

# BIOMASS AS POTENTIAL REBURN FUEL IN COAL-FIRED BOILERS

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## **Abstract**

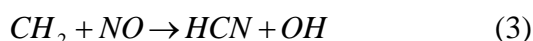
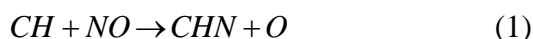
*Four world biomasses with volatility (VM/FC) ranging from 3.99 to 5.97 and Nitrogen content from 0.28-3.03% (daf) were evaluated as reburning fuels in a 20kW down-fired combustor. The effect of reburn fuel fraction  $R_{ff}$  on reburn zone stoichiometry ( $SR_2$ ), carbon burnout and NO reduction % was investigated. The effect of reburn zone residence time ( ) and primary zone NO level on NO emissions was also investigated. A 15%  $R_{ff}$  (thermal) of Cotton Stalk , Sheameal , Sugar cane bagasse and Wood Chips ) was found to be optimum resulting 84%,83%,81% and 75% NO reduction corresponding to 97.4 % 97.35%,97% and % 97% carbon burnout. The studied biomasses were found to be superior reburning fuels yielding higher NO reductions(%) and carbon burnout efficiencies compared to coal. The addition of 15%  $R_{ff}$  of the studied biomasses does not found to have any adverse effect on slagging and fouling.*

**Key Words:** *Residence time, Reburn fuel fraction, Reburn zone, Carbon burnout, Slagging, Fouling.*

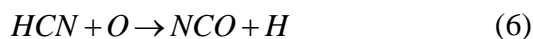
## **1. Introduction**

In post Kyoto protocol era, coal-fired power producing companies are striving for efficient and cost effective low emission retrofit technologies. Biomass co-firing is an attractive option in this regard, due to (nearly) CO<sub>2</sub> –neutral character of biomasses and lower NO<sub>x</sub> and SO<sub>2</sub> emissions than coal (Munir et al., 2010a). However, biomass injection according to the reburning configuration can result in substantial NO<sub>x</sub> emissions reductions (Ballester et al., 2008). The laboratory scale investigations of Kicherer et al., 1994; Abbas et al., 1994; Rudiger et al., 1996; Hein and Bemtgen, 1998; Spliethoff and Hein, 1998; Adams and Hardings, 1998; Maly et al., 1999; Hardings and Adams, 2000; Salzmann and Nussbaumer, 2001; Casca and Costa, 2005; Ballester et al., 2008 for NO<sub>x</sub> reburning using different reburn fuels concluded that reburning is an effective NO<sub>x</sub> control technique. Reburning or fuel staged combustion is a combustion modification technique to control NO<sub>x</sub> that utilizes the reaction of hydrocarbons with NO<sub>x</sub> to form molecular N<sub>2</sub>, under oxygen deficient conditions (Munir et al., 2010a). Reburning is a three stage combustion process in which the furnace is divided into three distinct combustion zones on the basis of air/fuel ratio. These

zones are defined as primary combustion zone, reburn zone and burnout zone. In the primary combustion zone, 70-80% of the coal is burned under fuel lean conditions (slightly oxidizing environment, i.e.  $SR_1 > 1$ ). The balance 20-30% of the fuel that may be the primary fuel (coal) or other secondary fuel is introduced in the reburn zone. The reburn fuel can also be different from the primary fuel. This zone is operated under fuel rich conditions (reducing environment,  $SR_2 < 1$ ). Additional air is added through overfire air ports situated just below the burnout zone to complete the combustion under oxidising conditions. This concept of three staged combustion was originally introduced by John Zink company and Wendt et al., and was based on the principle of Myerson et al. that hydrocarbon fragments (CH) from the fragmentation of reburn fuel can react with  $NO_x$  coming from primary combustion zone to produce molecular nitrogen (Harding and Adams, 2000) and the critical reactions involved in reburn zone are:



The HCN is then converted to other nitrogenous species via the following reactions (Thorne et al., 1988):



The subsequent conversion of N atoms is very fast and occurs through the rapid decay of NCO (Chen et al., 1986):

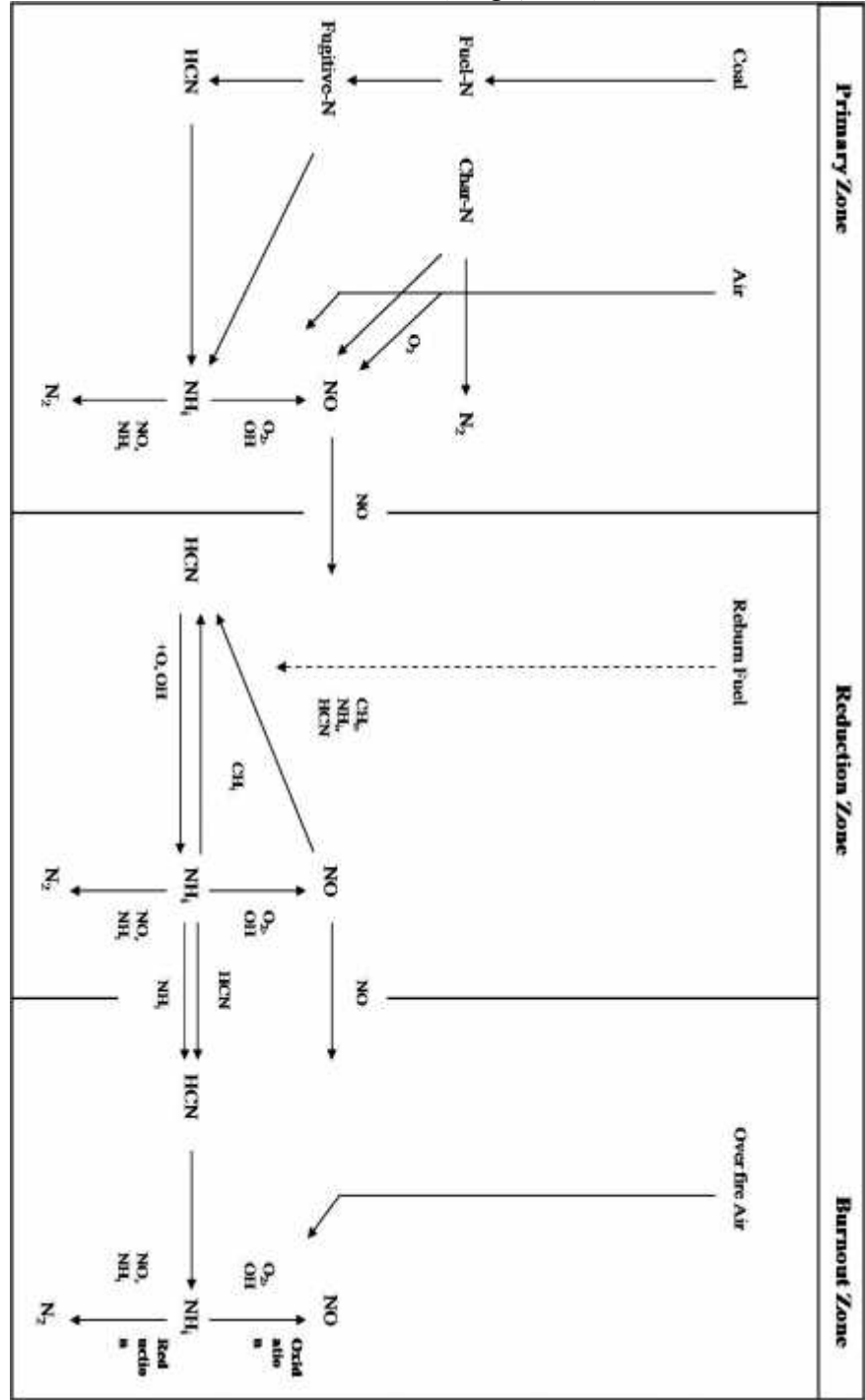


These N atoms are either recycled to form NO or converted to  $N_2$  via the reverse Zeldovich reaction:



Optimisation of these zones ensures the lowest unburnt carbon in the fly ash and minimum CO emission. Nitrogen content in the biomasses is beneficial since it leads to the additional reducing species (Salzmann and Nussbaumer 2001). Spliethoff et al. (2007) described the nitrogen formation and reduction in the fuel staging with pulverised coal as primary fuel and gas as reburn fuel (**Figure I**). Many commercial scale reburning demonstrations have been carried out in different countries of Europe, USA and Japan. There are few commercial scale reburning demonstrations given in **Table 1**.

Figure 1: Possible Chemical Pathways in Each of the Three Zones in Reburning Process (Singh, 2009)



**Table 1: Commercial Scale Reburning Demonstrations**

<b>Author</b>	<b>Company</b>	<b>Reburn fuel</b>	<b>Reactor type</b>	<b>Maximum NO reduction %</b>
<b>Smoot et al. (1998)</b>	B & W	Bituminous Coal ,20 – 30 %	60 – 110 MW, Cyclone coal fired Wisconsin	36 – 52 %
<b>Smoot et al. (1998)</b>	B & W	Sub-bituminous Coal ,20 – 30 %	-do-	53 – 62 %
<b>Smoot et al. (1998)</b>	EER	Natural Gas ,15 – 25 %	40 – 75 MW, tangential Illinois	67 %
<b>Smoot et al. (1998)</b>	EER	Natural Gas ,22 – 33 %	20 – 33 MW, cyclone Lakeside, Illinois	60 – 66 %
<b>Smoot et al. (1998)</b>	EER	Natural Gas, 5 – 20 %	172 MW, walled-fired Colorado	60 – 73 %
<b>Harding and Adams (2000)</b>	Eastman Kodak	Natural Gas, 20 – 21 %	Kodak # 43 ,605 K lb/h-cyclone	56 %
<b>Harding and Adams (2000)</b>	-do-	Natural Gas,20 %	Barrett 2,185 MW-corner	50 – 60 %
<b>Harding and Adams (2000)</b>	do	Natural Gas,5 %	Elrama,112 MW-roof	18 %
<b>Harding and Adams (2000)</b>	New York State Electric and Gas	Natural Gas, Up to 23 %	Greenidge 4,185 MW-corner	50 %
<b>Harding and Adams (2000)</b>	-do-	Natural Gas,20 %	Cherokee 3,158 MW-front wall	60 %
<b>Harding and Adams (2000)</b>	Illinois Power	Natural Gas,18 %	Hennepin 1,71 MW-corner	65 %
<b>Harding and Adams (2000)</b>	-do-	Natural Gas,16 %	Niles,112 MW-cyclone	50 %
<b>Harding and Adams (2000)</b>	Wisconsin Power & Light	Coal, Up to 30 %	Nelson Dewey,100 MW-cyclone	Upto 62 %
<b>DOE/FE-0391 (1999)</b>	Babcock & Wilcox	Bituminous Coal,29 – 30 %	110 MW-cyclone,	Greater than 50 %
<b>Lissianski et al. (1999)</b>	EER	Natural Gas,20 %	300 kW-BSF	~ 73 %
<b>Lissianski et al. (1999)</b>	EER	Walnut Shells 20 %	-do-	65 %
<b>Lissianski et al. (1999)</b>	EER	Willow wood 20 %	-do-	61 %
<b>Lissianski et al. (1999)</b>	EER	Furniture Waste 15 %	-do-	66 %
<b>Qiu et al. (2007)</b>	Yuanbaoshan Power Plant	Coal, 28.57 %	600 MW-tangentially fired	65.36 %

## 2. Experimental Section

### 2.1. Fuel Characterization

Coal, Shea meal and Wood Chips samples were provided by RWE nPower UK for this study. Russian coal received in two batches of the same lot is termed as RC1 and RC2. Shea meal (SM) is the residue from the nut of the shea tree (*Vitellaria paradoxa*) after the removal of fatty 'butter' for cosmetics and cooking. Sheameal contains the fleshy mesocarp, shell and husk. This biomass material is currently used as fuel in the UK power generating industry. UK is importing 5,420 tons of shea meal annually from Africa for co-firing for electricity production (DEFRA, 2007).

The Cotton Stalk and Bagasse samples were obtained from Pakistan. The Cotton Stalk sample (CS) was obtained from agricultural field of Lodhran, (Southern Punjab), Pakistan; cultivated during May-June season and handpicked in November-December season. Cotton stalk (*Gossypium*) is the stem of cotton plant without branches and leaves which is a leftover waste of the cotton crop. It is often burned in the fields as rotting vegetation since they harbour diseases that could affect future crops (Munir et al., 2010b; Akdeniz et al., 2004; Gemtos and Tsiricoglou, 1999; Reddy and Yang, 2009). CS has little value as a soil conditioner, and tillage operations, which bury the residue, have high-energy requirements and often degrade soil structure. Thus, cotton residue is considered a negative value biomass (Akdeniz et al., 2004; Coates, 2000). However, using it as supplementary fuel with coal will not only resolve disposal problem but also convert this bio-waste into a high value fuel.

Bagasse is the leftover of sugarcane after extraction of juice in the sugar mills. The bagasse sample used in this study (SB<sub>R</sub>) was collected from known sugar cane fields near Rahim Yar Khan City (South West Punjab), normally supplied to JDW sugar mills respectively. The crop harvested during February-March gives a good rated crop (for sugar) and the samples used in this study were taken from this crop.

The proximate and ultimate analysis along with bulk densities of the samples are given in *Table 2*.

**Table 2: Ultimate and Proximate Analysis and HHV of the Fuel Samples (As received basis)**

	SM	CS	WC	SB <sub>R</sub>	RC1	RC2
<b>Volatile Matter</b>	57.00	73.10	71.10	68.23	29.87	32.93
<b>Fixed Carbon</b>	24.58	18.00	11.90	17.11	45.48	49.15
<b>Ash</b>	4.29	4.90	1.70	9.56	14.00	11.69
<b>Moisture</b>	14.13	4.00	15.30	5.10	10.65	6.23
<b>Carbon</b>	41.70	45.20	42.20	42.34	60.36	66.30

	SM	CS	WC	SB <sub>R</sub>	RC1	RC2
Hydrogen	5.00	4.40	4.94	5.62	4.50	4.39
Nitrogen	2.47	1.00	0.28	0.24	1.84	2.09
Sulphur	0.09	0.00	0.10	0.001	0.30	0.35
Oxygen <sup>a</sup>	32.32	40.50	35.48	37.13	8.35	8.95
Bulk density (kg/m <sup>3</sup> )	490	310	270	180	620	619
HHV (MJ/kg)	17.70	17.70	16.39	17.37	27.29	27.16

<sup>a</sup>Calculated by difference

Volatility (ratio of volatile matter content to fixed carbon = VM/FC) of the reburn fuels calculated from Table 2 is given in Table 3

**Table 3: Volatility of the Reburn Fuels**

Fuels	VM/FC
SM	2.32
CS	4.06
WC	5.97
SB <sub>R</sub>	3.99
RC1	0.66
RC2	0.67

The particle sizes of the samples measured are given in Table 4. The average particle size was expressed as the volume mean diameter [4, 3] whereas d[0.1], d[0.5], and d[0.9] are the percentile diameters determined at the 10th, 50th, and 90th percentile of the undersized particles.

**Table 4: Particle size analysis**

Samples	D[4,3] μm	d[0.1] μm	d[0.5] μm	d[0.9] μm
SM	150.29	15.47	110.61	341.32
CS	209.89	19.08	141.89	507.50
WC	586.25	211.13	515.88	1070.86
SB <sub>R</sub>	586	206.85	511.90	1079.55
RC1	85.29	6.66	59.10	201.39
RC2	80.10	6.25	55.79	189.54

The results obtained for H<sub>2</sub>, CO and CH<sub>4</sub> from flash pyrolysis are presented in Table 5.

**Table 5: H<sub>2</sub>, CH<sub>4</sub> and CO Concentration during Flash Pyrolysis of Biomasses**

Gas species concentration	SM	CS	WC	SB <sub>R</sub>
H <sub>2</sub> (ml/mg)	0.049	0.068	0.0249	0.036
CH <sub>4</sub> (ml/mg)	0.015	0.034	0.016	0.014
CO (ml/mg)	0.032	0.089	0.051	0.050

The surface areas of char samples are presented in Table 6.

Table 6: Surface area of char samples

Feed stock chars	Surface area (m <sup>2</sup> /g)
SM	4.549
CS	3.958
WC	4.832
SB <sub>R</sub>	5.440
RC1	0.128

## 2.2 Experimental Methodology

The experimental set-up consists of a 20 kW down fired combustor, two fuel feeders, air and gas supply systems, calibration set-up, gas measuring analytical equipments, gas cylinder manifolds, water cooled sample probes, char sample collection quenching system, thermocouples, data logger and PC. The overall height of the combustor is 3.5 m (Figure 1). It comprises of nine bolted cylindrical sections of varying lengths with over forty utility ports available, distributed radially along the length of the furnace. This feature has made the system very flexible for fuel-staging, gas/solid sampling and convenient to vary the length reburn zone and residence time in the corresponding zone by moving the position of the burnout air. The axial distribution of the ports used in this study in the 20 kW combustor (Figure 2) for gas samples and burnout air injection locations along with thermocouple locations is given in Table 7.

Fuel is supplied by specially designed, metered and calibrated feeders. Coal and primary air are mixed in the inner section of the burner and secondary (swirl) air is introduced through an outer annulus. Fuel ignition and flame stabilisation takes place in a refractory lined quartz section. Primary air, secondary air, burnout air and reburn carrier nitrogen were metered through KDG 2000 rotameters. The combustor was heated up for 3 hours with natural gas before shifting to coal for every run. After 1 hour of operation with coal firing, steady state temperatures were achieved throughout the combustor. For reburning, the main Rospen feeder was used to supply primary coal to the burner and a second smaller Rospen feeder was used to inject reburn fuel in to the rig. The reburn fuel was pneumatically transported to the reburn zone using nitrogen as a carrier medium. The reburn fuels were injected into the rig through stainless steel lance.

The reburn fuel fraction is the ratio of the reburn fuel thermal output to the sum of primary fuel thermal output and reburn fuel thermal output and can be defined as:

$$R_{ff} (\%) = \frac{\text{Reburn fuel thermal output (MJ/h)}}{\text{Primary fuel thermal output (MJ/h)} + \text{Reburn fuel thermal output (MJ/h)}} \times 100 \quad (12)$$

The Primary zone stoichiometry ( $SR_1$ ) was fixed at 1.05 and reburn fuel injection location was fixed at port 3 (116.5cm from burner). The location of burnout air was varied (from port 4 to 9 (*Table 7*) to vary the residence time in the reburn zone. The primary zone  $SR_1$  and Reburn zone  $SR_2$  were estimated by using equation 13 and 14.

$$SR_1 = \frac{AFP}{STAR} \quad (13)$$

Primary air flow rate was fixed and secondary air was adjusted to get 1%  $O_2$  in the flue gases at exit. This was the confirmation that the primary zone is being operated at 5% excess air.

$$SR_2 = SR_1 \left[ 1 - \frac{RFF}{CFR + RFF} \right] \quad (14)$$

The reburn zone residence time was estimated using the following equation:

$$t_1 = \left( \frac{V_{Fr}}{V_{Fg}} \right) \times \left( \frac{T}{T_O} \right) \quad (15)$$

***Table 7: Ports and Thermocouples Axial Distance from Burner***

Port no.	Distance from burner (cm)	Thermocouple	Distance from burner (cm)
1	56.5	T1	57.5
2	86.5	T2	86.5
3	116.5	T3	161.5
4	146.5	T4	221.5
5	161.5	T5	299.0
6	191.5	Flue	304.0
7	221.5		
8	236.5		
9	259.5		
Flue	299.0		

The reburning experiments were designed with the following philosophy. We aimed to hold fixed the following operational parameters while investigating the effect of biomass addition for a range of reburning ( $SR_2$ ) conditions.

1. The overall stoichiometry was fixed at  $SR = 1.16$ . In practice this corresponds with a flue gas  $O_2$  level of about 3% (dry).
2. The primary air flow rate was fixed since it is used to transport the primary fuel into the combustor.



3. The overall thermal input to the combustor was fixed at 20 kW over the range of biomass ratios 5%, 10% and 15%, 20% and 25% (thermal).
4. Primary zone stoichiometry was fixed at 1.05.
5. Primary zone length was fixed by fixing reburn fuel injection location.

Variables:

- Reburn fuel fractions were varied (5%, 10%, 15%, 20% and 25%) to evaluate the effect of biomasses as reburn fuels for NO<sub>x</sub> control and reburn zone stoichiometry.
- Burnout air (BA) injection location was varied to determine optimum residence time in the reburn zone.

Gas samples were drawn through portable stainless steel water-cooled probes from any of the available ports. All the gas samples were dried and filtered before they enter individual online analysers. Instruments were calibrated before each run with certificated BOC special gases mixtures. Oxygen was measured using a Servomex Paramagnetic Analyser 570A; CO, CO<sub>2</sub> by NDIR analysers (Analytical Development Company; ABB Easyline IR CO<sub>2</sub> analyser); NO and NO<sub>x</sub> by a chemiluminescence analyser (Signal Ltd. series 440). In order that data for NO emission can be obtained at a particular plant condition, stable operation at that condition is achieved. Stability is deemed to occur when the measured variables (mainly O<sub>2</sub> and NO) do not drift from a constant average level for a period of up to 10 min. The data is logged every 10 s and post-run analysis for the period of the test within the run involves extracting data which has been averaged over 30–40 sampled data points. Statistical analysis of example data is presented in Table 8 for CS at 5% and 15% thermal contributions under reburning conditions.

**Table 8: Example Statistics of Data Analysis Method**

	5% CS +RC1	15% CS +RC1
O <sub>2</sub> Mean	2.9	3.1
Standard deviation	0.12	0.09
NO Mean	259	165
Standard deviation	3.7	2.7

NO measured at the furnace exit without reburning or addition of any biomass at SR=1.16 was taken as base line. The NO reduction was calculated by using equation:

$$NO\ red\ \% = \frac{(NO)_{baseline\ @\ 6\%O_2} - (NO)_{R_{ff}\ @\ 6\%O_2}}{(NO)_{baseline\ @\ 6\%O_2}} \times 100 \quad (16)$$

The base line value of NO was taken at the exit without reburning and without the addition of any biomass at an SR=1.16. This was then corrected at 6% O<sub>2</sub>. Similarly, all the NO values measured for different set of parameters were corrected to 6% O<sub>2</sub> to avoid any dilution effect.

Proximate analysis and ultimate analysis measurements were conducted using a thermo gravimetric analyser (Shimadzu TGA-50) and CE Instruments Flash EA1112 series, respectively. The calorific values given in *Table 2* were determined by using a Parr 6200 oxygen bomb calorimeter. The particle sizes of the samples given in *Table 4* were measured by laser diffraction (Malvern MasterSizer-2000). Flash pyrolysis of biomass samples was carried out by using GC-TCD (Gas chromatography coupled with thermal conductivity detector) technique. A series 204 chromatograph PYE UNICAM attached with thermal conductivity detector was coupled with pyroprobe 1000. The system was equipped with software PYE 204 GC/TCD. Argon was used as carrier gas. A maximum temperature of 1200°C was achieved at a heating rate 20°C/ms. The results obtained for H<sub>2</sub>, CO and CH<sub>4</sub> are presented in *Table 5*. Fly ash composition analysis of the samples was done using PANalytical Axios Advanced XRF spectrometer aided with PANalytical IQ+ Semi-quantitative software. For the determination of surface area (*Table 6*), the char samples were analyzed using surface area and pore size analyzer model (Quanta Chrome Nova 2200e) with N<sub>2</sub> adsorption technique.



### **3 Results and discussion**

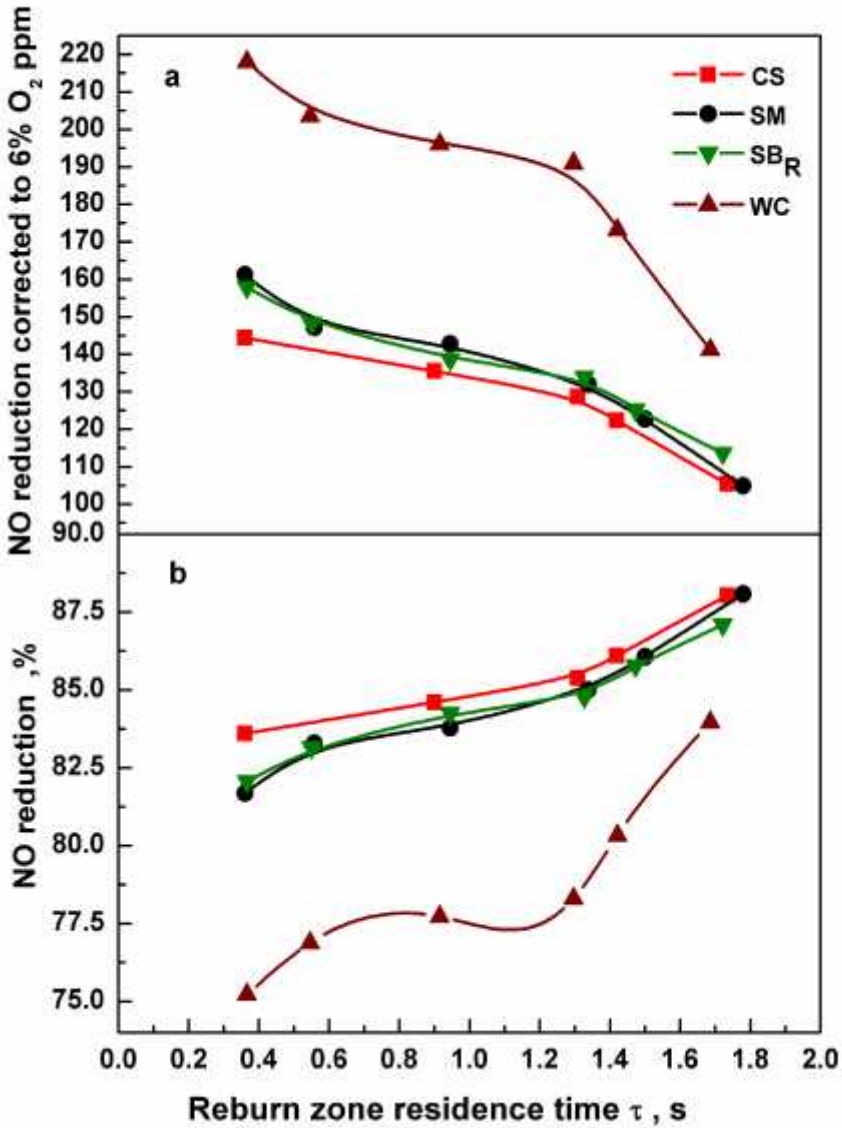
#### **3.1. Determination of Optimum Residence Time**

The residence time is the length of time spent by the reactants (fuel and air) in the furnace or a furnace zone for the reaction to occur. The residence time in the primary zone should be long enough to burnout the primary fuel. The reburn zone residence time must also be adequate enough for the decay of HCN, NH<sub>3</sub>, and NO and the formation of molecular nitrogen under the prevailing temperature conditions in the reburn zone (Zamansky et al., 1996).

As described above, the location of the reburn fuel injection was fixed at port 3 along with primary zone  $SR_1=1.05$  corresponding to a primary zone residence time of 1.3 s. The location of burnout air was varied (from port 4 to 9 *Table 7*) to vary the residence time in the reburn zone. A reburn fuel fraction ( $R_{ff}$ ) of 15% was used for CS, SM, WC, and  $SB_R$ . RC2 was used as primary fuel. The results shown in *Figure 3 (a & b)* revealed that NO emissions decreased with an increase in the reburn zone residence time. Ballester et al., 2008; Casaca and Costa, 2005; Kicherer et al., 1994; Spliethoff et al., 1996. Overmoe et al. (1985), Chen et al. (1986), Kilippinen et al. (1990) found a linear relationship between residence time and NO reduction efficiency. Moreover, they found that reburning effectiveness reduced significantly with the decrease in reburn zone residence time. However, they have reported contrasting results regarding optimum residence time in the reburn zone.

If the primary zone residence time is not long enough to consume the excess oxygen completely, the primary fuel will continue to oxidise in the reburn zone under oxidising conditions resulting a poor reburning efficiency. If the length of the reburn zone is increased too much, a large amount of unburned carbon could enter into the burnout zone leading to poor burnout efficiency. An adequate residence time along with oxygen content is required in the burnout zone for the completion of the combustion process. Therefore, an optimum location of the burnout air injection is required to be determined keeping in view the NO reduction efficiency and carbon burnout.

Figure 3 (a): Effect of Reburn Zone Residence Time on NO Emissions for 15%  $R_{fb}$ ,  $SR_1=1.05$ , RC2 as Primary Fuel, (b) Effect of Reburn Zone Residence Time on NO Reduction for 15%  $R_{fb}$ ,  $SR_1=1.05$ , RC2 as Primary Fuel



The carbon burnout (%) evaluated as a function of reburn zone residence time is given in Figure 4 and Figure 5.

Figure 4: Effect of Reburn Zone Residence Time on Carbon Burnout for RC2-15%  $R_{ff}$

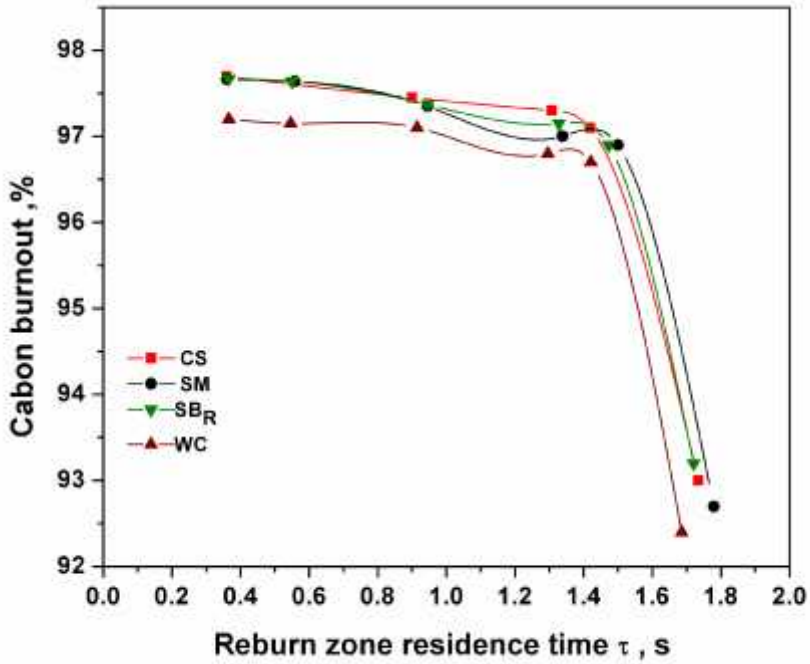
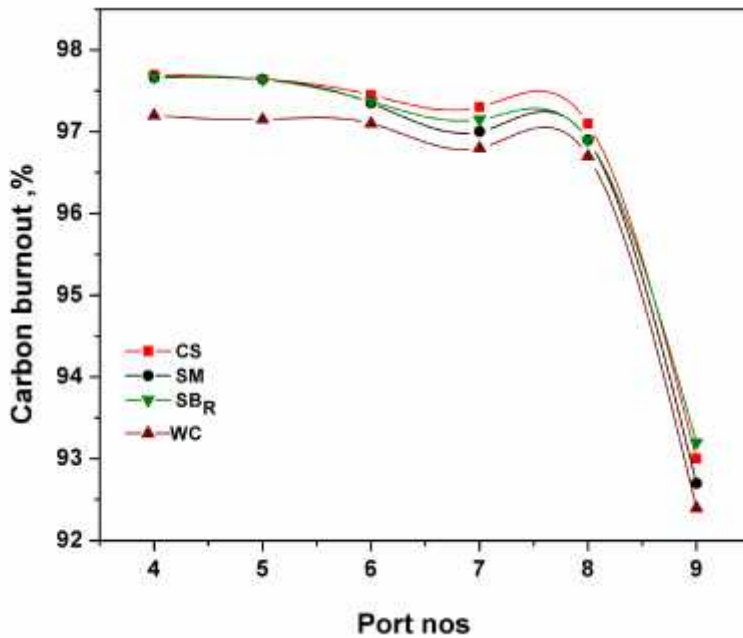


Figure 5: Effect of Burnout Air Injection Location on Carbon Burnout, 15 %  $R_{ff}$ , RC2 as Primary Fuel



It was estimated from the data plotted in *Figure 4* that reburn zone residence times of 1.42s, 1.5s, , 1.47s, and 1.42s for 15%  $R_{ff}$  of CS, SM,  $SB_R$ , and WC are the optimal where the carbon burnout begins to level off. These residence times corresponds to the burnout air (BA) injection location of port 8 at a distance of 236.5 cm from the burner (*Table 7, Table 9, Figure 4 and Figure 5*).

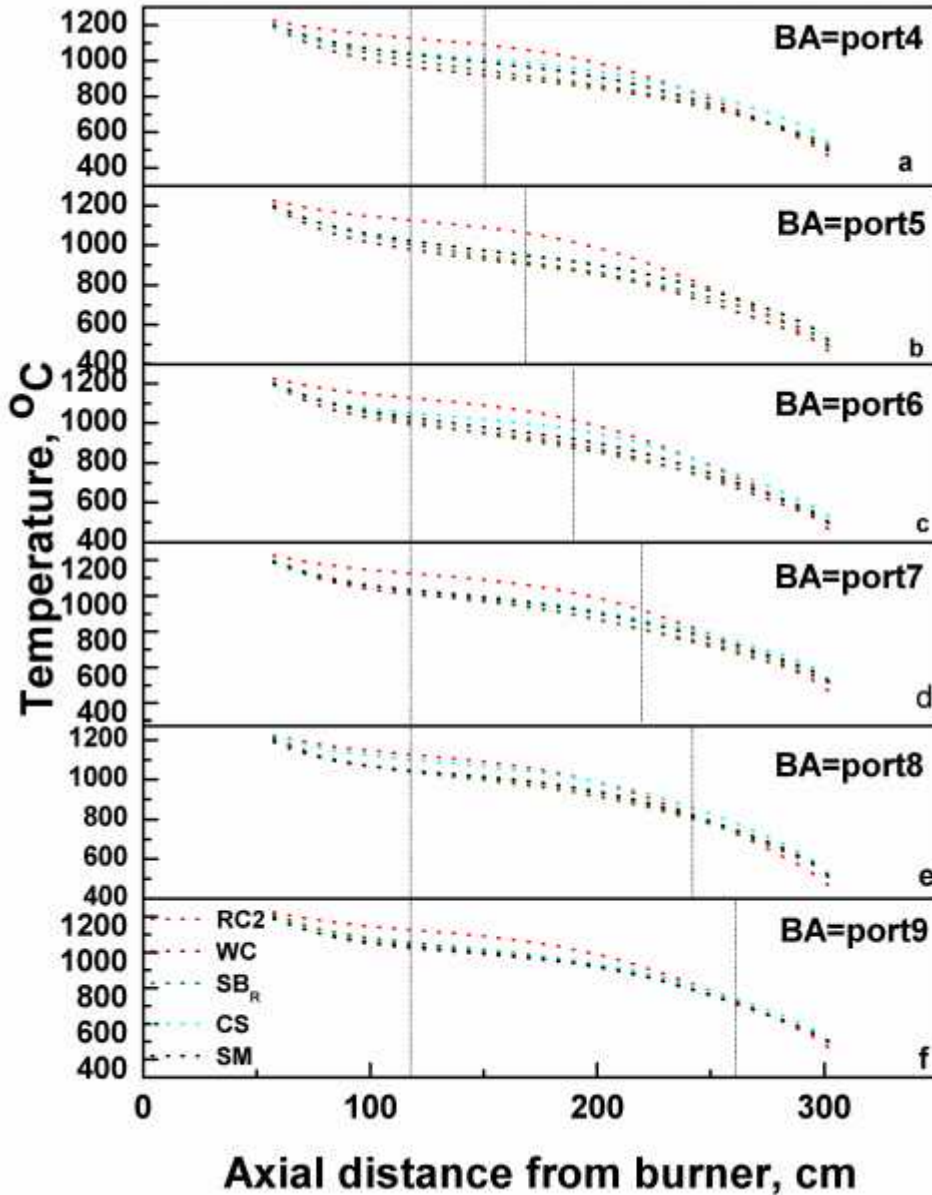
**Table 9: Estimated Reburn Zone Residence Times for Different Burnout Air Injection Location from Port 4 to 9**

Port no.	Axial distance from burner (cm)	(s) 15% $R_{ff}$ SM	(s)15% $R_{ff}$ CS	(s) 15% $R_{ff}$ $SB_R$	(s) 15% $R_{ff}$ WC
4	146.5	0.36	0.36	0.37	0.37
5	161.5	0.56	0.54	0.55	0.55
6	191.5	0.95	0.90	0.95	0.92
7	221.5	1.34	1.31	1.33	1.3
8	236.5	1.5	1.42	1.47	1.42
9	259.5	1.78	1.73	1.72	1.69

The difference in the residence time for the same thermal  $R_{ff}$  at the same burnout air (BA) injection location is due to a different air input (corresponding to their different mass flow rates due to their different calorific values) for same thermal input and different flow rates of carrier gas ( $N_2$ ) due to the variation in their bulk densities (*Table 2 and Table11*).

The temperature profiles for 15%  $R_{ff}$  of the studied biomasses with RC2 are shown in *Figure 6*. The temperature in between the two vertical dotted lines corresponds to the temperature in the reburn zone. The temperature before the first vertical line corresponds to the temperature in the primary combustion zone. The temperature after the second line corresponds to the temperature in the burnout zone. There was a general decrease in temperature in the reburn zone with reference to base line case. This could further reduce the formation of thermal  $NO_x$ . It was also found that the difference between temperature profiles for reburning and RC2 base line temperature profile continues to narrow as the residence time in the reburn zone increases (*Figure 6 a-f*). The optimum residence time is linked to the fuel type, fuel nitrogen content, initial  $NO_x$  concentration, furnace volume, the volumetric flow rate of the reactants into the furnace, temperature and mixing conditions in the reburn zone, so it is very difficult to make comparison between different experimental systems and furnaces. A rapid mixing can enhance the reaction rates leading to a reduced equilibrium time. At the same time, a rapid mixing may not be desired as slower mixing of fuel and combustion products may form fuel-rich pockets in the reburn zone which can improve NO reduction and prevent oxidation of nitrogen in the reburn fuel to NO (Yang et al., 1997; Naja, 1997).

Figure 6: Temperature Profiles for 15%  $R_{ff}$  of different Biomasses for different lengths of Reburn Zone and Burnout Zones,  $SR_1=1.05$ , RC2 as Primary Fuel

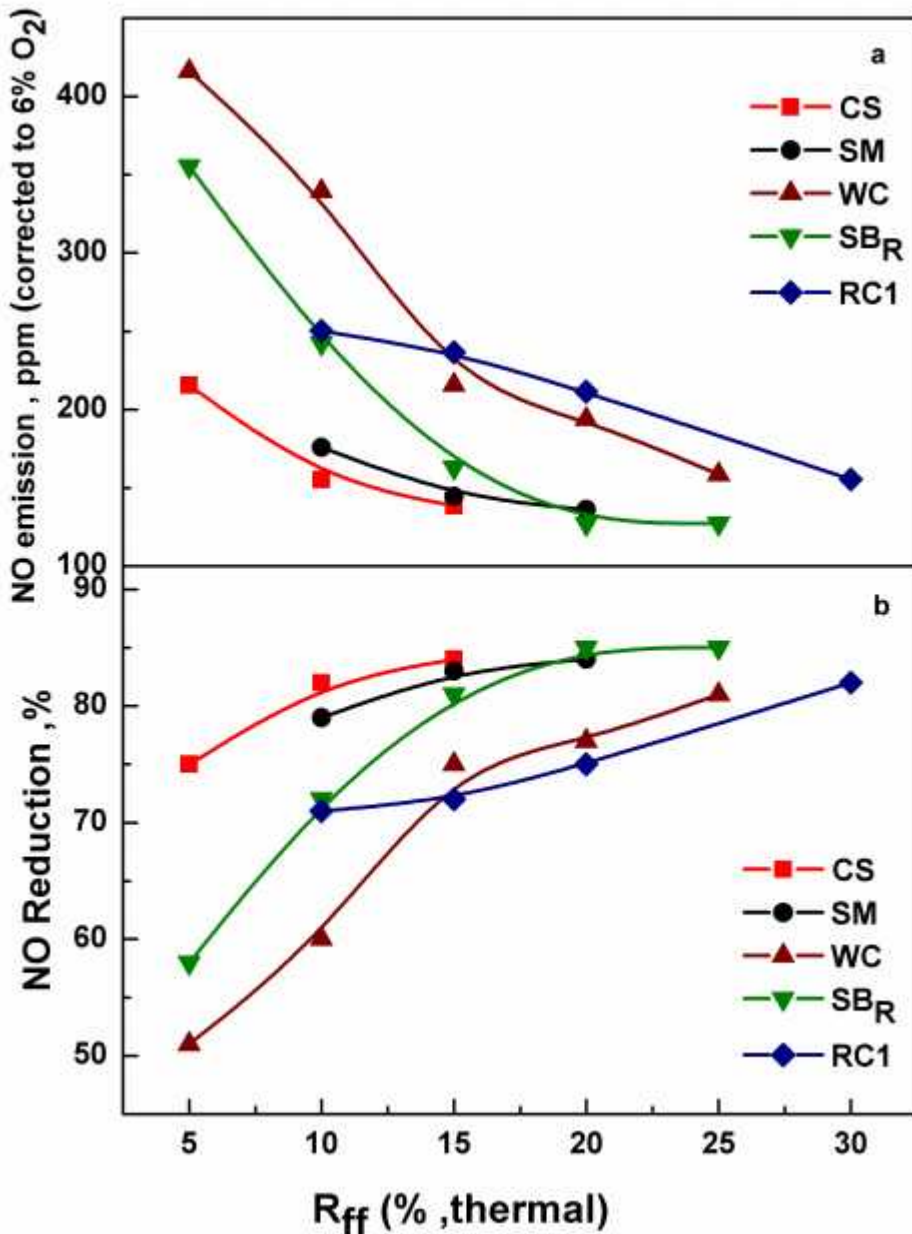


### 3.2. Influence of Reburn fuel fraction ( $R_{ff}$ )

Keeping in view the fundamental studies mentioned in section 1, a series of experiments have been conducted to examine the suitability of biomass as a secondary fuel for  $NO_x$  reburning. As described above,  $SR_1$  was fixed at 1.05 and the  $R_{ff}$  injection location at port 3 in order to achieve the optimum residence time. **Figure 7 (a)** shows the effect of  $R_{ff}$  on  $NO$  emissions and **Figure 7 (b)** shows the effect of  $R_{ff}$  on  $NO$  reduction (%).



Figure 7: (a) Effect of  $R_{ff}$  on NO emissions,  $SR_1=1.05$ ,  $SR=1.16$ , RC1 as Primary Fuel  
 (b) Effect of  $R_{ff}$  on NO reduction,  $SR_1=1.05$ ,  $SR=1.16$



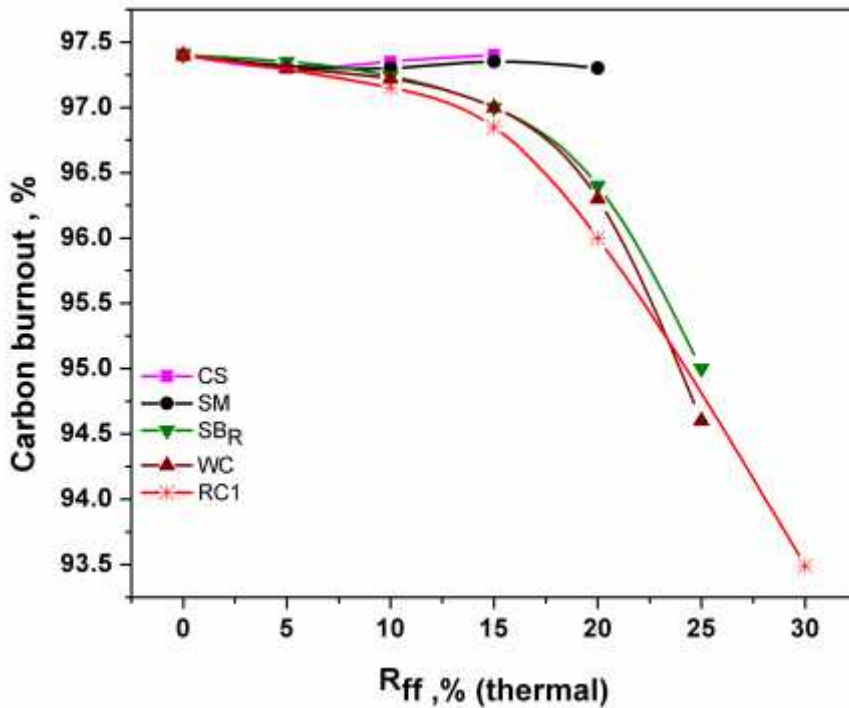
It was found that an increase in  $R_{ff}$  favoured NO reduction efficiency (Figure 7b). The maximum NO reductions were found to be 86%, 84%, 84%, 82%, and 81% for 25%, 20%, 15%, 30%, and 25%,  $R_{ff}$  of  $SB_R$ , SM, CS, RC1 and WC respectively. The  $R_{ff}$  combined with the  $SR_1$  defines the stoichiometric ratio ( $SR_2$ ) of the reburn zone (EQ-14). The relationship between  $R_{ff}$  and  $SR_2$  is

different for the fuels studied as  $SR_2$  is also dependent on the composition of the fuel (Casca and Costa, 2005).

The maximum NO reduction efficiency obtained by using RC1 as reburn fuel was 82% at 30%  $R_{ff}$  with  $SR_2 = 0.74$  (stronger reducing environment) (Figure 7 and Table 10) which resulted in lower carbon burn out of 93.49 (Figure 8). Similarly, SM at 20%  $R_{ff}$  yielded NO reduction of 84% at  $SR_2 = 0.76$  (Figure 7 and Table 10). The reburn zone stoichiometric ratios for  $SB_R$  at 20% and 25%  $R_{ff}$  were found to be 0.75 and 0.68 (Table 10) leading to a very low burnout (Figure 12 and Figure 8). Moreover, the reburn zone stoichiometric ratios for 20% and 25%  $R_{ff}$  of WC were found to be 0.73 and 0.66 (highly reducing) corresponding to a low burnout % (Figure 12 and Figure 13). A significant reduction in temperature, compared to the baseline temperature profile, was observed in the reburn zone when  $R_{ff}$  increased above 15% (Figure 10 a-d). For 20%  $R_{ff}$ , an average decrease of 200°C for WC and 167°C for  $SB_R$  was observed in the reburn zone. Similarly, for 25%  $R_{ff}$ , an average decrease of 200°C for WC and 250°C for  $SB_R$  in the reburn zone was observed (Figure 10 c-d). These reductions in temperatures are mainly due to a reduction in the primary fuel (RC1) input causing an average decrease of 225-250°C in the primary combustion zone for 80% and 75% input of RC1. This reduction in temperature may have a partial contribution in carbon burnout % reduction along with lower  $SR_2$ . Therefore, the optimum NO reduction efficiencies were found to be 84%, 83%, 81%, 75% corresponding to 15%  $R_{ff}$  of CS, SM,  $SB_R$  and WC respectively.

Different levels of NO reduction were obtained for similar levels of  $R_{ff}$  of biomasses. Moreover, NO reductions were found to be significantly higher for a  $R_{ff}$  of biomasses compared to same level of  $R_{ff}$  for RC1 (Figure 7b). This could be linked to VM content difference as biomasses have 1.9-2.4 times higher VM compared to coal (Table 2 and Table 3). Sami et al., 2001 also found that the higher the VM content, the larger the reduction in  $NO_x$  by the reburning process. The high volatile matter content in agricultural residue (Table 2) when released consists of mainly —CO,  $H_2$ ,  $CO_2$  and a high proportion of  $C_xH_y$  (mainly methane, ethane and tar vapours) (Werther et al., 2000) (Table 5). The values of NO recorded in the flue gas (corrected to 6%  $O_2$ ) were 214, 155 and 138 ppm for 5%, 10% and 15% thermal CS  $R_{ff}$ . The values of NO for SM found were 175, 144 and 136 ppm for 10%, 15% and 20%  $R_{ff}$  of SM. For  $R_{ff}$  of 5%, 10%, 15%, 20% and 25% of WC and  $SB_R$ , the NO levels (corrected to 6%  $O_2$ ) were found to be 416, 339, 215, 194, 158 ppm and 355, 242, 163, 127, 117 ppm respectively. The NO levels (corrected to 6%  $O_2$ ) for 10%, 15%, 20% and 30%  $R_{ff}$  of RC1 were found to be 250, 237, 211 and 155 ppm (Figure 7a).

The measured axial profiles of the gases in three distinct zones in the reburning process are shown in *Figures 9 (a-e)*. The dotted lines show the reburn fuel injection location at 116.5 cm and burnout air entering location at 236.5 cm downstream of the burner. The region before the injection of the reburn fuel (before first dotted line) is a fuel-lean zone and the region between the dotted lines represents the reburn zone. Whereas the region after the second dotted line (after the injection of BA) represents the burnout zone. The axial profiles of gas species given in *Figures 9 (a-e)* reveal that the combustor was operated in three well-defined, distinct zones with associated characteristics of fuel lean, fuel rich and fuel lean environments. The lowest oxygen concentrations, as expected, were found in the reburn zone for all  $R_{ff}$  of all the fuels. The lowest levels of oxygen and CO peaks in the reburn zone are an indication of a well-established fuel rich, oxygen-deficient zone. The concentration of CO was found to be significantly high in the reburn zone in the cases when biomasses were used as reburn fuel. Similarly, the consumption of oxygen was found to be higher in the case of biomass as reburn fuel compared to the case when RC1 was used as reburn fuel. For the same level of  $R_{ff}$ , the  $SR_2$  for biomass reburn fuels was found to be significantly lower than the case when coal was used as reburn fuel (*Table 10 and Figure 12*). This could be due to the fact that higher volatile content in the biomasses mainly consists of the gas species of CO and low grade hydrocarbons (*Table 5*) that has the tendency to evolve more easily than that in coal, even at low temperatures resulting in the formation of a stronger reducing environment in the reburn zone (Gani et al., 2005). A greater release of  $CH_i$  radicals as a result of biomass fragmentation in reburn zone (with stronger reducing environment) causes the drastic reduction in NO as CH are known to react with  $NO_x$  to convert it to molecular nitrogen.

Figure 8: Effect of  $R_{ff}$  on Burnout %

A  $R_{ff}$  of 15% was found to be optimum for CS, SM, WC and SB<sub>R</sub> (Figure 7, Figure 8 and Table 10). As evident from Figure 8 beyond an  $R_{ff}$  of 15% the carbon burnout (%) deteriorated rapidly except SM. This could be due to a significant decrease in the corresponding  $SR_2$  (Table 10). For 20%  $R_{ff}$  of SM, an increase of 1% in NO reduction was observed (Figure 7 b). An increase in SM  $R_{ff}$  from 15% to 20% corresponds to a 33% increase in mass input flow rate (Table 11). Keeping in view the NO reduction efficiency, carbon burnout % (Figure 7 and Figure 8) and slagging & fouling tendency, a  $R_{ff}$  of 15% was considered as an optimum value. Keeping in view the NO reduction % and corresponding carbon burnout efficiency, a  $R_{ff}$  of 10% for RC1 can be considered as an optimum value. An increase in  $R_{ff}$  beyond 10% of RC1 showed an adverse effect on burnout (%) (Figure 8). It was found that, as a reburn fuel, biomasses exhibited significantly higher NO reductions compared to RC1 when used as reburn fuel. An optimum 15%  $R_{ff}$  of CS, SM, WC and SB<sub>R</sub> exhibited NO reduction of 84%, 83%, 75%, 81%, respectively. To obtain a NO reduction efficiency of 82%, a  $R_{ff}$  of 30% RC1 was required that creates  $SR_2=0.73$  and deteriorates the burnout to 93.49% (Figure 8 and Figure 12). In the case of RC1 at 10% optimum  $R_{ff}$ , an NO reduction of 71% was found (Figure 7). The initial NO concentration measured in the primary zone was 854 ppm corrected to 6% O<sub>2</sub>. It was noticed that NO reduction (%) was limited to 10-15%  $R_{ff}$  for biomass fuels containing 1% nitrogen content (SM, CS, ) (Figure 7 and Table 2). For

WC and  $SB_R$  having nitrogen content of 0.28 and 0.24, NO reduction continued to increase at  $R_{ff}$  of 20-25%. Nevertheless, the magnitude of NO reduction (%) up to the respective optimum  $R_{ff}$  was found to be higher for the reburn biomass fuels containing nitrogen content 1% (Figure 7b and Table 2).

Figure 9: Axial Profile of  $NO$ -,  $CO$ -, and  $O_2$ -, in the Combustor,  $SR_1 = 1.05$ ,  $RC1$  as Primary Fuel, Reburn Fuel Injection Location = port 3, Burnout Air Injection Location = port 8, (a)  $R_{ff} = 15\%$  CS (b)  $R_{ff} = 15\%$  SM (c)  $R_{ff} = 15\%$  WC (d)  $R_{ff} = 15\%$   $SB_R$  (e)  $R_{ff} = 10\%$   $RC1$

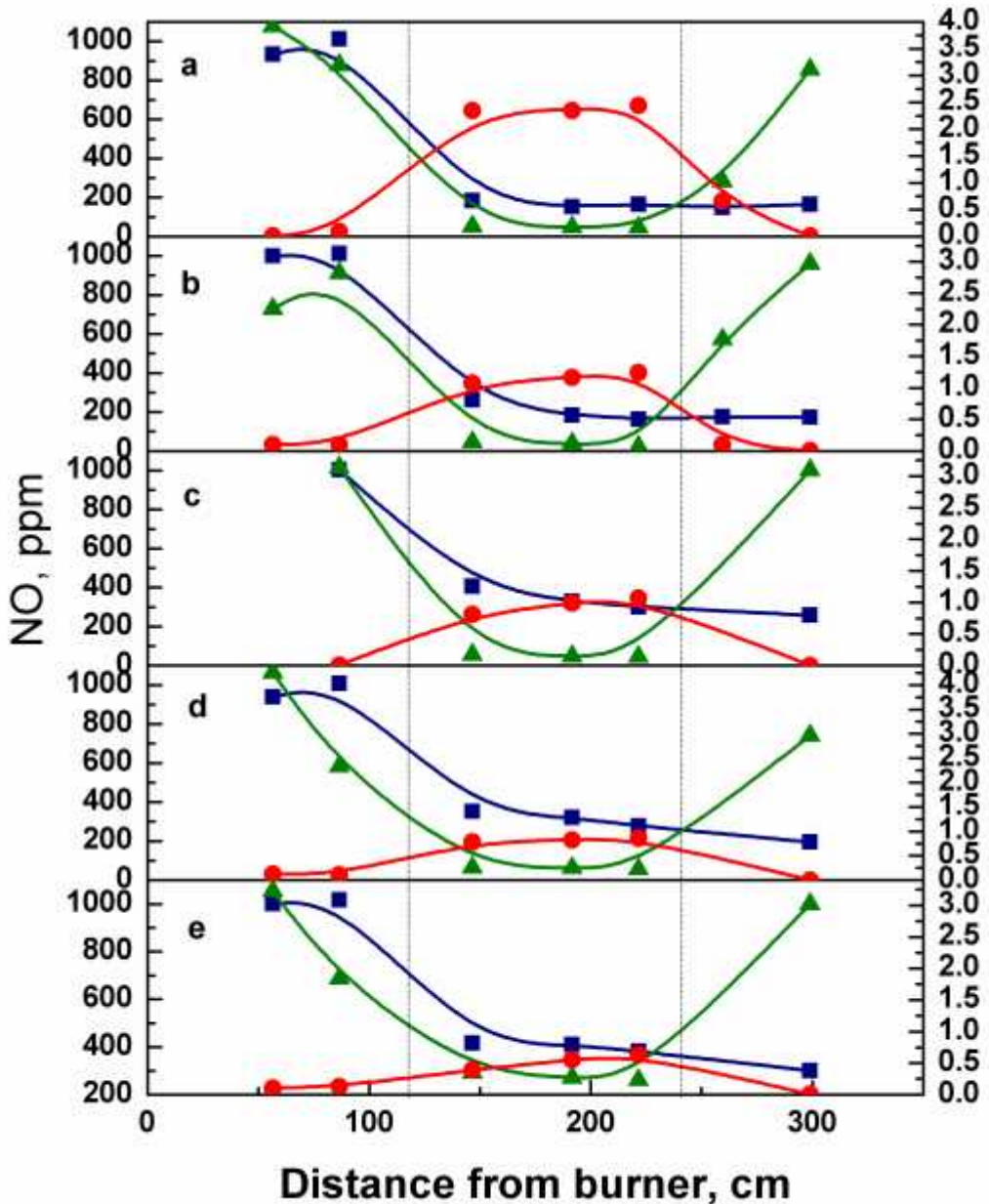
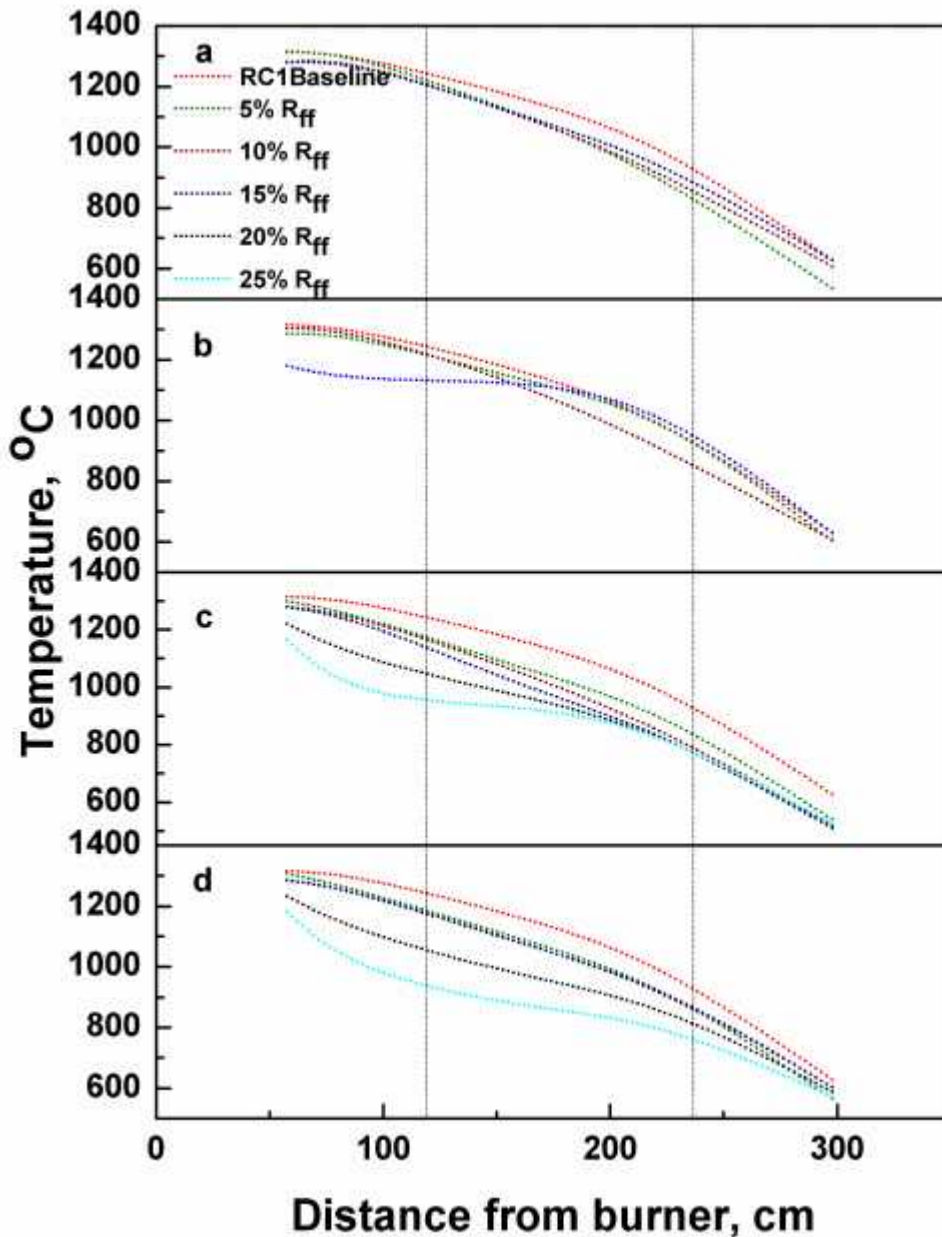


Figure 10: Temperature Profiles of different  $R_{ff}$  for Reburning, (a) CS (b) SM (c) WC (d)  $SB_R$ , Primary Fuel = RC1,  $SR_1 = 1.05$



### 3.3 Influence of Reburn Stoichiometry

The most important parameter that can influence the outcome of reburning process is reburn zone stoichiometry ( $SR_2$ ) and is considered to be a controlling parameter for  $NO_x$  reduction in the reburn zone (Chen and Ma, 1996; Harding and Adams, 2000). Reburn zone stoichiometry ( $SR_2$ ) is defined by EQ-14. The most important set of reactions involving devolatilization of reburn fuel in a fuel rich (oxygen deficient) environment producing  $C_xH_y$ , CO,  $NH_3$ , HCN species

and homogeneous reduction of NO to N<sub>2</sub> preventing the oxidation of nitrogenous species to NO taking place in the reburn zone (Ballester et al., 2008; Casca and Costa, 2005; Yang et al., 1997). The reactions involved have been described by EQ1 to 11 and *Figure 1*. An optimum value of the reburn zone stoichiometry is one which corresponds to a maximum NO reduction without much deterioration in carbon burnout efficiency.

Ballester et al., 2008; Smart and Morgan 1994; Kicherer et al., 1994, Hesselman 1994; Harding and Adams 2000; Salzmann and Nussbaumer 2001; Villas et al 2004 and Luan et al., 2009 have reported contrasting values for the optimum reburn zone stoichiometry. These contrasting results for the optimum SR<sub>2</sub> reported in literature could be due to the impact of different process parameters such as size of the combustor, mixing behaviour, oxygen content in the primary zone, reburn fuel types, residence time, nitrogen content of the reburn fuel and the temperature. The data plotted in *Figure 11 (a & b)* demonstrate the sensitivity of NO to the SR<sub>2</sub>.

It was found that a decrease in SR<sub>2</sub> favoured NO reduction efficiency. The reburn zone stoichiometry (SR<sub>2</sub>) was varied in the ranges 0.82-0.97, 0.76-0.90, 0.66-0.96, 0.68-0.97, and 0.73-0.95 for CS, SM, WC, SB<sub>R</sub> and RC1 as reburn fuels. The maximum NO reduction efficiencies were found to be 84%, 84%, 81%, 85%, and 82% for SR<sub>2</sub> of 0.82, 0.76, 0.66, 0.68, and 0.73 for 15% CS, 20% SM, 25% WC, 25% SB<sub>R</sub>, and 30% RC1 thermal reburn fuel fraction (R<sub>ff</sub>) (*Figure 7, Figure 11b, Figure 12 and Table 10*). Different values of SR<sub>2</sub> were obtained for the same thermal R<sub>ff</sub> of different fuels (*Figure 12 and Table 10*). The values of SR<sub>2</sub> were found to be significantly lowered compared to coal for the same thermal R<sub>ff</sub> (*Figure 12 and Table 10*). This could be linked to VM content difference as discussed above that biomasses have 1.91–2.4 times higher VM as compared to coal (*Table 2 and Table 3*).

The volatile matter content in the biomass samples ranges from 57-73.1% compared to volatile matter content of 29.87% for RC1. The volatility of reburning fuel which is measure of reactivity has an effect on NO<sub>x</sub> reburning. The VM/FC of the reburn fuel samples is given in *Table 3*. Biomasses have lower calorific value compared to coal. The amount of biomass fuels needed to produce the same thermal output is higher (*Table 11*). Therefore, in the case of biomasses as reburn fuel, a larger amount of reburn fuel with higher volatile matter content than coal produce higher concentration of CH fragments which converts primary NO to HCN and NH<sub>3</sub>. The biomasses on devolatilization mainly release CH radicals, CO and H<sub>2</sub>. The flash pyrolysis results of the samples are given in *Table 5*. However, the typical composition of the volatiles is strongly related to the fuel type and reburning conditions (Vilas et al., 2004).



Figure 11: (a) Effect of  $SR_2$  on NO emissions using different Reburn Fuels,  $SR_1=1.05$ , BA Injection Location = port 8. (b) Effect of  $SR_2$  on NO reduction using different Reburn Fuels,  $SR_1=1.05$ , BA Injection Location = port 8.

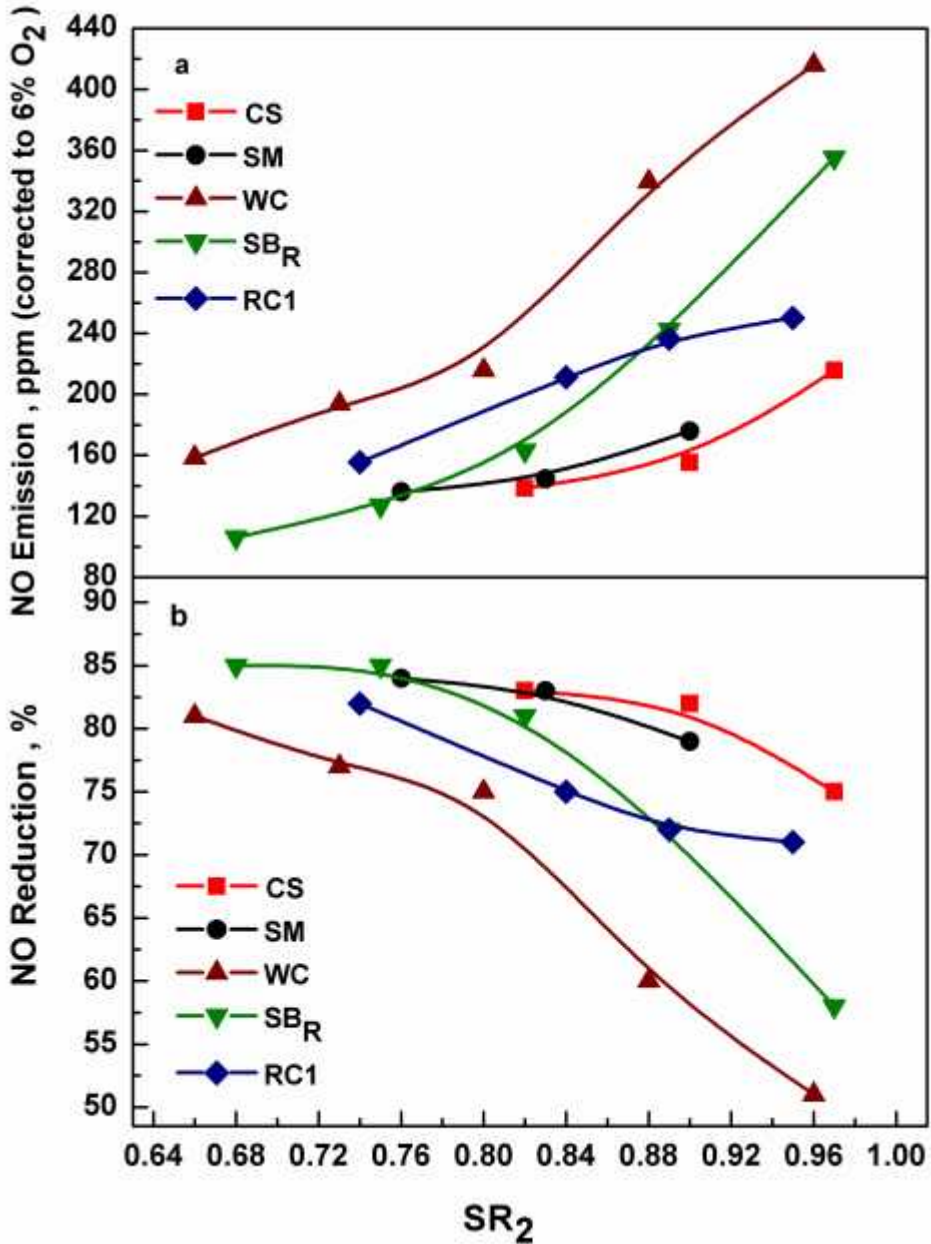




Table 10:  $SR_2$  Corresponding to  $R_{ff}$

$R_{ff}$ %, thermal	Reburn zone Stoichiometry ( $SR_2$ )					
	SM	CS	WC		$SB_R$	RC1
5		0.97	0.96		0.97	
10	0.90	0.90	0.88		0.89	0.95
15	0.83	0.82	0.80		0.82	0.89
20	0.76		0.73		0.75	0.84
25			0.66		0.68	
30						0.74

Figure 12: Effect of  $R_{ff}$  on  $SR_2$

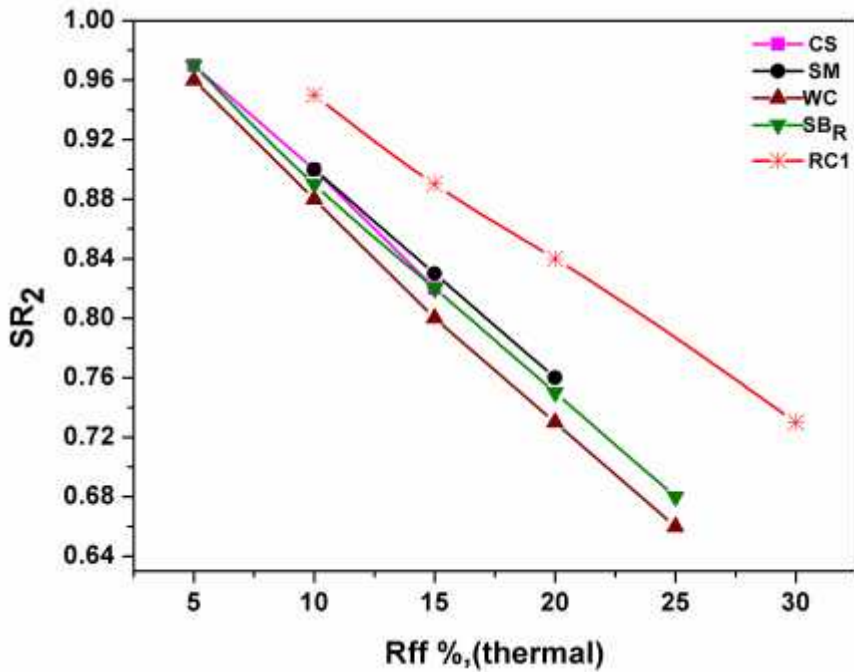
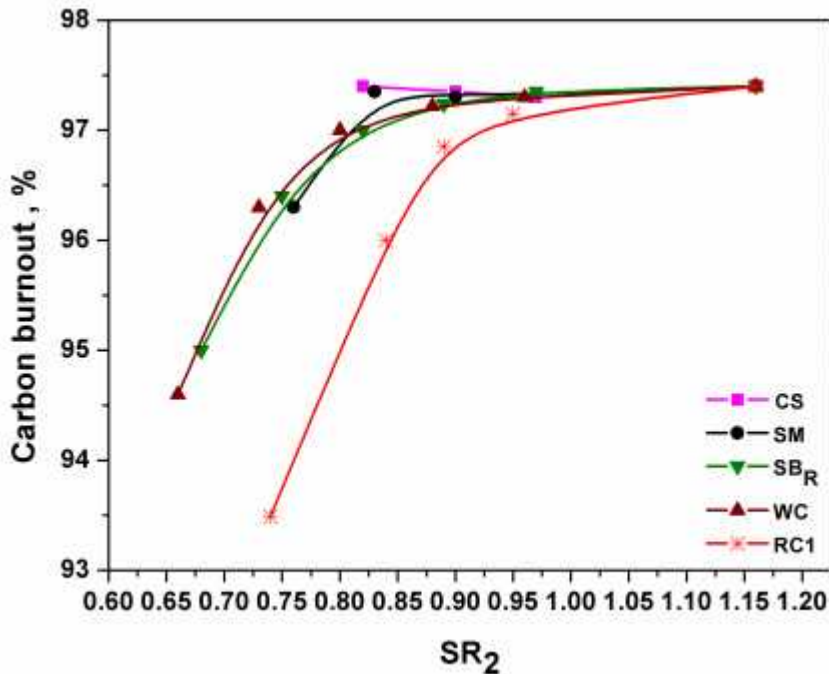


Table 11: Mass flow rates of the reburn fuels into the furnace for different thermal reburn fuel fractions

$R_{ff}$ %, thermal	Mass flow rate of the reburn fuels input (kg/hr)					
	SM	CS	WC		$SB_R$	RC1
5		0.22	0.24		0.23	
10	0.42	0.43	0.48		0.45	0.28
15	0.63	0.65	0.72		0.67	0.42
20	0.84		0.96		0.9	0.55
25			1.21		1.12	
30						0.83

Figure 13: Effect of  $SR_2$  on Carbon Burnout, %

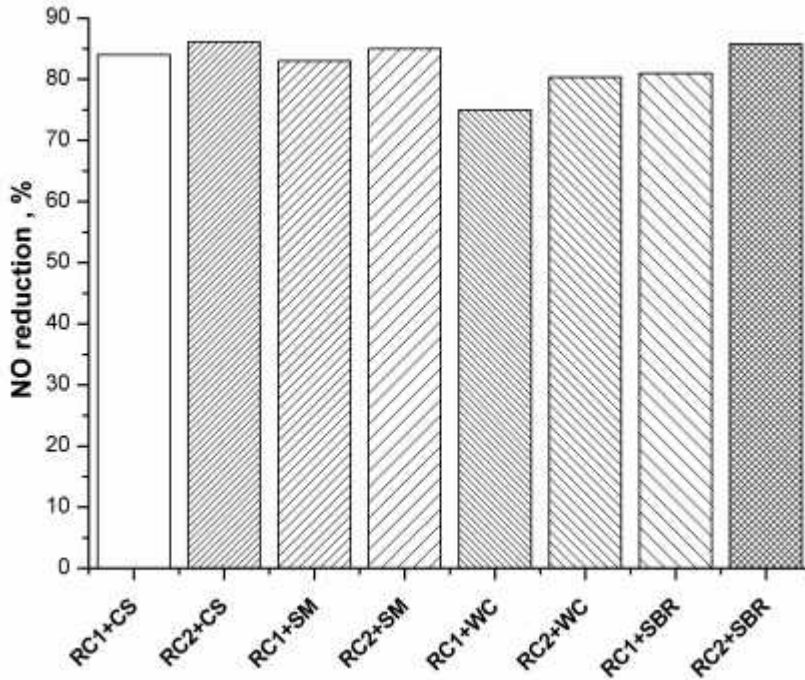
It was found from the analysis of the data plotted in Figure 11 and Figure 13 that the lower the  $SR_2$ , higher the NO reduction with reduced carbon burnout. It was found that by increasing the  $R_{ff}$ ,  $SR_2$  decreases (Figure 12) resulting an increase in NO reduction (Figure 11b). It can be seen from the data plotted in Figures 7 and Figure 13 that the higher the NO reduction, the lower the burnout efficiency. Therefore, 0.82 was found to be an optimum value of  $SR_2$  for CS and  $SB_R$ . The optimum values of  $SR_2$  for SM and WC were found to be 0.83 and 0.8 (Figures 11, 13 and Table 10). It was found that burnout rapidly decreases when  $SR_2 < 0.8$  (Figure 13). This was in agreement with the findings of Kicherer et al. (1994) and Casca and Costa (2005). For RC1, 0.95 was found to be the optimum  $SR_2$ . The results of reburning experiments plotted in Figure 8 revealed more adverse effect on burnout when coal was used as reburn fuel compared to biomasses. This could be due to significantly higher volatile matter content (Table 2, Table 3) creating stronger reducing environment. Furthermore, Munir et al., 2010a found that biomasses are more reactive than coal. The other reason could be the higher reactivity of biomass chars than coal (Munir et al., 2010c). The surface area of biomass chars was also found to be significantly higher than RC1 (Table 6).

### 3.4. NO concentration in the Primary Zone

Researchers have presented contrasting data on the relationship between initial  $NO_x$  concentration and  $NO_x$  reduction. Fujima et al. (1990) and Takashaki et al. (1982) concluded that  $NO_x$  reduction was independent of primary zone  $NO_x$

concentration. However, Mullholand et al. (1986, 1987) and Lanier et al. (1986) revealed that for lower initial  $\text{NO}_x$  concentrations, less  $\text{NO}_x$  reduction occurs. Harding and Adams (2000) used soft wood as reburn fuel and reported slight effect of initial  $\text{NO}_x$  concentration on  $\text{NO}_x$  reduction. Casca and Costa (2005) found that initial  $\text{NO}$  concentrations has an effect on  $\text{NO}$  reduction and at initial concentrations between around 500-970 ppm, the  $\text{NO}$  reduction obtained with biomass as reburn fuel was comparable with the levels obtained with ethylene and natural gas reburn fuels.

If the  $\text{NO}$  concentration is low at the point at which reburn fuel (containing fuel nitrogen) is injected, there could be a possibility that the balance between  $\text{NO}$ -forming reactions (from fuel nitrogen) and  $\text{NO}$ -reducing reactions (with fuel nitrogen-derived species) shifts in favour of  $\text{NO}$  formation leading to a decrease in  $\text{NO}$  reduction efficiency (Yang et al., 1997). This mechanism would also be dependent on the distribution of fuel-nitrogen between the volatile matter and residual char of the reburn fuel as volatile-nitrogen is believed to react as  $\text{HCN}$ . Biomasses contain higher volatile matter and very little char compared to coal. This could be the reason that despite the higher nitrogen content in SM than coal, a significant  $\text{NO}$  reduction was obtained (Table 2 and Figure 7). Salzmann and Nussbaumer (2001) concluded that reburning was a favourable method for fuels with high nitrogen content. A  $\text{NO}$  reduction % comparison of RC1-15%  $R_{ff}$  (biomasses) and RC2-15%  $R_{ff}$  (biomasses) is shown in Figure 14. The initial  $\text{NO}$  levels measured for RC1 and RC2 as primary fuel were 854 and 890 ppm corrected to 6%  $\text{O}_2$ . The residence times found in the reburn zone were 1.5 s, 1.42 s, 1.42 s and 1.47 s, for SM, CS, WC and  $\text{SB}_R$  respectively. The data plotted in Figures 3 (a & b) and Figure 14 show that  $\text{NO}$  reduction (%) was found to be higher in the case when RC2 (containing higher nitrogen (Table 2) and initial  $\text{NO}$  level than RC1) was used as primary fuel under the same operating conditions of residence time and  $\text{SR}_2$ .

Figure 14: NO reduction Comparison with RC1-15%  $R_{ff}$  and RC2-15%  $R_{ff}$ 

#### 4. Slagging and Fouling

Ash deposition on boiler surfaces is one of the major issues that needs to be addressed for designing and operating co-combustion equipment. Slagging is the deposition of fly ash on heat transfer surfaces exposed to heat radiation, adjacent to the flame. The depositions gathered in the heat recovery section surfaces (convective heat transfer section) are known as fouling. Biomasses have lower ash content as compared to coal (Table 2). At the same time, biomass ash materials are rich in alkali and alkaline earth metals (Table 12), and these are effective fluxes for alumina-silicates and lower the ash fusion temperature resulting an increase in slagging and fouling propensity. Despite the lower ash fraction in biomass, co-firing of biomass with coal can lead to an enhanced slagging and fouling propensity due to its lower fusion temperature depending on chemical and mineralogical composition of fly ash as well as on conditions (temperature and velocity distribution, reducing or oxidizing atmosphere and many others) in the furnace (Pronobis, 2005). The chemical composition of the ash samples is presented in Table 12.

**Table 12: Ash Chemical Composition of the Samples**

<b>Components (%)</b>	<b>SB<sub>R</sub></b>	<b>CS</b>	<b>SM</b>	<b>WC</b>	<b>RC1</b>
<b>Na<sub>2</sub>O</b>	0.67	1.90		3.64	0.247
<b>MgO</b>	1.79	2.50	3.67	3.79	1.225
<b>Al<sub>2</sub>O<sub>3</sub></b>	5.37	2.09	2.60	14.9	23.169
<b>SiO<sub>2</sub></b>	53.28	8.96	10.47	46.29	63.695
<b>P<sub>2</sub>O<sub>5</sub></b>	1.46	5.61	7.55	2.43	0.463
<b>SO<sub>3</sub></b>	3.31		13.94	1.95	0.046
<b>K<sub>2</sub>O</b>	7.72	34.57	42.49	4.79	2.229
<b>CaO</b>	11.68	18.15	6.92	8.43	1.333
<b>TiO<sub>2</sub></b>	0.60		0.27	2.41	0.970
<b>MnO</b>	0.42		0.23	0.68	0.085
<b>Fe<sub>2</sub>O<sub>3</sub></b>	9.97	2.41	7.66	10.4	5.527
<b>NiO</b>					0.003
<b>CuO</b>	0.167	0.11	0.14		0.031
<b>ZnO</b>	0.57	0.17	0.70		0.083
<b>Rb<sub>2</sub>O</b>		0.11	0.41		
<b>SrO</b>	0.21	0.56	0.19		0.149
<b>Y<sub>2</sub>O<sub>3</sub></b>			0.018		
<b>ZrO<sub>2</sub></b>			0.14		0.056
<b>BaO</b>					0.181
<b>PbO</b>					0.018

The most commonly used traditional S&F indices have been given in Table 13. The values calculated for approximation of propensity for slagging and fouling by using traditional S&F indices are presented in Table 14 for pure fuel firing.






**Table 13: Traditional Slagging and Fouling Indices**

<b>Slagging (basic to acidic compounds ratio) Index</b>	$\frac{B}{A} = \left( \frac{Fe_2O_3 + CaO + Na_2O + K_2O + MgO}{SiO_2 + Al_2O_3 + TiO_2} \right)$	B/A<0.5, low slagging inclination 0.5<B/A<1.0, medium B/A=1.00, high B/A 1.75, severe
<b>Simplified B/A</b>	$R_{(B/A)} = \left( \frac{Fe_2O_3 + CaO + MgO}{SiO_2 + Al_2O_3} \right)$	0.75 <R <sub>(B/A)</sub> low slagging
<b>Slagging (Babcock)-index</b>	$R_s = \frac{B}{A} \times S^d$ $S^d = \% \text{ of } S \text{ on dry basis}$	R <sub>S</sub> <0.6, low slagging inclination R <sub>S</sub> =0.6–2.0, medium R <sub>S</sub> =2.0–2.6, high R <sub>S</sub> >2.6, extremely high
<b>Fouling index</b>	$F_u = \left( \frac{B}{A} \right) \times (Na_2O + K_2O)$	F <sub>u</sub> 0.6, low fouling inclination F <sub>u</sub> =0.6–40, high F <sub>u</sub> 40, extremely high
<b>Ratio–slag viscosity index</b>	$S_R = \left( \frac{SiO_2}{SiO_2 + MgO + CaO + Fe_2O_3} \right) \times 100$	S <sub>R</sub> >72, low slagging inclination 72 S <sub>R</sub> >65, medium S <sub>R</sub> 65, high

Source: Masia et al. (2007); Pronobis (2005) and Skorupska (1993)

**Table 14: Calculated Values of the Traditional Ash Deposition Indices for Pure Fuels**

(Propensity indication key:

 - Severe,  - High,  - Medium,  - Low,  - Extremely low)

Index	SB <sub>R</sub>	CS	SM	WC	RC1
R <sub>b</sub>	31.85	59.54	60.75	31.05	10.56
B/A	0.5376	5.3867	4.5528	0.4882	0.1202
B/A(+P)	0.5623	5.8943	5.1192	0.5264	0.1255
R <sub>(B/A)</sub>	0.3998	2.0868	1.3969	0.3696	0.0931
R <sub>S</sub>	0.0054	0.00	0.4552	0.0586	0.0409
F <sub>u</sub>	4.5170	196.49	193.47	4.1156	0.2977
S <sub>R</sub>	69.44	27.98	36.44	67.17	88.74

It was noticed that the mean temperatures in the fuel rich reburn zone for optimum R<sub>ff</sub> of 15% CS, 15% SM, 15% WC and 15 % SB<sub>R</sub>, were about 1080°C, 1100°C, 960°C and 1039°C (Figure 10). The occurrence of fuel-rich zones at lower temperature in reburning configuration compared to pure coal firing (Figure 6 and Figure 10) can be comparatively advantageous for ash fusion propensity. The chemical composition of the ash for optimum R<sub>ff</sub> co-combustion experiments along with slagging and fouling indices is given in Table 15. The

evaluated S & F Indices for the optimum  $R_{ff}$  blends (Table 15) were found to be in the range attributed to lower inclination of S & F (Table 13).






**Table 15:- Ash Chemical Composition of Optimum  $R_{ff}$  Blends with their S&F**

Components (%)	RC1	15 % $R_{ff}$ RC1	15 % $R_{ff}$ CS	15 % $R_{ff}$ SM	15% $R_{ff}$ WC	15 % $R_{ff}$ SB <sub>R</sub>
Na <sub>2</sub> O	0.35	0.35	0.41	0.305	0.38	0.34
MgO	1.386	1.105	1.71	1.686	1.34	1.34
Al <sub>2</sub> O <sub>3</sub>	23.07	24.02	22.9	21.26	22.88	20.22
SiO <sub>2</sub>	63.35	62.08	61.1	60.17	63.21	61.66
P <sub>2</sub> O <sub>5</sub>	0.444	0.39	0.72	0.82	0.5	0.58
K <sub>2</sub> O	2.18	2.4	3.18	3.276	2.34	3.15
CaO	1.5	1.1	2.67	2.785	1.56	2.9
TiO <sub>2</sub>	0.995	0.976	0.94	0.91	0.998	0.9
Fe <sub>2</sub> O <sub>3</sub>	5.75	6.51	5.49	7.18	5.71	5.85
SO <sub>3</sub>	0.058	0.234	0.07	0.218	0.086	0.1
*Others						
Index	Slagging and Fouling Indices					
R <sub>b</sub>	11.166	11.465	13.46	15.232	11.33	13.58
B/A	0.1277	0.1316	0.158	0.185	0.13	0.164
B/A(+p)	0.1328	0.136	0.1669	0.195	0.1358	0.171
R <sub>(B/A)</sub>	0.0999	0.1012	0.1175	0.143	0.1	0.123
R <sub>S</sub>	0.0434	0.0447	0.041	0.0534	0.0373	0.042
F <sub>u</sub>	0.323	0.362	0.5689	0.66	0.3538	0.5725
S <sub>R</sub>	88.003	87.69	86.093	83.78	88.012	85.937

\*Include V<sub>2</sub>O<sub>5</sub>, Cr<sub>2</sub>O<sub>3</sub>, SrO, ZrO<sub>2</sub>, BaO, Mn<sub>3</sub>O<sub>4</sub>, NiO, CuO, ZnO, PbO, HfO

**Indices under Reburning Conditions**

(Propensity indication key:

 - Severe,  - High,  - Medium,  - Low,  - Extermely low)

**5. Conclusion**

The potential of biomasses as potential secondary fuel under reburning configuration was investigated. It was found that the same thermal fractions of reburn fuels (CS, SM, SB<sub>R</sub> and WC) produced different SR<sub>2</sub> for the same primary fuel flow rate, reburn zone length and SR<sub>1</sub> of 1.05. The biomasses studied produced significantly lower SR<sub>2</sub> compared to coal. This could be linked with 3.5 to 9 times higher volatility (VM/FC) of biomass compared to coal. Similarly, for the same reburn zone length, the reburn zone residence time was found different for each fuel that was due to different energy density of the fuels requiring different stoichiometric oxidant quantity. It was found that an increase in  $R_{ff}$  decreased SR<sub>2</sub> (stronger reducing environment) resulting an increase in NO reduction. At the same time, it was also found that higher the NO reduction,

lower is the carbon burnout. Using biomasses for NO<sub>x</sub> reburning exhibited significantly higher NO reductions and improved burnouts compared to the case when coal was used as reburn fuel or simple coal firing. A 15 % R<sub>ff</sub> of CS, SM, SB<sub>R</sub> and WC was found to be optimum resulting 84%, 83%, 81% and 75% NO reduction and carbon burnouts of 97.4%, 97.35%, 97% and 97%. To obtain a NO reduction efficiency of 82%, 30% R<sub>ff</sub> of RC1 was required producing a very low SR<sub>2</sub> of 0.73 and burnout of 93.49%.

The performance of biomasses as reburn fuel for NO<sub>x</sub> reburning proved to be excellent with much higher carbon burnout% than the case when coal (RC1) was used as reburn fuel.

It seems that combustion of pure SM and CS can cause slagging and fouling problems due to high percentages of low melting temperature compounds (K<sub>2</sub>O, CaO, Fe<sub>2</sub>O<sub>3</sub>) in their (biomasses) ashes. The evaluated S & F Indices for the blends with optimum biomass fraction were found to be in the range attributed to lower inclination of S & F. In the case of co-combustion of biomass with coal in reburning configuration studied revealed that the chemical composition of the biomass-coal blends ash does not differ significantly from the pure coal ash for optimum thermal fraction level of biomasses. Co-combustion of agricultural residues in reburning mode of operation with primary fuel (coal) seems more practicable than pure agricultural residues firing due to the potential risk of slagging and fouling. The biomasses as reburning fuels up to thermal fraction of 15% showed a synergistic effect with respect to slagging and fouling compared to pure biomass combustion and no adverse effect compared to pure coal firing.

### **Nomenclature**

AFP	=	Air flow rate supplied to the primary zone, litres /min at STP
STAR	=	Stoichiometric air requirement for fuel, litres/ min (fuel)
RFF	=	Reburn fuel flow rate, kg/hr
CFR	=	Coal (Primary fuel) flow rate kg/hr
V <sub>Fr</sub>	=	Volume of fuel rich zone, m <sup>3</sup>
V <sub>Fg</sub>	=	Volumetric flow rate of gases entering the fuel rich zone, m <sup>3</sup> /s
T	=	Average fuel rich zone gas temperature, K
T <sub>o</sub>	=	Ambient air temperature, K
Daf	=	Dry Ash free basis

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## **References**

- Abbas, T., Costen, P., Kandamby, N.H., Lockwood, F.C. and Ou, J.J. (1994). *The influence of burner injection mode on pulverized coal and biomass co-fired flames. Combustion and Flame*, 99(3-4), 617-625.
- Adams, B.R. and Harding, N.S. (1998). *Reburning using biomass for NO<sub>x</sub> control. Fuel Processing Technology*, 54(1-3), 249-263.
- Akdeniz, R.C., Acaroglu, M. and Hepbasli, A. (2004). *Cotton Stock as a Potential Energy Source. Energy Sources*, 26(1), 65-75.
- Ballester, J., Ichaso, R., Pina, A., González, M.A. and Jiménez, S. (2008). *Experimental evaluation and detailed characterisation of biomass reburning. Biomass and Bioenergy*, 32(10), 959-970.
- Casaca, C. and Costa, M. (2005). *The effectiveness of Reburning using Rice Husk as secondary fuel for NO<sub>x</sub> reduction in a furnace, Combustion Science and Technology*, 177(3), 539 - 557.
- Chen, S.L., McCarthy, J.M., Clark, W.D., Heap, M.P., Seeker, W.R. and Pershing, D.W. (1986). *Bench and pilot scale process evaluation of reburning for in-furnace NO<sub>x</sub> reduction. Symposium (International) on Combustion*, 21(1), 1159-1169.
- Chen, W.-Y. and Ma, L. (1996). *Effect of heterogeneous mechanisms during reburning of nitrogen oxide. AIChE Journal*, 42(7), 1968-1976.
- Coates, W. (2000). *Using cotton plant residue to produce briquettes. Biomass and Bioenergy*, 18(3), 201-208.
- DEFRA (2007). *UK Biomass Strategy. London: DEFRA. (www.Defra.gov.uk): Access 09, July 2009.*
- DOE/FE-0391. (1999). *The Babcock & Wilcox Company: Demonstration of Coal Reburning For Cyclone Boiler NO<sub>x</sub> Control. U.S. Department of Energy. DOE Report No. DOE/FE-0391.*
- Fujima, Y., Takahashi, T., Kunimoto, T. and Kaneko, S. (1990). *Field Application of MACT. Proceedings of the Reburning Workshop, Nordic Gas Technology, Sweden.*

Gani, A., Morishita, K., Nishikawa, K. and Naruse, I. (2005). *Characteristics of Co-combustion of Low-Rank Coal with Biomass. Energy & Fuels*, 19(4), 1652-1659.

Gemtos, T.A. and Tsirocoglou, T. (1999). *Harvesting of cotton residue for energy production. Biomass and Bioenergy*, 16(1), 51-59.

Harding, N.S. and Adams, B.R. (2000). *Biomass as a reburning fuel: a specialized cofiring application. Biomass and Bioenergy*, 19(6), 429-445.

Hein, K.R.G. and Bemtgen, J.M. (1998). *EU clean coal technology-co-combustion of coal and biomass. Fuel Processing Technology*, 54(1-3), 159-169.

Hesselmann, G. (1994). *Air stage and Reburning. Proceedings of the Nottingham Coal Conference: Prospects for Clean Coal Technology*, Nottingham, UK.

Kicherer, A., Spliethoff, H., Maier, H. and Hein, K.R.G. (1994). *The effect of different reburning fuels on NO<sub>x</sub>-reduction. Fuel*, 73(9), 1443-1446.

Kilpinen, P., Hupa, M., Glaborg, P. and Hadvig, S. (1990). *Kinetic parameter study of NO reduction chemistry in reburning. Proceedings of reburning Workshop, Nordic Gas Technology Center, Sweden.*

Lanier, W.S., Mulholland, J.A., Beard, J.T. (1988). *Reburning thermal and chemical processes in a two-dimensional pilot-scale system. Symposium (International) on Combustion*, 21(1), 1171-1179.

Lissianski, V.V., Zamansky, V.M. and Maly, P.M. (1999). *Kinetic Study of Biomass Reburning. in: 1999 Joint Meeting of the United States Sections of the Combustion Institute, Energy and Environment Research Cooperation Irvine, CA 92618.*

Luan, T., Wang, X., Hao, Y. and Cheng, L. (2009). *Control of NO emission during coal reburning. Applied Energy*, 86(9), 1783-1787.

Maly, P.M., Zamansky, V.M., Ho, L. and Payne, R. (1999). *Alternative fuel reburning. Fuel*, 78(3), 327-334.

Masiá, A.A.T., Buhre, B.J.P., Gupta, R.P. and Wall, T.F. (2007). *Characterising ash of biomass and waste. Fuel Processing Technology*, 88 (11-12), 1071-1081.

*Mullholland, J.A. and Hall, R.E. (1986). The effect of Fuel Nitrogen in Reburning Applications to a Firetube Package Boiler. Proceedings of the 1985 Joint Symposium on Stationary Combustion NO<sub>x</sub> Control.*

*Mullholland, J.A. and Hall, R.E. (1987). Fuel Oil Application for NO<sub>x</sub> Control to Firetube Package Boiler. Journal of Engineering for Gas Turbines and Power, ASME, 9, 207.*

*Munir, S., Nimmo, W., Gibbs, B.M. (2010 a). Sheameal and Cotton Stalk as potential fuels for co-combustion with coal. Bioresource Technology, 101(19), 7614-7623.*

*Munir, S., Nimmo, W., Gibbs, B.M. (2010 b). Co-combustion of agricultural residues with coal: Turning waste into Energy. Energy & Fuels, 24 (3), 2146-2153.*

*Munir, S. (2010 c). Co-combustion of Biomass with Coal. PhD Thesis, School of Process, Environmental and Materials Engineering, University of Leeds, UK.*

*Naja, T.A. (1997). Coal As reburn fuel for NO<sub>x</sub> reduction. PhD Thesis. Department of Fuel and Energy, University of Leeds, UK.*

*Overmoe, B.J., McCarthy, J.M., Chen, S.L., Seeker, W.R., Silcox, G.D. and Pershing, D.W. (1985). Pilot Scale Evaluation of NO<sub>x</sub> Control from Pulverized Coal Combustion by Reburning. Proceedings of the 1985 Joint Symposium on Stationary Combustion NO<sub>x</sub> Control.*

*Pronobis, M. (2005). Evaluation of the influence of biomass co-combustion on boiler furnace slagging by means of fusibility correlations. Biomass and Bioenergy, 28(4), 375-383.*

*Qiu, P., Wu, S., Sun, S., Liu, H., Yang, L. and Wang, G. (2007). Industrial test on coal reburning at a 600 MW utility boiler and NO<sub>x</sub> reduction. Korean Journal of Chemical Engineering, 24(4), 683-687.*

*Reddy, N. and Yang, Y. (2009). Properties and potential applications of natural cellulose fibers from the bark of cotton stalks. Bioresource Technology, 100 (14), 3563-3569.*

*Rudiger, H., Greul, U., Spliethoff, H. and Hein, K.R.G. (1996). Pyrolysis Gas of Biomass and Coal as a NO<sub>x</sub> Reductive in a Coal Fired Test Facility. Combustion Science and Technology, 121(1), 299 - 315.*

Salzmann, R. and Nussbaumer, T. (2001). Fuel Staging for NO<sub>x</sub> Reduction in Biomass Combustion: Experiments and Modeling. *Energy & Fuels*, 15(3), 575-582.

Sami, M., Annamalai, K. and Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. *Progress in Energy and Combustion Science*, 27(2), 171-214.S

Singh, S. (2009). Waste tyres and plastics as potential reburn fuels for reduction of NO<sub>x</sub> in large scale combustion systems. PhD Thesis, Energy and Resource Research Institute, University of Leeds, UK.

Skorupska, N.M. (1993). Coal specifications-impact on power station performance, IEACR/52, London, UK, IEA Coal Research, 120.

Smart, J.P. and Morgan, D.J. (1994). The effectiveness of multi-fuel reburning in an internally fuel-staged burner for NO<sub>x</sub> reduction. *Fuel*, 73(9), 1437-1442.

Smoot, L.D. Hill, S.C., and Xu, H. (1998). NO<sub>x</sub> control through reburning. *Progress in Energy and Combustion Science*, 24(5), 385-408.

Spliethoff, H. (2007). Advanced Solid Fuel Conversion-Fundamentals, Technologies and Research Demand, Lehrstuhl für Energiesysteme TUM. The 9<sup>th</sup> International Conference on Energy for a Clean Environment (Clean Air 2007), Oporto, Portugal. July, 2007.

Spliethoff, H., Greul, U., Rüdiger, H. and Hein, K.R.G. (1996). Basic effects on NO<sub>x</sub> emissions in air staging and reburning at a bench-scale test facility. *Fuel*, 75(5), 560-564.

Spliethoff, H., and Hein, K.R.G. (1998). Effect of co-combustion of biomass on emissions in pulverized fuel furnaces. *Fuel Processing Technology*, 54(1-3), 189-205.

Takahashi, Y., Sakai, M., Kunimoto, T., Ohme, S., Haneda, H., Kawamura, T. and Kaneko, S. (1982). Development of MACT In-furnace NO<sub>x</sub> Removal Process for Steam Generation. *Proceedings of the 1982 Joint Symposium on Stationary Combustion NO<sub>x</sub> Control*.

Thorne, L.R., Branch, M.C., Chandler, D.W., Kee, R.J. and Miller, J.A. (1988). Hydrocarbon/nitric oxide interactions in low-pressure flames. *Symposium (International) on Combustion*, 21(1), 965-977.

*Vilas, E., Skifter, U., Jensen, A.D., López, C., Maier, J. and Glarborg, P. (2004). Experimental and Modeling Study of Biomass Reburning. Energy & Fuels, 18(5), 1442-1450.*

*Werther, J., Saenger, M., Hartge, E.-U., Ogada, T. and Siagi, Z. (2000). Combustion of agricultural residues. Progress in Energy and Combustion Science, 26(1), 1-27.*

*Yang, Y.B., Naja, T.A., Gibbs, B.M. and Hampartsoumain, E. (1997). Optimization of operating parameters for NO reduction by Coal Reburning in a 0.2 MWt Furnace. Journal of Institute of Energy, 70, 9-16.*

*Zamansky, V.M., Ho, L., Maly, P.M. and Seeker, W.R. (1996). Reburning promoted by nitrogen and sodium-containing compounds. 26<sup>th</sup> Symposium (International) on Combustion, The Combustion Institute, Pittsburg, 26, 2075.*