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New Technology Research & Development Program
Grant Contract 582-5-65591-0015

Task 2 Deliverable

The preparation of this report is based on work funded in part
by the State of Texas through a Grant from the
Texas Commission on Environmental Quality.

NO_X AND Hg CAPTURE USING COAL, FEEDLOT BIOMASS (CATTLE MANURE) AS REBURN FUELS

Task 2: Reburn Experiments for NO_x and Hg Reduction

Subtask 1: Reburn Experiments
Subtask 2: Fouling Study
Subtask 3: Hg Emissions

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The preparation of this report is based on work funded in part
By the State of Texas
Through a Grant from the Texas Commission on Environmental Quality.

Submitted to
Reported to: Texas Commission on Environmental Quality
Austin, Texas 78711
July 31, 2006

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ABSTRACT

Coal fired power plants produce NO_x at unacceptable levels. In order to control these emissions without major modifications to the burners, additional reburn fuel is fired under rich conditions (10 – 30% by heat) after the coal burners. Additional air called overfire air (about 20% of total air) is injected in order to complete combustion. Typically the reburn fuel is natural gas (NG). From previous research using a small scale 30 kW (100,000 BTU/h) boiler burner in Texas A&M Research Facility, it was found that firing feedlot biomass (FB) as a reburn fuel lowers the NO_x emission at significant levels compared to NG. The present research was conducted to determine the optimum operating conditions for the reduction of NOx. Experiments were performed using Low Ash Partially Composted FB (LAFB-PC; Saturn Mean Dia (SMD) of 56 microns) with the equivalence ratio ranging from 1 to 1.15. The results of these experiments show that NO_x levels can be reduced by as much as 90 % when firing pure LAFB-PC and results are almost independent of the equivalence ratio. The reburn fuel was injected with normal air (O2 %: 21%) and then vitiated air (O2 %: 12.5%). Further, the angles of the reburn injectors were set at 0° (normal to main gas flow), and at 45° upward. For LAFB-PC no significant changes were observed; but High Ash Partially Composted FB (HAFB-PC) revealed better reductions with a 45° injector and vitiated air. This new technology has the potential to reduce NO_x emissions in coal fired boilers located near cattle feedlots and also relieves the cattle industry of the waste material. The equivalence ratio also has a great influence on NO_x reduction. The performance was compared with those of Texas Lignite and PRB Wyoming coal as standard reburn fuels.

For the fouling study, the small scale boiler burner with the feedlot biomass was tested under the transient condition. The fouling research comprises of two parts: (1) determining the overall heat transfer coefficient with the heat exchanger in order to gauge its performance and (2) determining the combustion performance by analyzing of ash formed during the fouling tests. It was found that the fouling prevents the heat transfer from the gas stream in the reactor to the heat exchanger tube. The effect of the feedlot biomass on the NO_x reduction was found to be significant with the increment of the proportion of biomass in the fuel.

Experiments were conducted to observe the variations of mercury oxidation with presence or absence of NO_x. It can be interpreted that elemental mercury is least observed when the equivalence ratio is 1.05, i.e., when the reactor is burnt at 5% excess air. The oxidation level of the 80:20 Wyoming sub-bituminous coals: LAFB-PC blend is found to be higher than that of pure coal used at the reburn zone. LAFB-PC helps in oxidation of mercury which in turn signifies that Hg can be captured more effectively at the exhaust by Flue Gas Desulphurization (FGD) type of devices.

1. INTRODUCTION

With the increasing usage of fossil and renewable fuel sources, there is growing concern on emissions. Coal-fired power plants consume about 300 million short tons of coal per year (as of 2003) and produce approximately 90 percent of NO_x emitted by electric utilities [1]. Utility power plants emit about 41 tons of mercury (Hg) through stack while Hg input through coal is about 75 tons per year [2]. A cap of 7.5 tons/yr has been proposed. As of 1999, the CO_2 equivalent emission is 5 billion tones per plant for industrial, transportation and electric plants. United States Environmental Protection Agency (U.S. EPA) estimated the annual amount of NO_x increased from 2.6 million tons in 1900 to 25 million tons in 2000 [3, 4]. Power plants produce 21% of the annual NO_x emission in the United States, or 6.1 million tons of NO_x per year in 1998 [4, 5]. The U.S. EPA plans to reduce emission rate to 0.15 lb/mmBTU for the year 2009 to 2014 (the first Clean Air Interstate Rule (CAIR) phase) and an NO_x emission rate to 0.125 lb/mmBTU for 2015 and later (the second CAIR phase) [6]. Thus many NO_x control technologies have been recently developed for coal-fired boiler burners**.** Coal properties play a major role on the NO_x generated during the combustion process. These properties include the nitrogen content, the makeup of the mineral matter, and the size of the coal particles. Fuels that have less nitrogen content emit less fuel NO_x [7].

Extensive research has been conducted in the area of biomass combustion as a technology to reduce coal consumption, lower emissions, and dispose off animal wastes (biomass) from CAFO. The use of biomass for combustion is favorable to utilities because it is a CO_2 neutral fuel. The use of animal wastes, a biomass, as reburn fuel was first experimented by Thien and Annamalai [8] and the results revealed about an 80% reduction in NO_x. It was found that co-firing 10% biomass with coal reduced NO_x emissions by about 10 %, but the CO emissions increased [9]. It was suggested that the higher volatile matter in the feedlot biomass depletes the oxygen rapidly, which inhibits NO_x formation. The process has resulted in an US patent (patent # US Patent # 6,973,883 issued to Annamalai and Sweeten). The Texas Panhandle region (the largest region of the cattle feeding in Texas) produces about 7.2 million fed cattle, and the amounts of animal wastes have doubled since 1978 [10]. Several different types of cattle manures (or feedlot biomass, FB) are produced from different surfaces and collection techniques. The FB collected on soil surfaces contains high amounts of ash and is termed high ash FB (HAFB-PC) while those collected on fly ash paved surfaces contain less ash termed as low ash FB (LAFB-PC). Thus the use of FB as a reburn fuel instead of natural gas generates more ash in the boiler resulting in more ash deposition on heat exchanger (HEX) tubes and hence can build up slag. The primary purpose of the boiler is to transfer heat from hot flue gases to the cold water/steam circulated through HE tubes. Hence heat transfer is affected. Thus the effects of ash build up on fouling and heat transfer behavior must be studied. Small ash particles stick to the surface of the heat exchanger while large ash particles impact them [11]. The ash fouling can also cause 60% depreciation of the heat transfer [12]. These problems increase undesirable operating cost of boiler burners. Annamalai *et al.* used NETL's 150 kW (500,000 BTU/h) pilot plant facility for combusting coal:FB mixtures and reported that ash deposition causes heat transfer rate to decrease with time due to ash buildup [13] and are more severe for coal:HAFB-PC blend than for coal. The extent of combustion and fouling depend on the type of the FB and amount of ash. Thus ash fouling potential must be evaluated when fuel is used for co-firing or reburning.

In coal combustion systems, mercury (Hg) has been targeted for control due to its unique characteristics such as high volatility, bio-accumulation and other toxic properties. Mercury in flue gases exists in 3 forms, viz., elemental (Hg^0), oxidized (Hg^{2+}) and particulate (Hg^P) forms. The particulate Hg was not of much importance during this research due to the fact that it can be easily captured at the filters and does not cause a polluting threat. Unlike other trace metals that are emitted in particulate form, mercury is released in vapor phase in elemental or oxidized form. Out of 158 tons mercury emitted annually into the atmosphere by anthropogenic sources in the United States, approximately 87% is from

combustion point sources [14]. The U.S. EPA has released Clean Air Mercury Rule (CAMR), which establishes standards of performance limiting mercury emissions from new and existing coal power plant and introduce a strict cap to reduce nationwide utility emissions of mercury. The first phase cap of CAMR is 38 tons and emissions will be reduced by taking advantage of "co-benefit" reductions. In the second phase, due in 2018, coal-fired power plants will be subject to a second cap, which will reduce emissions to 15 tons upon full implementation. Efforts have been made to study the mercury behavior in flue gases from coal power plants, and have been reported elemental mercury is difficult to capture, while oxidized form of mercury can be captured at the Flue Gas Desulphurization (FGD) unit, since oxidized mercury is soluble in water. Elemental mercury, owing to its volatile nature, exists in vapor phase in the flue gases which escapes into the atmosphere without being captured in any of the environmental emission capture devices. If the elemental mercury is by some means converted to the oxidized form, it can be effectively removed at the FGD unit.

2. OBJECTIVES

The first objective (sub task 2.1) of the current research is to use FB as a reburn fuel for reduction of NO_x. The small scale 30 kW (100,000 BTU/h) boiler burner is located at Renewable Energy Laboratory of the Mechanical Engineering, Texas A&M Research Facility in College Station, TX. The current research focuses on investigating the levels of NO_x reduction with FB as a reburn fuel and to determine the operating conditions for optimum NO_x reduction. The results from the current experiments provide guidelines for coal fired utilities to fire feedlot biomass in their boilers to reduce NO_x. The use of feedlot biomass also relieves the cattle industry of the excess manure, which can itself cause adverse effects on the environment. By developing this technology, coal fired utilities can meet the NO_x emissions requirements and also help the cattle industry dispose of their excess manure.

The second objective (sub task 2.2) is to investigate the ash fouling behavior and its effect on the overall heat transfer coefficient and combustibles loss (Loss on ignition, LOI).

The third objective (sub task 2.3) is to introduce and present a new technology to control mercury emissions from coal fired power plants. The scheme basically involves the use of FB, coal and coal:FB blends as reburn fuels to effectively convert elemental mercury to its oxidized form which can be captured more easily using traditional environmental devices. The reason for using biomass with coal is that biomass has high proportions of chlorine in it, which helps oxidation of elemental mercury to mercuric chloride, thus helps in easy mercury capture.

3. FUEL PROPERTIES

3.1 Primary Fuel

Natural gas (NG) from the standard natural gas lines in the lab was fired in the primary combustion zone for all experiments. There was very little change in the composition of the natural gas (Table 3.1) . The average fuel composition was 95% methane. All other components of the fuel were in small quantities and were considered negligible. For all calculations performed for the current research, the total fuel composition was assumed to be methane. Because the furnace operates at a relatively low temperature, NO_x is generated with ammonia (NH_3). The ammonia is injected with the primary fuel and is converted to NO_x during combustion.

3.2 Reburn Fuels

Several fuels and fuel blends were used as reburn fuels. The fuels consisted of Low Ash Partially Composed Feedlot Biomass (LAFB-PC), High Ash Partially Composed Feedlot Biomass (HAFB-PC), Texas Lignite Coal (TXLC), Wyoming Subbituminous Coal (WYC), and blends of FB and TXLC. Each of the fuels used and their respective proximate analyses are listed in Table 3.2 [15]. All of the biomass used for this project were collected and prepared at the TAES, Bushland, TX.

Table 3.1: Average Fuel composition of Natural Gas

Gas Analysis Report

Analysis id: 93006400 — Test Number: 352786

Source Information

Operator	Texas A & M University
Source	Texas A&m Power Plant(ireland Dr)
County	Brazos
State	Tx
Freq	Daily

Field Data

Date Sampled from to 03/06/2006

Static Pressure (psia)	249
Diff Pressure (inches)	0
Flowing Temp (deg. f.)	64
Water Vapor (lbs/mmcf)	4
Hydrogen Sulfide (ppm)	0
Sampled by	BOND
Field BTU @ 14.65D	1027
Field Rel Den (R)	0.599

Analysis Results

Constituent	MOL %	Gal/MCF
Helium	0.00	
Carbon Dioxide	1.69	
Oxygen	0.00	
Nitrogen	0.45	
Methane	94.45	
Ethane	2.34	0.62
Propane	0.59	0.16
Isobutane	0.12	0.04
N-Butane	0.14	0.04
Isopentane	0.06	0.02
N-Pentane	0.04	0.01
Hexanes+	0.12	0.05
Hydrogen Sulfide	0.00	
Totals	100.00	0.94

Laboratory Data

Calculated BTU @ 14.65 Dry	1027.839
Calculated BTU @ 14.65 Saturated	1009.852
Relative Density(real)	0.5991
Total Inerts	
Interchange Factor	1312
Date Reported	03/14/2006

Composite Contract Quality Requirements

	Minimum	Maximum
BTU	950	1100
Relative Density		0
Interchange	0	0
Water Vapor(lbl/mmcf)		7
Carbon Dioxide(%)		2
Oxygen(%)		0.05
Nitrogen(%)		
CO2+N2		
Total Inerts(%)		4
Hydrogen Sulfide(gr/ccf)		0.25
Hydrocarbon Dew Pt(F)		40

Remarks

Approved by DT

The HAFB-PC was collected from feedlots with a soil surface and then composted in windrows for 55 days. The LAFB-PC was collected from feedlots paved with fly ash. It was also composted in windrows for 55 days. Less soil is collected with the manure gathered from paved feedlots and therefore less ash is in the fuel. After composting the biomass, it was dried and finely ground. The reburn fuel blends consisted of 90:10, 70:30, and 50:50 TXLC:LAFB-PC and 90:10, 70:30, and 50:50 TXLC:HAFB-PC on a mass basis. The properties of fuel blends are calculated based on properties of pure fuels on a mass basis. The moisture content of the FB fuels is low and very similar; 17% for HAFB-PC and 19.64% for LAFB-PC, while that of coals is very high; 38.34% for TXLC and 32.88% for WYC. Unlike the moisture content, the ash content of the FB fuels varies greatly; 53.58% for HAFB and 16.50% for LAFB-PC, while that of coals is very low; 11.46% for TXLC and 5.64% for WYC. Ultimate analyses of reburn fuels are reported in elsewhere [15].

Table 3.2: Average fuel compositions for all fuels in pure form

AVERAGE FUEL COMPOSITIONS								
	HAFB-PC		LAFB-PC		TXLC		WYC	
Proximate (%)	As Rec.	Dry	As Rec.	Dry	As Rec.	Dry	As Rec.	Dry
Moisture	17.00	0.00	19.64	0.00	38.34	0.00	32.88	0.00
Ash	53.85	64.88	16.50	20.53	11.46	18.59	5.64	8.40
Volatiles	25.79	31.07	52.33	65.11	24.79	40.20	28.49	42.45
Fixed C	3.36	4.05	11.54	14.36	25.41	41.21	32.99	49.15

Table 3.3. Ash Elemental Analysis (% mass)

(Ash was calcined @ 1100 °F (600 °C) prior to analysis)					
Compositions	HAFB-PC	LAFB-PC	TXLC	WYC	Melting Point (°C)
Silicon, SiO_2	65.55	20.78	48.72	31.73	1712.85
Aluminum, Al_2O_3	11.2	4.94	16.04	17.27	2040
Titanium, TiO_2	0.52	0.22	0.85	1.35	1829.85
Iron, Fe_2O_3	2.99	1.71	7.44	4.61	1564.85
Calcium, CaO	7.47	21	11.70	22.20	2298.85
Magnesium, MgO	2.29	7.54	1.93	5.62	2799.85
Sodium, Na_2O	1.38	5.26	0.29	1.43	1132
Potassium, K_2O	4.66	14.6	0.61	0.67	763
Phosphorus, P_2O_5	2.43	13.77	0.1	0.8	300
Sulfur, SO_3	1.3	4.47	10.80	10.40	16.9
Chlorine, Cl	0.41	5.07	<.01	<.01	-101.55
Carbon dioxide, CO_2	0.51	0.59	0.08	0.37	-
Total ash analysis	100.71	99.95	98.56	96.45	-

Source: Annamalai *et al.* [15] Pyrolysis, Ignition, and Fuel Characteristics of Coal, Feedlot Biomass, and Coal:Feedlot Biomass Blends. Final Report for TCEQ, March 31, 2006.

The mineral analysis of ash for the reburn fuels tested are very important since it affects the ash deposition rate, corrosion rate, and erosion rate of HEX tubes. The mineral analysis is presented in Table 3.3. The dominant compositions of reburn fuels are silicon (SiO_2), aluminum (Al_2O_3), and calcium (CaO). Higher alkaline oxide content results in a higher probability of fouling due to the oxide layers on a HEX surface grows faster. The total amounts of ash acids (SiO_2, Al_2O_3, TiO_2) are higher than that of basic components (Fe_2O_3, CaO, MgO, Na_2O, and K_2O) for HAFB-PC, TXLC, and WYC. Though the ash fusion temperatures are typically hard to obtain, they depend upon the ratio of ash acid and the basic components as well as their melting points [15]. The higher the amount of basic components, the lower the fusion temperature.

4. EXPERIMENT FACILITY AND PROCEDURES

4.1 Experiment Facility

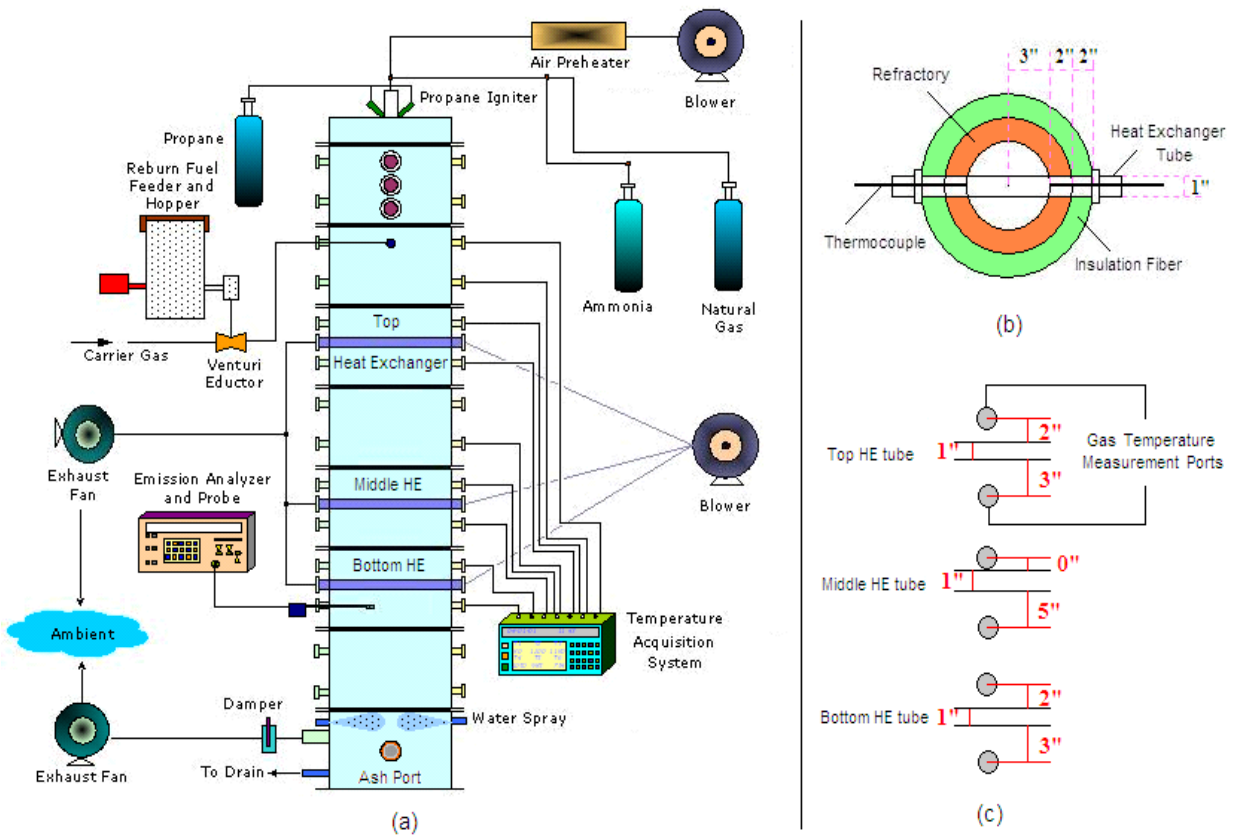


Figure 1. Schematic of Reburn Facility with Modification for Ash Fouling Tests

A schematic of the reburn setup is shown in Figure 1. The diagram contains all of the major components of the setup that was used to conduct the research experiments. The reburn furnace consists of a 15.24 cm (6 in) diameter, 182.88 cm (6 ft) long downward fired combustor. The main burner at the top burns natural gas and the reburn zone is equipped with an injection setup for solid fuels. The furnace is made with a steel frame containing a two inch layer of insulation and a two inch section of refractory. Along the walls of the furnace are several gas sampling and temperature measurements ports. Water jets are used to cool the hot exhaust gases before they enter the exhaust system. The NO_x is generated using ammonia (NH_3) injection with the primary fuel and the NH_3 is converted to NO_x during combustion. The primary air for the main burner is supplied from a large blower. After leaving the blower, the air is heated in an air pre-heater to between 29 and 93 °C (85 and 200 °F) before entering the furnace. A feeder and venturi system entrains the solid reburn fuel in air and the mixture is blown into the furnace 45.72 cm (18 in) below the main burner. The reburn fuel is injected into the burner laterally or at a 45° angle. The 45° injection angle is used to increase the residence time of the reburn fuel and to give time for more NO_x reduction.

4.2 Procedures for Reburn Experiments

Each reburn fuel and fuel blend was fired for equivalence ratios from 1.00 to 1.15 in increments of 0.05. The equivalence ratio was varied by varying the motive airflow for the reburn fuel. The use of vitiated air (air with combustion products) in the reburn zone has also been reported to reduce NO_x. It is difficult to re-circulate exhaust gases with the reactor used in the current study; therefore the oxygen concentration of the motive air was reduced with nitrogen gas in an effort to simulate vitiated air.

In order to ensure that the furnace was near steady state and that temperature changes during the experiment would not affect the data, each operating condition was set and maintained until all reactor temperatures were near steady state. After the temperatures were steady, the emission gas analyzer was used to determine NO_x levels. In order to determine the level of NO_x and excess oxygen present in the gas stream before the reburn zone, gas composition measurements were conducted before the reburn fuel was injected. After the level of NO_x was determined and the primary zone equivalence ratio was at the desired level, the reburn fuel was fired. The levels of O_2, NO_x, CO, CO_2, and combustibles (C_xH_y) were then measured 137.16 cm (54 in) below the reburn zone. After the measurements were taken, the reburn fuel was shut off and a check was done to ensure that the level of NO_x generation was still consistent with the initial setting. This process was followed for each measurement.

4.3 Procedure for Fouling Studies

A procedure has been developed to study the fouling potential in a small scale test facility where time duration of tests is very limited and steady temperature is difficult to achieve particularly for the HEX .The procedure is still under refinement. Three single-pass heat exchangers whose surfaces are clean and dry were laid perpendicular to the downward flow of flue gases. Heat exchanger tubes were located below the reburn zone (RZ) between 12 in (30.48 cm) and 18 in (45.72 cm), between 36 in (91.44 cm) and 42 in (106.68 cm), and between 48 in (121.92 cm) and 54 in (137.16 cm), respectively. As shown in Figure 3.1 (b), the entrance and exit temperatures of the HEX tubes were measured 3 inches (7.5 cm) from the reactor center at the inner surface of the refractory. The locations of temperature measurement ports to the HEX tubes are illustrated in Figure 1(c). The gas temperatures linearly decrease along the two measurement ports. The usage of water as cooling fluid in HEX in the past led to difficulties in measuring the temperature difference accurately; hence air was used as HEX fluid and air flow was set 20 SCFH (9.4388 SLPM based on standard ambient temperature and pressure, SATP). The dimension of a HEX tube is 2.7 cm (1.06 in) O.D., 2.1 cm (0.83 in) I.D. 15.24 cm (6 in) long.

The experiment started with preheating the primary air up to 250 ºF (about 120 ºC), and then injecting it into the reactor with the primary fuel. Before the cold air started to flow into HEX tubes, the temperature difference between the entrance and exit temperatures for all HEX tubes was maintained between 20 and 30 ºF. After the reburn fuel and carrier gas were injected, the temperatures in HEX tube kept increasing due to the combustion of the reburn fuel. Due to the smaller size of reactor, steady temperature difference could not be obtained; further the reactor clogged when FB was burnt over longer periods, particularly with the combustion of HAFB-PC. Finally, the instantaneous temperatures of the airflow and the gas stream were monitored under the conditions of various equivalence ratios. The combustion of reburn fuels was limited to 2 to 3 hours due to safely reasons. The whole procedure of a single experiment, including the combustion of reburn fuels, lasted 8 to 10 hours.

The ash deposits on the surfaces of the HEX tubes consisted of small and sticky particles. Large ash particles may not adhere to the surface of the HEX tubes due to impaction and bouncing off of surfaces. The ash samples from the surface of each HEX tube and from the ash port at the bottom of the furnace were scraped off after the furnace completely cooled down and sent for analyses. Texas Lignite Coal (TXLC) is used as the baseline reburn-fuel, and its mixtures with FB are used to compare the results. In the fouling study, the high ash FB was not tested due to frequent clogging and safety reasons.

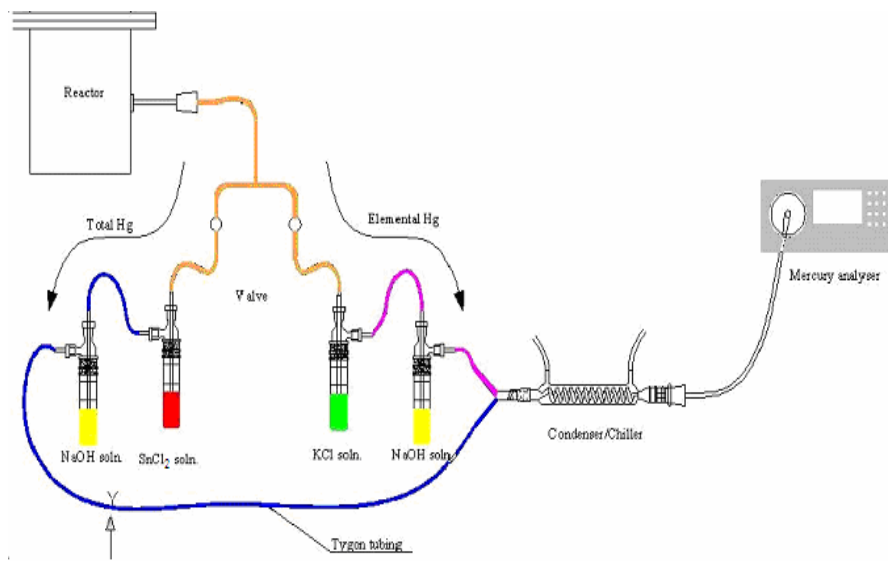


Figure 2. Schematic of the wet chemistry setup for Measuring $Hg^{(0)}$ and $Hg^{(2+)}$

4.4 Procedure for Mercury Measurements

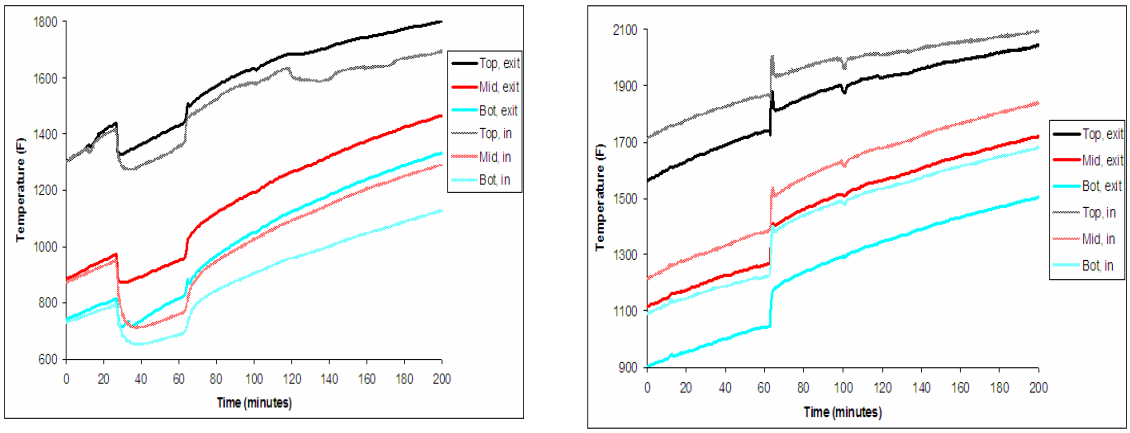
Mercury measurements were conducted using Mercury instrument VM3000, which works on cold vapor atomic absorption (CVAA) technique. For measurement purpose, flue gas was sampled from a gas exit port 54 inches below the reburn zone inside the instrument. Mercury in flue gases exists in 3 forms, viz., elemental (Hg^0), oxidized (Hg^{2+}) and particulate (Hg^P) forms. The particulate Hg was not of much importance during this research due to the fact that it can be easily captured at the filters and does not cause a polluting threat. The mercury instrument is capable of measuring only elemental mercury concentration in flue gases.

To estimate the oxidized mercury form, a wet chemistry method was adopted. The wet chemistry method used is basically modified Ontario Hydro method of mercury speciation to measure all forms of mercury on an online basis. The wet chemistry setup is used between the reactor and mercury instrument to condition the flue gases to read total mercury content ($Hg^0 + Hg^{2+}$). Its working is illustrated in Figure 2. The flue gas is made to pass through either one of the two streams, one for elemental and other for total mercury. For the elemental stream, flue gas is made to pass through two impingers, first with potassium chloride solution (KCl) and second with sodium hydroxide solution (NaOH) solution. The KCl absorbs the oxidized mercury present in the stream, and NaOH helps in absorbing SO_2 and other acidic gases, while the chiller removes water vapor, thus ensuring the flue gas stream leaving the conditioning system has only elemental mercury which was originally in the flue gas. The need to remove SO_2 and water vapor is that they may interfere with the absorption of UV light inside the instrument. For the total mercury, the flue gas is made to pass through another set of two impingers, first stannous chloride solution ($SnCl_2$), and second through NaOH solution, then through the common chiller into the instrument. The $SnCl_2$ solution acts as a reducing agent to reduce oxidized mercury to its elemental form. The flue gas thus leaving this stream consists of total mercury, which is the sum of originally elemental mercury and the oxidized mercury converted to elemental form, which can be observed in the instrument.

To estimate the oxidized mercury concentration, it is just the difference of total mercury reading and the elemental mercury reading.

4.5 Uncertainty

It should be pointed out that some conditions of uncertainty existed during the experiments. First, the refractory could have been offset from the reactor center. Second, the refractory wall could have been



(a) **(b)**

Figure 3. Temperature distributions of the hot flue gas stream and the cold gas in HEX tubes producing 100% of the total heat without ash depositions: a) Temperature of the cold gas in HEX tubes, (b) Temperature of the gas stream

thicker than the original thickness because of the accumulation of the ash fouling from previous experiments. Third, thermocouple probes could have been covered by ash particles. Fourth, thermocouple probes may not have been located at the center of the HE tube because of gravity. Fifth, the reburn feeding system made an unstable feed rate. The fluctuation of the feed rate is caused by the density fluctuations of the reburn fuel. For the uncertainty calculation, known parameters and values were applied. The solid fuel was fed to the system with a volumetric feeder. Though the feed rate was calibrated for each fuel before experimentation, it had an error range of ± 1.85%. The Lancom III Combustion Gas Analyzer was used for all measurements. The concentration of gas species fluctuate in the range of ± 5.0% during the reading. The gas flow rates were all controlled with Rotameters with the exception of the natural gas flow rate. Rotameters have an error range of ± 3.7%. The natural gas flow rate was controlled by the use of a digital flow controller made by OMEGA Inc which has an error range of ± 1.66%. The uncertainty of experiments was determined to be ± 6.7%.

There could be also uncertainties in the measurement of Hg due to the fact that Hg could be absorbed on the refractory walls of the reactor due to limited time of operation when changing fuels. This could be partially eliminated by preheating the reactor for 3 hours before conducting the experiments. The other uncertainty involves in measuring total Hg is due to condensation of water vapor on the connecting pipes between the reactor and wet chemistry conditioning system. This was partially minimized by cleaning and drying the tubes at regular intervals.

5. EXPERIMENTS

5.1 Experimental Cases

Two injection angles (0° & 45°) of the reburn injector were compared for two different oxygen concentrations (20.9% & 12.5%). The 20.9% oxygen concentration represents the pure air or non-vitiated air. The 12.5% oxygen concentration represents the vitiated air. In these experiments, the oxygen concentration was reduced to 12.5% with N_2 gas in an effort to simulate exhaust gas recirculation. The equivalence ratio was also varied from 1.00 to 1.15 in increments of 0.05 during experiments.

5.2 Operating Conditions

The total heat input for each experiment was set to 30 kW (100,000 BTU/hr). The primary combustion zone supplied 21 kW (70,000 BTU/hr) and the reburn zone supplied 9 kW (30,000 BTU/hr). The primary zone combustion conditions were maintained the same for each experiment.

5.3 Temperature Profile

The temperature profile for each experiment was important because the reaction rates for the NO_x reduction are very sensitive to temperature. For each experiment, the temperature profile was measured using K-type thermocouples. The measured temperature profiles revealed decreasing temperature with increasing distance from the reburn port and the temperature profile for vitiated cases shows a similar trend. The temperature for the vitiated case was slightly lower than the temperature for the non-vitiated case. This lower temperature is expected since some heat is required to heat the added nitrogen. On average, the temperature profile was 17 °C (30 °F) lower for the vitiated case as compared to the non-vitiated case.

There was also a difference in the temperature profiles for the lateral versus 45° injection setups. There was a steeper drop in temperature at the reburn zone for the 0° injection as compared to the 45° injection. This may suggest that for the 45° injection, combustion occurs more quickly and gives rise to hotter temperatures just after the reburn zone. The higher temperatures found with the 45° injection scheme should reduce NO_x levels better since the NO_x reduction reactions are highly dependent upon temperature.

5.4 Criteria Adopted for Fouling Studies

In order to understand how temperatures changed in the current reactor without the ash deposition, temperatures of the airflow and gas stream were measured first with main burner supplying 70 % heat input and then raising the heat input by 30 % after about 60 min. Figure 3(a) shows temperature distributions of the cold gas at each end of HEX tubes. The exit temperature was higher than the inlet temperature as expected. The air flowed into HEX tubes after about 25 minutes, so that all temperatures decreased for a while, then soon they increased again. After 60 minutes, all temperatures jumped up due to 30 % additional heat. It was shown that the local temperature differences ($\Delta T = T_{exit} - T_{in}$) between the inlet and the exit of each HEX tube increased over time.

Figure 3 (b) presents temperature variation of hot flue gas stream measured above (inlet) and below (outlet) the HEX tubes as shown in Figure 1(c). The temperature distributions shown in Figure 3 for the case of no ash deposition are defined as reference temperature distributions for future discussions.

Table 4.1. Average rates for no ash deposition

Location	OHTC [W/m^2·K·min]	LMTD [K/min]
Top	0.026	-0.335
Middle	0.012	-0.521
Bottom	0.042	-0.504

Based on the hot gas and coolant temperatures log mean temperature differences (LMTD) were calculated and overall heat transfer coefficients were estimated. Due to transient nature of the experiments, LMTD decreases with time, and also varies with the position of the HEX tube along the reactor. The average LMTD rates are listed in Table 4.1. Figure 3 is used as a basis for evaluation of the fouling potential of solid reburn fuels. When ash is deposited, the temperature variation assumes different distribution. By comparing the temperature distributions with and without ash, the effect of ash deposition on heat transfer rate is discussed later under Results and Discussion. Particularly the rate of increase of OHTC under ash deposition will be compared with OHTC under zero ash deposition.

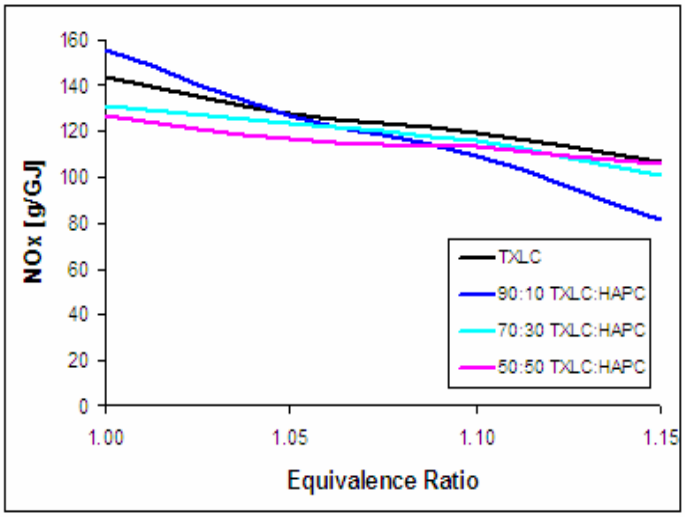


Figure 4. Base case fuel (TXLC) compared to HAFB-PC under the condition of the 0° reburn injection and pure air.

6. RESULTS AND DISCUSSION

6.1 Effects of Equivalence Ratio (ϕ)

The result of Texas Lignite Coal (TXLC) was used as a standard case in this research. Figure 4 shows NO_x emissions TXLC:HAPC-FB blends under the condition of the lateral reburn injection and pure air. The pure HAPC-FB was not performed due to severe amounts of slag built up in the area near the reburn injectors in the furnace. The combustion of TXLC emits NO_x 143.5 g/GJ at ϕ = 1.0, and 106.36 g/GJ at ϕ = 1.15 while for WYC , they are 123.42 g/GJ at ϕ = 1.0, and 93.52 g/GJ at ϕ = 1.15. The NO_x emissions of 90:10 TXLC:HAFB-PC blend are 155.87 g/GJ at ϕ = 1.0, and 81.24 g/GJ at ϕ = 1.15. NO_x emissions of 50:50 TXLC:HAFB-PC blend are measured 126.74 g/GJ at ϕ = 1.0, and 105.95 g/GJ at ϕ = 1.15. With increased equivalence ratio, the oxygen in the combustion zone is depleted quickly. Low levels of oxygen slow down the NO formation reaction and allow the NO reduction reaction to be

dominant in the combustion zone. The greatest influence on NO_x emission levels was the equivalence ratio.

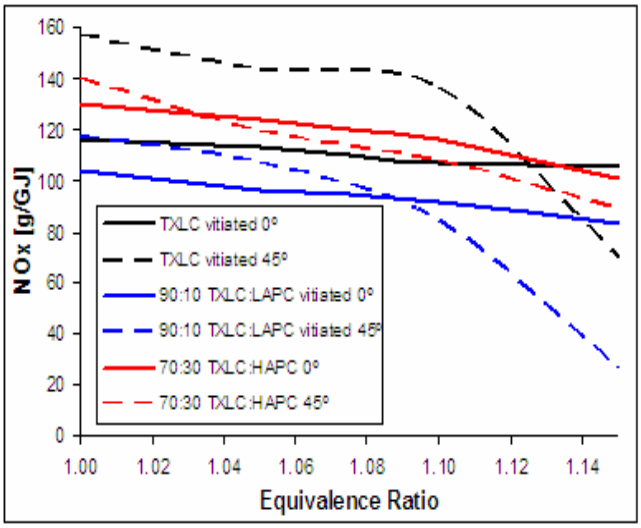


Figure 5. NOx levels for several reburn fuels with 0° and 45° injection angles

NO_x reductions were obtained based on the initial NO_x emission, approximately 400 ppm. The average NO_x reduction is defined as the average value of NO_x reductions measured at equivalence ratios. In the current research, the pure TXLC achieved the average NO_x reduction of 11.0% while the pure WYC achieved 22.5% reduction. Much lower NO_x emissions were measured for LAFB-PC and blends indicating almost as high as 90 % reduction (not shown). The greater reduction with FB is achieved due to higher VM released at lower temperature (TGA studies, [15]), reverse prompt NOx due to gases released during pyrolysis and possibly release of N in the form of NH_3. The 90:10 TXLC:HAFB-PC blend obtained NO_x reduction of 14.3%, the 70:30 TXLC:HAFB-PC blend obtained 12.8%, and the 50:50 TXLC:HAFB-PC blend obtained 12.0%.

6.2 Vitiated and Non-vitiated Cases

The experiments attempted to simulate the exhaust gas recirculation by injecting nitrogen gas with the reburn fuel motive air. The same amount of the total air was used; however, the oxygen concentration was lowered to 12.5%. In these experiments, the levels of NO_x are reported on mass per heat output basis (g/GJ). This reporting method allows for better comparison of the results between the vitiated and non-vitiated cases. Nitrogen gas is used to simulate the vitiated air. If CO2 is used to vitiate instead of N2, and because the specific heat of nitrogen (34.5 kJ/kmol·K) is different from that of CO_2 (57.7 kJ/kmol·K), there could be change in the reduction results. However no study has been conducted on the effect of CO2 vitiation. All cases show higher NO_x reduction for the vitiation than for the non-vitiation. When the average reduction of entire lateral injection cases is considered, the level of NO_x reduction caused by vitiation and by non-vitiation was 36.5% and 26.5%, respectively. For entire 45° injection cases, the level of NO_x reduction was measured 41.2% for the vitiated air and 38% for the non-vitiated air. This shows that the vitiation has a greater effect on the NO reduction for both injection angles.

6.3 Effects of Injection Angles

All cases show higher NO_x reduction for the 45° injections than for the lateral injection (Figure 5). After taking the average NO_x reduction for all fuels, the 45° injections has an average of 8.1% (average over all equivalence ratios) greater compared to the lateral injection. This shows that the injection angle

has a greater effect on the NO reduction. This can be explained by several factors such as a mixing time, a residence time or a gas temperature. The estimation of the mixing time for the lateral injection was 0.32 seconds when a linear mixing model was used with a mixing length of 30.48 cm (12 in). The vitiated air reduced oxygen concentration by dilution while better mixing reduced oxygen concentration by mixing it with the oxygen depleted main combustion stream. Better mixing also caused the fuel to combust faster and thus reduced the oxygen levels. The reduced oxygen levels inhibited the NO_x formation mechanisms. Also the 45° injection scheme had slightly higher temperatures in the reburn zone. Higher temperatures gave rise to better NO_x reduction.

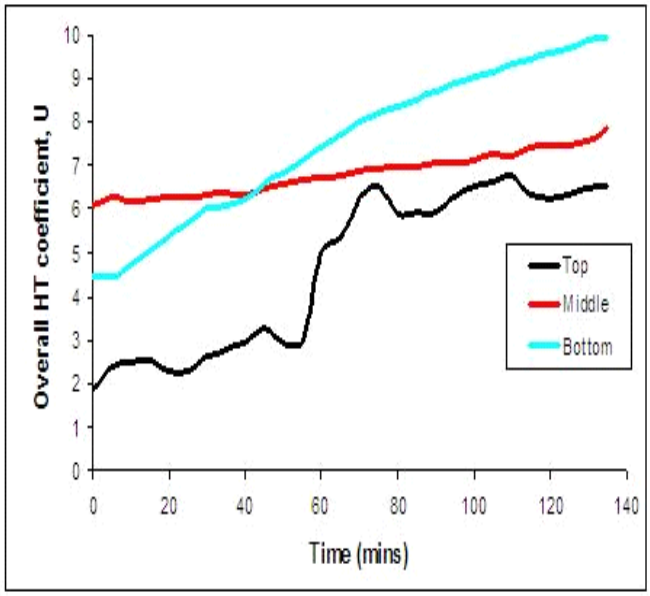


Figure 6. Overall heat transfer coefficients for burning the primary fuel only to produce 100% of the total heat without ash depositions.

6.4 CO2 and CO Emissions

The level of CO_2 in the exhaust decreases slightly when the equivalence ratio increases. Another distinct trend in the levels of observed CO_2 is noted in the difference between the vitiated and the non-vitiated reburn air experiments. Because nitrogen was added to the reburn air to simulate vitiation, the level of CO_2 in the exhaust was diluted. Also, as can be noted, it is more difficult to notice the downward trend of the CO_2 levels with increased equivalence ratio when vitiation is used.

The limited data is available for CO emission. The emission of CO from the furnace is expected to be quite high since no overfire is used to complete combustion. The CO emission of the LA PC FB case is much higher than that of the TXLC case since there is more oxygen in the fuel for LAPC-FB. This is because of the fuel rich environment present in the combustion chamber. The level of CO should increase with increased equivalence ratio.

6.5 Fouling Results

Using the LMTD, the overall heat transfer coefficient (OHTC) are obtained at four different equivalence ratios, and the average OHTC and LMTD are defined as the mean value of the obtained OHTCs and LMTDs in the further discussion. Figure 6 presents the OHTC using the data of temperature presented in Figure 3.

The OHTC increased with time. This is due to transient nature of experiment where preheating of air in HEX occurs at inlet due to heat transfer from the 4 " section (2" refractory and 2" insulation fiber) of the wall surrounding the combustor and due to low air flow selected (20 SCFH). The sudden jump of U_{Top} around 60 minutes was caused by the decrease of the coolant temperature (Figure 3) but it is not important because it may happen by the adjustment of the experimental setting. OHTC of the top and

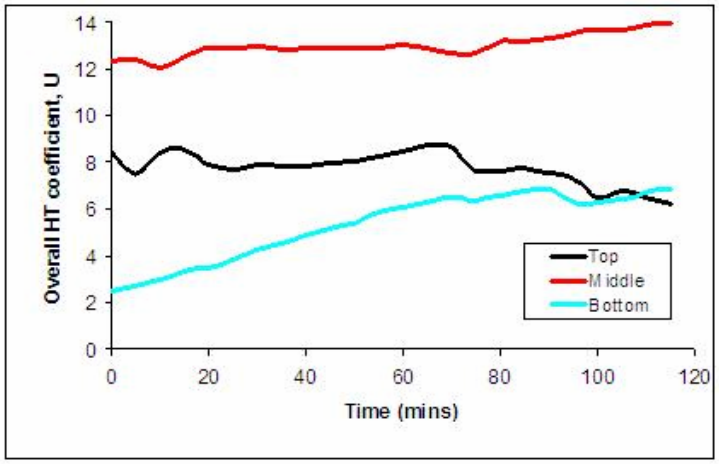


Figure 8. Overall heat transfer coefficients for the pure LA PC-FB.

middle HEX tubes slowly increased while that of the bottom HE tube increased significantly. The rates of increase of OHTC are listed in Table 6.1 for several cases.

When solid reburn fuel is fired ash is deposited on the HEX. The Texas Lignite Coal contains 11.46 % of ash which is the lowest amount among the tested reburn fuels, and the pure LAPC-FB contains 16.50 % of ash. Since the amount of ash contents, much more ash depositions are formed for LAPC-FB than other reburn fuels as shown in . Thicker ash deposits were formed on the surface of the bottom HEX tube than on the surface of other HE tubes (Figure 7). The top HEX tube was mostly covered by the thin layer of the black slag and little amount of ash particles while the middle and bottom HEX tubes were mostly covered by the ash particles. The bottom surfaces of all HEX tubes were typically very clean due to the ash deposit on the bottom surfaces is relatively hard to form. Figure 8 presents the OHTC when LAPC-FB was fired. Figure 6.5 (a) shows that the OHTC of the top HEX tube was reduced and OHTCs of the middle and bottom HE tubes were increased. The 90:10 and 70:30 TXLC:LAFB-PC mixtures on a mass basis are tested under the similar operating conditions. The average rates comparing the average rates without ash deposition were found in Table 6.1.

(a) (b)

Figure 7. Top and bottom views of heat exchanger tubes for the pure LAFB-PC as the reburn fuel. (a): Top views of HEX tubes; (b) Bottom views of HEX tubes

Comparing all of three cases, the lower average rate of increase of OHTC and LMTD were observed which means the ash deposition lowered the heat transfer rate. Comparing 90:10 and 70:30 mixtures, the OHTC for the top keeps decreasing with time {d(OHTC)/d(time),see Columns 4 and, Table 6.1} with higher rate of decrease for 70: 30 mixture than for 90:10 mixture the OHTC of the bottom for 70:30 mixture increase less. This is due to black slag forming at top tube. However the OHTC of the middle and bottom tubes containing powdered ash increases with time but at

lesser rate compared to no ash case indicating that the effect of ash formation cause decrease in overall heat transfer rate.

Table 6.1 Average rates of OHTC and LMTD for the fuel mixtures.

Location	No ash deposition		90:10 mixture		70:30 mixture	
	OHTC or U [W/m^2·K·min]	LMTD [K/min]	OHTC [W/m^2·K·min]	LMTD [K/min]	OHTC [W/m^2·K·min]	LMTD [K/min]
Top	0.026	-0.335	-0.020	-0.436	-0.058	-0.818
Middle	0.012	-0.521	0.010	-0.526	0.010	-0.228
Bottom	0.042	-0.504	0.041	-0.355	0.009	-0.628

6.6 Mercury

The analysis was conducted for the following fuels: pure TXLC, pure WYC, and 80:20 WYC:LAFB-PC. Table 6.2 presents the mercury content for each of these fuels on dry and as received basis [16]. The mercury data was reported on bomb calorimeter analysis on each of the fuel by a commercial laboratory. Table 6.2 shows that the mercury present in FB is very low compared to the coal samples, and in coal, WYC has higher mercury content than TXLC. Experiments were conducted to observe the variations of mercury oxidation with presence or absence of NO_x. NO_x was generated by addition of ammonia at the main burner up to a reference range of 400 ppm, while absence of NO_x was simulated by just stopping the supply of ammonia. Table 6.3 summarizes the mercury concentrations for different fuels with and without NO_x respectively

Table 6.2 Mercury content in reburn fuels.

Sample Identification:	TXLC	WYC	LAFB
Air Dry Loss, %	30.79	24.17	7.21
Residual Moisture, %	4.16	4.59	4.45
As Received Moisture, %	33.67	27.65	11.34
Mercury (Air Dry Basis), mg/kg	0.25	0.19	0.07
Mercury (As Received Basis), mg/kg	0.17	0.14	0.06
Mercury (Dry Basis), mg/kg	0.26	0.20	0.07
Mercury in Ash, mg/kg	0.00	0.00	0.00

It can be interpreted that elemental mercury is least observed when the equivalence ratio is 1.05, i.e., when the reactor is burnt at 5% excess air. The fluctuations appearing evidently in the total mercury concentrations which should typically remain constant comes from the fact that the fuel is burnt at a very low feed rate (36.9 g/min for the blend to 30.6 g/min for TXLC) which emits very low mercury almost reaching the bottom value of mercury detection range of the instrument which is 0.1 μg/m^3 to 100 μg/m^3,

and also due to the adherence and re-emission of mercury to and from the walls of the reactor during a steady combustion.

Table 6.3 Mercury concentration in the unit of μg/m^3 for reburn fuels with and without NO_x at 400 ppm.

		with 400 ppm NOx			without NOx		
Fuels	Equivalence Ratio	Elemental Hg	Total Hg	Oxidized Hg (% of total Hg)	Elemental Hg	Total Hg	Oxidized Hg (% of total Hg)
WYC	0.95	0.7	2.5	1.8 (72)	1.8	2.7	0.9 (33.3)
	1	0.9	1.8	0.9 (50)	2.5	3.2	0.7 (21.9)
	1.05	0.5	1.7	1.2 (70.6)	2	3.2	1.2 (37.5)
	1.1	0.6	2.3	1.7 (73.9)	2.3	3.3	1 (30.3)
TXLC	0.95	0.3	0.9	0.6 (66.7)	0.5	0.8	0.3 (37.5)
	1	0.5	0.8	0.3 (37.5)	0.6	0.8	0.2 (25)
	1.05	0.2	0.7	0.5 (71.4)	0.4	0.7	0.3 (42.9)
	1.1	0.7	0.9	0.2 (22.2)	0.8	1	0.2 (20)
80:20 Blend	0.95	0.5	1.6	1.1 (68.8)	0.8	1.9	1.1 (57.9)
	1	0.8	1.7	0.9 (52.9)	1.2	1.9	0.7 (36.8)
	1.05	0.4	1.7	1.3 (76)	1	2	1 (50)
	1.1	0.6	1.6	1 (62.5)	1.1	1.8	0.7(38)

It can seen from Table 6.3 (without NOx) that oxidation capacity of the 80:20 WYC:LAFB-PC blend is higher than the pure coal used at the reburn zone since less elemental Hg is evolved for 80:20 (TXLC and FB) compared to pure TXLC indicating higher oxidized Hg. For e.g. the elemental Hg should be 0.8*2 = 1.6 at equivalence ratio of 1.05 while measured Hg is only 1 μg/m^3. Thus it can be deduced that LAFB-PC helps is oxidation of mercury which in turn signifies that mercury can be captured more effectively at the exhaust by FGD type of devices. It is also noted that presence of NOx reduces the elemental Hg possibly due to reaction $Hg + NO \rightarrow HgO + \frac{1}{2} N_2$.

7. CONCLUSIONS

1. Based on current research using a smalls cale burner facility, the most suitable reburn fuel is pure LAFB.
2. The effects of vitiation and injection angle are very small for LAFB-PC .
3. Vitiated air reduces the level of NO_x for both injection schemes.
4. Higher equivalence ratios reduce NO_x levels to a greater extent than lower equivalence ratios.
5. The ash depositions lowers the rate of increase of the overall heat transfer coefficient (OHTC)
6. It is also found that the log mean temperature difference (LMTD) tends to decrease with time and with the decrease of the equivalence ratio though it is varies with the type of the fuel and the position of the HEX tube along the reactor.
7. Elemental mercury is least observed when the equivalence ratio is 1.05, i.e., when the reactor is burnt at 5% excess air.

8. The oxidation capacity of the 80:20 WYC:LAFB-PC blend is higher than the pure coal used at the reburn zone. LAFB-PC helps in the oxidation of mercury which in turn signifies that mercury can be captured more effectively at the exhaust by Flue Gas Desulfurization (FGD).

8. REFERENCES

[1] US EPA (2006). Nitrogen Oxides Reduction under Phase II of the Acid Rain Program. Accessed July 2006. http://www.epa.gov/air markets/arp/nox/phase2.html.

[2] Bajura, R.A., (2002). Clean Coal Power Initiative, National Energy Technology Laboratory, CCPI Draft Solicitation Meeting, January 17, 2002. Accessed July 2006. www.netl.doe.gov.

[3] Gutt, E., Patton, V., Spencer, N., and Tyree, R., (2000). Building on 30 Years of Clean Air Success: The Case for Reducing NO_x Air Pollution. Environmental Defense. Accessed July 2006. www.environmentaldefense.org/ documents/398_CAAReport.PDF.

[4] US EPA (2000). National Air Pollutant Emission Trends: 1900 - 1998 Report. Accessed July 2006. http://www.epa.gov/ttn/ chief/trends/trends98/trends98.pdf.

[5] Shore, M., Munger, A., and Patton, V., (2002). A Plan for All Seasons: Costs and Benefits of Year-Round. NO_x Reductions in Eastern States. Environmental Defense. Accessed July 2006. www.environmentaldefense.org/docu ments/2533_seasons.pdf.

[6] US EPA (2005). Proposed Federal Implementation Plan for Clean Air Interstate Rule and Proposed Response to North Carolina's Section 126 Petition Federal Register Notice, Part , v 70, n 163, August 2005. Accessed July 2006. **Error! Hyperlink reference not valid.**.

[7] Williams A, Pourkashanian M, Jones JM, and Rowlands L. A Review of NO_x Formation and Reduction Mechanisms in Combustion Systems, with Particular Reference to Coal. J Institute of Energy 1997; 70: p.102-13. < S '97>

[8] Thien, B. and Annamalai, K., (2001). Reduction of NO through Reburning with Coal and Feedlot Biomass. National combustion conference, Oakland, Ca. March 25-27, 2001.

[9] Annamalai K, Thien B, and Sweeten B. Co-Firing of Coal and Cattle Feedlot Biomass (FB) Fuels. Part II. Performance Results from 30 kW (100,000) BTU/h Laboratory Scale Boiler Burner. Fuel 2003; 82: p.1183-93.

[10] Sweeten J.M., Annamalai K., Thien B., and McDonald L.A., (2003). Co-Firing of Coal and Cattle Feedlot Biomass (FB) Fuels. Part I. Feedlot Biomass (Cattle Manure) Fuel Quality and Characteristics. *Fuel*, v 82, n 10 July 2003, p 1167-1182.

[11] Walsh, P.M., Sarofim, A.F., and Beer, J.M., (1992). Fouling of Convection Heat Exchangers by Lignitic Coal Ash. *Energy & Fuels*, v 6, n 6, Nov-Dec 1992, p 709-715.

[12] Kalisz, S. and Pronobis, M., (2005). Investigations on Fouling Rate in Convective Bundles of Coal-Fired Boilers in Relation to Optimization of Sootblower Operation. *Fuel*, v 84, n 7-8, May 2005, p 927-937.

[13] Annamalai, K., Sweeten, J., Freeman, M., Mathur, M., O'Dowd, W., Walbert, G., and Jones, S., (2003). Co-Firing of Coal and Cattle Feedlot Biomass (FB) Fuels, Part III: Fouling Results from a 500,000 BTU/h Pilot Plant Scale Boiler Burner. *Fuel*, v 82, n 10, July 2003, p 1195-1200.

[14] US Environmental Protection Agency, 'Mercury Study report to congress', volume 1, executive summary, Dec 1997.

[15] Annamalai, K., Martin, B., Sweeten, J.M., and Heflin, K., (2006). Pyrolysis, Ignition, and Fuel Characteristics of Coal, Feedlot Biomass, and Coal:Feedlot Biomass Blends. Final Report, Texas Commission on Environmental Quality, March 31, 2006.

[16] Fuel properties – source from Hazen Research Inc., Golden, CO, Nov 2005.

[17] Annamalai, K. and Puri,I., Combustion Science and Engineering, Taylor and Francis, Under proof correction, 2006

9. ACRONYMS

The following acronyms are commonly used in the literature for agricultural and feedlot biomass fuels and in the Hg literature.

FUELS

AB: Agricultural Biomass
AW: Agricultural Wastes
ARS: Agricultural Research Station
AWDF: Animal Waste Derived Biomass Fuels
CAFO: Concentrated Animal Feeding Operations
CB; Cattle biomass
CCI: Clean Coal Initiative
CGW: Cotton gin waste
CO_2: Carbon Dioxide
DAF: Dry Ash Free
DB: Dairy Biomass
DOE: Department of Energy
EPA: Environmental Protection Agency
FB: Feedlot biomass (Cattle manure or Cattle Biomass CB)
FC: Fixed Carbon
FR: Feed Ration
GIS: Geographic Information Systems
GRA: Graduate Research Assistant
HA-FB-Raw: High Ash Feedlot Biomass Raw form
HA-FB-PC: High Ash Feedlot Biomass Partially Composted
HP: High Phosphorus
HHV: Higher Heating Value
HV: Heating value
IAC: Industrial Advisory Council
LA-FB-Raw: Low Ash Feedlot Biomass
LA-FB-PC: Low Ash Feedlot Biomass Partially Composted
LALP: Low ash/Low Phosphorus feedlot biomass
LAHP: Low ash/High Phosphorus feedlot biomass
LB: Livestock Biomass
LP: Low Phosphorus
MAF: Moisture Ash Free, Dry Ash Free
mmBTU: million BTU
MMF: Mineral Matter Free
NETL: National Energy Technology Laboratory
N2: Nitrogen
NOx: Oxides of Nitrogen
O2: Oxygen
PC: Partially composted (45 days)
PM: particulate matter
RM; Raw Manure
S: Sulfur
SCR: Selective catalytic reduction
SGP: Sun Grant Program

SR: Stoichiometric ratio, Air: Fuel/ (Air: Fuel) $_{stoich}$
SS: Soil surfaced or high ash feedlot biomass
TAMU: Texas A&M University
TCEQ: Texas Commission on Environmental Quality
TEES: Texas Engineering Experiment Station
TAES: Texas Agricultural Extension Service
TXL: texsaLignite
TXU: Texas Utilities
USDA: US Dept of Agriculture
VM: Volatile matter
WYC: wyoming coal

Hg Literature and Others

AC: Activated Carbon
ACF: actual cubic feet of flue gas
ACI: activated carbon injection
APCD: Air Pollution Control Device
APH: Air Pre-heater
BPAC: Brominated AC
CAIR: Clean air Interstate Rule
CAMR: Clean Air Mercury Rule
CCMS: Continuous Mercury Monitoring System
CEM: Continuous Emission Monitoring
COHPAC: Compact Hybrid Particulate Collector
CS: Cole side
Dncm: dry normal cubic meter
EPA: Environmental Protection Agecy
EPRI: Electric Power Research Institute
ESP: electrostatic Precipitator
FGD: flue gas Desulfurizer
FF: Fabric Filter
HEX: heat Exchanger
HS: Hot side
IEP: innovations Existing Plants
LMTD: Log Mean Temperature Difference
LNB: Low NOx Burner
LOI: Loss on Ignition
Macf: Million cubic feet
mmacf: million cubic feet
OHTC: Overall heat transfer coefficient or U
PAC: powdered AC
PJFF: Pulse jet FF
PM: particulate Matter
PRB: Permian river Basin
PS: Particulate Scrubber
SCA: specific Collection area; ft^2/kacfm
SCFH: standard cubic feet per hour
SCLP: Standard Liter per minute
SCR: Selective catalytic reduction
SDA: Spray Dryer Absorber

SEA: Sorbent Enhancement Additive
TBTU: Trillion BTU
UNDEERC: University of North Dakota Energy and Environmental Research Center

10. SUMMARY VARIOUS STANDARD VOLUMES IN LITERATURE
(Combustion Science and Engineering, Annamalai and Puri, Taylor and Francis, 2006, [17])

Volume of 1 kmol (SI) and 1 lb mole (English) of an ideal gas at STP conditions as defined below:

Scientific (or SATP, standard Ambient T and P)	US standard (1976) or ISA (International Standard Atmosphere)	Chemists-Standard	Normal Temperature and Pressure (NTP; gas industry Reference Base)
STP:25ºC (77ºF), 101.3kPa (14.7 psia,29.92 " Hg)	STP: 15ºC (60ºF), 101.33kPa (1 atm, 14.696 psia, 29.92 " Hg)	STP : 0ºC (32ºF), 101.33 kPa (1 atm, 14.7 psia, 29.92 " Hg or 760 mm of Hg)	NTP: 20°C (68°F) and 101.3 kPa (1 atm ; 760 torr or 29.92 inches Hg)
24.5 m^3/kmol (392 ft^3/lb mole)	23.7 m^3/kmol (375.6 ft^3/lb mole)	22.4 m^3/kmol (359.2 ft^3/lb mole)	24.06 m^3/kmole (385 ft3/lb mole)