problems caused by the high moisture content in manure, and minimize the corrosion effects of high Cl. The cofiring approach would also have greater potential for commercialization. Blend technology has been used before for refuse derived fuels (RDF), using special binder-densified RDF that made up 20% of the RDF–coal blend.[6]

The characteristics of coal and feedlot manure differ. Feedlot manure contains 25–75% volatile matter [(VM), gaseous matter released on heating in an inert atmosphere], on an as-received basis,[7] as opposed to coal that contains volatile matter in the range of 20–40%. The heating value of feedlot manure, on average, is 15,000 kJ/kg (5000 Btu/lb) vs coal, which is 35,000 kJ/kg (14,000 Btu/lb). Because the characteristics of the two fuels are different, burner performance in terms of flame stability, combustion behavior, and most importantly, emission characteristics of blended mixtures, must be studied directly. This blend technology, if successful, might provide an

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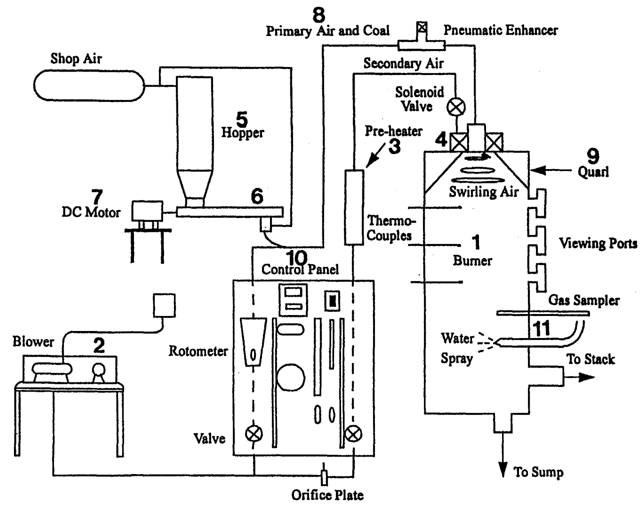

**Fig. 1 Texas A&M boiler burner facility.**

alternative method of animal waste disposal that is environmentally sound and beneficial.

## Experimental Setup

Research on blend combustion was conducted using an experimental boiler burner, a schematic of which is shown in Fig. 1. The boiler burner, **(1)**, was 0.152 m (6 in.) in diameter and 1.575 m (62 in.) in height. The entire boiler was constructed from stainless-steel pipe. The boiler contained three viewing ports mounted 5.1 cm (2 in.) apart and located underneath the quarl. The windows were fused quartz housed in a stainless-steel 316 body. Three sampling ports allowed emissions sampling. The combustion air was supplied by a secondary air blower, **(2)**, driven by an adjustable-speed dc motor. The secondary air was preheated to a minimum of 200°C with the use of a circulation heater (3 kW), **(3)**, before it entered the boiler through a swirler. **(4)** The fuel feed system consisted of a feed hopper, **(5)**, with a capacity of 14 kg (30.8 lb). Compressed air was supplied through the top of the feed hopper to maintain a positive pressure higher than the boiler burner. An auger screw, **(6)**, ran through the conical section of the feed hopper and was driven by an adjustable dc motor (1/2 hp, 1725 rpm). The auger, **(7)**, could deliver up to 200 g/min (0.41 lb/min) of coal into the boiler burner. The primary air, **(8)**, was supplied by the laboratory and could deliver up to 432 g/min. The purpose of the primary air was to carry the fuel, and to a lesser extent provide a fraction of the combustion air. The fuel suspension was then fired through the quarl, **(9)**, of the boiler burner. The boiler burner walls were insulated on the outside using a fibrous alumina-silica blanket rated to operate at a maximum temperature of 1300°C (2372°F). Dual water jets, **(11)**, were injected into the boiler to catch particulates and ash. The waste water empties into a 113.6-l (30-gal) polyethylene tank. The products of combustion were exhausted with an induced draft fan, capable of providing a vacuum of 0.5-in. water gauge inside the boiler burner. The entire facility was operated from a central control panel, **(10)**. The diagnostic system consisted of an orifice plate for measuring the secondary airflow rate, and sheathed, type K and type S thermocouples, in the boiler, the secondary airstream, and in the exhaust. Rotometers were employed to measure the primary as well as hopper airflow rates. Emission measurements were performed using a Lancom 6500 emission measuring system that used Electro Chemical Cells as sensors. The system could measure gases including $SO_2$, NO, $NO_2$, CO, and $O_2$. The probe also contained a type K thermocouple mounted at the tip for temperature measurements. The sampling probe for each measurement was inserted just before the water-quenching ports at the centerline of the boiler far enough downstream to ensure complete combustion.

## Burner Characteristics

The burner was a concentric downward firing swirl burner. Further details of the burner arrangement may be found in Ref. 8. The primary air/fuel nozzle was 1.905 cm ($\frac{3}{4}$ in.) in diameter, and the secondary air duct was 3.175 cm ($1\frac{1}{4}$ in.) in diameter. An impeller plate at the primary air/fuel exit served to split the thick stream of coal into thin streams and to direct the coal into the hot recirculation zone. Radially attached swirlers provided the necessary swirl to create a recirculation zone.

A swirl greater than 0.6 is necessary to create a recirculation zone.[9] For the burner in this experiment the swirl angle was 60 deg, and the swirl number was 1.4. The quarl was constructed from ceramic fiber boards rated for 1300°C continuous service temperature. The quarl had an *L/D* ratio of 1.8. The quarl half-angle was 24 deg, which is nearly optimum as determined by Fricker and Leuckel.[10] The burner was fitted with a propane torch that served to preheat the boiler and initiate combustion. The torch rating was ~1% of the total burner rating, which ensured that the influence of the propane torch was negligible. Typical burner characteristics and operating conditions are shown next:

1) Burner characteristics: burner rating = 35,400 W; primary air/fuel nozzle diameter = $\frac{3}{4}$ in.; secondary air nozzle diameter = $1\frac{1}{4}$ in.; swirl angle = 60 deg; swirl number = 1.4; quarl half angle = 24 deg; quarl *L/D* = 1.8; primary air velocity (cold flow) = 4.2 m/s; and secondary air velocity (cold flow) = 24.4 m/s.

2) Operating conditions/coal firing: primary airflow = 270 standard cubic feet per hour (SCFH) or 146 g/min; secondary air = 1140 SCFH or 616 g/min; feed rate = 100 g/min (25% of rates rpm of feeder); air/fuel = 7.61; average velocity in the combustor = 0.6 m/s (2 ft/s, cold), 2.4 m/s (8 ft/s, hot); and average residence time in the combustor = 4 s, cold, 1 s, hot.

## Fuel Characteristics

The ultimate and proximate analyses of the coal, raw manure (RM), partially composted (PC) manure, and finished composted (FC) manure are shown in Tables 1 and 2, whereas the ash analyses are shown in Table 3. The Wyoming coal and manure ashes have lignite-type ash because CaO + MgO > $Fe_2O_3$. For lignite-type ash, the $Na_2O$ content can be used to indicate the fouling potential. The ash analyses of coal and manure indicate that Wyoming coal and all manure ashes have low to medium fouling potential ($Na_2O$ < 3%), which indicates that the rate of deposition would be similar for coal and manure ashes. The low-sulfur coal was supplied by Southwest Public Utilities, and later pulverized to 70%, passing through 200 mesh (75 $\mu$m). The manure samples were air dried at 80°F, ground to 8-mesh (2-mm) particle size, dried again, and then pulverized to 60 mesh (200 $\mu$m).

The heating values on a dry ash-free basis for RM, PC, (2–3 weeks old), and FC manure (10–12 weeks old) were the

**Table 1 Coal and manure characteristics**

| Parameter | Coal | RM | PC | FC |
|---|---|---|---|---|
| Moisture | 10.8 | 36.61 | 30.02 | 35.35 |
| Ash | 5.68 | 25.25 | 28.01 | 30.73 |
| Volatile matter | 30.72 | 31.57 | 34.11 | 27.86 |
| Fixed carbon | 52.80 | 6.57 | 7.86 | 6.06 |
| Heat value (as received), kJ/kg | 26,535 | 8865 | 8305 | 6610 |
| Carbon | 54.9 | 19.24 | 20.65 | 16.62 |
| Hydrogen | 4.33 | 2.22 | 2.30 | 1.72 |
| Oxygen | 23.32 | 14.68 | 16.43 | 12.92 |
| Nitrogen | 0.76 | 1.47 | 1.86 | 1.82 |
| Sulfur | 0.34 | 0.53 | 0.73 | 0.84 |

**Table 2 Empirical formulas and adiabatic equilibrium flame temperatures**

| Parameter | Coal | RM | PC | FC |
|---|---|---|---|---|
| Empirical formula[a] (DAF) | $CH_{0.94}O_{0.32}N_{0.012}S_{0.0023}$ | $CH_{1.37}O_{0.57}N_{0.065}S_{0.01}$ | $CH_{1.32}O_{0.597}N_{0.077}S_{0.0132}$ | $CH_{1.23}O_{0.585}N_{0.0937}S_{0.019}$ |
| Adiabatic flame temperature, K[b] | 2474 | 1701 | 1851 | 1689 |
| Molecular weight[c] (DAF) | 18.3 | 23.8 | 24.4 | 24.5 |
| $A:F_{\text{stoichiometric}}$[c] | 6.9 | 2.5 | 2.6 | 1.9 |
| $A:F_{\text{stoichiometric}}$[c] (DAF) | 8.2 | 6.2 | 5.9 | 5.8 |

[a] Determined from ultimate analysis and spreadsheet software.
[b] Stoichiometric conditions: $T_{\text{air}} = T_{\text{fuel}} = 298$ K; determined from ultimate analysis and spreadsheet software.
[c] Including ash and moisture in fuel.

**Table 3 Ash constituents of coal and manure**

| Mineral | Wyoming coal | Fresh feedlot manure | Composted manure |
|---|---|---|---|
| Silica ($SiO_2$) | 29.69 | 53.49 | 59.51 |
| Alumina ($Al_2O_3$) | 13.63 | 7.75 | 9.78 |
| Iron ($Fe_2O_3$) | 6.12 | 1.71 | 1.27 |
| Calcium (CaO) | 13.21 | 13.88 | 7.22 |
| Magnesium (MgO) | 3.38 | 3.65 | 2.28 |
| Sodium ($Na_2O$) | 0.53 | 2.04 | 1.39 |
| Potassium ($K_2O$) | 0.25 | 6.43 | 4.22 |
| Phosphorus ($P_2O_5$) | 0.89 | 2.98 | 4.65 |
| Sulfur ($SO_3$) | 10.84 | 2.80 | 3.68 |
| Chlorine (Cl) | —— | 3.84 | 3.60 |
| Titania ($TiO_2$) | 1.11 | 0.33 | 0.41 |

same as the heating value of rations fed to the cattle. The experimentally obtained heating values were found to agree with the following empirical Boie equation for higher/gross heating value (HHV):

$$\text{HHV (kJ per kg of fuel)} = 35{,}160C_m + 116{,}225H_m - 11{,}090O_m + 6{,}280N_m + 10{,}465S \qquad (1)$$

where $C_m$, fraction of carbon mass, kilogram of C/per kilogram of fuel.

For a specified composition of fuel, stoichiometric $O_2$ can be determined and the energy released per liter of stoichiometric oxygen is found to be almost a constant for most of the natural fuels, with the value being 20 kJ/l. Equation (1) has been tested for 16 biomass fuels and 67 oil fuels including alcohols. Recently, it has been used for 47 types of plants and 6 different feedlot manures,[11] glucose, and fats.[12] The heating value for liters of stoichiometric oxygen or the similarity of heat values per unit volume of stoichiometric oxygen yields similar values in adiabatic flame temperatures.

The thermogravimetric analysis of manure indicated that moisture release occurred between 50–100°C, pyrolysis starts at about 225°C,[5] and the minimum ignition temperature is 528°C.[5] To initiate combustion, pilot burners are necessary to provide hot gases higher than 528°C.

## Procedure

The experimental procedure for firing was as follows: the secondary air was preheated to a minimum of 475 K using a circulation heater and the boiler burner was preheated to the desired temperature (≈800 K) using two propane torches. Once the appropriate temperatures were reached in the boiler, coal or blend was injected and the experimental data were recorded. The air:fuel ratio was kept constant at near-stoichiometric conditions. As the experiment continued, data were taken to determine the temperature along the centerline of the boiler at various locations, airflow rates, and the composition of the flue gases. The flue gas temperature was also recorded using the emission monitoring probe mounted in the sampling port farthest from the burner just prior to water quenching. These transient measurements were made to understand the relative rates of coal and blend gasification and $NO_x$ and $SO_x$ release. Combustion experiments were generally conducted over a period of 30 min. The first data were taken with coal followed by coal:RM, coal:PC, and coal:FC manure blends.

## Results and Discussion

Boiler performance will be discussed in terms of the burn fraction and emission measurements.

### Temperature

Typically, the quarl and the swirler create a recirculation zone (RZ), near the entry point of the fuel, where the hot gases recirculate toward the burner, promote rapid ignition of fresh mixture, and stable combustion. The RZ is more a function of burner aerodynamics than of the fuel type, and as such, the shape is unaffected by changing to blend; however, the temperature of the RZ can be affected by the quality of the fuel. A spread sheet program was used to estimate the adiabatic flame temperature of any C–H–O–N–S fuel under equilibrium conditions for coal and 80:20 coal:RM blend as 2474 K and 2443 K. The lower temperature for blends are a result of lowered heating values.

The measured temperature distributions with and without the manure blend were not significantly affected. This suggests that the addition of 20% feedlot manure to coal did not adversely affect flame stability. The radial temperature distribution was relatively flat downstream of the RZ, varying by >50 K. The maximum axial temperature occurred at 28 cm (11 in.) from the burner nozzle exit, which coincides with the boundary of the recirculation zone. Syred and Beer[13] suggested an RZ length of 22 cm for the swirl number and quarl dimensions used in these experiments. As with the firing of coal, the maximum axial temperature for manure:coal blends occurred at ~28 cm (11 in.) from the burner nozzle exit. This suggests that the addition of feedlot manure did not adversely affect flame stability. Again, the radial temperature distribution was relatively flat downstream of the RZ, varying by less than 50 K.

### Burned Fraction

Typically, as the fuel enters a relatively cool reactor (≈250°C), a large percentage of the fuel remains unburned. As the fuel burns, the reactor and the probe temperature will slowly increase, accompanied by an increase in the BF and a reduction in the oxygen content in the flue gas. The rate of decrease of $O_2$ was an indication of the rate of the coal combustion rate. Therefore, there exists an important relationship between the burned fuel fraction, oxygen content, and reactor temperature. At the same time, the ash percentage in the fuel will decrease as a result of combustion, which can also be used to extract the BF.

Both exhaust gas analysis and ash tracer methods have been used to determine the extent of a coal gasification/burned fraction.[14] There are certain inaccuracies and limitations in the ash tracer method during transient combustion. Because fine soot particles were not captured in the ash tracer method, the ash tracer method can give higher gasification values compared with the exhaust gas technique. Further inaccuracies in the ash tracer method arise because of 1) devolatization of ash at high temperatures that will lower the ash percentage, and 2) dissolution of ash in the quench water, if combustion is transient.

In one of the combustion experiments involving the coal:RM blends, the average combustion efficiency using the ash tracer method was about 67%, whereas the exhaust gas analysis indicated 97%. The low ash tracer combustion efficiency was caused by the collection of ash mass over a long time period during which the BF slowly increased. Because of the transient nature of combustion, the exhaust gas analysis technique has been found to be more accurate, and hence, was used to determine the BF:

$$\mathrm{BF} = \frac{[1 - (X_{\mathrm{O}_2}/X_{\mathrm{O}_2,\infty})]}{\varphi\left(1 - \left\{\dfrac{X_{\mathrm{O}_2}[(m/4) - (n/2) + (p/2)]}{[1 + q + (m/4) - (n/2)]}\right\}\right)} \tag{2}$$

$$\phi = \frac{[1 + q + (m/4) - (n/2)][1 - (X_{\mathrm{O}_2}/X_{\mathrm{O}_2,\infty})]}{\{[(m/4) - (n/2)](1 - X_{\mathrm{O}_2}) + (p/2)X_{\mathrm{O}_2} + 1 + q\}} \tag{3}$$

where the empirical formula for fuel is given as $\mathrm{CH}_m\mathrm{O}_n\mathrm{N}_p\mathrm{S}_q$, oxygen mole fraction in exhaust as $X_{\mathrm{O}_2}$ oxygen mole fraction in air as $X_{\mathrm{O}_2,\infty}$. The airflow in moles is given as:

$$a = \frac{[1 + q + (m/4) - (n/2)]}{\varphi X_{\mathrm{O}_2,\infty}} \tag{4}$$

and, the equivalent ratio as $\phi$ ($\phi < 1$ for lean, $\phi > 1$ for rich mixture). The CO emission was of the order of 4000 ppm and was ignored in arriving at expression (2).

The feeder was first calibrated using a vacuum bag collection and verified later by weighing the mass loaded and mass left after combustion. Typically the fuel feed rate was selected at around 100 g/min. As a check, the vacuum bag collection indicated 92 g/min, whereas the exhaust gas analyses indicated 82 g/min for known airflow rate.

A maximum BF of 97% was recorded at 30 min when firing coal alone. A similar BF of 97% was recorded when firing the coal:raw manure blend. The similarity in the trend of BF suggested again that flame stability was maintained with the addition of 20% feedlot manure.

### Emission Measurements

All emission measurements have been normalized with 3% $\mathrm{O}_2$ in the products as prescribed by EPA guidelines. The sampling probe for each measurement was located at the centerline of the boiler far enough downstream to achieve maximum de-

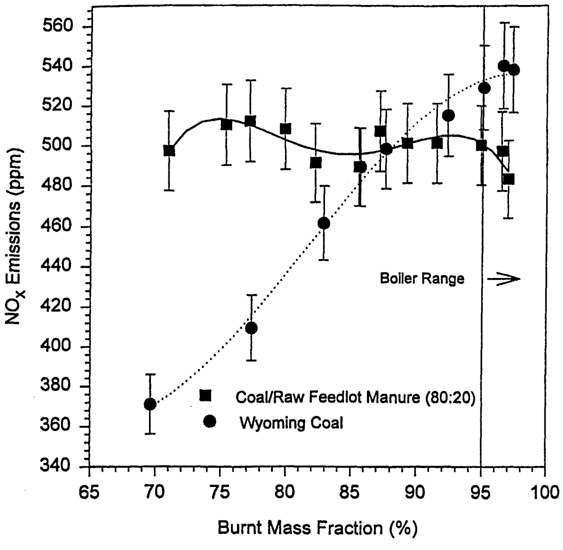

**Fig. 2** **$\mathrm{NO}_x$ emission: coal and RM blend.**

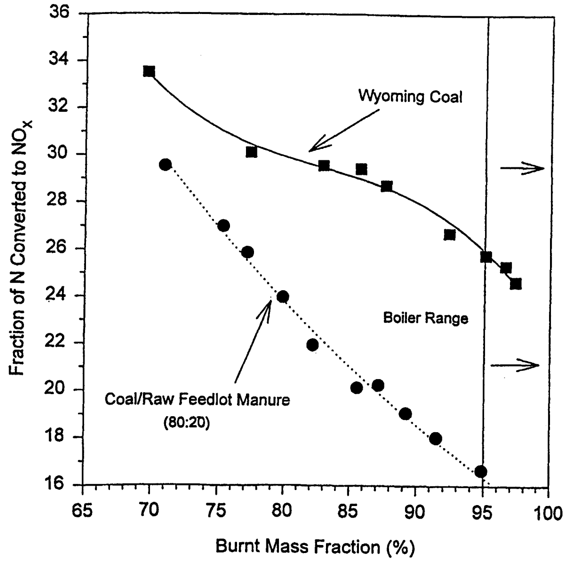

**Fig. 3** **N to $\mathrm{NO}_x$ conversion efficiency, coal and coal: RM blend.**

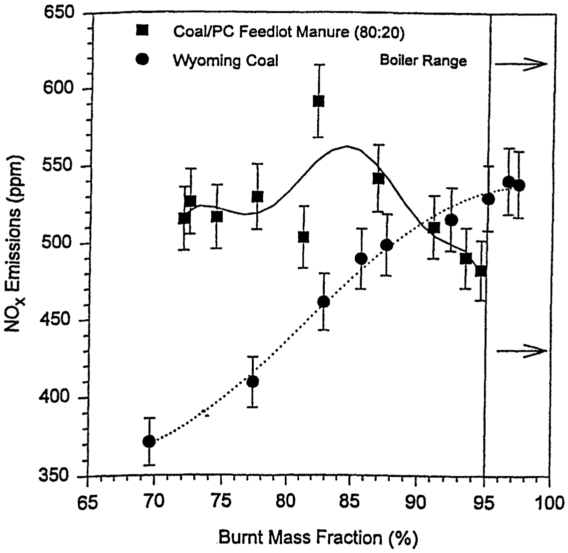

**Fig. 4** **$\mathrm{NO}_x$ emission: coal and coal:PC blend.**

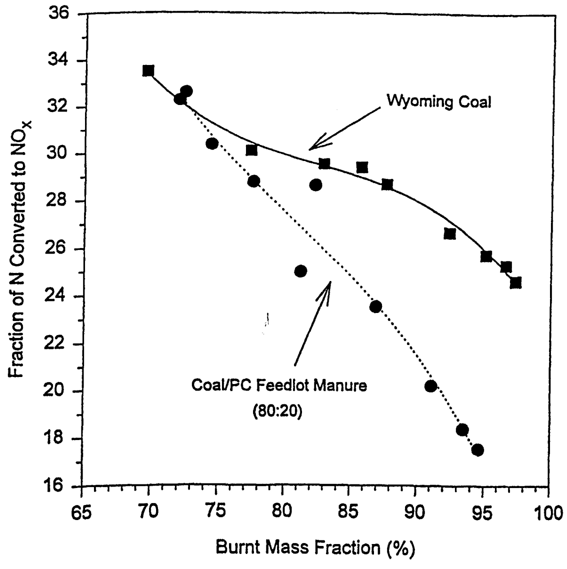

**Fig. 5** **N to $\mathrm{NO}_x$ conversion efficiency, coal and coal:PC blend.**

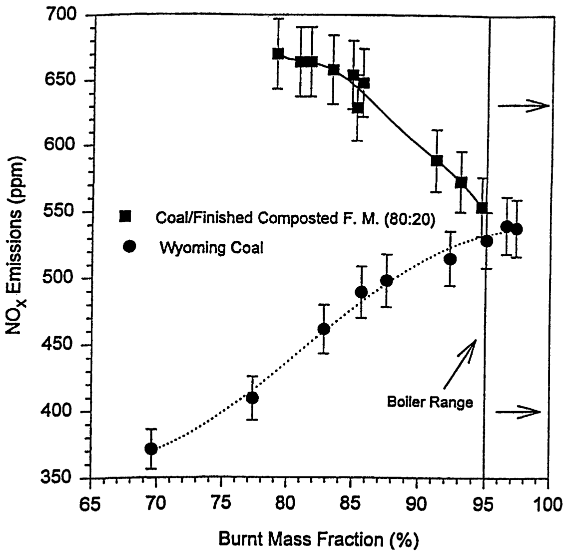

**Fig. 6 NO$_x$ emission: coal and coal:FC blend.**

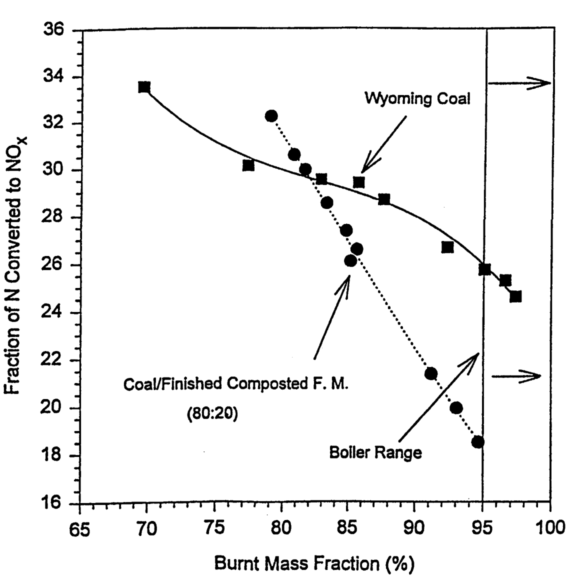

**Fig. 7 N to NO$_x$ conversion efficiency, coal and coal:FC blend.**

**Table 4 Emissions and conversion of N to NO at 95% BF**

| Fuel | NO$_x$, ppm | SO$_x$, ppm | N to NO$_x$, % |
|---|---|---|---|
| Coal | 530 | 200 | 26 |
| Coal:RM | 500 | 80 | 16.5 |
| Coal:PC | 480 | 35 | 17.5 |
| Coal:FC | 555 | 11 | 19 |

gree of combustion. The NO$_x$ production increased rapidly with BF. Because thermal NO$_x$ occurs at temperatures above 1500 K while fuel NO$_x$ is readily formed at low temperatures, the primary contribution to NO$_x$ is from the fuel N (Figs. 2–7). However, as a larger fraction of fuel was burned, the O$_2$% decreased, and, therefore, the rate of production of NO$_x$ slowed down. Maximum NO$_x$ emission (540 ppm) occurred at BF = 0.97 (Fig. 2). Note that typical pulverized coal-fired boilers released 375–550 ppm for tangential-fired burners, 500–825 ppm for wall-fired burners, and, finally, 250–400 ppm for stoker-fired boilers. Table 4 compares the NO$_x$ emission at 95% BF for coal and the three blends. Even though the emission obtained in the small-scale boiler facility is within the range of emission levels of pf fired industrial boilers, long-duration studies in a pilot plant are required to validate the current experimental data.

The emissions of NO$_x$ when firing coal alone vs firing coal and raw feedlot manure blend are compared in Fig. 2. As expected the emission of NO$_x$ generally increased throughout the range of BF for coal. Because the raw feedlot manure had nearly twice as much fuel nitrogen as Wyoming coal (Table 1), the production of NO$_x$ was higher even at lower BF (Fig. 2). The TGA studies reveal that the feedlot manure devolatilizes ($T_p$ = 225°C) more readily than coal ($T_p \approx$ 320°C), and it is probable that N was released much earlier in the experiments, even at low temperatures. Thus, even at a low BF or low temperature, the nitrogen released from the manure in the blend was readily oxidized. This observation is consistent with the literature that states that conversion of fuel N to NO is weakly dependent on temperature, but is a strong function of local stoichiometry. While N will readily form NO in an oxidizing atmosphere, i.e., at lower BF in the current experiment, it can be converted into molecular N$_2$ in a reducing atmosphere and at higher temperature, i.e., at higher BF. Thus, the rate of growth of NO is slowed down[15] with an increasing BF.

Knowing the fuel composition and the exhaust gas analysis, the fraction of N converted to NO$_x$ can be calculated as follows.

N conversion efficiency:

$$\frac{X_{\mathrm{NO}}}{pX_{\mathrm{CO}_2}} \tag{5}$$

Figure 3 shows the fraction of N converted to NO$_x$ when firing coal alone and various blends. Both curves show the percent of N converted to NO$_x$ decreases for all ranges of burned mass fraction tested. This trend would seem to indicate that the NO$_x$ is readily formed even at low temperatures. The increasing BF reduces the oxygen concentration that reduces the conversion rate of N to NO$_x$. The results show that the effect of oxygen concentration is greater than the effect of temperature on N to NO$_x$ conversion.

It is evident from Fig. 3 that N to NO conversion was lower for coal–manure blends. If synergism is ignored, Fig. 2 can be used to estimate NO contribution by manure alone. For instance, at the BF of 70%, Wyoming coal produced 370 ppm NO$_x$, whereas the blend produced ~490 ppm. Thus, 194 ppm (=490 − 0.8 × 370) was caused by the combustion of 20% manure, thereby indicating that the manure was burning. Thus, if one neglects the synergistic effect, the manure alone contributed to 970 ppm (=194/0.2) at BF of 70%.

Typical boilers operate with an efficiency above 96 to 99%. At 95% BF, the NO$_x$ emission for coal alone was 530 ppm (Table 4). For the coal–manure blends at 95% burned mass fraction, the contribution of coal N to NO$_x$ was 425 ppm (0.8 × 530), whereas the manure (20%) released ~75 ppm (=500 − 425). Thus, if manure alone was burned, it would have contributed 375 ppm (=75 ppm ÷ 0.20) which is a significant decrease compared with emissions at lower temperatures. Emission measurements were repeated for 80:20% blends coal: PC and coal:FC (Figs. 4–7). The NO$_x$ emissions were again lower for coal/manure blends above 95% BF. The N to NO conversion efficiencies for partially and finished composted manure were lower than coal for BF > 70%. The NO$_x$ emission was highest for FC manure (Fig. 6), because the fuel N content on a DAF basis was the highest.

The N to NO conversion for coal and blends at 95% BF are summarized in Table 4. The N to NO conversion efficiencies were lower for RM, PC, and FC than for coal only, and were consistent with coal literature where conversion efficiencies decrease with increasing N content of coal.

Figure 8 shows the emission of SO$_x$ for coal and blend. The SO$_x$ emissions for coal were higher than for coal:raw manure blends. Generally most of the S in coal is converted into SO$_2$, whereas 5–50% of the SO$_2$ may be retained in the coal ash,

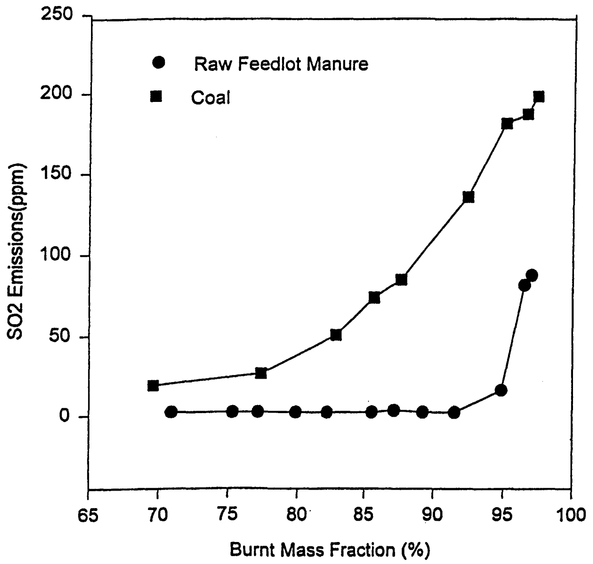

**Fig. 8 SO$_x$ emission:coal and coal:RM blend.**

depending on the type of coal used.[16] As more fuel was burned (Fig. 8), the temperature increased, more sulfur was converted into $SO_2$, and the $SO_2$ emissions increased. This indicates that $SO_2$ emission was a strong function of the burned mass fraction but was weakly dependent upon the $O_2$ concentration. This is in contrast to the N to $NO_x$ conversion. This is consistent with the previous observation that the NO is controlled through a reduction in excess oxygen and the $SO_x$ is not subject to combustion control,[17] which indicates an insensitivity to oxygen concentration.

The surprising finding is that the blend $SO_x$ emissions were less than the emissions when firing coal alone. It had been shown in earlier literature that coal ash captures up to 33% of $SO_x$ from low S coals in fluidized beds[18] and 5–50% of $SO_x$ for bituminous and lignite coals.[16] Typical composition of Wyoming coal and manure ashes are shown in Table 3. The volatile ash was 17% for coal, whereas the blend contained 20%. Apparently, the manure ash captures the $SO_x$ emitted by coal.

Table 4 compares the emission of $SO_x$ for coal and blends. Because the experiments were conducted over a short period of time, the results need reconfirmation, over longer periods of time, using a pilot scale unit. The $SO_x$ concentration for blends of RM, PC, and FC were 40, 17, and 5% of the $SO_x$ concentrations emitted from coal.

## Summary

A small-scale boiler burner facility was constructed and instrumented for measuring temperature distribution, pollution emissions, and composition of flue gases. For an 80:20 blend of coal and manure, the firing of blends did not change the temperature distribution or size of the recirculation zone, indicating that the flame stability was maintained. The formation of $NO_x$ generally increased with the burned mass fraction. However, the contribution of $NO_x$ from the 20% feedlot manure decreased with the burned fraction. In all cases, the emissions were within the USEPA guidelines. The conversion of N to $NO_x$ decreased as the oxygen content decreased. The most surprising finding was that the $SO_x$ emissions were lower for blended fuels than for pure coal, probably because of capture by the alkaline ash of the feedlot manure. Using blend technology, one can convert chemical energy to thermal energy and replace a part of the fossil fuels; at the same time the emission of volatile gases from the storage of manure is reduced along with a reduction in $NO_x$ and $SO_x$ emissions from coal-fired powerplants. Formulas were presented for determining the air:fuel ratio from measured $O_2$% and/or $CO_2$%, burned fraction, and N conversion efficiency.

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## References

[1] Sweeten, J., Testimony to Congress, House Committee on Agriculture, Stephenville, TX, June 30, 1989.

[2] Sweeten, J. M., and Amosson, S. H., "Manure Stockpiles: Economic and Environmental Aspects," *Total Quality Manure Management Manual*, Texas Cattle Feeders Association, Amarillo, TX, 1995, pp. 1–7, Chap. 1.

[3] Sweeten, J., "Livestock and Poultry Waste Management, a National Overview," ASAE 03-92, 1992.

[4] Sweeten, J., Korenberg, J., Annamalai, K., Lepori, W., and Parnell, C. B., "Combustion of Cattle Manure for Energy Production," *Journal of Energy in Agriculture*, Vol. 5, Apr. 1986, pp. 55–72.

[5] Annamalai, K., Ibrahim, Y. M., and Sweeten, J., "Experimental Studies on Combustion of Cattle Manure in a Fluidized Bed Combustor," *Journal of Energy Resources and Technology*, Vol. 109, No. 2, 1987, pp. 49–57.

[6] Office of Industrial Technologies, Dept. of Energy, CH10093-194, DE93000059, Nov. 1993.

[7] Sweeten, J. M., and Amosson, S. H., "Manure Quality and Economics," *Total Quality Manure Management Manual*, Texas Cattle Feeders Association, Amarillo, TX, 1995, pp. 24–33, Chap. 4.

[8] Frazzitta, S., and Annamalai, K., "Performance of a Small Scale Boiler Burner in the Firing of Low Sulfur Wyoming Coal," *American Society of Mechanical Engineers/Energy Technology Conference and Exhibition*, Vol. PD-57, pp. 101–105.

[9] Beer, J. M., and Chigier, N. A., *Combustion Aerodynamics*, Applied Science Publishers, London, 1972.

[10] Fricker, N., and Leuckel, W., "The Characteristics of Swirl Stabilized Natural Gas Flames; Part 3: The Effect of Swirl and Burner Mouth Geometry on Flame Stability," *Journal of the Institute of Fuel*, Vol. 152, 1976, pp. 152–159.

[11] Annamalai, K., Sweeten, J., and Ramalingam, S. C., "Estimation of the Gross Heating Values of Biomass Fuels," *Transactions of the American Society of Agricultural Engineers*, Vol. 30, No. 4, 1987, pp. 1205–1208.

[12] Annamalai, K., Morris, T., and McNicholls, D., "A Thermodynamic Analysis of Fever in Chemotraphs," *Proceedings of the 1997 ASME Congress and Exposition*, Vol. 37, Advanced Energy Systems Div., 1997, pp. 239–247.

[13] Syred, N., and Beer, J. M., "Combustion in Swirling Flows: A Review," *Combustion and Flame*, Vol. 23, No. 2, 1974, pp. 143–201.

[14] Ubhayakar, S., Stickler, D. B., and Gannon, R. E., "Rapid Evolatilization of Pulverized Coal in Hot Combustion Gas," *16th Symposium on Combustion*, The Combustion Inst., Pittsburgh, PA, 1976, pp. 427–436.

[15] Song, Y. G., Pohl, H., Beer, J., and Sarofim, A. F., *Combustion Science and Technology*, Vol. 28, 1982, pp. 31–39.

[16] Lawn, C. J., and Godridge, A. M., *Matching the Combustion Equipment to the Boiler, Principles of Combustion Engineering for Boilers*, edited by C. J. Lawn, Academic, New York, 1987, Chap. 1.

[17] Essenhigh, R. H., "Coal Combustion," *Coal Conversion Technology*, edited by C. Y. Wen and E. S. Lee, Addison–Wesley, Reading, MA, 1979.

[18] Hoyt, H. R., and Gill, H. W., "The Combustion of Coal in Fluidized Beds," *Principles of Combustion Engineering for Boilers*, edited by C. J. Lawn, Academic, New York, 1987.