NITROGEN OXIDES EMISSION CONTROL THROUGH REBURNING WITH

BIOMASS IN COAL-FIRED POWER PLANTS

A Thesis

by

SENTHILVASAN ARUMUGAM

Submitted to the Office of Graduate Studies
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Mechanical Engineering

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Approved as to style and content by:

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ABSTRACT

Nitrogen Oxides Emission Control Through Reburning with Biomass in Coal-Fired

Power Plants. (December 2004)

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Chair of Advisory Committee: Dr. Kalyan Annamalai

Oxides of nitrogen from coal-fired power stations are considered to be major

pollutants, and there is increasing concern for regulating air quality and offsetting the

emissions generated from the use of energy. Reburning is an in-furnace, combustion

control technology for NOx reduction. Another environmental issue that needs to be

addressed is the rapidly growing feedlot industry in the United States. The production of

biomass from one or more animal species is in excess of what can safely be applied to

farmland in accordance with nutrient management plans and stockpiled waste poses

economic and environmental liabilities. In the present study, the feasibility of using

biomass as a reburn fuel in existing coal-fired power plants is considered. It is expected

to utilize biomass as a low-cost, substitute fuel and an agent to control emission. The

successful development of this technology will create environment-friendly, low cost

fuel source for the power industry, provide means for an alternate method of disposal of

biomass, and generate a possible revenue source for feedlot operators. In the present

study, the effect of coal, cattle manure or feedlot biomass, and blends of biomass with

coal on the ability to reduce NOx were investigated in the Texas A&M University 29.31

kW (100,000 Btu/h) reburning facility. The facility used a mixture of propane and ammonia to generate the 600 ppm NOx in the primary zone. The reburn fuel was injected using air. The stoichiometry tested were 1.00 to 1.20 in the reburn zone. Two types of injectors, circular jet and fan spray injectors, which produce different types of mixing within the reburn zone, were studied to find their effect on NOx emissions reduction. The flat spray injector performed better in all cases. With the injection of biomass as reburn fuel with circular jet injector the maximum NOx reduction was 29.9 % and with flat spray injector was 62.2 %. The mixing time was estimated in model set up as 936 and 407 ms. The maximum NOx reduction observed with coal was 14.4 % and with biomass it was 62.2 % and the reduction with blends lay between that of coal and biomass.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Power generation is a significant source of pollution that contributes toward the impairment of human health and the environment. The prevailing pattern of winds leads to interstate and long range transport of emissions that play a significant role in these problems whereby emissions are no longer considered a point source problem.

The International Energy Outlook projects growth in coal use for power generation at an average annual rate of 1.5 % (on a tonnage basis) between 2001 and 2025 [1]. The combustion of coal produces several types of emissions that adversely affect health and environment. Oxides of nitrogen from coal-fired power stations are considered to be major pollutants, and there is increasing concern for regulating air quality and offsetting emissions generated from the use of energy. NOx, a generic term for the various oxides of nitrogen like nitrogen dioxide (NO_2), nitric oxide (NO) and nitrous oxide (N_2O), is a key issue due to its impact on the environment and health.

The Intergovernmental Panel on Climate Changes' special report on the emission scenarios ranks the United States at thirteenth among the countries of the world in the total NOx emissions per populated area [2] and the Organization for Economic Cooperation and Development ranks the United States third in the NOx generated per capita [3]. The United States generates 1.29 thousand metric tons of NOx per square kilometer of populated land area and 80 kg weight of NOx per capita. The weighted world average stands at 1.79 thousand metric tons of NOx per populated land area and

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This thesis follows the style of *Combustion and Flame*.

41.11 kg weight of NOx per capita. NOx emissions cost society billions of dollars

annually from illness and deaths and a suite of year-round environmental problems.

Environmental and health effects of NOx emissions

The Environmental Protection Agency, United States of America (EPA) has

identified NOx as a pollutant that impacts health and environment. Significant concerns

identified with NOx emissions are generation of ground level ozone, contribution toward

acid rain and global warming, production of toxic chemicals and fine particles in the

atmosphere, deterioration of water quality, and impairment of visibility [4].

NOx reacts with Volatile Organic Compounds (VOC) in the presence of sunlight

to form ground-level ozone, a major component of smog in cities and many rural areas.

Although naturally occurring ozone in the stratosphere provides a protective layer above

the earth shielding inhabitants from the hazardous effects of ultraviolet rays from the

sun, ground-level ozone is detrimental. It irritates the eyes, exacerbates asthma, leads to

chronics lung damages, and increases the susceptibility of young children and the elderly

to respiratory infections. It is our most widespread and intractable urban air pollution

problem. Ozone also reduces agricultural production and the growth rate of trees by

impairing their ability to produce and store food.

NOx is a precursor to the formation of acid rain. The interaction of NOx with

certain substance present in the atmosphere produces acids that may fall to the earth in

various forms like rain, fog, or snow. Acid rain acidifies sensitive soils and waters

where it falls, killing plants, fish, and the animals that depend on them. Acid rain also

causes property damage through accelerated decay of materials, paint, buildings, and cultural artifacts such as historical monuments, and sculptures.

Fine particles are formed in the atmosphere by the conversion of NOx emissions when they react with ammonia, water vapor and other compounds. These small particles penetrate into the sensitive parts of the lungs when inhaled and can cause or worsen respiratory diseases and aggravate existing heart ailments. They also scatter light and create hazy conditions, decreasing visibility and contributing to a regional haze. Distinct hazes that identify particular pollutants are grey for lead, yellow for sulfur, and brown for nitrogen oxides. Additionally NOx reacts readily with common organic compounds to produce toxic chemicals like nitrate radicals that trigger biological mutations.

Excessive amounts of nitrogen in coastal waters from atmospheric deposition are thought to be a contributor to nitrification, i.e., over fertilization of wet lands and bays. This leads to harmful algal blooms, such as the red tides which upset the balance of nutrients between aquatic plants and animals, killing millions of fish each year.

A constituent of NOx, nitrous oxide, is a greenhouse gas which contributes to global warming, the gradual increase in the temperature of the earth due to the heat-trapping ability of these gases. The accelerated global warming due to the increased concentration of these gases may lead to drastic climatic changes.

NOx has also been found to have an indirect effect on radiative forcing [5]. Radiative forcing is the change in the balance between the radiation entering and leaving the earth's atmosphere. A positive radiative forcing tends on an average to warm the earth's surface and a negative radiative forcing tends to cool the earth's surface.

Increased concentrations of NOx lead to a decreased lifetime of CH_4 and HFC's via OH

and thereby reduces the radiative forcing. The increase in ozone concentration due to

the presence of NOx increases the radiative forcing. The radiative forcing is reduced

when the NOx emissions increase the N deposition through fertilization and increased

CO_2 uptake.

Theories of NOx formation in combustion systems

The combustion of fuel and air results in conversion of nitrogen present in the air

or the fuel into various oxides of nitrogen like nitric oxide (NO), nitrous oxide (N_2O),

and nitrogen dioxide (NO_2) that are collectively given a generic name, NOx. The

formation of NOx can occur in the pre-combustion, combustion, and post-flame regions.

It is worth noting that NOx can be produced in isolated sections of the flame, and it is

not unusual for over 80 % of the combined NOx to be produced in only 10 % of the

flame volume.

The NO_2 to NOx ratio is approximately 0.1 in typical methane/air flames and 0.9

in low temperature, low-NOx flames with high HNO concentrations. The NO_2 formed is

very sensitive to the fluid dynamics in the flame zone and its formation from NO tends

to occur in regions where rapid cooling takes place (mixing region of hot gases with inlet

air). The measurement process is sensitive to measurement technique as NO_2 can form

inside the sampling probe.

N_2O contributes to the greenhouse effect in the troposphere and participates in

ozone depletion in the stratosphere. N_2O emissions are not significant in coal

combustion systems as they rapidly react with H and OH radicals to form N_2. They

survive only in the hotter, fuel-rich, flame regions and are destroyed downstream. Peak N_2O in coal systems is less than 2 % of peak NO. N_2O formation in the post-flame zone (1175 K-1525 K) is negligible; whereas, it forms in fluidized-bed combustion due to lower operating temperature. As N_2O is stable only in the high temperature regions of the flame and readily converts to N_2, NOx is generally considered to be composed of NO and NO_2.

There are three identified homogeneous gas phase reaction pathways for the formation of NO known as thermal, prompt, and fuel NO mechanisms [6, 7]. Thermal NO originates from the nitrogen present in the air supplied for combustion under fuel-lean conditions. The formation of thermal NO has a strong dependence on temperature, residence time, and a linear dependence on the concentration of oxygen atoms. The generation of thermal NO is described by the widely accepted two-step Zeldovich mechanism given below.

$$N_2 + O \Leftrightarrow NO + N \qquad\qquad (I.1)$$

$$N + O_2 \Leftrightarrow NO + O \qquad\qquad (I.2)$$

In the case of fuel-rich flames where the OH radicals are present in higher concentrations than atomic hydrogen or oxygen, the two-step mechanism under-predicts NO generated, so a third elementary step that considers the effect of OH radicals is used as given by the extended Zeldovich mechanism.

$$N + OH \Leftrightarrow NO + H \qquad\qquad (I.3)$$
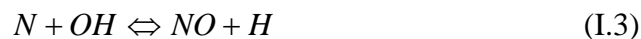
Prompt NO is formed in fuel-rich environments with short flame-residence times; formation being initiated through various hydrocarbon fuel fragments like CH and CH_2. The prompt NO formation is described by the Fennimore reaction given below:

$$N_2 + CH_x \Leftrightarrow HCN + N + \cdots \qquad \text{(I.4)}$$
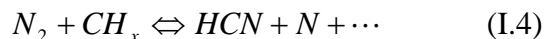
The cyano species reacts further to form NO though the following reaction.

$$HCN + O_2 \Leftrightarrow NO + \cdots \qquad \text{(I.5)}$$
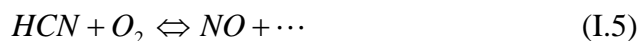
The amount of prompt NO is proportional to the number of carbon atoms present in the molecule of the hydrocarbon fuel.

Fuel bound nitrogen is released during combustion through the formation of HCN or NH_3 which then oxidizes to form fuel NO or N_2 depending on the local stoichiometric conditions. The fuel NO is formed in fuel-rich zones. When nitrogen is bound in the fuel, it more readily forms fuel NO than thermal NO as the N-C and N-H bonds found in fuels are much weaker than the N-N triple bonds of the nitrogen molecule. The overall reaction can be represented as follows.

$$HCN / NH_3 + O_2 \Leftrightarrow NO + \cdots \qquad \text{(I.6)}$$
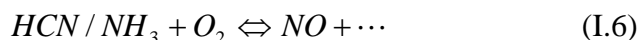
Control of NOx emissions

The various techniques for the control of NOx emissions fall into two broad categories namely, combustion control and post-combustion control. Combustion control refers to techniques which aim to regulate the NOx emissions during the formation stages of combustion by inhibiting the conditions necessary for the production of NOx through the various mechanisms given above. Combustion control techniques

achieve reduction of NOx by lowering the flame temperature, creating fuel-rich regions at the maximum flame temperature, or by lowering the residence time under oxidizing conditions. Among the various combustion control systems, low-NOx burners, fuel staging, reburning, flue-gas recirculation, over-fire air, and water/steam injection provide substantial reductions in NOx; whereas, air staging, fuel biasing, burner out-of-service, and other operational modifications are low cost methods with limited reduction capabilities. The post-combustion control methods reduce NOx emissions after the NOx is formed by converting them into N_2 with reagents. Two important post-combustion treatments are Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR).

Reburning is an in-furnace, combustion control technology for NOx reduction. The reduction is achieved through the staged introduction of fuel into the combustion device. Reburn combustion control requires changes to the furnace and the additional operating expense of the reburn fuel but offers the potential advantages of reducing unburned carbon, also known as Loss On Ignition (LOI) and CO emission control. The overall reburning process occurs within three delineated physical zones, namely, primary zone, reburn zone, and burnout zone [8]. The fuel supplied in the primary zone generates 70-90 % of the total rated heat throughput of the system with normal to low excess air conditions. The lower fuel firing rate and O_2 concentrations lead to reduced fuel and thermal NOx compared to conventional systems without reburning. At the reburn zone, the remaining 10-30 % heat throughput is generated by the reburn fuel injected into the products from the primary zone combustion. The addition of reburn

fuel creates localized fuel-rich regions that act as reducing environments to convert NOx from the primary zone into molecular nitrogen through the reverse prompt NOx Fennimore mechanism. The extent of this conversion depends on the stoichiometry and mixing achieved in the reburn zone. Any unburnt fuel from the reburn zone is consumed in the burnout zone through the supply of overfire air, usually at excess air of 15-25 %. The conditions in the burnout zone should be optimized such that it is not conducive for generation of thermal NO. The extent of reduction of NOx achieved from reburning varies from 10 to 90 % depending on the operating conditions of the system.

Biomass

Another environmental issue that needs to be addressed is the rapidly growing feedlot industry. In the United States, 94 million total head generated 110 million tons of waste in 1997 and the increase in animal waste generation was 12 % for the previous decade [9]. Each animal leaves approximately 1 ton of collectible biomass over a 5 month period [10]. In many cases, the production of biomass from one or more animal species is in excess of what can safely be applied to farmland in accordance with nutrient management plans, and the stockpiled waste poses economic and environmental liabilities. Hence, biomass can contribute to surface or ground water contamination and air pollution problems with the release of greenhouse gases. Disposal of the vast quantity of manure produced as a by-product of the cattle feeding industry is one of the major operating tasks of the industry. It is both an economic burden on the industry and a potential environmental hazard to air, water, and land. The traditional means of disposal was the use of manure as fertilizer. An alternative and attractive way of

overcoming this threat is to develop processes that make use of manure as a resource. Some of the possible methods include utilizing the generated manure as fuel or as raw materials in other industries. These will alleviate the ever increasing burden placed both on the industry and the natural resources. The use of biomass as the sole source of energy reported in the literature [10-13] has met with limited success. In the present study, the feasibility of using of biomass as a reburn fuel in existing coal fired power plants is considered. It is expected to utilize biomass as a low-cost, substitute fuel and an agent to control emission. The opportunity for the adoption of this technology is particularly attractive in the high plain areas where many feedlots are located. Successful development of technology to use biomass as a reburn fuel will create an environment-friendly, low cost fuel source for the power industry and provide means for an alternate method of disposal of biomass and a possible revenue source for feedlot operators.

CHAPTER II

LITERATURE REVIEW

This chapter provides a review on reburning fuels and parameters that influence the reburning process in the literature.

Parameters that influence NOx reduction

Numerous parameters have been identified in the literature that influences the extent to which NOx reduction may be achieved. Among them, the significant factors include the reburning zone temperature, reburning zone stoichiometry, mixing between reburning fuel and main combustion gas, residence time, primary zone NOx level, boiler load, reburn fuel percentage of total boiler heat input, reburn fuel composition, reburn burner stoichiometry, reburn burner pulverized fuel fineness, reburn system characteristics and location, over fire air characteristics and location, economizer outlet O_2 %, flow and combustion parameters, and fuels and firing configurations.

Reburning with different fuels

A wide range of fuels have been considered for reburning with varying effectiveness for NOx reduction. These fuels had demonstrated NOx reductions from 10-90 % for varying operating and modeling conditions.

Hydrocarbons

Nazeer et al [14] used natural gas as the reburning fuel and achieved a maximum of 70 % NOx reduction. Spliethoff et al [15] performed reburning experiments with methane and synthetic pyrolysis gases and found that the concentration of hydrocarbons

in the pyrolysis gas had no effect on reburn efficiency. They also showed a strong influence of residence time and stoichiometry which should not be considered separately, and determined that in pulverized bituminous coal combustion, reburning was superior to air staging for NOx reduction. Nitrous oxide reduction by hydrocarbons, like methane and ethane, was evaluated by Rutar et al [16] in fluidized bed combustors. N_2O destruction was found to depend more on the amount of reburning fuel added rather than on the absolute reactor temperature. In propane, natural gas, and residual oil reburning studies, Chen et al [17] showed that propane and natural gas were the most effective reburn fuels. They concluded that fuel volatility was not of first order importance so long as the rich zone residence time and stoichiometry were adequate to insure overall, fuel-rich conditions. Their studies indicated that the reburning process was relatively insensitive to burnout air mixing.

Coal and Coal Water Slurry

Zarnescu et al. [18] studied the potential of coal water slurry as a reburn fuel. For a 30 % reburn heat input, they achieved 39 % NOx reduction with coal water slurry. Hardy and Kordylewski [19] used Polish lignite as reburn fuel in a laboratory scale drop tube furnace and found 60-80 % effectiveness for NOx reduction, depending on the stoichiometric ratios of 0.7 to 1.0. Their experiments showed that volatile matter and calcium content had significant roles in the effectiveness.

Biomass

Hard and soft wood were utilized as reburning fuels by Hardy and Adams [20, 21]. NOx reduction of 70 % was observed with approximately 10-15 % of wood heat

input. It was also observed that the initial NOx value had a more significant effect on the reduction than temperature. In further studies in a cyclone fired boiler, opposed injection was found to be most effective in reducing NOx emissions with wood reburning. Experimental and modeling studies in an entrained flow reactor with wheat straw as the reburning fuel were performed by Vilas et al [22] and Kicherer et al [23].

Mixing effects in reburning

Reburning is a mixing-influenced process due to the relatively fast chemistry times of reburning kinetics which are comparable to the mixing times in full and pilot scale installations [24]. Mixing effects were identified to be more important in down-fired combustor units than tangentially fired units as it has been suggested that mixing changes the selectivity of the reactions at the reburn fuel injection and at the rich-lean transition, controls the dispersion of the reburning fuel within the furnace, and influences the stoichiometry and residence time [25-28]. Though the quantity of reburn fuel is only a fraction of the primary fuel, the high velocity and momentum associated with the reburn jet determine the degree of mixing and dispersion produced in the reburning zone. Varying degrees of mixing may be achieved through variation in the configuration of the reburn fuel injector and the momentum associated with the reburn fuel. The effects of the injector geometry and configuration have been reported in the literature [29, 30]. The mixing time in the reburning zone depends on several factors including configuration of the reburning fuel injection, velocities, temperatures of the reburning fuel and flue gas streams, and compositions of each stream [31]. Mixing time is important under low-temperature conditions and a limitation with space limitations.

CHAPTER III

OBJECTIVE AND TASKS

The overall objective of this investigation is to develop a technology to employ biomass as a reburn fuel. The tasks performed to accomplish the overall objectives are summarized as follows:

1. Investigate the effect of coal, biomass, and their blends on NOx reduction.

2. Fabricate a new flat spray injector and install it in the burner.

3. Estimate the impact of different firing configurations on NOx reduction.

CHAPTER IV

EXPERIMENTAL FACILITY

The Texas A&M University experimental facility is a laboratory-scale, down-fired, boiler-burner with a rated heat throughput of 29.3 kW (100,000 Btu/h). Pulverized solid fuels like coal, biomass, and blends of coal and biomass were the principal fuels tested. The facility can be adapted to perform co-firing and reburning experiments with minor modifications. The system was initially built to perform co-firing experiments and it had insufficient reactor length to include the burnout zone where overfire air is injected to complete combustion. Hence, it was adapted to simulate only the reburning zone of a typical reburning facility. The primary zone was simulated with the combustion of propane and ammonia. Potential for NOx reduction through reburning with coal, biomass, and blends of coal and biomass were studied. A schematic sketch of the setup is depicted in figure IV.1. The facility was made of five sub-systems: furnace, primary NOx generation, reburn fuel supply, exhaust, and diagnostics. A brief description of these systems is given below.

Furnace

The furnace, a modular construction of 9 stacked sections which, from the top down, are: burner, flame control, reburn fuel supply, reburning, water injection, and exhaust and ash collection. A sectional view of the modular section and the dimensions of the furnace are given in figures IV.2 and IV.3. Each modular section was made of a ceramic refractory liner enclosed by two layers of thermal insulation blanket within a steel casing. The alumina based ceramic refractory liner, cast from GREENCAST 94,

had a hollow core of diameter 152.4 mm (6") that formed the combustion space. The INSWOOL ceramic blanket provided additional thermal insulation. The sections were bolted together with GRAFOIL gaskets between the flanges to seal against gas leaks. All the sections except the burner, water injection, and exhaust and ash section had diametrically opposite ports for gas sampling and temperature measurement. The ports were located every combustion chamber diameter (152.4 mm (6")) from the viewing section down to the water spray section. In the burner section the propane or the propane-ammonia mixture was ignited with the required amount of air by two igniter torches. The flame from the ignited mixture was observed through three quartz view ports located in the flame viewing section. During startup, the flame was monitored through the view ports and the flow rates of air and propane were adjusted to achieve a stable flame at the required stoichiometry. The reburn fuel supply section had two separate ports to accommodate the reburn injectors. Fuel injected through the reburn ports mixed and reacted with the products of the primary zone along the four reburning sections until the exit plane where the measurements were made. At the water injection section, two radial sprays of water were directed into the cross flowing stream of reacting gases. The sprays trapped the unburnt fuel and burnt ash particulates from the streaming gases and ensured that the particle loading in the exhaust stream, which could have damaged the exhaust fan, was minimal. The particulates collected with the water spray settled to the bottom of the exhaust and ash section.
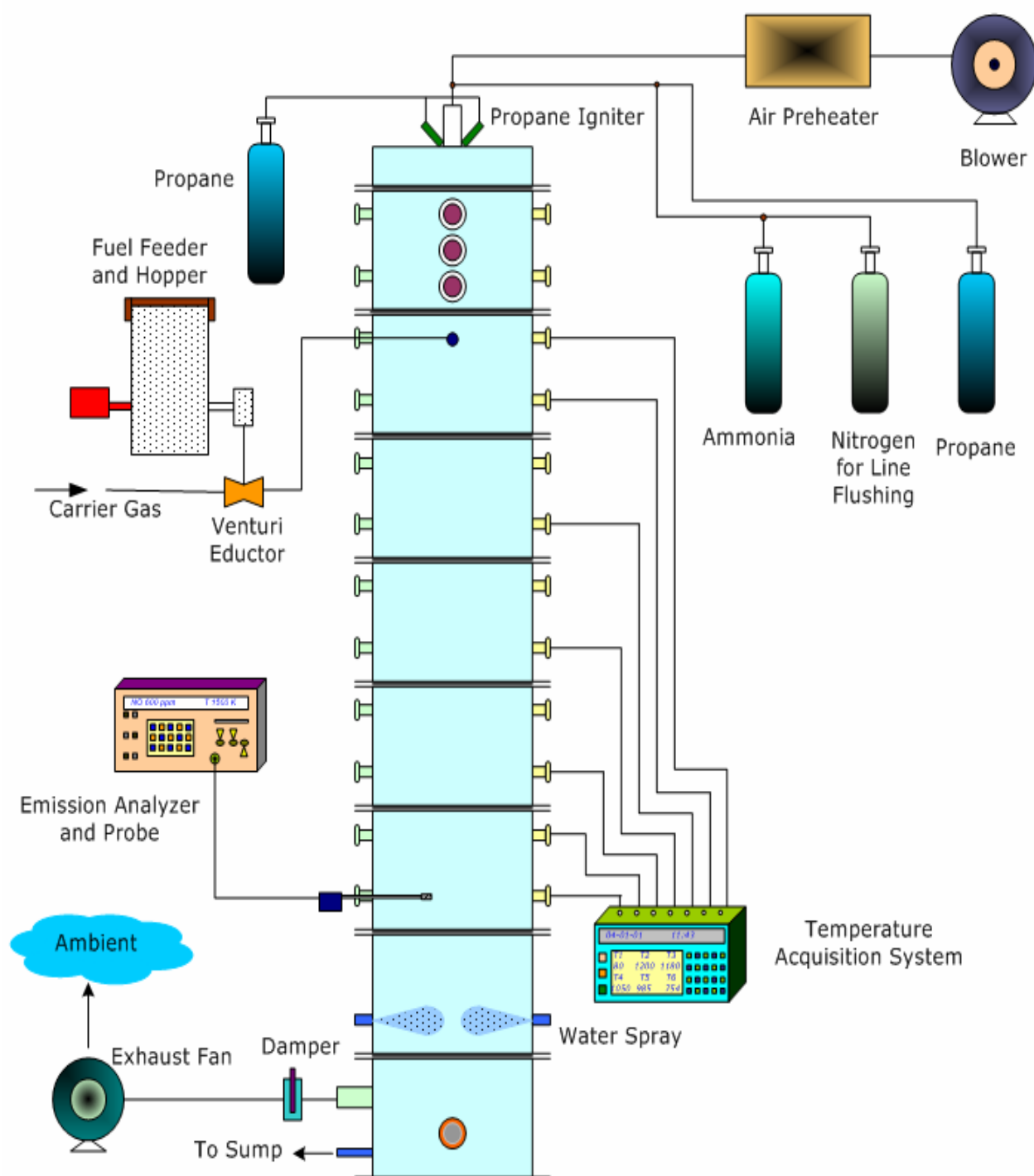
Fig. IV.1: Schematic sketch of the TAMU 29.3 kW (100,000 Btu/h) reburning facility
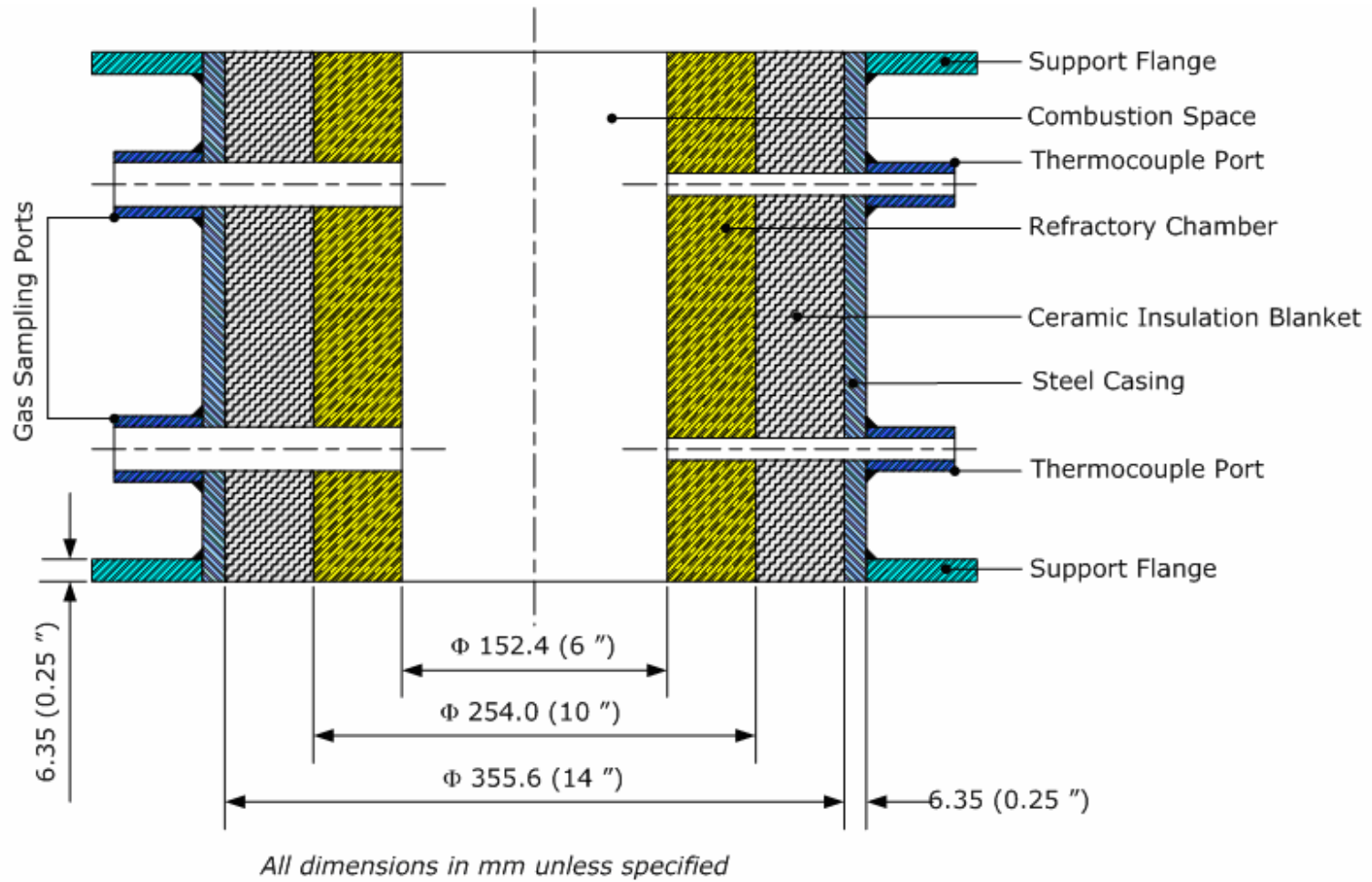
Fig. IV.2: Cross section of the furnace module

Support Flange

Combustion Space

Thermocouple Port

Refractory Chamber

Ceramic Insulation Blanket

Steel Casing

Thermocouple Port

Support Flange

Gas Sampling Ports

6.35 (0.25 ")

Φ 152.4 (6 ")

Φ 254.0 (10 ")

Φ 355.6 (14 ")

6.35 (0.25 ")

All dimensions in mm unless specified
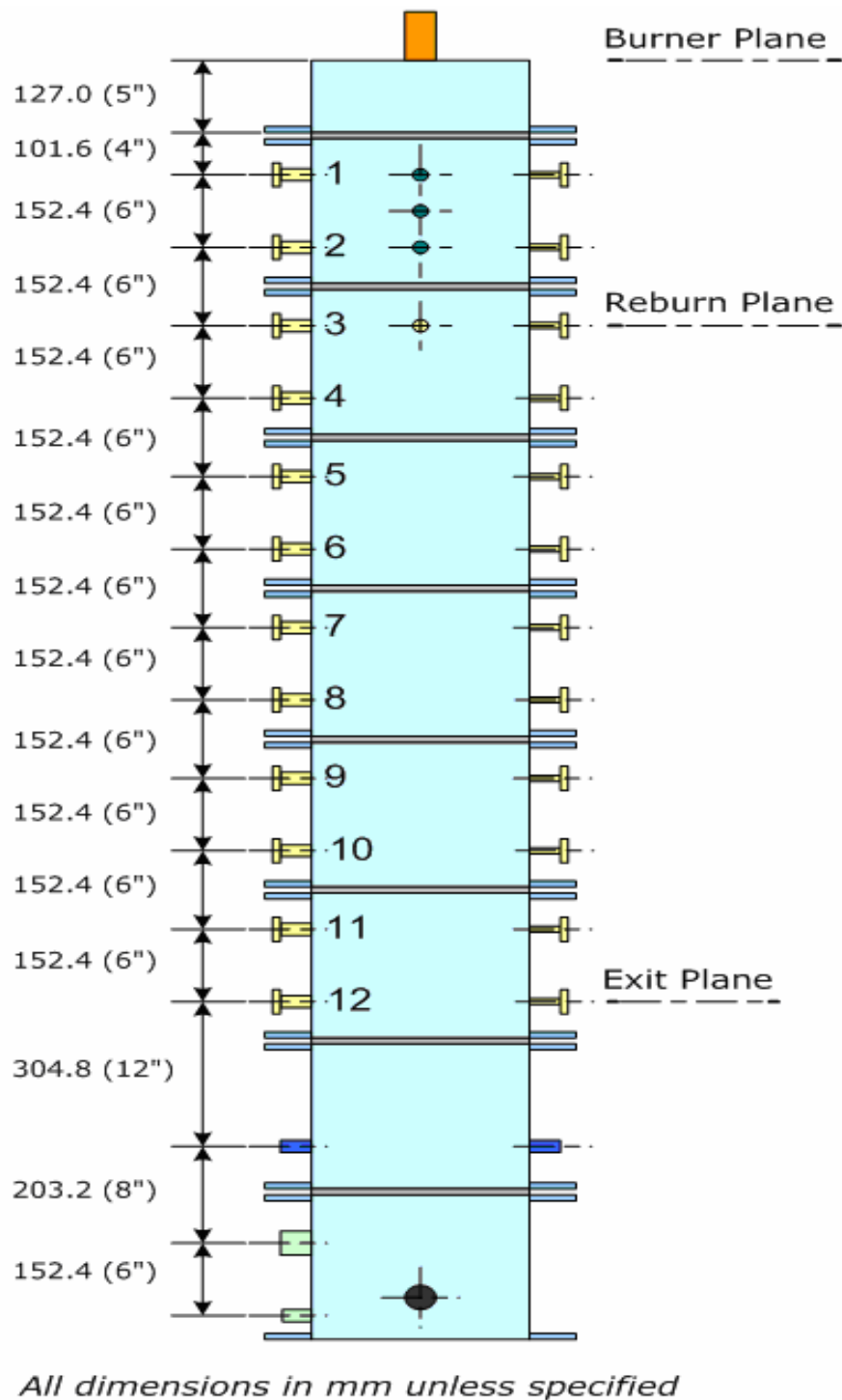
Fig. IV.3: Sketch depicting the dimensions of the furnace

Primary NOx generation system

The primary NOx generation system produced the specified amount of NOx at the primary zone. The amount of NOx generated was representative of the NO_x at the exit of a coal-fired power plant which was studied for reduction. It was simulated through the combustion of propane doped with small amounts of ammonia. The ammonia was assumed to be fully converted into NOx in the primary zone, and by regulating the flow of ammonia different primary NOx concentrations were obtained. The propane flow in the primary zone was regulated to generate 70 % of the rated thermal throughput while the remaining 30 % was supplied by the reburning fuel. The propane and ammonia, premixed with the requisite quantity of air, was ignited inside the furnace by means of two igniter torches fueled by propane at the burner section of the furnace. The air required for the combustion of the propane-ammonia mixture was supplied from a mechanical blower. The air was preheated to about 395 K (250 ºF) by a circulation heater to aid easier ignition. The ammonia supply lines were flushed of any remaining trace gases between experiments with nitrogen purge gas. The nitrogen supply was also used to hold the flow rate of ammonia steady without any fluctuations.

Reburn fuel supply system

The reburn fuels used in the present study were coal, biomass, and blends of coal and biomass. The fuel was fed into the fuel line from a commercial dry solids feeding system. The feeder had a central auger to dispense fuel and two agitating augers to prevent bridging and creation of dead zones in the hopper. The feeder was calibrated to

the required flow rate before every experiment by collecting and weighing the amount of fuel supplied by the feeder over a period of 1 minute.

Air was used as the carrier medium to convey the fuel from the hopper to the furnace through a venturi eductor valve on the fuel line that facilitated the mixing of the fuel and carrier gas. The venturi valve aspirated ambient air that was about 0.4 to 1.0 times the motive air supplied. So the carrier gas flow rate was adjusted to account for this aspiration. The quantity of aspirated air was determined from knowledge of the concentration of oxygen within the reactor. The air supply from the mechanical blower was diluted with nitrogen gas such that the concentration of O_2 was reduced within the furnace. The concentrations at the reburn zone and exit zone were measured. When the reburn air was turned on, air was aspirated through the venturi eductor valve. The O_2 concentration measured at the exit zone within the furnace indicated the amount of aspirated air. The procedure was repeated for various values in the range of motive reburn air supply required during the experiment. The plot of the aspirated air for various values of motive air supply is given in figure IV.4. Another principle that may be used in these studies is given in appendix D.

The fuel along with the carrier gas was injected into the furnace through two reburn injectors located at the reburn fuel supply section. Two types of injectors were studied for the effect of mixing on the reduction of NO_x: i) a nozzle with a circular cross-section and ii) a nozzle with an elliptical cross-section producing a flat fan shaped spray. These stainless steel injectors produced a velocity of 10 to 15 m/s, depending on flow

rates, as the fuel was injected into the furnace. The photograph and cross section of the

two injectors is shown in figure IV.5.
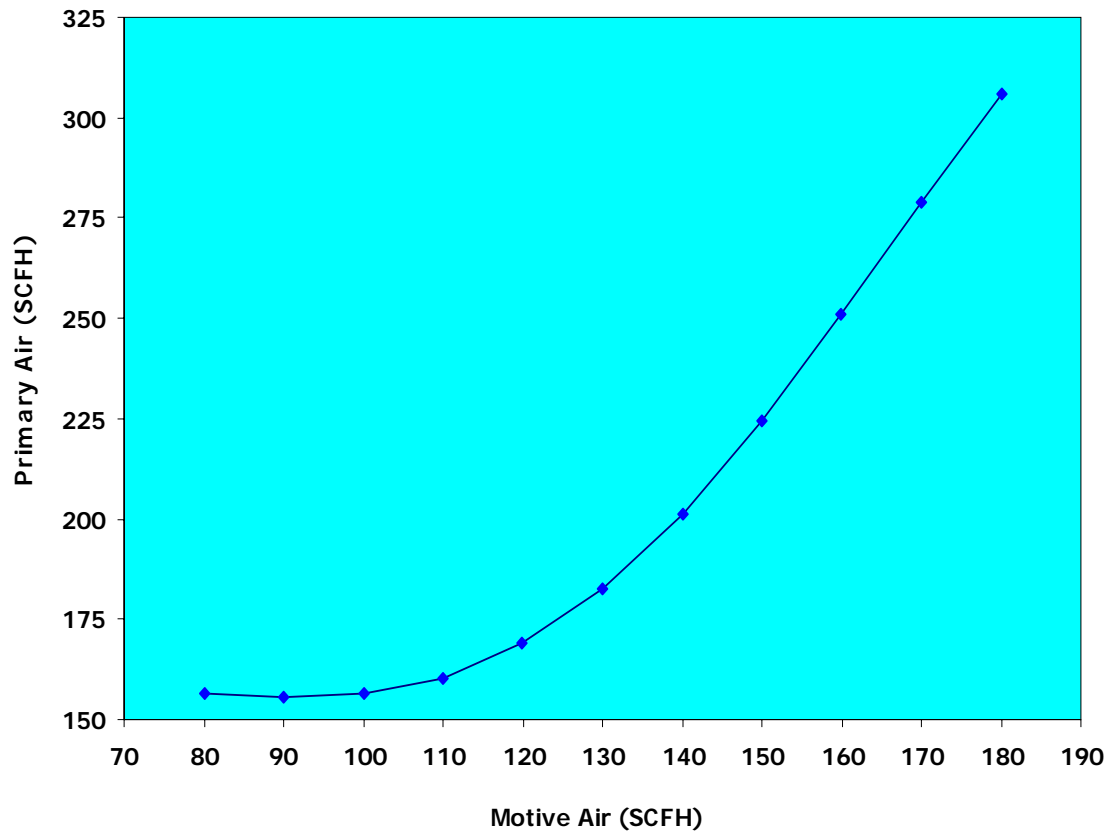
Fig. IV.4: Aspiration of ambient air through the venturi eductor

Fig. IV.5: Reburn injectors and their cross sections

Exhaust and ash system

The stream of exhaust gases with the particulate materials removed by the water spray was conveyed by ducts to an exhaust fan from where they were released into the atmosphere. The exhaust fan created a slight negative pressure within the furnace, the extent of which was controlled by a damper provided in the exhaust duct work. This negative pressure provided a safety measure by averting flame leap when the gas ports were opened during measurements. During the course of the experiments the damper was adjusted to maintain a negative pressure of approximately 0.025 kPa (0.1" of water). This low amount of suction, apart from ensuring safety during operation, also made sure that the negative pressure did not draw ambient air into the furnace thereby diluting the required stoichiometry of the system. The particulates of unburnt fuel and burnt ash, gathered by the mist of water spray, settled at the bottom of the exhaust and ash section. The water was drained out of the furnace and the particulates settled down. After the experiments were completed the residue was collected through the ash port. Analyses of the sediments may be performed to determine the fraction of fuel that was completely burnt and the composition of ash.

Diagnostic system

The diagnostic system consisted of instruments to aid in maintaining the conditions of the furnace while in operation and for the analysis of the furnace exhausts gases. The flow of gases and air were measured using flow meters. An orifice plate calibrated with a water tube manometer was used to measure higher flow rates of air from the mechanical blower. The calibration curve for the blower is given in figure

IV.6. The 0.75" orifice plate was used in the reburning experiments. The temperatures inside the furnace and at the air pre-heater were measured using thermocouples. A record of the temperature history during the course of the experiment and at every gas concentration measurement was obtained with an OMEGA data acquisition system. Exposed tip S-type thermocouple and sheathed K-type thermocouples were used. An ENERAC 3000E emission analyzer was used measure the emission concentrations. The analyzer may be used to measure the concentrations of O_2, CO, SO_2, NO, and NO_2 on a dry basis to an accuracy of about 3 % at every gas port. As the concentrations of CO were very high during reburning experiments, which caused the analyzer to malfunction, the CO sensor was isolated and only concentrations of O_2, NO, and NO_2 were measured. The analyzer was calibrated before every experiment against standard calibration gases.
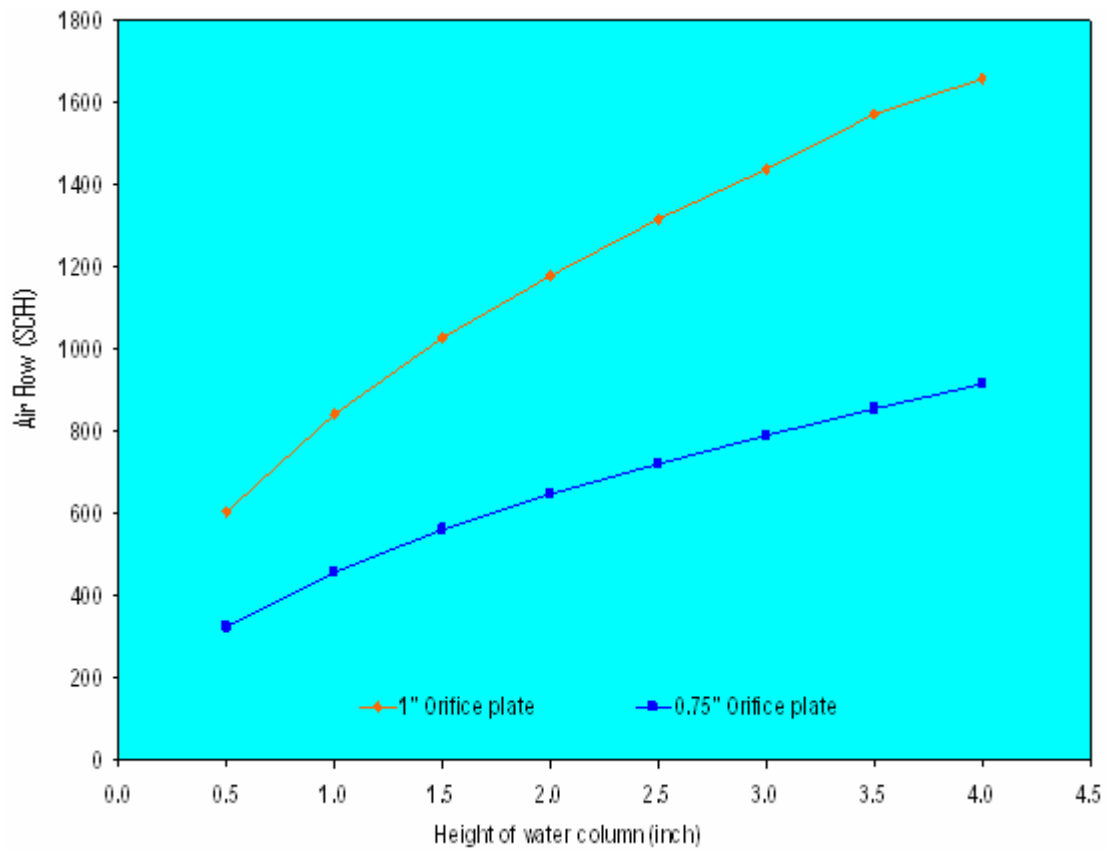
Fig. IV.6: Blower air supply calibration curve for two different orifice plates [32]

CHAPTER V

EXPERIMENTAL PROCEDURE

The procedure for conducting the reburning experiments is detailed in this section.

Fuel and furnace preparation

The reburn experiments were performed with coal, biomass, and blends of coal with biomass. The proximate and ultimate analyses of the fuel were completed at Huffman Labs, CO prior to the trials. The values for the blends of coal and biomass were calculated based on the blend ratio. The ash from previous experiments was collected through the ash port and saved to perform ash analysis and determine its composition. The fuel hopper was topped and an extra container with the fuel kept handy to refill the hopper if the fuel ran out during the experiment (This was more essential during co-firing than reburning experiments). The blends of coal and biomass were prepared by weighing definite proportions of coal and biomass and then mixing them thoroughly. The thermocouples were withdrawn from the furnace and cleaned of ash deposits on the insulation. The air filter of the mechanical blower was inspected for clogging and cleaned. All gas, view, and temperature ports were closed with the cover plug and made sure there was no air leak into the system. The ENERAC 3000E emission analyzer was calibrated using the standard calibration gases.

Calibrating the fuel feeder

The feeder was disconnected from the fuel feed line. An empty pan of known weight was placed under the feeder and the feeder motor was turned on. The fuel was collected for a period of 1 minute and weighed. If the required feed rate was not obtained, then the controller was adjusted accordingly and the process was repeated until the required feed rate was achieved. Then the feeder was reconnected to the fuel line.

Preheating the air and furnace

The propane tanks for the igniter torches and primary supply were connected. After gas, view, and temperature ports were closed with cover plugs, the exhaust fan was turned on. The blower for the primary air supply was started and set close to the required value. The blower was always used in the forward mode. The temperature at locations along the axis of the furnace was recorded in the data acquisition system. The air pre-heater was switched on and set to the maximum value. After the temperature of the primary zone air had reached approximately 395 K (250 ºF), the valve of the propane tank for the igniter torches was opened such that the flow rate was within the safety limit shown on the regulator. The water injection was turned on so that the lower zone of the furnace was cooled. The damper was set such that suction pressure of approximately 2.54 mm (0.1") of water prevailed inside the furnace. The igniter torches were lit and the furnace was heated till the temperature in the reburn zone reached approximately 422 K (300 ºF). The flame from the torches was viewed through the view ports. The torches were damaged by burnout of the ignition wire due to long operating durations at very

high temperatures. To overcome this problem, the torches were switched off and then withdrawn once the primary zone combustion was established and stabilized. The openings for the torches were later properly sealed to prevent any leak of air into the reactor.

Establishing the primary zone combustion

The valve of the primary propane supply tank was opened and the flow rate was set to the required value using the regulator. If the torches were blown out, then the damper position was adjusted, the primary propane supply was cut off and the torches were reignited. If a stable flame was difficult to be established, the flame was cautiously ignited with one of the view ports open. Once the flame was stable, the air flow rate was set to the required value. Following a 30 minutes period of primary propane combustion, the air for the reburn fuel was turned on and set at stoichiometric condition. The damper was adjusted to maintain the suction pressure. Then the reburn fuel was turned on. The extent of combustion was observed from the ash collected by the cooling water spray. The furnace was heated for a period of 45 minutes until the temperature at the reburn zone reached approximately 1366 K (2000 °F). The reburn fuel and air were switched off, the damper readjusted and thermal NO and O_2 % readings using the ENERAC 3000E emission analyzer were taken at the exit zone. The O_2 % was ensured to be very close to 1 % implying that an equivalence ratio of 0.95 existed at the primary zone; any deviation was annulled by adjusting the propane flow rate or the exhaust damper.

Setting the required primary zone NOx

The ammonia tank was opened and set to the required flow rate. The flow rate was adjusted till the required amount of NO was measured at the exit zone. The NO generated at the primary zone stabilized after 10-15 minutes. The nitrogen purge gas was used to stabilize any fluctuations in the ammonia flow.

Reburning

The reburn air was supplied at the required flow rate accounting for the aspiration of ambient air at the venturi eductor valve. The NO value measured at the exit zone gave an indication of the reduction with only the supply of air i.e., the dilution effect. The feeder motor was switched on and the reburn fuel was fed into the system. A steady NO measurement was obtained at the reburn zone after 10-15 minutes. The temperature was recorded during all the measurement stages. The sintered filter at the tip of the analyzer probe got clogged with the particulates in the exhaust stream while operating at higher equivalence ratio. It was cleaned between measurements by flushing it with air. The reburning was started at stoichiometric condition and after concentrations of O_2, NO, and NO_2 are measured with ENERAC 3000E emission analyzer, the reburn motive air supply was reduced to simulate richer conditions of reburn zone stoichiometry.

System shut off

The reburn fuel and air supply were first turned off. The primary propane supply was stopped by closing the valves of the propane tanks and disconnected from the lines.

The primary air supply was turned off. All the gas ports and temperature ports were opened to allow the furnace to cool. The water spray was continued until the temperature at port 2 subsided to about 422 K (300 ℉). The reburn fuel lines were flushed of traces of ammonia with nitrogen. A period of one day was allowed before the next experiment was conducted.

Error analysis

The error analysis was performed to quantify the errors that might occur in the parameters calculated. Based on these values, the errors in the measurements were determined. The errors given by the instrument manufacturer and the calculated errors are provided in tables V.1 and V.2. The error bars in the results were based on these calculations.

Table V.1: Instrument errors

Parameter	Instrument Error
Motive air gage	± 3 SCFH
Secondary air gage	± 6 %
O_2 sensor	± 0.2 %
NO sensor	± 4 %
NO_2 sensor	± 4 %
Fuel feeder	± 2 g/min
Thermocouple at reburn zone	± 2.8 K
Thermocouple at exit zone	± 2.2 K

Table V.2: Errors in measurement

Parameter	Calculated Error
Equivalence ratio	2.97 %
Normalized NOx	5.76 %
NOx reduction	2.6 %

CHAPTER VI

RESULTS AND DISCUSSION

This chapter presents the results of the reburning experiments and a discussion on the results.

Initial trials

The Texas A&M University boiler burner facility was also used to perform co-firing experiments with coal, biomass, and their blends. Co-firing is a process in which coal was blended with biomass and used as the fuel in the down-fired reactor. These were the first ever studies that demonstrated the ability of coal blended with biomass to reduce NOx emissions. The details of the experimental facility, parameters under which the trials were conducted, and discussion of the results are provided in references [32, 33]. The investigation at different blend ratios indicated that though the fuel nitrogen increased due to the blending of biomass with coal, the NOx emissions reduced as depicted in figure VI.1. The same trend was observed at different excess air values. This was a significant finding which directly connoted that blends of coal and biomass can be used as effective reburn fuels. Fuel bound nitrogen is considered to be a significant source of NO in coal fired reactors but, these results from literature indicate the opposite. The reduction with biomass is thought to originate from the following factors: higher volatile content of biomass, rapid release of volatile contents, and the release of fuel bound nitrogen in the form of ammonia. Based on these trials it was decided to test biomass as a reburn fuel.

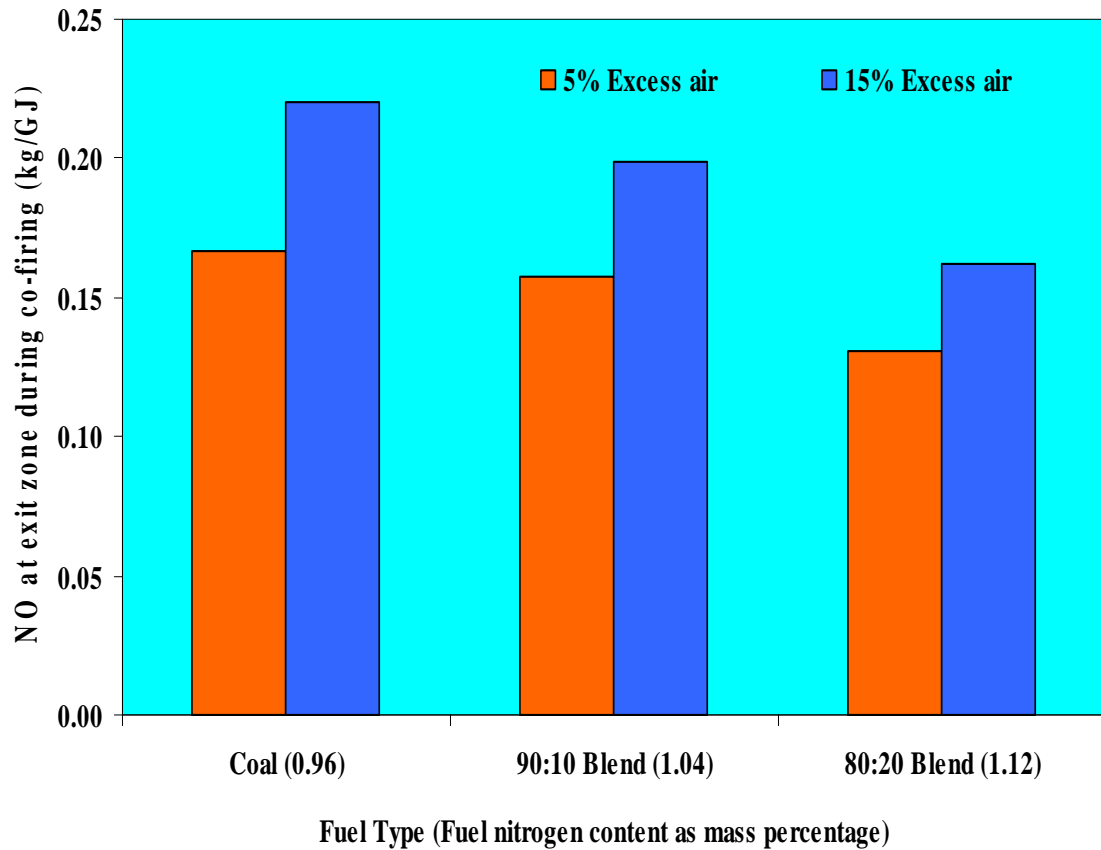Fig. VI.1: NO generation from co-firing for different fuels [33]

Fuel analysis

The fuels used for the reburning experiments were coal, biomass, and blends of coal and biomass. Two blend ratios of coal: biomass, 50-50 and 90-10 on a mass basis, were investigated. Prior to the experiments the ultimate and proximate analyses were performed for the coal and biomass. The results from the analyses were used to

calculate the values for the blends. Table VI.1 summarizes the analyses and calculated results for the four fuels used for the experiments.

Table VI.1: Comparison of various fuels used for reburning on an as received basis

	Parameter	Coal	Biomass	50-50 Blend	90-10 Blend
Ultimate	Carbon (mass %)	60.3	39.13	49.72	58.18
	Hydrogen (mass %)	3.62	6.14	4.88	3.87
	Nitrogen (mass %)	0.96	2.99	1.98	1.16
	Oxygen (mass % by difference)	14.50	38.56	26.53	16.91
	Sulfur (mass %)	0.23	0.56	0.40	0.26
	Chlorine (mass %)	< 0.10	0.56	-	-
Proximate	Ash (mass %)	5.33	15.58	10.46	6.36
	Dry Loss (mass %)	15.12	7.10	11.11	14.32
	Volatile Matter (mass %)	37.17	63.56	50.37	39.81
	Fixed Carbon (mass %)	42.38	15.58	28.07	39.52
	HHV (kJ/kg)	23710	16473	20091	22986

From the analyses results in table VI.1 it was observed that biomass was a low energy fuel. The combustion of biomass would generate 30 % lower thermal rating as compared to the same quantity of coal. Hence, when biomass is used as the sole source of energy, the fuel feed rate should be increased to achieve similar heat throughput as achieved with coal burning. The ash content of biomass was about three times higher than that of coal. The higher ash content, higher fuel feed-rate, and higher chlorine

content are likely to pose problems of ash deposition on boiler tube walls when biomass

is used as the primary fuel. Fuel bound nitrogen is the principal source for the

generation of fuel NO. A comparison of biomass with coal indicated that the fuel

nitrogen in biomass was about three times higher than that of coal. The results from co-

firing studies indicated that the higher nitrogen content of biomass did not necessarily

lead to higher NO production. A comparison of the volatile contents of biomass

revealed a value two times higher than coal. This implies, with biomass, the volatile

release rate would be faster and thus biomass will have better combustion characteristics.

Thus the comparison of coal and biomass indicated that biomass was a more volatile,

low energy, high ash, and high nitrogen fuel.

The size distribution of the coal and biomass was performed adopting the

procedure according to the ASTM standards [34]. Sieves of mesh numbers 325, 200,

100, 50, 20, 16, and 10 with mesh sizes respectively of 45, 75, 150, 300, 840, 1191, and

2000 microns were used. The results of the sieve analysis of the fuels are illustrated in

figure VI.2. It may be observed that coal has about 70 % of it mass less than 100 μm

whereas, in biomass only 50 % of the mass is less than 100 μm. Thus the biomass

particle size distribution was coarser than that of coal. The higher fiber content of the

biomass during the process of collection renders the grinding process difficult and finer

grains were not produced as the fibrous materials of biomass were not broken into

powder during the grinding operation but rather compressed. The difference in size

distribution between coal and biomass might lead to differences in combustion

characteristics. The presence of a greater fraction of biomass particles over the 300

micron range led to the problem of clogging at the venturi during the feeding of
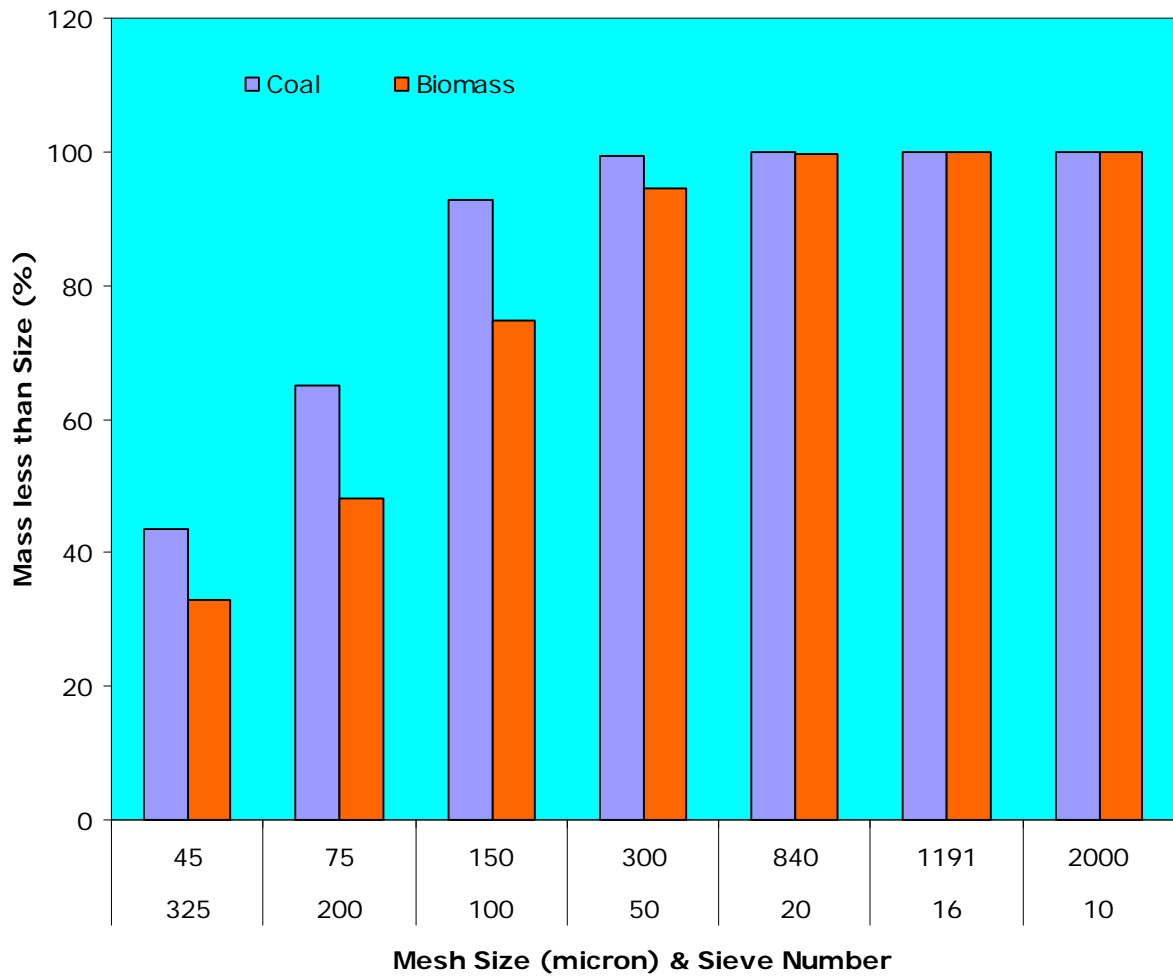
reburning fuel.

Fig. VI.2: Size distribution of coal and biomass

Mixing time scale

The mixing time distribution within the furnace gives a great deal of information about the state of mixing. The formulation of the mixing model and the description of the experiment to determine the mixing time distribution of the furnace are detailed below.

<u>Formulation</u>

Based on the work of Zwietering [35] as adapted in Alzeuta et al [36], the mixing of the reburn fuel with the stream of primary gases within the furnace was defined by a simple approach. The mixing process in the reburn zone was modeled as a jet in cross flow problem, where the jet corresponded to the injection of the reburn fuel and the cross flow symbolized the products of primary combustion. In this inverse-mixing model, the products of primary combustion were gradually entrained and diluted the reburn jet as opposed to practical conditions where the reburn fuel was injected into the flow of the products of primary combustion. This may enable the definition of the histories in the mixing zone in terms of those of the reburn fuel rather than on the products of primary combustion. A schematic of the mixing model is given in figure VI.3. The model assumed an exponential mixing rate in which the cross flow mass advancing into the jet at a given time was proportional to the mass of the cross flow. The proportionality constant was a value that depended on the mixing time, which may be determined by experiment or estimated. This approach did not describe the physical process of mixing of the reburn jet and the products of primary combustion that take place in the mixing region. Still, it characterized mixing i.e., the reburn fuel reacts from an initial fuel-rich

to fuel-lean condition as it was entrained into the cross flow. This characteristic mixing time may be compared with the kinetic time scale.

To estimate a mixing time τ_{mix}, the mass flow of the bulk flow at any time, when the reburn and cross flow jets were 97.28 % mixed, is represented by the following equation [37].

$$m_{bulk}(t) = m_{reburn}(t=0) + m_{crossflow}(t=0) \cdot \left[1 - \exp\left(-\frac{t}{\tau_{mix}}\right)\right]$$

(IV.1)

The relation between the mass flow of the two jets and the mixing time offers a way of determining the mixing time. Rearranging the above equation leads to a relation for the mixing time in terms of the concentration of oxygen as shown in the appendix B.

$$\frac{t}{\tau_{mix}} = -\ln\left\{1 - \left[\frac{3.85 \cdot \dfrac{N_{total,reburn}(t=0)}{N_{total,crossflow}}}{\left(\dfrac{1}{x_{O_2,bulk}(t)} - 3.85\right)}\right]\right\}$$

(IV.2)

Considering a mean value for the velocity of the reburn and cross flow, the variation in oxygen percentage along the length of the section downstream of the reburn fuel injection can be used to determine the characteristic mixing time.

Products of Primary Combustion
(Cross Flow)

Reburn Fuel
(Jet Flow)

Reacted Gases
(Bulk Flow)

Mixing Zone
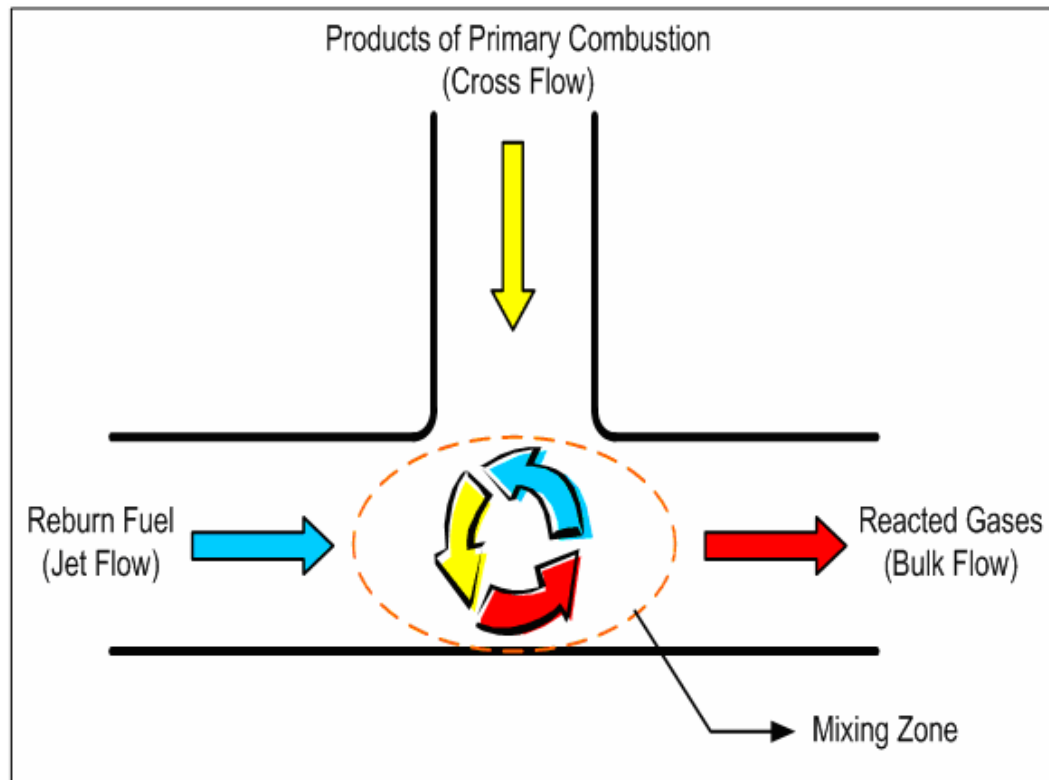
Fig. VI.3: Schematic of the jet in cross flow inverse mixing model

Test facility and experiments

The mixing time studies were conducted in a model test set up built similar to the

Texas A&M University 29.31 kW (100,000 Btu/h) boiler burner facility. Figure VI.4

illustrates the schematic of the model facility. The reacting multiphase flows of the

laboratory facility were simulated by cold gas flow system in the model. A clear acrylic

cast tube model of inner diameter 152.4 mm (6") represented the combustion chamber of

the actual test facility with identical dimensions. The main flow comprising the products

from the combustion of propane and ammonia in the test facility was replaced in the model facility through ambient air supplied from the mechanical blower. The reburn fuel and air mixture was substituted with a pure nitrogen flow from a regulated cylinder. The reburn ports were positioned at locations similar to that in the test facility. The main flow rate was identical to that in the test facility. The number of measurement ports in the model was increased with lesser spacing than the laboratory facility. Three ports upstream and 24 ports downstream of the reburn port, at 25.4 mm (1") spacing, were used as measurement ports whereas, the laboratory facility has ports spaced every 152.4 mm (6"). The flow field oxygen concentration was measured using the ENERAC 3000 E emission analyzer system.

The initial experiments were conducted in the model that was not completely operational to test under the conditions similar to that of the laboratory facility. Reburn flow rates similar to that for actual test cases could not be produced with the available configuration of N_2 cylinders. It was decided to use a low-momentum reburn jet in order to predict the mixing time. The test conditions of 5.0 m/s air flow and 2.2 m/s nitrogen jet were used that represented the respectively the cross flow and reburn jet. The main flow from the mechanical blower was started and then the nitrogen supply was also set to the required flow rate. The mixing of the main and reburn jets were left to attain a steady mixing for about 15 minutes. The oxygen concentrations were measured at the centerline and at the wall, at every measurement port downstream of the reburn port. Readings above the reburn port were also made to check for upward mixing at the reburn zone.
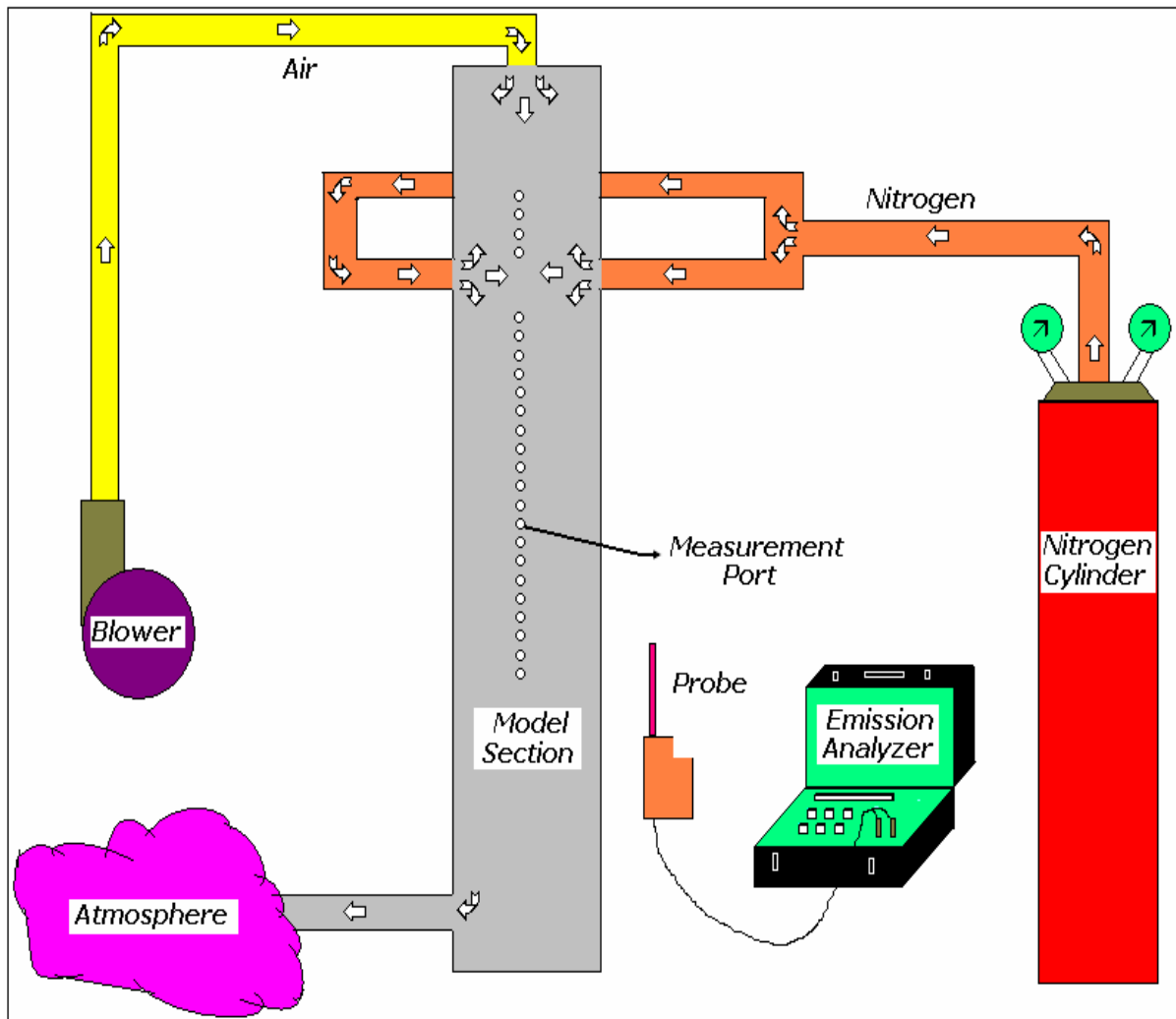
Fig. VI.4: Schematic sketch of the model facility for mixing time experiments

Determination of mixing time

The experimentally measured oxygen concentration along the length of the

model section for a specified reburn and cross flow rate was correlated as shown in the

appendix. The correlation was used to determine the mixing time. For two cases of

mixing, 97.28 % and 90 % this correlation was plotted as shown in figures VI.5. The slope of these curves gives an indication of the mixing time. From the values of the reburn and cross flow rates, the mixing time was estimated as 936 ms and 407 ms respectively for 97.28 % and 90 % mixed condition. The mixing time of 400 ms was reported in literature for 90 % mixed condition.
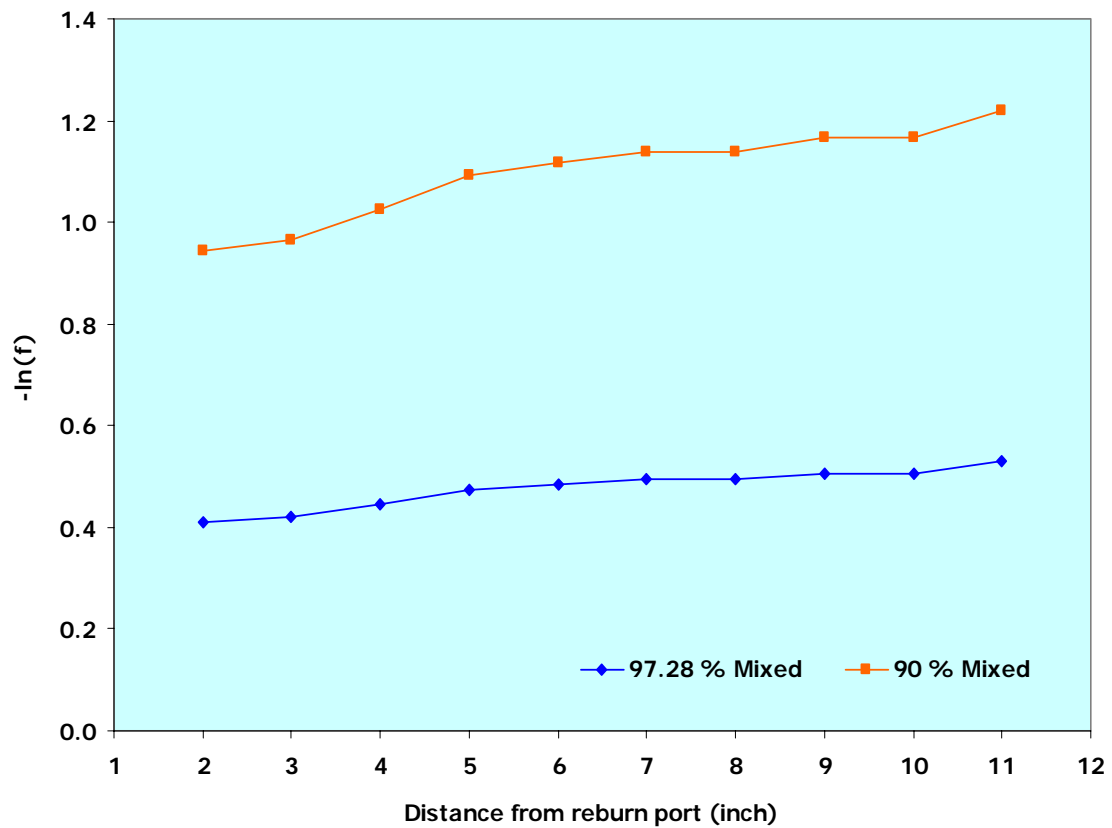

Fig. VI.5: Mixing time correlation

Reburning

The analysis of the nature of the fuels used for reburning will enable the interpretation of the results from reburning trials. Table VI.2 summarizes the various reburning trials were conducted. The different reburning fuels used were coal, biomass, 50-50 blend, and 90-10 blend on a mass basis. The two injectors used were circular jet and flat spray injector. These various configurations were tested for reburn zone equivalence ratios of 1.00, 1.05, 1.10, 1.15, and 1.20 i.e., from stoichiometric condition at 1.00 to slightly fuel-rich conditions at 1.20. The experiment with coal as the reburn fuel and circular jet injector was considered the base case for all the comparisons. The reburn fuel supplied 30 % of the total rated heat throughput of the facility. During all experiments the total heat throughput was kept identical thus, when the reburn fuel was changed, the fuel feed rate was increased for the same air flow rates. The reburning experimental conditions are given in table VI.3.

Table VI.2: Reburning parametric matrix

Experiment	Fuel	Injector	Equivalence Ratio
1	Coal*	Circular Jet*	1.00, 1.05, 1.10, 1.15, 1.20
2	Coal	Flat Spray	1.00, 1.05, 1.10, 1.15, 1.20
3	Biomass	Circular Jet	1.00, 1.05, 1.10, 1.15, 1.20
4	Biomass	Flat Spray	1.00, 1.05, 1.10, 1.15, 1.20
5	50-50 Blend	Circular Jet	1.00, 1.05, 1.10, 1.15, 1.20
6	50-50 Blend	Flat Spray	1.00, 1.05, 1.10, 1.15, 1.20
7	90-10 Blend	Circular Jet	1.00, 1.05, 1.10, 1.15, 1.20
8	90-10 Blend	Flat Spray	1.00, 1.05, 1.10, 1.15, 1.20

*Base case experiment

Table VI.3: Reburning experimental parameters

Parameter		Value
Total Burner Rating		29.31 kW (100,000 Btu/h)
Reburn Rating		8.79 kW (30,000 Btu/h)
Primary Zone	Propane flow rate	27.7 SCFH
	Air flow rate	700 SCFH
	Equivalence Ratio	0.95
	O_2 %	1.00
	NOx	600 ppm @ 3% O_2
Reburn Zone	Fuel flow rate	18-27 g/min
	Motive air flow rate	118-143 SCFH
	Aspiration	~ 50 % of motive air
	Equivalence ratio at reburn zone	1.00-1.20
	Equivalence ratio of reburn supply	1.15-1.42
	Temperature	~ 1420 K (2100 ºF)

Effect of reburn air dilution on NOx reduction

The supply of reburn air through the reburn port dilutes the stoichiometry at the reburn zone, the very nature of which is a change in the local concentration of NOx. This pseudo-reduction in NOx was evaluated to isolate the effect of dilution and identify the reduction produced from the reburn fuel. The propane burner was fired at the total rated heat throughput. The ammonia injection system generated specified amounts of NOx in the primary zone. The oxygen concentration at the exit zone was at 1 %

implying a primary zone equivalence ratio of 0.95. With the addition of reburn air, the

O_2 concentration and the NOx concentration reduced. The reduction with dilution is

calculated using the formula:

$$NOx \cdot reduction = \left(\frac{NOx_{with \cdot reburn \cdot air} - NOx_{without \cdot reburn \cdot air}}{NOx_{without \cdot reburn \cdot air}} \right) \times 100 \qquad \text{(VI.3)}$$

The effect of dilution at different initial NOx levels is depicted in figure VI.6. It

can be observed that the reduction in NOx with the addition of reburn air increased with
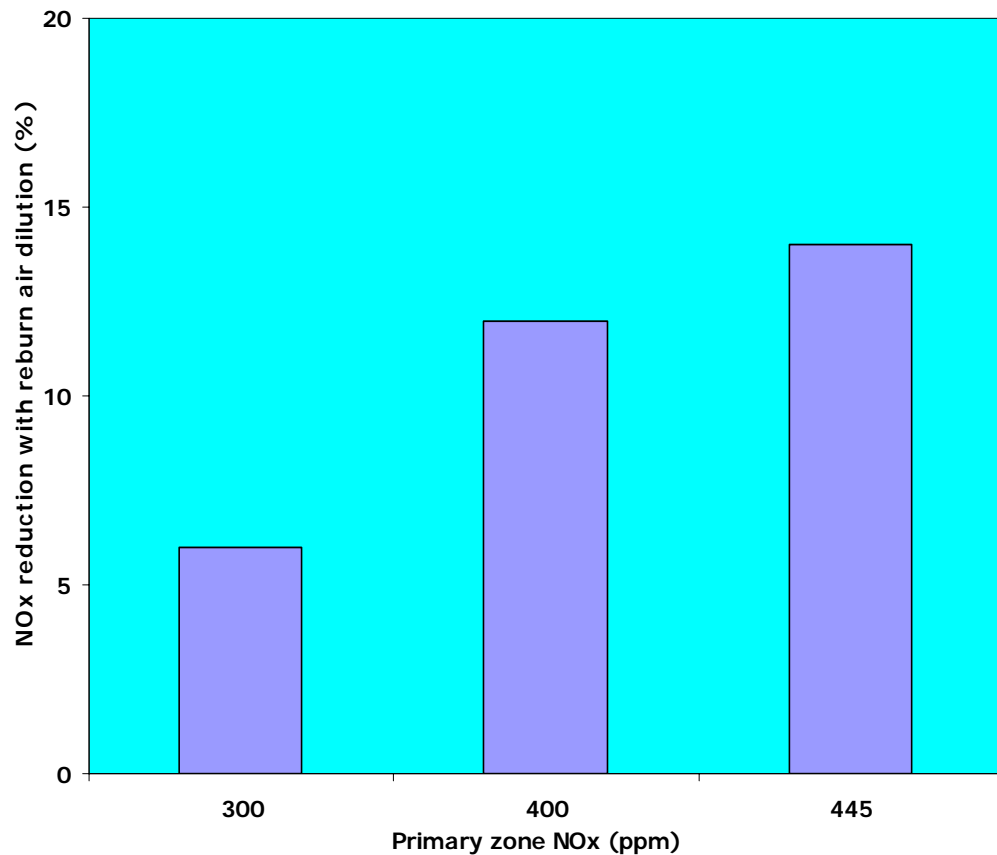
the increase in primary zone NOx.

Fig. VI.6: NOx reduction due to the dilution with reburn air supply

Effect of reburn injector type on reburn zone temperature

The two injectors used in the present study, circular jet and flat spray, differed in the nature of mixing produced in the reburn zone between the reburn supply and primary zone flow. The differences in mixing pattern may cause variations in temperature distribution at the reburn zone. From prior studies in literature [14-18], it was known that the temperature at the reburn zone was an important factor for NOx reduction since

it affects the kinetic time scale. The typical temperature at the reburn zone before the addition of reburn fuel-air mixture was about 1370 K (2000 ºF). The shop air supplied along with the reburn fuel was at ambient conditions of about 300 K (80 ºF). Thus the temperature of the mixture between the hot gases and cooler reburn air at the location of the reburn zone may depend on the extent of mixing produced locally. Once the reburn fuel and air were supplied the reburn fuel ignited as the temperature at the reburn zone was higher that the self ignition temperature. This increased the temperature at the reburn zone as the combustion of the reburn fuel progressed and reached almost steady state within 45 min. After this duration, the temperature increased gradually.

It was observed that the use of flat spray injector for reburn fuel injection resulted in a higher reburn zone temperature as compared to the circular jet nozzle. The higher temperature with flat spray was found to be similar in all types of reburn fuel tested: coal, biomass, and their blends. Most NOx control techniques aim to achieve lower levels of NOx with reduced temperatures i.e., by suppressing the environment favorable for the production of thermal NO. In our studies the temperatures were much lower than 1800 K (2800 ºF) required for significant amounts of thermal NO to be produced. At these conditions, the overall stoichiometry at the reburn zone has more effect on the NOx reduction process. The higher temperatures at the reburn zone with the flat spray injector implied that there was a better mixing of the reburn fuel with the stream of primary zone gases. The temperature rise at the reburn zone as the equivalence ratio was increased had a linear trend for pure coal and biomass as reburn

fuels whereas, in the case of blends the temperature decreased for the reburn zone equivalence ratio of 1.10 and then increased for other values.

Effect of reburn injector type on exit zone temperature

The exit zone was located in the lower end of the furnace before the water spray captures the particulates in the exhaust stream and formed the end of reburn zone. The knowledge of the temperature at this exit plane may give an estimate of the extent of burning achieved. The temperatures in the exit zone showed a trend that was opposite of that observed in the reburn zone. The trials with circular injector exhibited higher temperature at the exit that those with the flat spray injector indicating that combustion occurred a later time. This trend was identical in all type of fuels: coal, biomass, and their blends. There was a rise in temperature at the exit plane as the reburn zone equivalence ratio was increased from stoichiometric condition to slightly fuel-rich condition. However, similar to that observed at the reburn zone, the temperature dropped to lower values at an equivalence ratio of 1.10. The lower temperatures with the circular injector as compared to the flat injector indicated that the mixing produced by the flat injector was better and the fuel burned further down the reactor with the circular jet injector than with the flat spray injector.

It was observed that there was a temperature difference between the two types of injectors. To eliminate the effect of temperature on NOx formation and destruction process, it was essential that the various configurations of the experiments were repeated at similar temperature conditions. Figures VI.7 and VI.8 show temperatures in the reburn and exit zone for the different experiments. It may be observed that the

temperatures in the reburn and exit zone were similar for the various fuels at different equivalence ratios both for the circular injector and flat spray injector. The maximum variations in temperature at the reburn and exit zone for the circular injector were respectively, 84 K and 46 K and for the flat spray injectors were 92 K and 34 K.
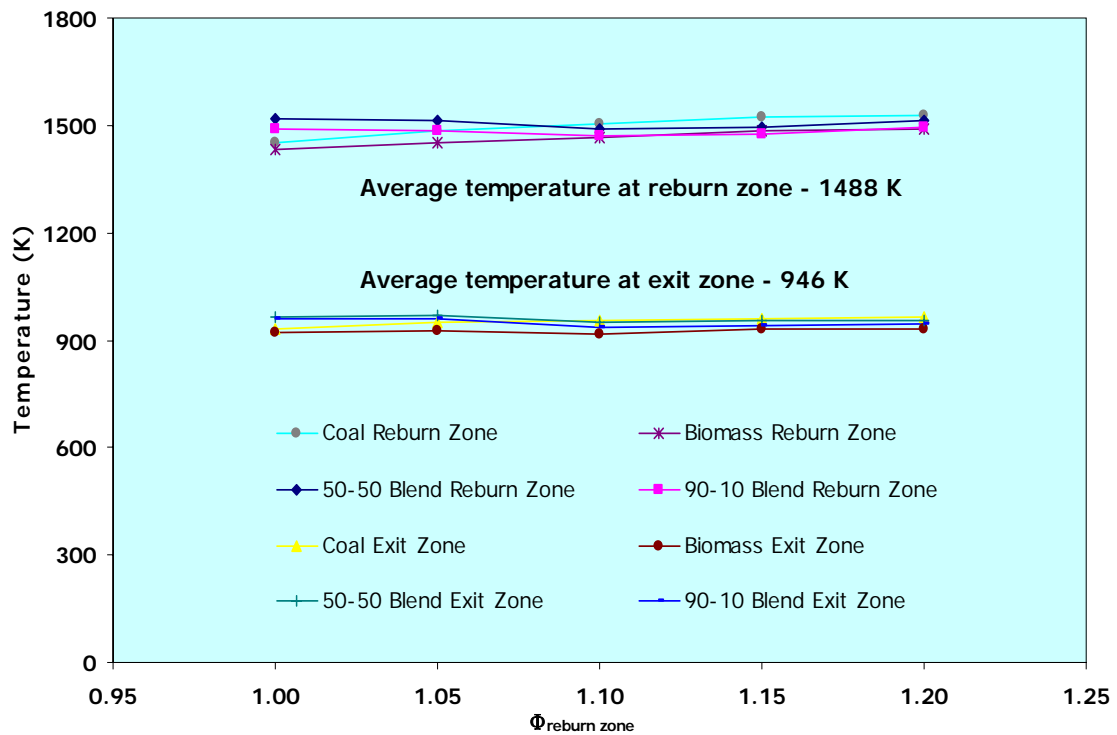

Fig. VI.7: Temperature at reburn zone and exit zone for circular jet injector
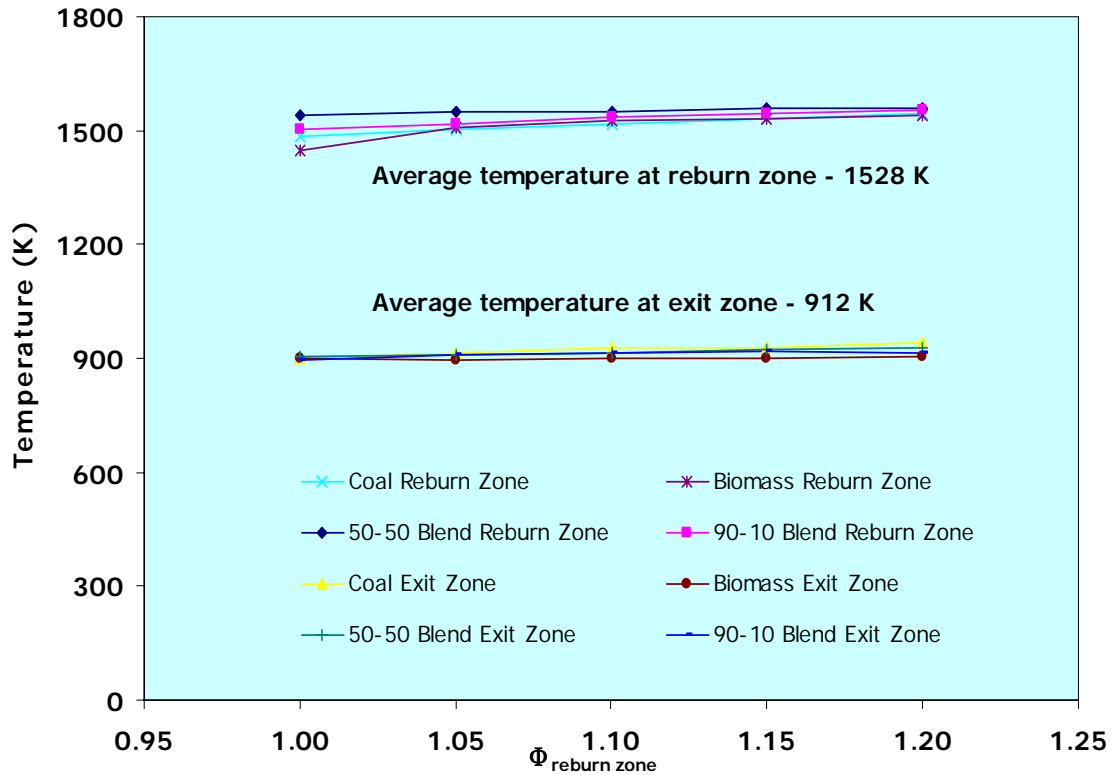
Fig. VI.8: Temperature at reburn zone and exit zone for flat spray injector

Effect of fuel type on NOx reduction

To study the effect of fuel type on their effectiveness in NOx reduction four

types of fuels were considered. They were coal, biomass, and blends coal and biomass

in the ratio of 50-50 and 90-10 by mass. Coal as reburn fuel with circular jet injection

was used as the base case for comparison of all the results. The base case NOx

reduction obtained when coal was used as reburning fuel is shown in figure VI.9. The

NOx reduction exhibited an increasing trend with increased reburn zone equivalence

ratio. The maximum reduction achieved was 10.4 % at reburn zone equivalence ratio of

1.20. The reduction was calculated based on NOx values corrected on the basis of 3 %

oxygen in the exhaust as given below:

$$NOx \cdot (reference \cdot O_2) = NOx \cdot (measured \cdot O_2) \cdot \left[\frac{ambinet \cdot O_2 - reference \cdot O_2}{ambient \cdot O_2 - measured \cdot O_2} \right] \quad \text{(IV.4)}$$

$$NOx \cdot reduction \cdot (\%) = \left(\frac{NOx \cdot (reference \cdot O_2) - NOx \cdot (initial)}{NOx \cdot (initial)} \right) \times 100 \quad \text{(IV.5)}$$
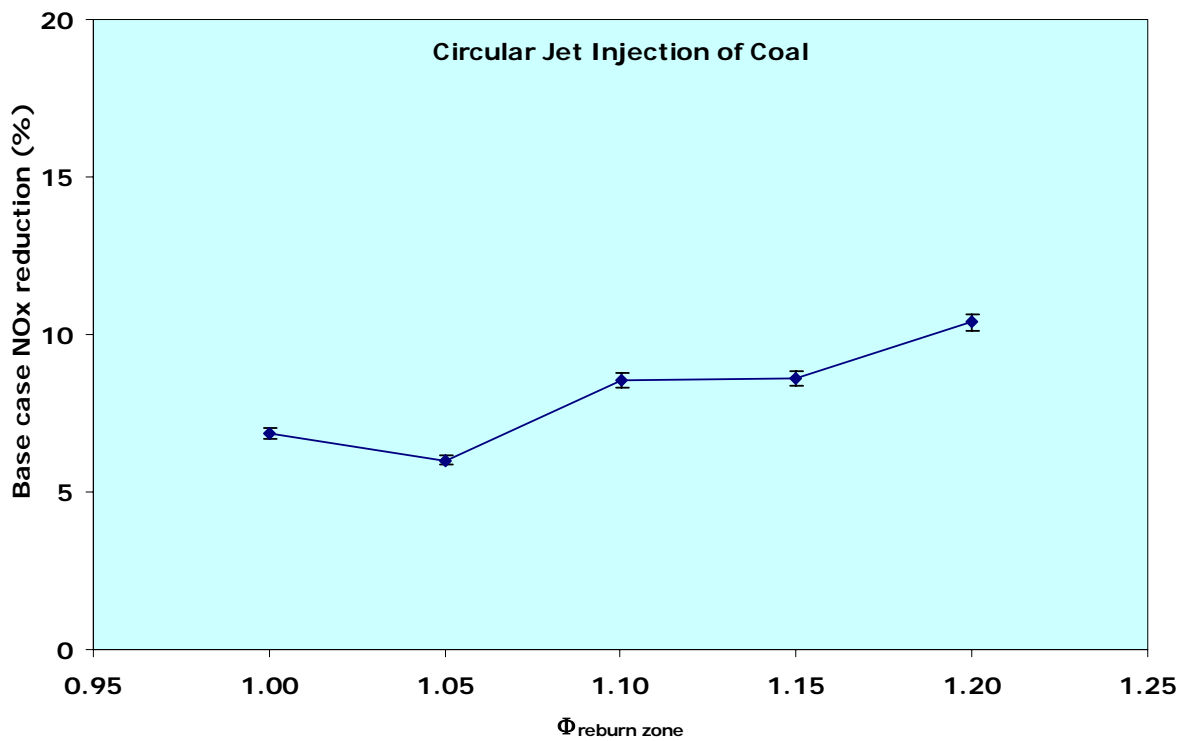

Fig. VI.9: Base case NOx reduction with coal and circular jet injector

It was observed that the reduction of NOx by biomass also increased with increase in the reburn zone stoichiometry. However, at lower equivalence ratios biomass seemed to produce higher NOx and the reduction was less than that observed for coal. At higher equivalence ratios, the biomass reduced NOx at a higher rate than coal. The maximum reduction 29.9 % was achieved at an equivalence ratio of 1.20. The NOx reduction when biomass was used as reburning fuel is shown in figure VI.10. The primary NO generation mechanism was through fuel NO as the temperatures are insufficient to produce significant amounts of thermal NO. Biomass with a higher percentage of fuel bound nitrogen should have produced higher NOx. On the contrary, it was seen that biomass reduced NOx better than coal. The form of the release of fuel bound nitrogen during oxidation plays an important role in the amount of reduction. With coal the fuel bound nitrogen may have been released in the form of HCN and in the case of biomass there might have been a higher proportion of NH_3. Both HCN and NH_3 are reducing agents for the conversion of NOx into molecular nitrogen but, the reaction rates differ. The NH_3 reduction mechanism proceeds at a much higher rate than HCN reactions. Thus, under similar residence times for both coal and biomass, biomass exhibited twice as much capacity to reduce NOx. An essential condition for effective reburning is local fuel-richness. At fuel-lean conditions, biomass being coarser than coal does not have sufficient time to burn and reduce NO_x. The mixing pattern produced at the reburn zone from the circular injector could have been insufficient to disperse the available fuel appropriately to generate numerous fuel-rich locations that were potential sites for NOx reduction.
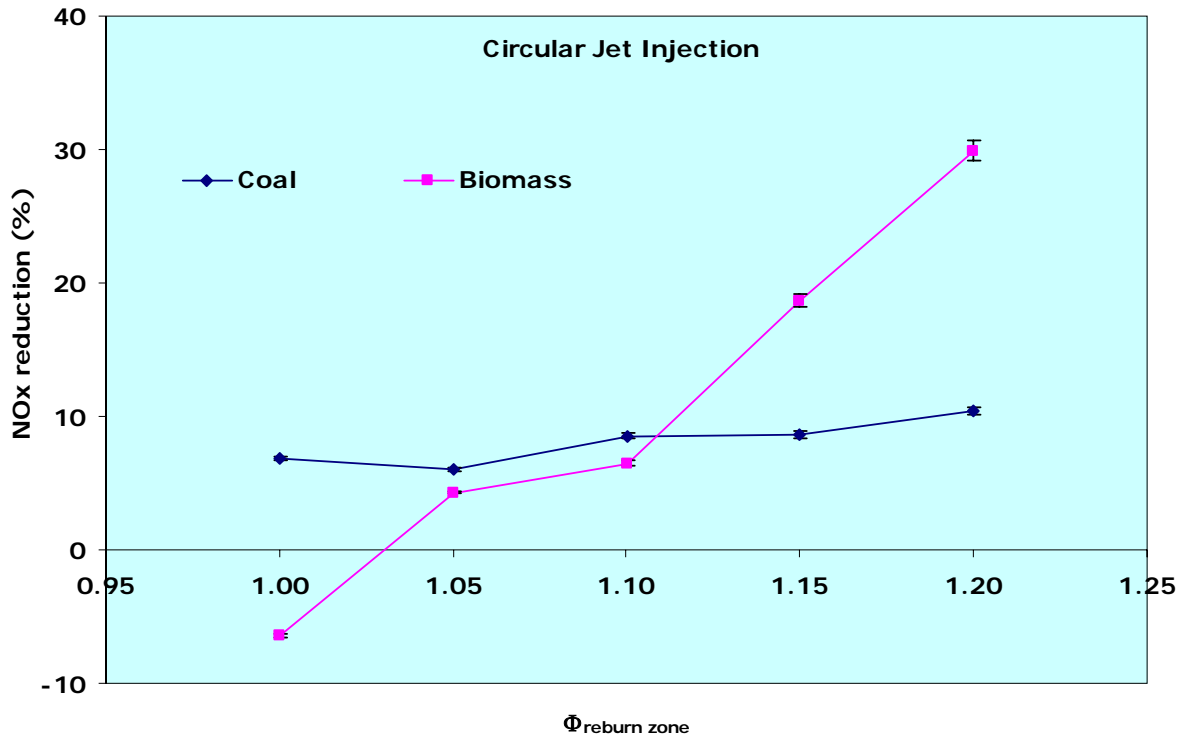
Fig. VI.10: NOx reduction with biomass as reburn fuel compared to base case coal

The properties of biomass such as low heat content, high ash, and high chlorine
and phosphorus contents do not make it a sole source energy fuel. But if the same were
blended with coal we could exploit the advantages of both the coal and biomass. Thus,
biomass blends with coal were also investigated. The two blends studied were 50-50
and 90-10 on a mass basis. The result of NOx reduction with a 50-50 blend of biomass
with coal on a mass basis is given in figure VI.11. It was observed that the behavior of
50-50 blend was similar to coal. The maximum NOx reduction of 16.8 % occurred at an
equivalence ratio of 1.20 which was about 60 % higher than that obtained with coal as

the reburning fuel. But the 50-50 blend did not show higher reduction potential at lower equivalence ratios. At an equivalence ratio of 1.10, the lower reduction could be due to the reduced temperature at the reburn zone implying there was incomplete burning of the reburn fuel.
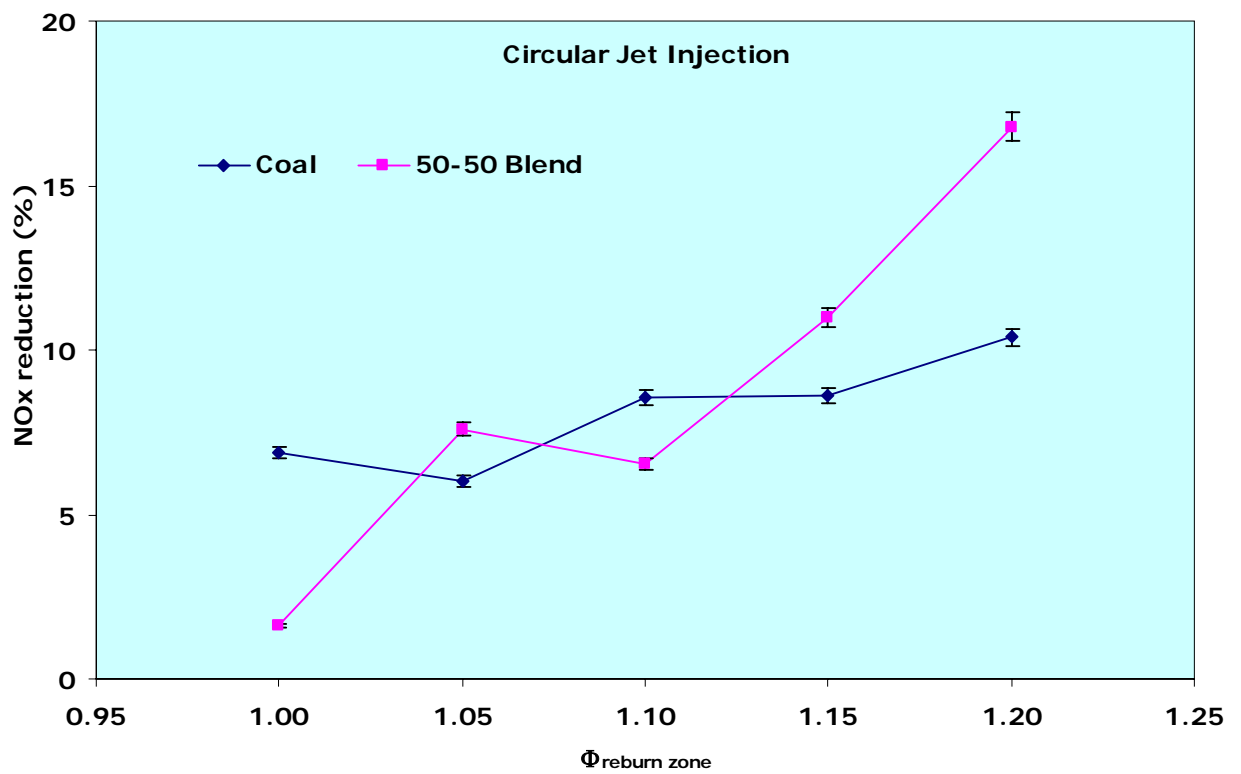

Fig. VI.11: NOx reduction with 50-50 blend as reburn fuel compared to coal

Figure VI.12 shows that the performance of 90-10 blend was similar to that of coal. But the maximum reduction with the 90-10 blend was about 71 % higher than that of coal.

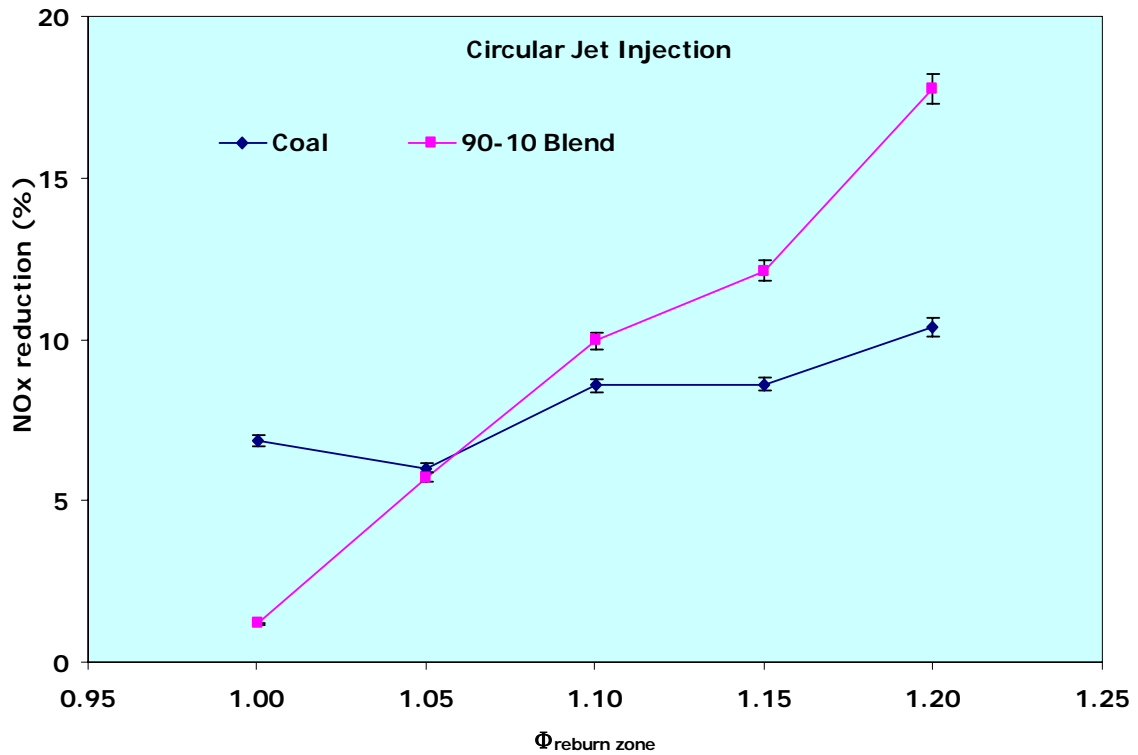Fig. VI.12: NOx reduction with 90-10 blend as reburn fuel compared to coal

A comparison of effect all the different reburn fuel on NOx reduction with the use of circular injector is shown in figure VI.13. From the figure it may be observed that at higher equivalence ratio biomass had the ability to reduce NOx whereas, at other values it did not reduce as well as coal. The reduction with blends was similar to coal

and the maximum reduction is about 71 %. Thus, it may be inferred that biomass can be used as reburn fuel but it is required that the reburn fuel should be dispersed well within the reburn zone. The need for sufficient dispersion of reburn fuel implied that when temperature effects were eliminated, the stoichiometry of the reburn zone and the generation of local fuel-rich regions were significant factors to achieve high NOx reduction.
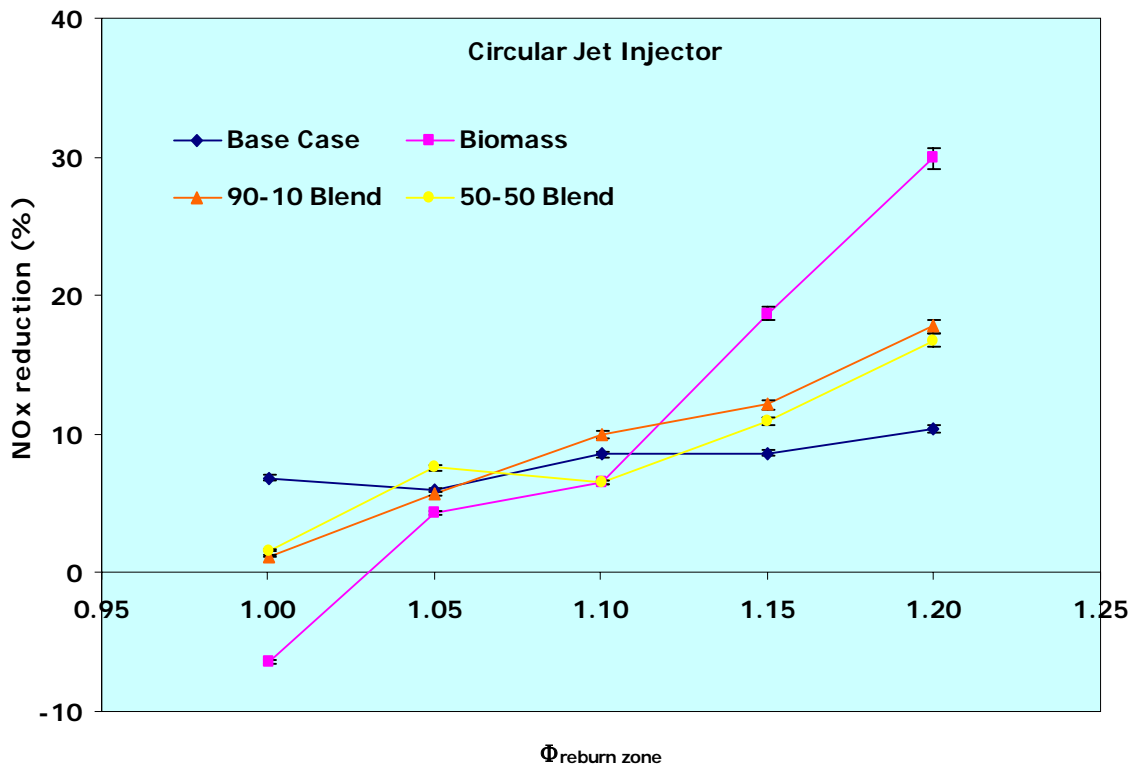

Fig. VI.13: NOx reductions with circular injector for various reburn fuels

Effect of injector type on NOx reduction

The mixing of the reburn jet into the stream of primary zone combustion products has a major impact on the effectiveness of NO_x reduction. Trials were performed with a modified injector to study this mixing effect. The initial experiments were performed with circular jet injector. In order to improve mixing, the circular injector was replaced by a flat spray nozzle. The flat spray spread the reburn fuel at a wider angle of 11º than the circular injector at the reburn zone. The flattening of the nozzle to produce an elliptical cross section also increased the momentum of the spray. The even spreading of the fuel at the reburn zone may have created more regions of localized fuel-richness that were ideal sites for NOx reduction. Also the better dispersion with a flat spray led to better combustion and faster release of volatiles in the case of biomass. This had an impact on the temperature at the reburn zone as discussed earlier. All the fuels were tested with the flat spray to determine the effect of mixing.

A comparison of the NOx reduction with coal injected through the flat spray against the base line case is given in figure VI.14. The use of flat spray for coal reburning showed that the NOx reduction improved at all equivalence ratios except at near stoichiometric conditions of the reburning zone.
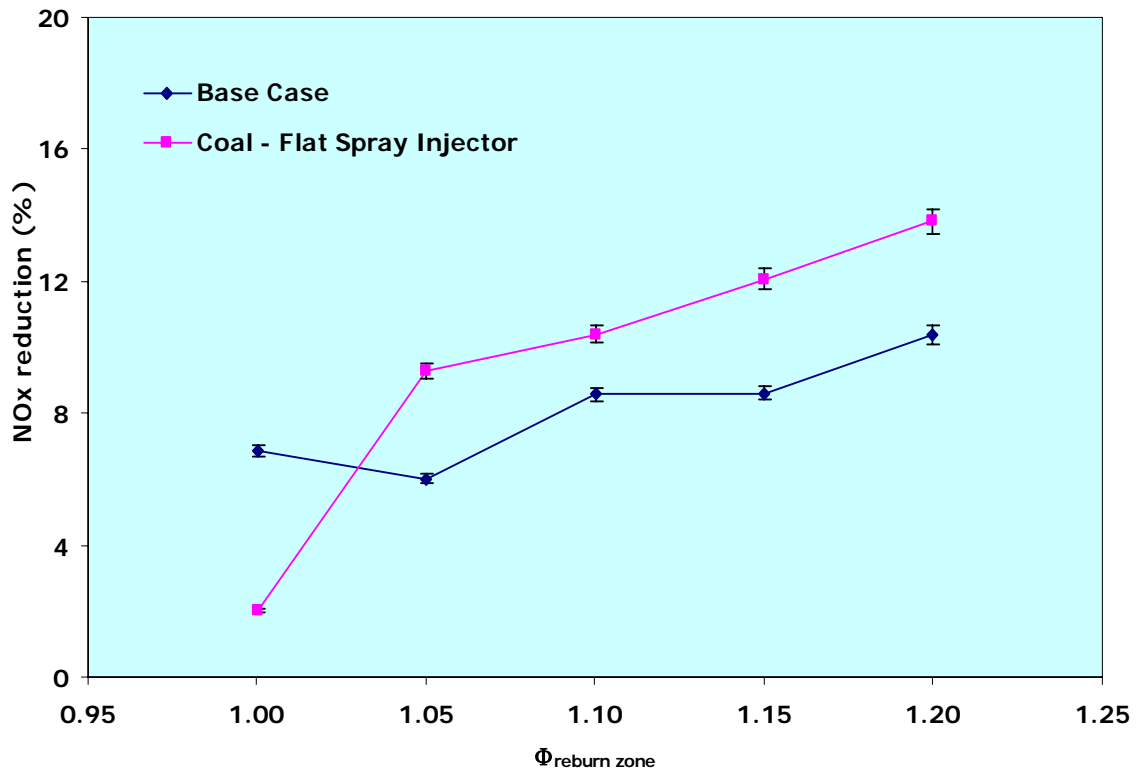
Fig. VI.14: NOx reduction with circular and flat injector for coal reburning

The NOx reduction with the flat injector and biomass is compared with the base case in figure VI.15. It was found that biomass showed much higher reduction potential of NOx than coal at all equivalence ratios. The maximum reduction of 62.2 % occurred at an equivalence ratio of 1.20 which was over 5 times higher than that produced with coal as the reburning fuel. The reduction potential of coal levels off as the equivalence ratio was increased but in the case of biomass, it showed a continuous increasing trend. This may imply that the flat spray created higher mixing within the reburn zone and

when coupled with the properties of biomass, very high reductions may have been achieved. When biomass was dispersed within the reburn zone, the higher volatile contents of biomass would have been released at a higher rate and created localized fuel-rich zones.
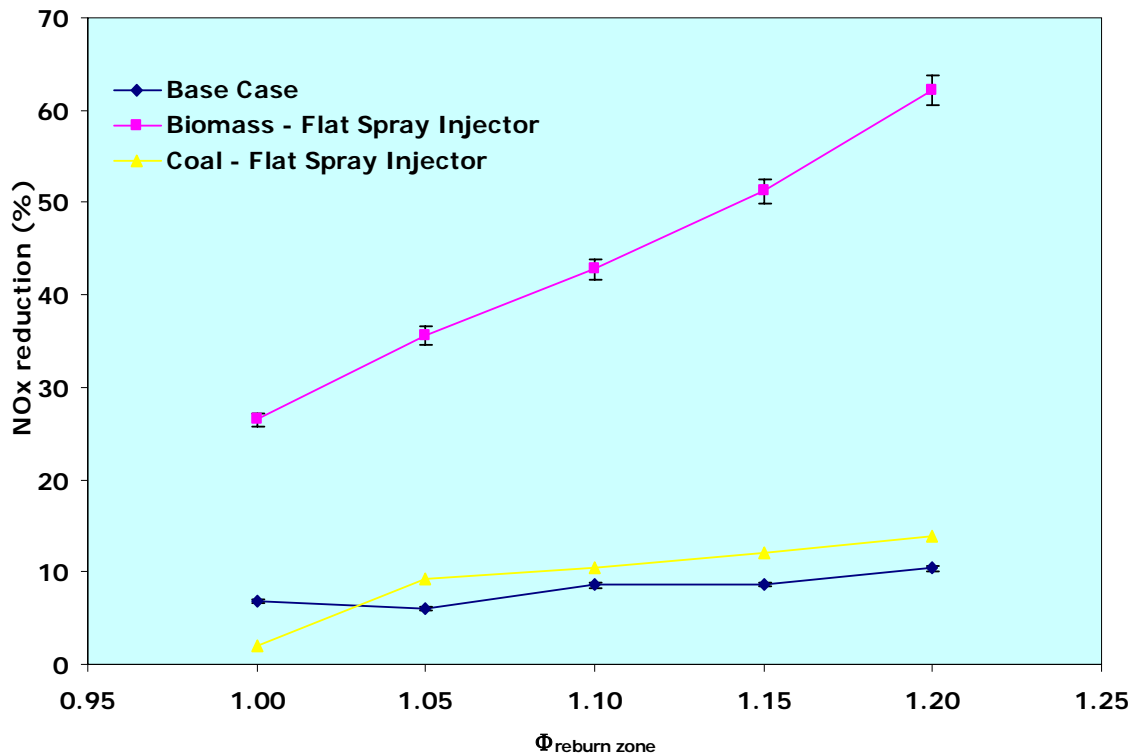

Fig. VI.15: NOx reduction with flat injector for biomass reburning

The effect of flat spray injection of 50-50 and 90-10 fuel blends are given in figure VI.16 and V.17. The blends also exhibited higher reductions as compared to coal but, the reduction was lower at low equivalence ratios. At higher equivalence ratios

much higher reductions were observed. The maximum reduction with 50-50 and 90-10

blends are respectively 44.7 %and 34.2 %.

A comparison of all NOx reduction with different fuels injected as a flat spray is

exhibited in figure VI.18. It was observed that coal had the least reduction and biomass

showed the highest reduction at all equivalence ratios. The reduction with blends lied

between that of biomass and coal. When the percentage of biomass was higher in the

blend then the NOx reduction was higher at higher equivalence ratios.
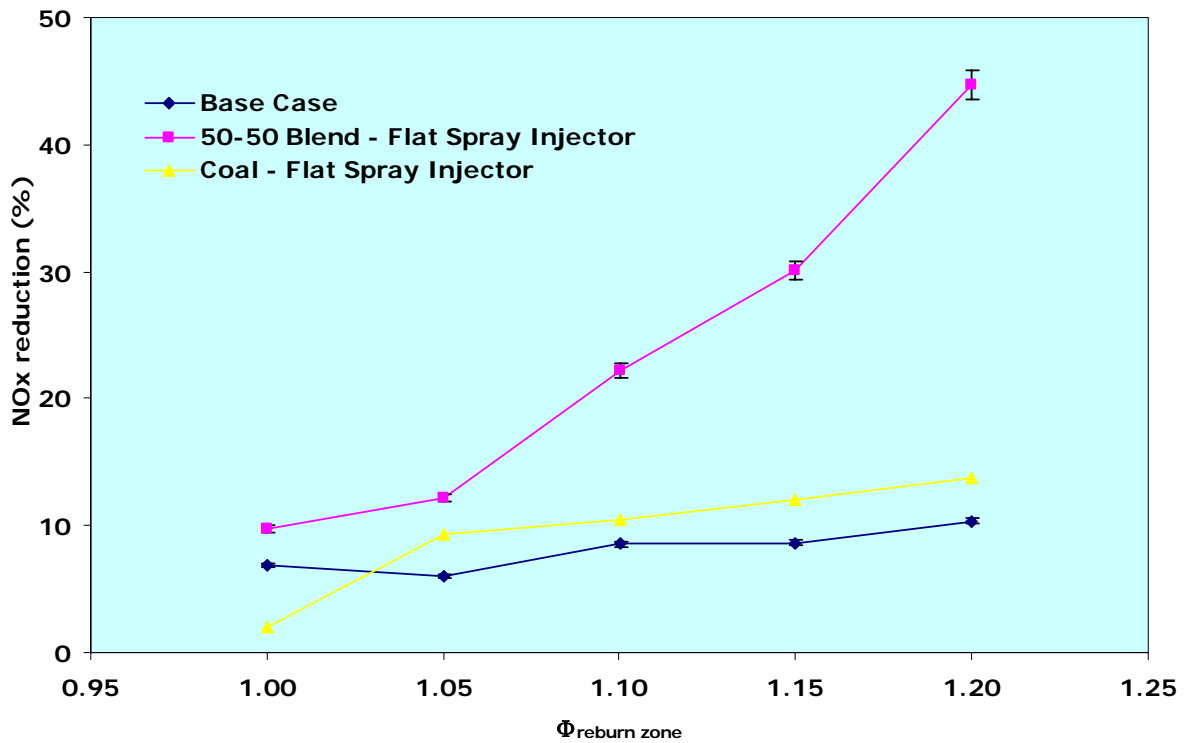
Fig. VI.16: NOx reduction with flat injector for 50-50 blend reburning
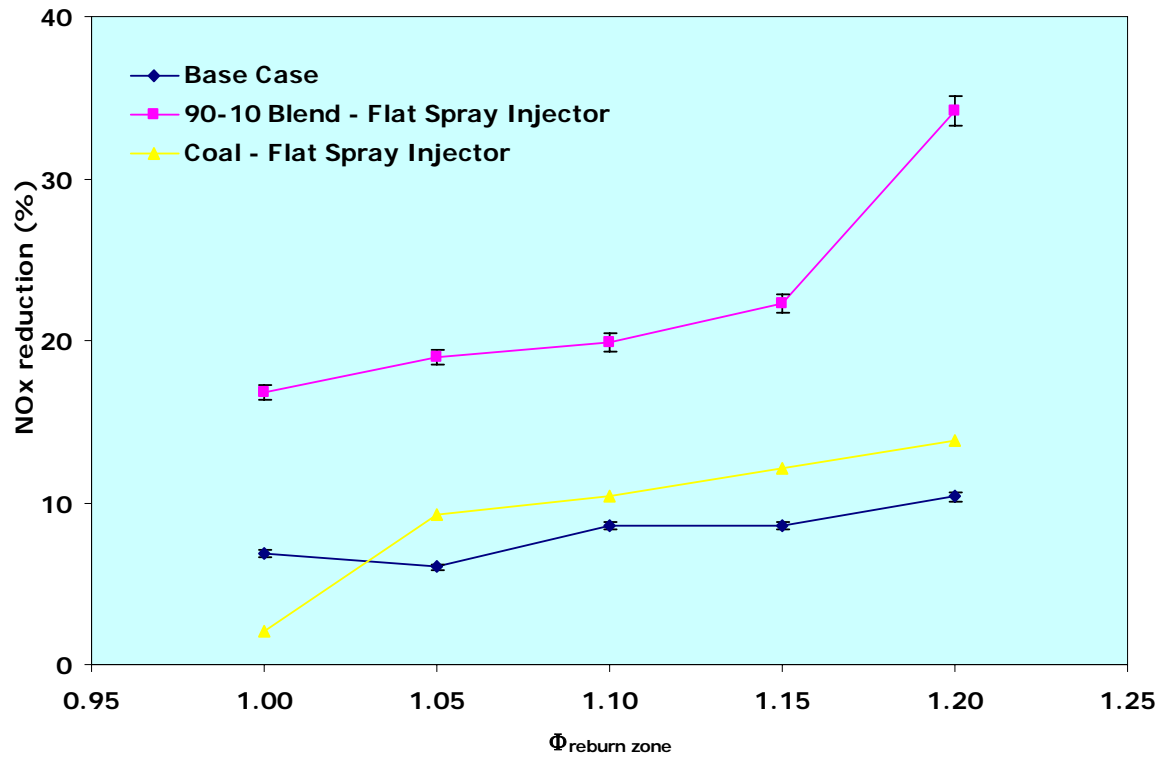
Fig. VI.17: NOx reduction with flat injector for 90-10 blend reburning
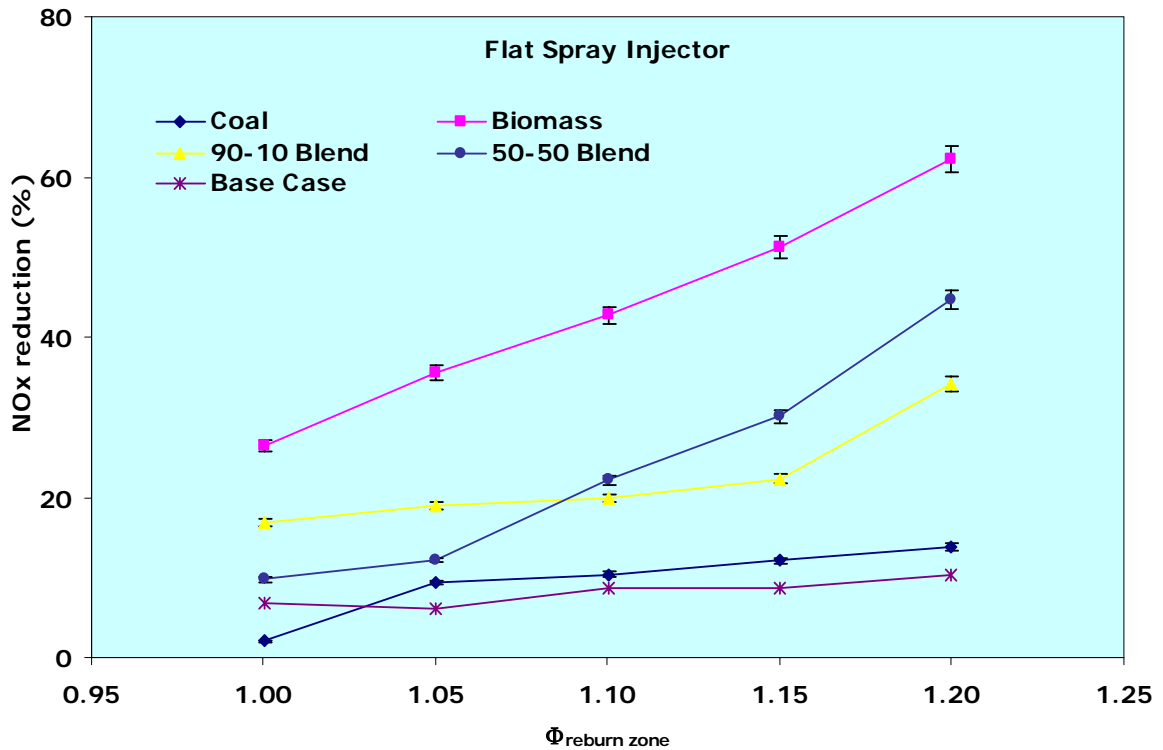
Fig. VI.18: NOx reduction with flat spray injector for various reburn fuels

Effect of ash content of biomass on NOx reduction

Thien [32] had performed reburning experiments with biomass that had higher ash content that the one used in the present studies. Table VI.4 compares the properties of the two biomass fuels. It was observed that the low ash biomass of the present studies had about 75 % higher heat content, 68 % higher fuel bound nitrogen, and 54 % higher volatile matter. It also had about 35 % lower ash and 30 % lower chlorine content. The NOx reduction comparison between these two biomasses is given in figure VI.19. It was

seen that the low ash biomass had lower NOx reduction and exhibited an increasing

trend whereas the high ash biomass had a constant reduction at all equivalence ratios.

Table VI.4: Comparison of low and high ash biomass properties

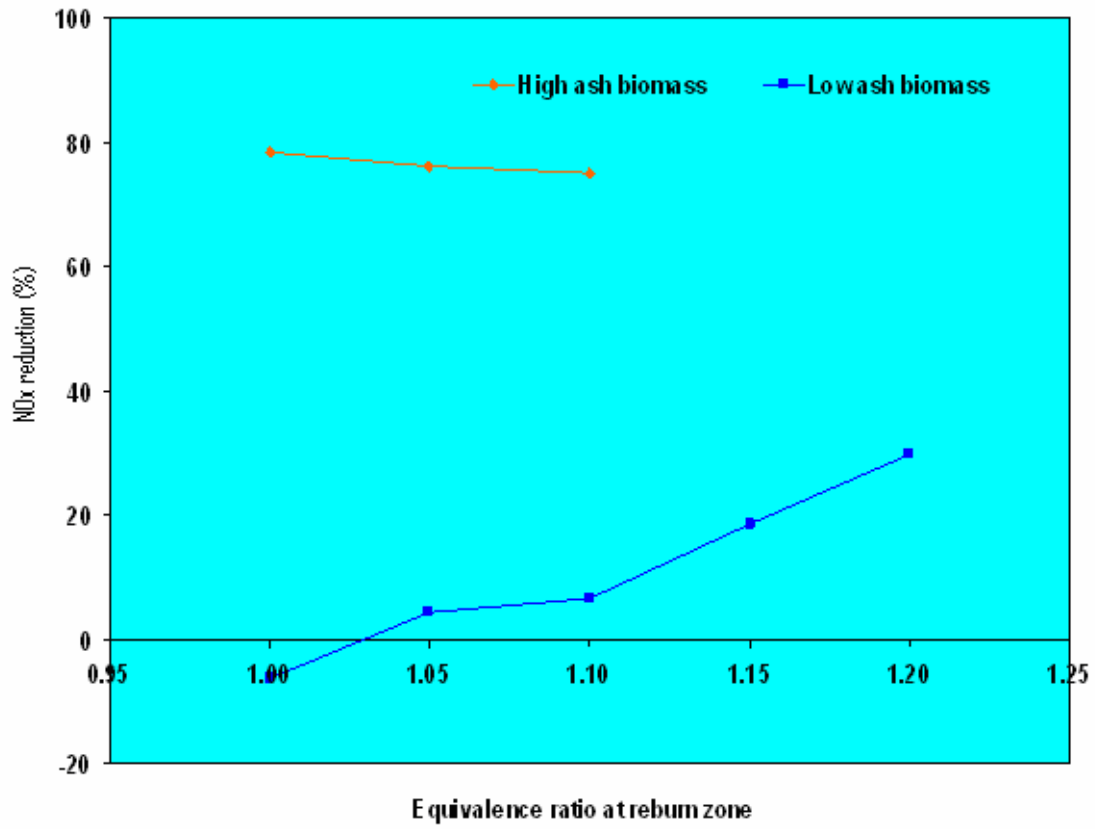|	Parameter	High Ash Biomass [32]	Low Ash Biomass
Ultimate	Carbon (mass %)	23.60	39.13
	Hydrogen (mass %)	2.90	6.14
	Nitrogen (mass %)	1.78	2.99
	Oxygen (mass % by difference)	19.10	38.56
	Sulfur (mass %)	0.50	0.56
	Chlorine (mass %)	1.85	0.56
Proximate	Ash (mass %)	44.20	15.58
	Dry Loss (mass %)	7.70	7.10
	Volatile Matter (mass %)	41.40	63.56
	Fixed Carbon (mass %)	6.50	15.58
Higher Heating Value (kJ/kg)		9423	16473
Fuel Nitrogen per Heat Content (kg/GJ)		1.89	1.82
Fuel Nitrogen per Heat Content (lb/mmBtu)		9.69	9.31

Fig. VI.19: NOx reduction with low and high ash biomass [32]

CHAPTER VII

CONCLUSIONS

1. The size analysis of coal and biomass indicate that biomass is coarser than coal. In coal, 70 % of the sample was below 100 μm in size, whereas in biomass only 50 % of the sample was below 100 μm in size.

2. The mixing time scale for 90 % mixed condition is estimated as 407 ms from cold flow studies.

3. The reduction in NOx with dilution by the addition of reburn air increases with the increase in primary zone NOx. About 15 % reduction in NOx was observed from dilution with reburn air at an initial NO value of 445 ppm.

4. The temperature at the reburn zone is higher for the flat spray than with circular jet reburn injector at all conditions of the reburn zone equivalence ratio and fuel. The average temperature with circular jet injection at the reburn zone is 1488 K and with flat spray injector is 1528 K.

5. The temperature at the exit zone is lower for the flat spray that with circular jet reburn injector at all conditions of the reburn zone equivalence ratio and fuel. The average temperature with circular jet injection at the exit zone is 946 K and with flat spray injector is 912 K.

6. The temperature profiles at the reburn exit zone for the two injectors were similar for the different fuels at all values of reburn zone equivalence ratio.

7. The flat spray injector had higher NOx reduction than circular jet injector.

8. Biomass is a better reburn fuel than coal at all conditions of equivalence ratio at the reburn zone.

9. Maximum NOx reduction of 62.2 % was obtained with biomass as the reburn fuel which was about five times higher than that achieved with coal.

10. The NOx reduction ability of blends lay between that of coal and biomass.

CHAPTER VIII

FUTURE WORK

The following work would be a desirable extension of the results that have been presented here.

- The reburn supply air should be vitiated with nitrogen and simulated flue gases to study their effect on NOx reduction.

- Other injection configurations like the top hat injectors should be evaluated for their effect on NOx reduction.

- Provisions should be made to measure the concentrations of CO, CO_2, and combustibles along with NOx measurements.

- The nitrogenous species such as NH_3 and HCN should be measured with dedicated analyzers so that the actual kinetics could be quantified.

- The sampling system should be improved so the interference of the particles in the flow stream and water spray currently injected to capture them does not hinder the measurements.

- The length of the furnace should be increased to include the over fire zone.

- Mass flow controllers should be included to obtain precise flow settings.

- Primary zone propane ignition system should be modified to prevent frequent igniter torch blow out.

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APPENDIX A

NOMENCLATURE

Symbols

A - Stoichiometric coefficient of water vapor in air

$\left(\dfrac{A}{F}\right)$ - Air to fuel ratio, kmol air/kmol fuel

B - Stoichiometric coefficient of nitrogen in air

e   - Energy, J

g   - Acceleration due to gravity, m/s^2

$\dot{m}_{species}$ - Mass flow rate of species, kg/s

$MW_{species}$ - Molecular weight of species, kg/kmol

$\dot{n}_{species}$ - Mole flow rate of species, kmol/s

p   - Pressure

$P_{C_3H_8}$ - Thermal power rating from propane combustion, kW

P_{reburn} - Reburn thermal power rating, kW

P_{Total} - Total thermal power rating

r - Rating fraction, %

t   - Time, s

v - Velocity, m/s

$x_{species}$ - Mole fraction of species

z   - Elevation, m

Greek Symbols

ϕ - Equivalence ratio

$\rho_{species}$ - Density of species, kg/m3

τ - Mixing time, s

$\dot{v}_{species}$ - Volume flow rate of species, m3/s

Subscript

1, 2, 3   - Location

amb   - Ambient condition

g   - Gage

r   - Reburn condition

s   - Stoichiometric condition

Abbreviations

EPA   - Environmental Protection Agency

HFC   - Hydro Fluoro Carbon

HHV   - Higher heating value species, kJ/kg

LOI   - Loss On Ignition

RH   - Relative humidity

SCR   - Selective Catalytic Reduction

SNCR   - Selective Non Catalytic Reduction

VOC   - Volatile Organic Compounds

APPENDIX B

RELATIONSHIP FOR MIXING TIME

The calculation of mixing time based on the inverse mixing model is given in this appendix.

The mass flow of the bulk flow at any time is given by,

$$m_{bulk}(t) = m_{reburn}(t=0) + m_{crossflow}(t=0) \cdot \left[1 - \exp\left(-\frac{t}{\tau_{mix}}\right)\right]$$

(B.1)

Converting the mass flow equation into that of mole flow, we obtain the following equation:

$$N_{bulk}(t) = MW_{bulk} \cdot m_{bulk}(t)$$

(B.2)

$$N_{bulk}(t) = MW_{bulk} \left\{ m_{reburn}(t=0) + m_{crossflow}(t=0) \cdot \left[1 - \exp\left(-\frac{t}{\tau_{mix}}\right)\right]\right\}$$

(B.3)

$$N_{bulk}(t) = MW_{bulk} \left\{ MW_{reburn} \cdot N_{reburn}(t=0) + MW_{crossflow} \cdot N_{crossflow} \left[1 - \exp\left(-\frac{t}{\tau_{mix}}\right)\right]\right\}$$

(B.4)

The mole fraction oxygen in the bulk flow is given as follows.

$$x_{O_2,bulk}(t) = \frac{N_{O_2,bulk}(t)}{N_{total,bulk}(t)}$$

(B.5)

Rewriting the mole fraction in terms of equation (2) leads to the following expressions.

$$x_{O_2,bulk}(t) = \frac{MW_{O_2,bulk}\left\{MW_{O_2,reburn} \cdot N_{O_2,reburn}(t=0) + MW_{O_2,crossflow} \cdot N_{O_2,crossflow}\left[1-\exp\left(-\frac{t}{\tau_{mix}}\right)\right]\right\}}{MW_{total,bulk}\left\{MW_{total,reburn} \cdot N_{total,reburn}(t=0) + MW_{total,crossflow} \cdot N_{total,crossflow}\left[1-\exp\left(-\frac{t}{\tau_{mix}}\right)\right]\right\}}$$

(B.6)

Taking reciprocal,

$$\frac{1}{x_{O_2,bulk}(t)} = \frac{MW_{total,bulk}\left\{MW_{total,reburn} \cdot N_{total,reburn}(t=0) + MW_{total,crossflow} \cdot N_{total,crossflow}\left[1-\exp\left(-\frac{t}{\tau_{mix}}\right)\right]\right\}}{MW_{O_2,bulk}\left\{MW_{O_2,reburn} \cdot N_{O_2,reburn}(t=0) + MW_{O_2,crossflow} \cdot N_{O_2,crossflow}\left[1-\exp\left(-\frac{t}{\tau_{mix}}\right)\right]\right\}}$$

(B.7)

The equation B.7 relates the mixing time, τ_{mix} and the O_2 concentration in the

bulk flow, $x_{O_2,bulk}(t)$. This expression is used to estimate the mixing time from the

experiments as described in the text.

APPENDIX C

GAS REACTIONS

The calculations for conducting the reburning experiments are described in this appendix.

The stoichiometric coefficient of nitrogen and water in air supplied for propane combustion in the primary zone and reburn air is calculated as follows.

$$B = \frac{\left(100 - x_{O_2,amb}\right)}{x_{O_2,amb}}$$

(C.1)

$$A = \frac{RH_{amb} \cdot p_g}{p - \left(RH_{amb} \cdot p_g\right)} \cdot (1 + B)$$

(C.2)

The flow rate of propane is given by:

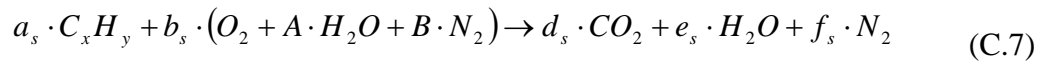$$\dot{m}_{C_3H_8} = \frac{P_{C_3H_8}}{HHV_{C_3H_8}}$$

(C.3)

$$P_{C_3H_8} = P_{Total} \cdot r$$

(C.4)

$$\dot{n}_{C_3H_8} = \dot{n}_{C_3H_8} \cdot MW_{C_3H_8}$$

(C.5)

$$\dot{v}_{C_3H_8} = \frac{\dot{m}_{C_3H_8}}{\rho_{C_3H_8}}$$

(C.6)

The stoichiometric reaction of propane and the coefficients are expressed as:

$$a_s \cdot C_x H_y + b_s \cdot \left(O_2 + A \cdot H_2O + B \cdot N_2\right) \rightarrow d_s \cdot CO_2 + e_s \cdot H_2O + f_s \cdot N_2$$

(C.7)

$$a_s = \dot{n}_{C_3H_8}$$

(C.8)

$$b_s = a_s \cdot \left(x + \frac{y}{4} \right)$$

(C.9)

$$d_s = a_s \cdot x$$

(C.10)

$$e_s = a_s \cdot \left[\frac{y}{2} + A \cdot \left(x + \frac{y}{4} \right) \right]$$
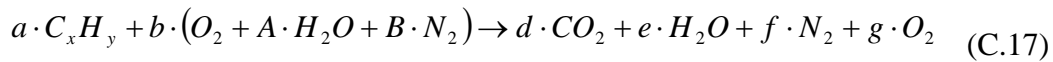
(C.11)

$$f_s = a_s \cdot B \cdot \left(x + \frac{y}{4} \right)$$

(C.12)

$$\left(\frac{A}{F} \right)_s = \frac{b_s}{a_s} \cdot (1 + A + B)$$

(C.13)

$$\dot{n}_{Air_s} = b_s \cdot (1 + A + B)$$

(C.14)

$$\dot{m}_{Air_s} = \dot{n}_{Air_s} \cdot MW_{Air}$$

(C.15)

$$\dot{v}_{Air_s} = \frac{\dot{m}_{Air_s}}{\rho_{Air}}$$

(C.16)

The reaction of propane with specified O_2 % in the exhaust is,

$$a \cdot C_x H_y + b \cdot (O_2 + A \cdot H_2 O + B \cdot N_2) \rightarrow d \cdot CO_2 + e \cdot H_2 O + f \cdot N_2 + g \cdot O_2$$

(C.17)

$$a = \dot{n}_{C_3 H_8}$$

(C.18)

$$b = a \cdot \left(x + \frac{y}{4} \right) + g$$

(C.19)

$$d = a \cdot x$$

(C.20)

$$e = a \cdot \frac{y}{2} + b \cdot A + g$$

(C.21)

$$f = b \cdot B$$

(C.22)

$$g = a \cdot \left[\frac{x + B \cdot \left(x + \dfrac{y}{4} \right)}{\dfrac{1}{x_{O_2,dry}} - 1 - B} \right]$$
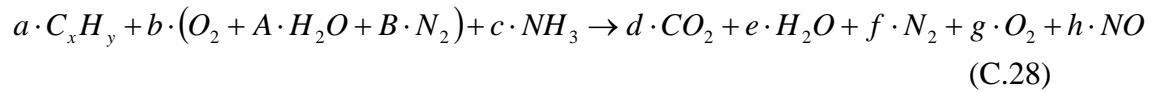
(C.23)

$$\left(\frac{A}{F} \right) = \frac{b}{a} \cdot (1 + A + B)$$

(C.24)

$$\dot{n}_{Air} = b \cdot (1 + A + B)$$

(C.25)

$$\dot{m}_{Air} = \dot{n}_{Air} \cdot MW_{Air}$$

(C.26)

$$\dot{v}_{Air} = \frac{\dot{m}_{Air}}{\rho_{Air}}$$

(C.27)

The reaction of propane with specified O_2 % and NO ppm in the exhaust from the addition of NH_3 is given below.

$$a \cdot C_x H_y + b \cdot (O_2 + A \cdot H_2O + B \cdot N_2) + c \cdot NH_3 \rightarrow d \cdot CO_2 + e \cdot H_2O + f \cdot N_2 + g \cdot O_2 + h \cdot NO$$

(C.28)

$$a = \dot{n}_{C_3H_8}$$

(C.29)

$$b = d + a \cdot \frac{y}{2} + h \cdot \left(\frac{x_{O_2,dry}}{x_{NO,dry}} + \frac{5}{4} \right)$$

(C.30)

$$c = h$$

(C.31)

$$d = a \cdot x$$

(C.32)

$$e = a \cdot \frac{y}{2} + b \cdot A + \frac{3}{2} \cdot h$$

(C.33)

$$f = b \cdot B$$

(C.34)

$$g = h \cdot \frac{x_{O_2,dry}}{x_{NO,dry}} \tag{C.35}$$

$$h = \frac{d + \dfrac{B \cdot d}{2} + B \cdot a \cdot \dfrac{y}{4}}{\dfrac{1}{x_{NO,dry}} - 1 - B \cdot \left(\dfrac{x_{O_2,dry}}{x_{NO,dry}} + \dfrac{5}{4} \right) - \dfrac{x_{O_2,dry}}{x_{NO,dry}}} \tag{C.36}$$

$$\left(\frac{A}{F} \right) = \frac{b}{a} \cdot (1 + A + B) \tag{C.37}$$

$$\dot{n}_{Air} = b \cdot (1 + A + B) \tag{C.38}$$

$$\dot{m}_{Air} = \dot{n}_{Air} \cdot MW_{Air} \tag{C.39}$$

$$\dot{v}_{Air} = \frac{\dot{n}_{Air}}{\rho_{Air}} \tag{C.40}$$

$$\dot{n}_{NH_3} = c \tag{C.41}$$

$$\dot{m}_{NH_3} = \dot{n}_{NH_3} \cdot MW_{NH_3} \tag{C.42}$$

$$\dot{v}_{NH_3} = \frac{\dot{m}_{NH_3}}{\rho_{NH_3}} \tag{C.43}$$

The calculations for the flow rate of reburn fuel are,

$$\dot{m}_{reburn} = \frac{P_{reburn}}{HHV_{reburn}} \tag{C.44}$$

$$P_{reburn} = P_{Total} \cdot (1 - r) \tag{C.45}$$

$$\dot{n}_{reburn} = \dot{n}_{reburn} \cdot MW_{reburn} \tag{C.46}$$

The stoichiometric reaction of reburn fuel and the coefficients are,

$$a_{s,r} \cdot CH_m O_n N_p S_q + b_{s,r} \cdot \left(O_2 + A \cdot H_2O + B \cdot N_2\right)$$
$$\rightarrow c_{s,r} \cdot CO_{2,r} + d_{s,r} \cdot H_2O + e_{s,r} \cdot N_2 + f_{s,r} \cdot NO + g_{s,r} \cdot SO_2 \tag{C.47}$$

$$a_{s,r} = \dot{n}_{reburn} \tag{C.48}$$

$$b_{s,r} = a_{s,r} \cdot \left(1 + \frac{m}{4} - \frac{n}{2} + \frac{p}{2} + q\right) \tag{C.49}$$

$$c_{s,r} = a_{s,r} \tag{C.50}$$

$$d_{s,r} = a_{s,r} \cdot \frac{m}{2} + b_{s,r} \cdot A \tag{C.51}$$

$$e_{s,r} = b_{s,r} \cdot B \tag{C.52}$$

$$f_{s,r} = a_{s,r} \cdot p \tag{C.53}$$

$$g_{s,r} = a_{s,r} \cdot q \tag{C.54}$$

$$\left(\frac{A}{F}\right)_{s,r} = \frac{b_{s,r}}{a_{s,r}} \cdot \left(1 + A + B\right) \tag{C.55}$$

$$\dot{n}_{Air_{s,r}} = b_{s,r} \cdot \left(1 + A + B\right) \tag{C.56}$$

$$\dot{m}_{Air_{s,r}} = \dot{n}_{Air_{s,r}} \cdot MW_{Air} \tag{C.57}$$

$$\dot{v}_{Air_{s,r}} = \frac{\dot{m}_{Air_{s,r}}}{\rho_{Air}} \tag{C.58}$$

To calculate the reburn air for specified reburn zone equivalence ratio, the following expressions are used.

$$\phi_{rs} = \frac{1}{\left(\dfrac{1}{\phi_{rz}} - \dfrac{g}{b_{s,r}}\right)}$$

(C.59)

$$\dot{n}_{Air,r} = \frac{b_{s,r}}{\phi_{rs}}$$

(C.60)

$$\dot{m}_{Air,r} = \dot{n}_{Air,r} \cdot MW_{Air}$$

(C.61)

$$\dot{v}_{Air,r} = \frac{\dot{n}_{Air,r}}{\rho_{Air}}$$

(C.62)

APPENDIX D

ENTRAINMENT CALCULATIONS

The principal used to determine the aspirated air is discussed in this appendix.

Eductors are used in applications like automobiles and residential where mixing of two or more streams occur. The two streams may be of different densities. The schematic of the mixing process that occurs in an eductor is given in figure D.1. The problem required to be addressed is how to calculate the flow conditions at 3 with the knowledge of the flow conditions at 1.
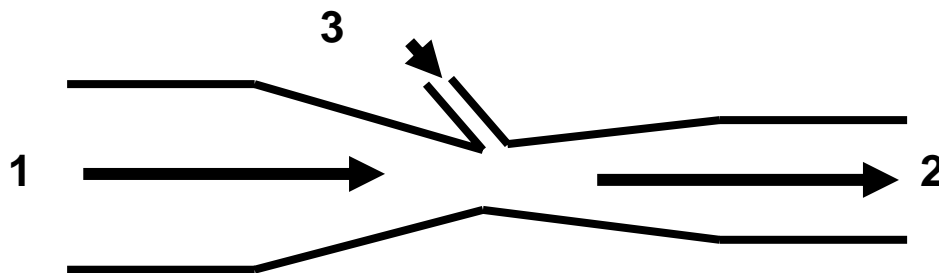

Fig. D.1: Schematic of the mixing process in an eductor

Assuming a control volume encompassing two inlets and the exit, the use of energy balance gives the following expression:

$$\dot{m}_1 \cdot e_1 + \dot{m}_3 \cdot e_3 = \dot{m}_2 \cdot e_2 \tag{D.1}$$

We know that the total energy may be expressed as the sum of pressure, velocity, and elevation heads. Using this we obtain,

$$\dot{m}_1 \cdot \left(\frac{p_1}{\rho_1} + \frac{v_1^2}{2} + g \cdot z_1 \right) + \dot{m}_3 \cdot \left(\frac{p_3}{\rho_3} + \frac{v_3^2}{2} + g \cdot z_3 \right) = \dot{m}_2 \cdot \left(\frac{p_2}{\rho_2} + \frac{v_2^2}{2} + g \cdot z_2 \right) \quad \text{(D.2)}$$

Assuming that there is not elevation difference between the inlets and exit, the velocity at inlet, 3 is negligible, we get:

$$\dot{m}_1 \cdot \left(\frac{p_1}{\rho_1} + \frac{v_1^2}{2} \right) + \dot{m}_3 \cdot \left(\frac{p_3}{\rho_3} \right) = \dot{m}_2 \cdot \left(\frac{p_2}{\rho_2} + \frac{v_2^2}{2} \right) \quad \text{(D.3)}$$

From mass conservation within the control volume, we note that the mass flow at exit, 3 should be the sum of those entering inlets 1 and 3. Hence,

$$\dot{m}_1 \cdot \left(\frac{p_1}{\rho_1} + \frac{v_1^2}{2} \right) + \dot{m}_3 \cdot \left(\frac{p_3}{\rho_3} \right) = \left(\dot{m}_1 + \dot{m}_3 \right) \cdot \left(\frac{p_2}{\rho_2} + \frac{v_2^2}{2} \right) \quad \text{(D.4)}$$

Dividing throughout by $\dot{m}_1$ and transferring all terms to the left hand side,

$$\frac{p_1}{\rho_1} + \frac{v_1^2}{2} + \frac{\dot{m}_3}{\dot{m}_1} \cdot \left(\frac{p_3}{\rho_3} \right) - \left(1 + \frac{\dot{m}_3}{\dot{m}_1} \right) \cdot \left(\frac{p_2}{\rho_2} + \frac{v_2^2}{2} \right) = 0 \quad \text{(D.5)}$$

Substituting $x = \dfrac{\dot{m}_3}{\dot{m}_1}$ and using the relation between velocity and mass flow rate,

$v = \dfrac{\dot{m}}{A \cdot \rho}$, equation D.5 is simplified to the following expression.

$$\frac{p_1}{\rho_1} + \frac{1}{2} \cdot \left(\frac{\dot{m}_1}{A_1 \cdot \rho_1} \right)^2 + x \cdot \frac{p_3}{\rho_3} - \left(1 + x \right) \cdot \left[\frac{p_2}{\rho_2} + \frac{1}{2} \cdot \left(\frac{\dot{m}_2}{A_2 \cdot \rho_2} \right)^2 \right] \quad \text{(D.6)}$$

Rewriting this equation,

$$\frac{p_1}{\rho_1} + x \cdot \frac{p_3}{\rho_3} - (1+x) \cdot \frac{p_2}{\rho_2} = (1+x) \cdot \frac{1}{2} \cdot \left(\frac{\dot{m}_2}{A_2 \cdot \rho_2}\right)^2 - \frac{1}{2} \cdot \left(\frac{\dot{m}_1}{A_1 \cdot \rho_1}\right)^2 \qquad \text{(D.7)}$$

Simplifying this leads to the expression that relates the entrained flow, x in terms of flow conditions at the inlet, 1 and 3.

$$\frac{p_1}{\rho_1} + x \cdot \frac{p_3}{\rho_3} - (1+x) \cdot \frac{p_2}{\rho_2} = \frac{1}{2} \cdot \left(\frac{\dot{m}_1}{A_1 \cdot \rho_1}\right) \cdot \left[(1+x)^3 \cdot \left(\frac{A_1 \cdot \rho_1}{A_2 \cdot \rho_2}\right)^2 - 1\right] \qquad \text{(D.8)}$$

VITA

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