

# **AIR AND FUEL STAGED CO-COMBUSTION OF COAL WITH BIOMASS IN POWER STATION BOILERS**

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## **Abstract**

*The overall objective of this investigation is to develop a technology to employ biomass as substitute fuel for coal to help reduce NO<sub>x</sub>. It was achieved by governing NO<sub>x</sub> formation kinetics through in-furnace air and fuel staged co-combustion technology. An extensive series of experimentation was carried out in a 20 kW down fired combustor to evaluate the effect of co-firing of Shea meal, Cotton stalk and Wood chips on NO<sub>x</sub> emissions and combustion efficiency. Shea meal, Cotton stalk and Wood chips were co-fired under unstaged, air- staged and fuel- staged (Reburning) configurations. For air staging, optimum value of primary zone stoichiometry  $SR_1=0.9$  was kept fix and, biomass blending ratio (BBR) was varied 5%, 10% 15% on thermal basis. A BBR of 10% was found optimum yielding a NO reduction (%) of 51%, 60% and 53% for Shea meal, Cotton Stalk and Wood chips respectively. The lengths of the reburn zone and burnout zone were kept fix during fuel staging experiments. Shea meal, Cotton stalk and Wood chips were evaluated as reductive fuel using different reburn fuel fractions ( $R_{ff}$ ) and reburn zone stoichiometry ( $SR_2$ ) values. A reburn fuel fraction of 15% (thermal) was found to be optimum for Shea meal Cotton stalk and Wood chips displaying a NO reduction of 83%, 84% and 75% at an optimum reburn zone stoichiometry ( $SR_2$ ) of 0.83, 0.82 and 0.8 respectively.*

**Keywords:** *Biomass blending ratio, Reburn fuel fraction, Stoichiometry, Co-combustion, Air-staged, Fuel staging.*

## **1. Introduction**

Air pollution has become a threat for the stability of the world's climate, economy and population mainly as a result of energy conversion and consumption processes. Coal is one of the major sources of pollutant emissions. At present, coal is the largest source of electricity generation contributing a share of 41% in the total World electricity generation mix (IEA, 2008).

Regional environmental legislation bodies have imposed more stringent limits for regulating air quality and off-setting the emissions from coal- fired power plants (Sami et. al., 2001). For post 2015, European Parliament has set limit of 200mg/Nm<sup>3</sup> for NO<sub>x</sub> emissions (at 6% O<sub>2</sub> content) from large combustion plants (>500MWth) (EC, 2001.80).

Of the available techniques and methods for reducing gaseous emissions of NO<sub>x</sub>, SO<sub>2</sub> and CO<sub>2</sub> from existing coal fired power plants, probably the fastest, easiest and the most economical way is to replace the combusted fossil fuels by biomass through co-firing. (IEA., 2009; Sami et al., 2001; Narayanan, K.V. and Natarajan E., 2007; Demirbas, 2005; Baxter, 2005; Tillman, 2000). However, an extensive amount of research and development is required to explore and realize the potential of co-firing of biomasses with coal to control NO<sub>x</sub> and SO<sub>2</sub> emissions from large scale combustion plants (Sami et al., 2001; Demirbas, 2005; Kwong et al., 2007; Broek et al., 1996; Bain et al., 1998; Hein and Bemtgen, 1998; Spliethoff and Hein, 1998; Tillman., 2000; Demirbas, 2003; Hartmann and Kaltschmit, 1999).

Agricultural residues are a form of biomass that is renewable and largely not utilized in the energy recovery schemes (Putun et al., 2005). Many of the agricultural residues are considered as wastes and are often land filled causing CH<sub>4</sub> release having 21 times higher global warming potential (Sami et al., 2001). The volatiles from agricultural residues are mainly the combustibles—CO, H<sub>2</sub>, C<sub>x</sub>H<sub>y</sub> (Werther et al., 2000). It was found by Munir et al., 2009 that combustion of volatiles was the dominant step during the combustion of agricultural residues. A greater concentration of CH<sub>i</sub> radicals from biomass devolatilization process would enable us to utilize reductive power of the hydrocarbons, under low O<sub>2</sub> conditions, as HC are known to react with NO<sub>x</sub> to produce molecular N<sub>2</sub>. (Splietoff and Hein, 1998; Werther et al., 2000; Baxter, 2005). These facts indicate that co-combustion of agricultural residues with coal may have a positive effect on NO<sub>x</sub> reduction when operated under air and fuel staged conditions.

This article discusses the potential of co-firing Sheameal ,Cotton stalk and Wood Chips with coal for the reduction of NO<sub>x</sub> under air staging and reburning conditions in a 20 kW down fired combustor. The effect on SO<sub>2</sub> e mission during NO<sub>x</sub> reburning has also been studied.

## **2. Experimental Methodology**

### **2.1 Samples**

Cotton stalk (CS) samples were obtained from southern agricultural fields of the Punjab in Pakistan. Pakistan's cotton vision program targets cotton production at 15 million bales by the year 2010 (Hanif et. al. 2004). The cotton plant residue generated is equivalent to three to five times the weight of the fibre produced (Reddy and Yang, 2009). Cotton stalk is the stem of cotton plant (*Gossypium*) without branches and leaves which is a leftover waste of the cotton crop. It has been estimated that nearly 2.5–3.5 tons of stalks are generated per acre of cotton grown. Cotton Stalks are often burned in the field as leaving them may result in damage to future crops due to diseases, infestation, etc (Reddy and Yang., 2009, Munir et al., 2009; Gemtos and Tsericoglou, 1999; Koopmans and Koppejan,

1998; Akdeniz et al., 2004). The annual amount of cotton stalk (residue) generated in Pakistan is 20.249 million tons per year (Memon et. al., 2006). Shea meal (SM) is the residue from the nut of the shea tree (*Vitellaria paradoxa*) after the removal of fatty ‘butter’ and contains the fleshy mesocarp, shell and husk. This biomass material is currently used as fuel in the UK power generating industry (Munir, S., et al., 2009). UK is importing 5,420 tons of shea meal annually from Africa for co-firing for electricity production (DEFRA, 2007). Shea meal, Wood chips and coal (Russian coal) RC for this study was provided by (RWE nPower) UK.

## 2.2 Fuel Characterization

Proximate analysis and ultimate analysis measurements were conducted using a thermogravimetric analyzer (Shimadzu TGA-50) and CE Instruments Flash EA1112 series, respectively. The proximate TG method involves heating the sample (under N<sub>2</sub>) at a rate of 10°C/min to 110°C then holding for 10 min to obtain the weight loss associated with moisture. The temperature is then ramped from 110°C at a rate of 25°C/min to 910°C (under N<sub>2</sub>) and held for 10 min to obtain the weight loss associated with volatiles release. Air is then introduced into the furnace chamber to oxidize the carbon in the char and the weight loss associated with this is the fixed carbon. The remaining material after combustion is the ash. The calorific values were determined by using Parr 6200 oxygen bomb calorimeter.

Ultimate and proximate analysis and HHV of the coal used RC, SM and CS, are given in **Table 1**. It is evident from **Table 1** that CS, SM and WC contain a higher proportion of oxygen, hydrogen and less carbon. The H/C ratio of SM=0.12, WC=0.12 and O/C ratio of SM =0.77, WC=0.84 fall in the overlapping region attributed to biomass and RDFs on a Van Kerevelin type diagram (**Figure1**) whereas CS (H/C=0.09; O/C=0.89) is located in the region that is typically attributed to biomass (Figure1). This indicates a difference of volatility among the fuels.

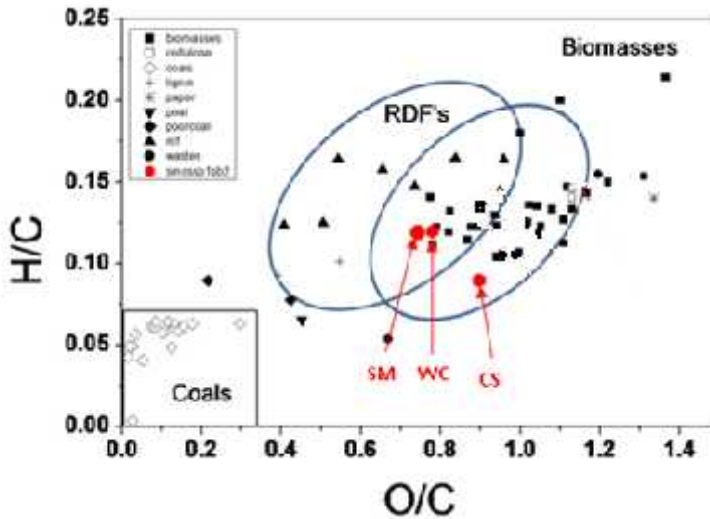
**Table 1: Ultimate and Proximate analysis and HHV of fuels (as received basis)**

Fuel	Ultimate Analysis					Proximate Analysis				Bulk density (kg/m <sup>3</sup> )	HHV (MJ/kg)
	C (%)	H (%)	O <sup>a</sup> (%)	N (%)	S (%)	Ash (%)	FC (%)	VM (%)	H <sub>2</sub> O (%)		
<b>CS</b>	45.20	4.40	40.50	1.00	0.00	4.90	18.00	73.10	4	310	17.70
<b>SM</b>	41.70	5.00	32.32	2.47	0.09	4.29	24.58	57.00	14.13	490	17.70
<b>WC</b>	42.20	4.94	35.48	0.28	0.10	1.70	11.90	71.10	15.30	270	16.39
<b>RC</b>	60.36	4.5	8.35	1.84	0.30	14.00	45.48	29.87	10.65	620	27.29

<sup>a</sup>Calculated by difference

FC = fixed carbon, VM = volatile matter, HHV= higher heating value

Figure 1: Van Kerevelin type diagram



The particle size of the samples given in Table 2 was estimated by using laser diffraction Malvern MasterSizer-2000. 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 2: The fuel particle sizes obtained by Malvern Master-Sizer

Samples	D[4,3] $\mu\text{m}$	d[0.1] $\mu\text{m}$	d[0.5] $\mu\text{m}$	d[0.9] $\mu\text{m}$
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
RC	85.29	6.66	59.10	201.39

Cellulose and lignin are generally recognized as main components in agricultural residues. The chemical analysis results presented in Table 3 reveals the difference in the structure of SM and CS and WC.

Table 3: Chemical composition of CS and SM

Fuel	NDF%	ADF%	Hemicellulose	Cellulose	Lignin	Silica
CS	85.02	67.12	17.9	32.7	30.66	3.76
SM	49.41	41.87	7.54	5.55	31.8	4.52
WC	64.25	58.12	6.13	21.09	33.66	3.37

Neutral detergent fibre (NDF) represents cellulose, hemicellulose and lignin fractions of the plant cell-wall while acid detergent fibre (ADF) is characterized by the presence of cellulose and lignin only (Sharma, 1996).

The weight fraction except for the cellulose and lignin fraction corresponds to the fraction of acid-soluble hydrocarbons in the biomass (Gani and Naruse, 2007). *Table 3* shows that SM contains more lignin than cellulose as opposed to CS. Moreover, SM contains a higher value of acid soluble hydrocarbons with smaller fraction of cellulose. SM appeared quite unique kind of biomass compared to traditional ligno-cellulose biomasses.

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 4*.

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

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

*Ash composition analysis of the samples was done using PANalytical Axios Advanced XRF spectrometer aided with PANalytical IQ+ Semi-quantitative software.*

### **2.3. Experimental Facility**

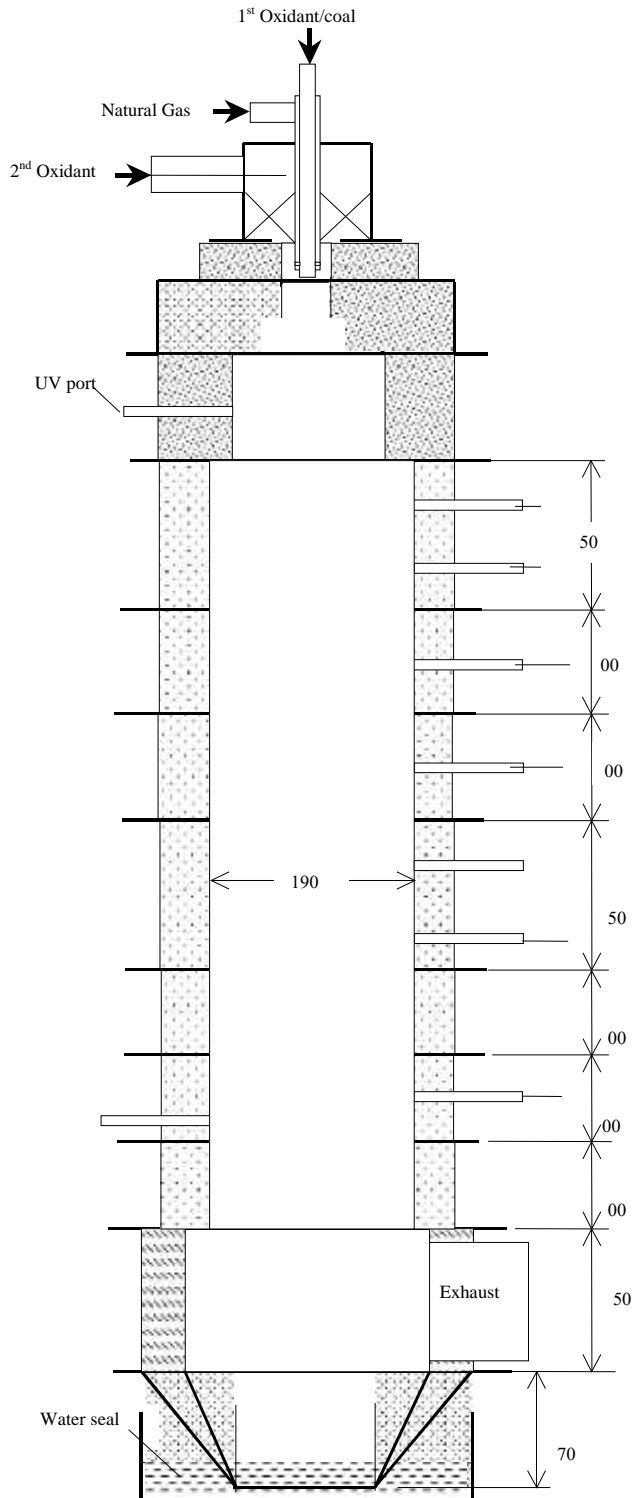
The experimental furnace is a 20 Kw down fired combustor. It is additionally equipped with three different fuel feeders, air and gas supply systems, calibration set-up, gas measuring analytical equipments, gas cylinder manifolds, water cooled sample probes, char sample collection quenching system, thermocouples, data logger and PC. The internal dia of the furnace is 190mm. The facility was designed so that various air and fuel staging configurations could be tested. It is also convenient to vary the length of various zones and residence times in the corresponding zones by moving the the position of the staged air, burn our air and reburn fuel. The schematic diagram of the combustor is given in *Figure 2*. Fuel is supplied by especially designed, metered and calibrated feeders. Primary air, secondary air, burnout air and reburn carrier nitrogen are regulated by KDG 2000 rotameters. The staged air and reburn fuel was injected into the rig through stainless steel 11.5 mm lances.

For the biomass and coal co-firing tests, an arrangement of three feeders could be utilised. While pre-blending coal with biomass, the main feeder (Rospen) was used in conjunction with a smaller (Dowson DB1-3/4) which permitted mixing of coal and biomass on the spreader tray. For fuel- staging with biomass as the

secondary fuel, a smaller Rospen type feeder was used. Feeders were pre-calibrated before each test run that were performed under unstaged, air-staged and fuel- staged conditions.

Analyzing instruments were calibrated before each run with standard BOC gases of known concentrations. Analyzers used for gases measurement were; Taylor Servomex Paramagnetic Analyzer 570° for O<sub>2</sub> , NDIR analyzers (Analytical Development company) for CO, ABB Easyline IR for CO<sub>2</sub>, and a chemiluminiscent analyzer (Analysis Automation Ltd series 440-signal) for NO and NO<sub>x</sub>.

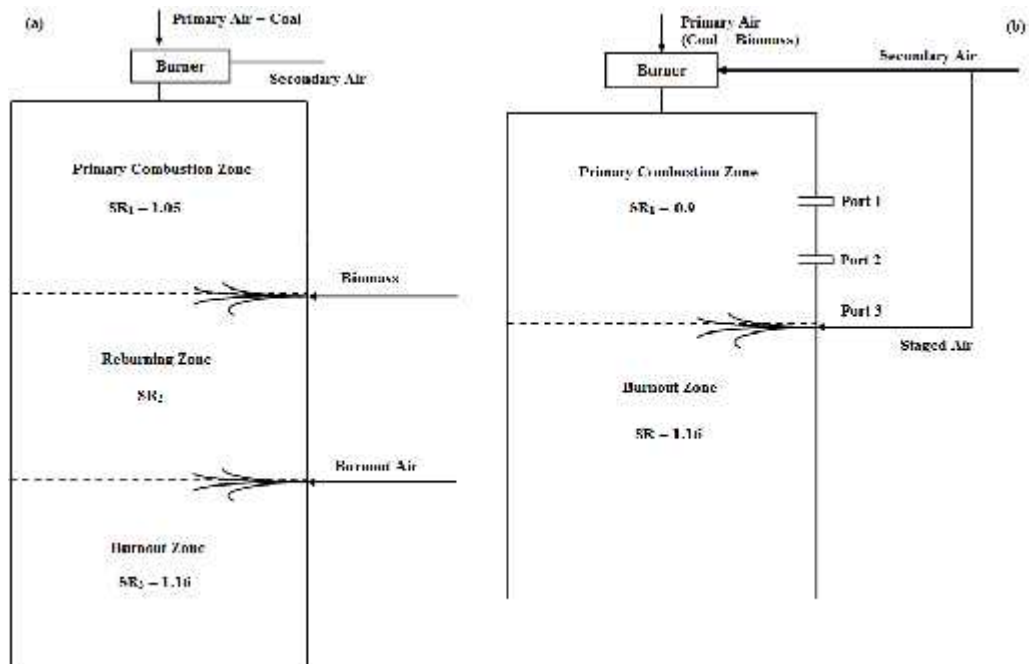
Figure 2: Schematic of the 20 kW wn fired combustor (all ensions in mm)



## 2.4. Method

After heating up by natural gas combustion, the combustor was shifted to coal on 20 kW basis. The overall stoichiometry was kept at 1.16 during the tests. For unstaged co-firing, required measured amount of biomass from calibrated Dowson feeder was continuously fed on the vibratory tray of the Main Rospen Coal feeder. From where, it is transported to burner with primary air. The gas samples were continuously measured with online gas analyzers. Each gas analyzer and R-type sheathed thermocouples were connected with PC through data logger which registers the measured value after every ten seconds on the excel sheet supported by software Daq-View. For air staging tests, primary zone/near burner zone stoichiometry was varied from 1.16 to 1 to 0.9 to 0.8 and staged air was provided at port 3, 116.5cm from the burner. The staged air location was fixed at port three (116.5cm) after optimization (**Figure 3a**). Based on the optimization findings,  $SR_1=1.05$  and reburn fuel fraction ( $R_{ff}$ ) location was fixed at port 3 during fuel staged experiments (**Figure 3b**). Small Rospen feeder was used to feed  $R_{ff}$  amount on estimated thermal basis. To avoid any variation in the reburn zone stoichiometry, Nitrogen was used as carrier gas to transport  $R_{ff}$  to the injection port.

Figure 3: (a) Schematic of Fuel Staging Process, (b) Schematic of Air Staging Process





The primary zone  $SR_1$  and reburning zone  $SR_2$  were estimated by using standard formulae used by Munir et al, (2010a, b). The air and fuel staging configuration used in this study is shown in *Figure 3*.

The location of the burn out air was taken at 236.5 cm from the burner for each of the test quoted in this article. Keeping in view possible slight variations during operation and to make comparison of gases on fixed basis results are also quoted at 6%  $O_2$  using equation 1 and 2.

$$NO_{@6\%O_2} = NO \left( \frac{20.9\% - 6\%}{20.9\% - \%O_2} \right) \quad (1)$$

$$SO_{2@6\%O_2} = SO_2 \left( \frac{20.9\% - 6\%}{20.9\% - \%O_2} \right) \quad (2)$$

NO red (%) and residence time } in the fuel rich zones were calculated using equation3 and 4

$$NO_{red(\%)} = \left[ \frac{NO_i - NO_f}{NO_i} \right] \times 100 \quad (3)$$

$NO_i$  = Initial NO measured at the flue exit without staging

$NO_f$  = Final NO measured at the exit after staging

### **3. Results and Analysis**

#### **3.1. Air staged Co-combustion of Coal with Biomass**

Preblended mixtures of biomass–coal were used in unstaged and staged co-combustion experiments. Biomass blending ratio (BBR) was varied in the blends on thermal basis. Three blends with BBR (thermal) 5, 10 and 15% were tested in all experiments. The overall SR was kept at 1.16. It was estimated from *Figure 4* that an unstaged co-combustion of Sheameal-Coal yielded NO reduction of 2.78, 5 and 7.16% compared to pure coal combustion. It is evident from *Figure 4* that the primary zone stoichiometry ( $SR_1$ ) has direct relationship with the NO level at the combustor exit. The value of NO decreases with the decrease in  $SR_1$ . A decrease in  $SR_1$  may increase the formation of reducing species in the primary combustion zone, which is conducive to  $NO_x$  destruction (S. Li et al., 2008). During air-staged co-firing, it is expected to achieve few benefits associated with  $NO_x$  formation kinetics. Firstly, the devolatilization of biomass (containing higher volatiles) in the oxygen deficient near burner region could convert fuel nitrogen to molecular nitrogen instead of  $NO_x$ . Secondly, the presence of oxygen

deficient primary zone along with subsequent fuel lean zone due to aerodynamic control of air–fuel mixing in two stage combustion could delay combustion process by imparting less mixing (air–fuel) resulting suppression of  $\text{NO}_x$  formation due to oxygen deficiency. Thirdly, the presence of peak temperature in the oxygen deficient zone could also reduce Thermal  $\text{NO}_x$ . On the other hand, if  $\text{SR}_1$  is kept too low, incomplete combustion in the primary zone is more likely. This could increase the unburnt char inflow to the burnout zone resulting negative effects on the combustion efficiency. On the basis of  $\text{NO}$  reduction and char burnout efficiency tradeoff, 0.9 was found to be the optimum value for  $\text{SR}_1$  (Munir, S., 2010c). Figures 4, 5 and 6 revealed that an increase in BBR has a positive effect on  $\text{NO}$  reduction. For SM-RC blends at  $\text{SR}_1=0.9$  with 5, 10 and 15% BBR, the  $\text{NO}$  levels recorded (corrected to 6%  $\text{O}_2$ ) were 456, 415 and 406 ppm respectively. It was a reduction of 47, 51 and 52% in  $\text{NO}$  (Figure7 and Figure4) compared to a  $\text{NO}$  reduction of 2.78, 5 and 7.16 % with the same BBR during unstaged co-combustion ( $\text{SR}=1.16$ ).

**Figure 4: Effect  $\text{SR}_1$  on the  $\text{NO}$  during co-combustion of SM and coal**

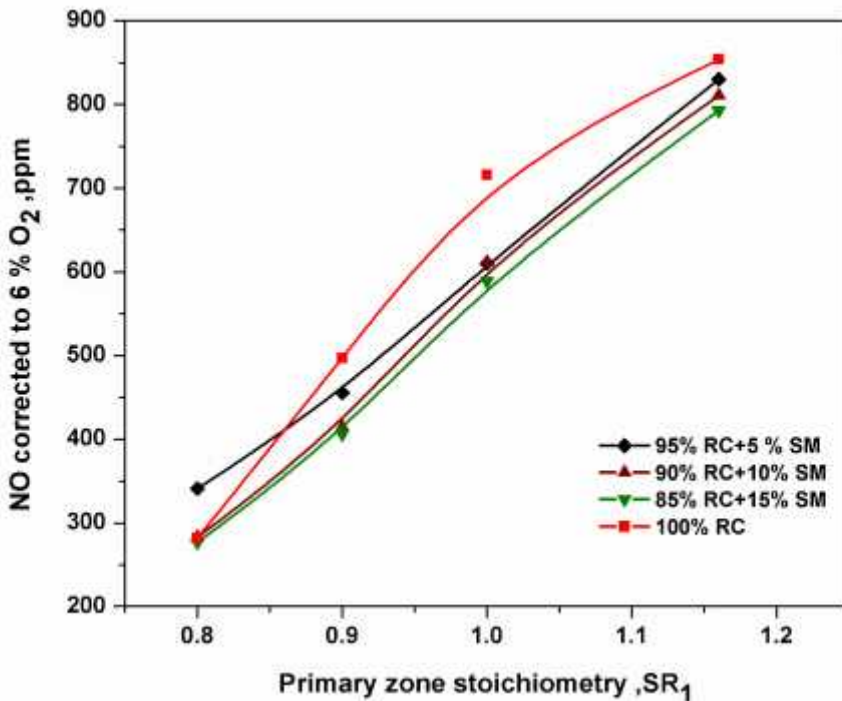


Figure 5: Effect  $SR_1$  on the NO during co-combustion of CS and Coal

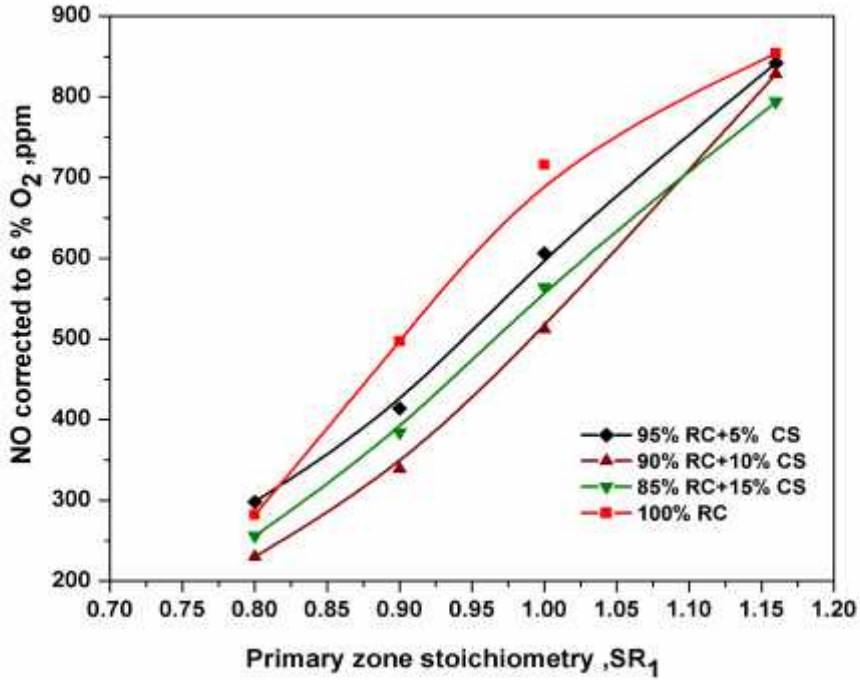
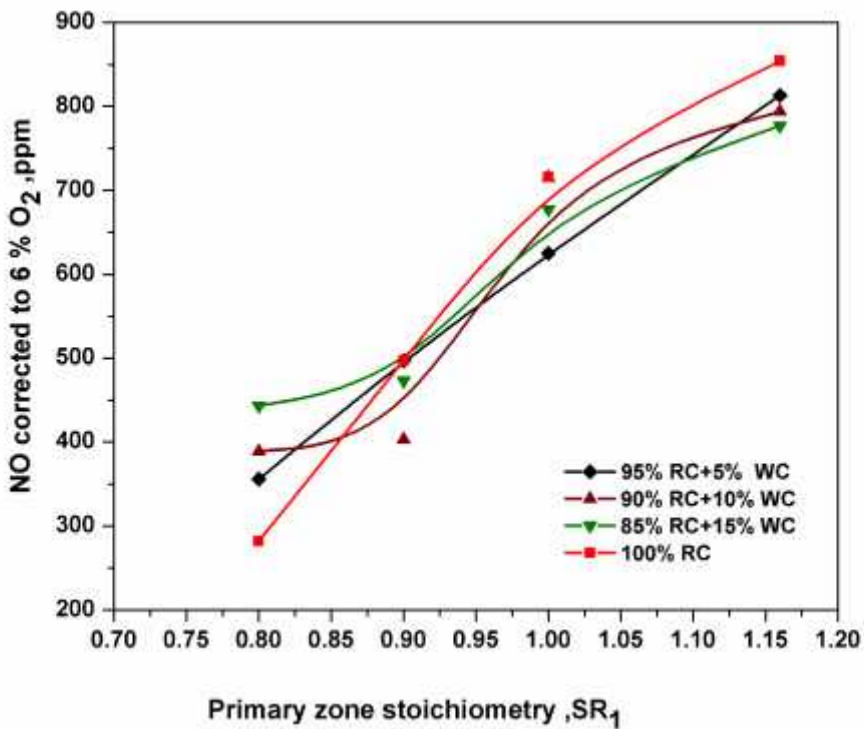


Figure 6: Effect  $SR_1$  on the NO during co-combustion of WC and Coal



The values of NO reduction (%) calculated from *Figure 5* for CS-RC blends were found to be 1.4, 4.74 and 9.74 % for 5, 10 and 15% BBR under unstaged conditions. Whereas staged air results for 5%, 10% and 15% BBR with  $SR_1=0.9$  (*Figure 5*) exhibited NO concentrations (corrected to 6%  $O_2$ ) of 414, 339 and 384 respectively. These were NO reductions of 52, 60 and 55% for BBR of 5, 10 and 15% respectively. Similarly, for WC- Coal blends unstaged combustion, NO reduction (%) was found to be 4.8, 7 and 9% for BBR of 5, 10 and 15%. Whereas NO reductions of 42, 53 and 47% were obtained with air staged co-combustion ( $SR_1=0.9$ ) of WC-RC same BBR of 5, 10 and 15 %. The NO concentrations (corrected to 6%  $O_2$ ) in the flue were found to be 497, 403 and 473 ppm.

It can be seen from *Figures 4, 5 and 6* that all the fuels exhibited significantly lower NO emissions under staged conditions compared to unstaged combustion and co-combustion at  $SR=1.16$ . A maximum NO reduction (%) was found at BBR of 10% for CS and WC at  $SR_1=0.9$  and OFA location port 3 (*Figure 5 and Figure 7*). For SM, maximum NO reduction was found at 15% BBR. For SM, 52% NO reduction was obtained with 15% BBR compared to NO reduction of 51% with 10% BBR that is, just 1% more than the NO reduction achieved with 10% BBR of SM.

It was calculated that to obtain one percent more NO reduction the mass fraction of SM in the blend increases from 14.38% to 21.05% (mass basis), which is approximately an increase of 46%. It was also found that maximum burnout % was obtained at 10% BBR (*Figure 8*). Keeping in view the NO reduction (%) and carbon burnout (%), a BBR of 10% was considered to be the optimum yielding NO reductions of 60%, 53%, 51% in the case of CS WC and SM respectively (*Figure 7 and Figure 8*). The difference in the % NO reduction for biomass samples could be linked to the difference in their proximate and ultimate constituents (*Table 1*). The NO reduction was found to be 42% in the case of RC staged firing with  $SR_1=0.9$ . As discussed above, all the coal-biomass blends exhibited higher NO reduction compared to coal alone for  $SR_1=0.9$ .

As shown in *Figure 9*, the effect on temperature drop was not significant in the primary zone when the combustor was operated at  $SR_1=0.9$  with 10% thermal BBR of CS and SM in comparison with pure RC operation. In the case of WC, large particle size, higher density and higher moisture content than rest of the biomasses could be limiting factors. This trend of decreasing burnout with the addition of coarser particle biomass is in agreement with the findings of Spliethoff and Hein 1998. The axial temperature profiles of the biomass-coal blends co-combustion for  $SR_1=0.9$  are shown in *Figure 9 (a-c)*. It is clear that the addition of biomass has a positive effect on carbon burnout (except for WC (*Figure 8*)). It is linked with the proximate constituents of sample parent sources

(Table 1) as biomass samples contain a higher VM content (Denis et. al., 2005). Good burn out depends on the feed particle size, the residence time at high temperature and the design of the furnace. However, the higher porosity of biomass chars makes them more reactive, relative to coal, and could be a reason for improved burnout (Campbell et al, 2002; Van Loo and Koppejan, 2008).

A temperature difference of 75-120°C was observed in the primary zone for RC-WC blend (*Figure 9c*). This could be due to higher particle size, density and moisture content (*Table 1 and Table 2*) causing a delay on the ignition of WC permitting the coal to ignite ahead of the WC in the near burner zone resulting lower burnout (*Figure 8*).

**Figure 7: Effect of BBR on NO reduction at  $SR_1=0.9$**

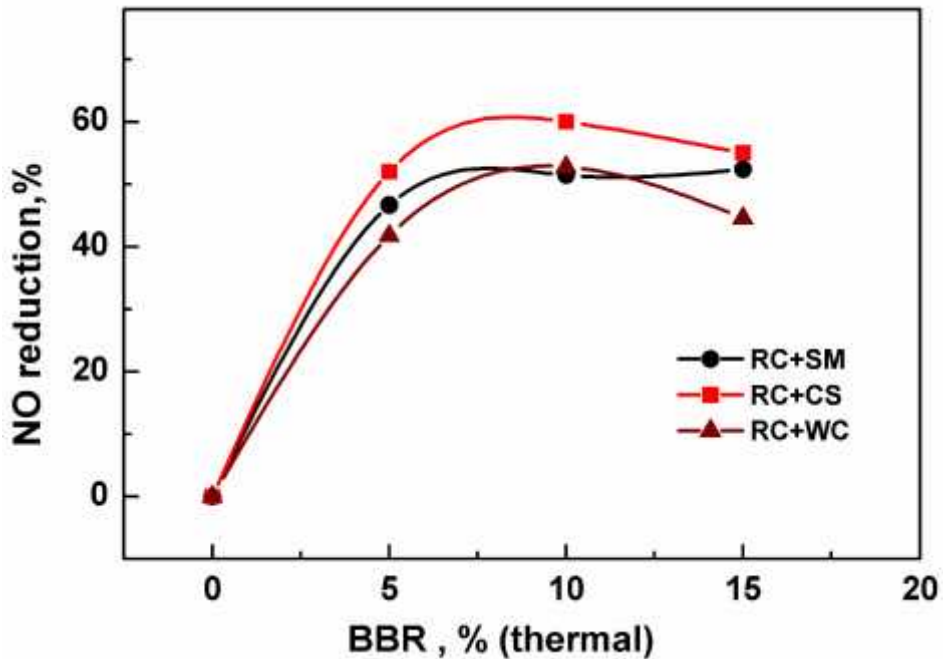


Figure 8: Burnout of coal-biomass blends,  $SR1=0.9$

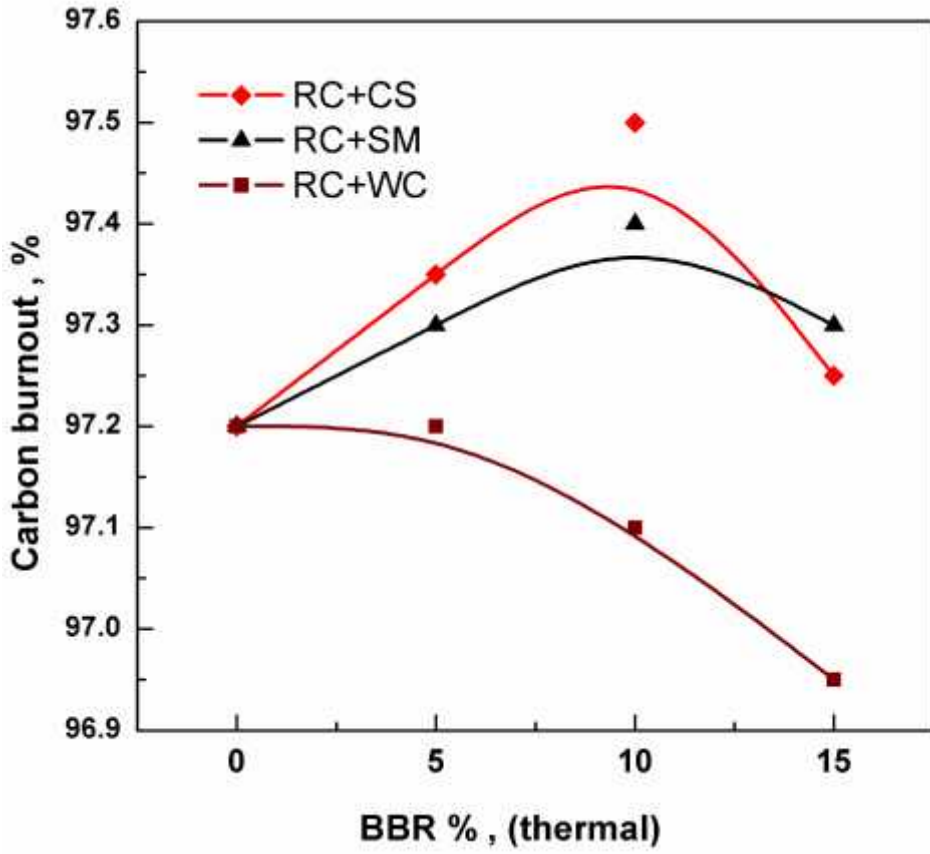
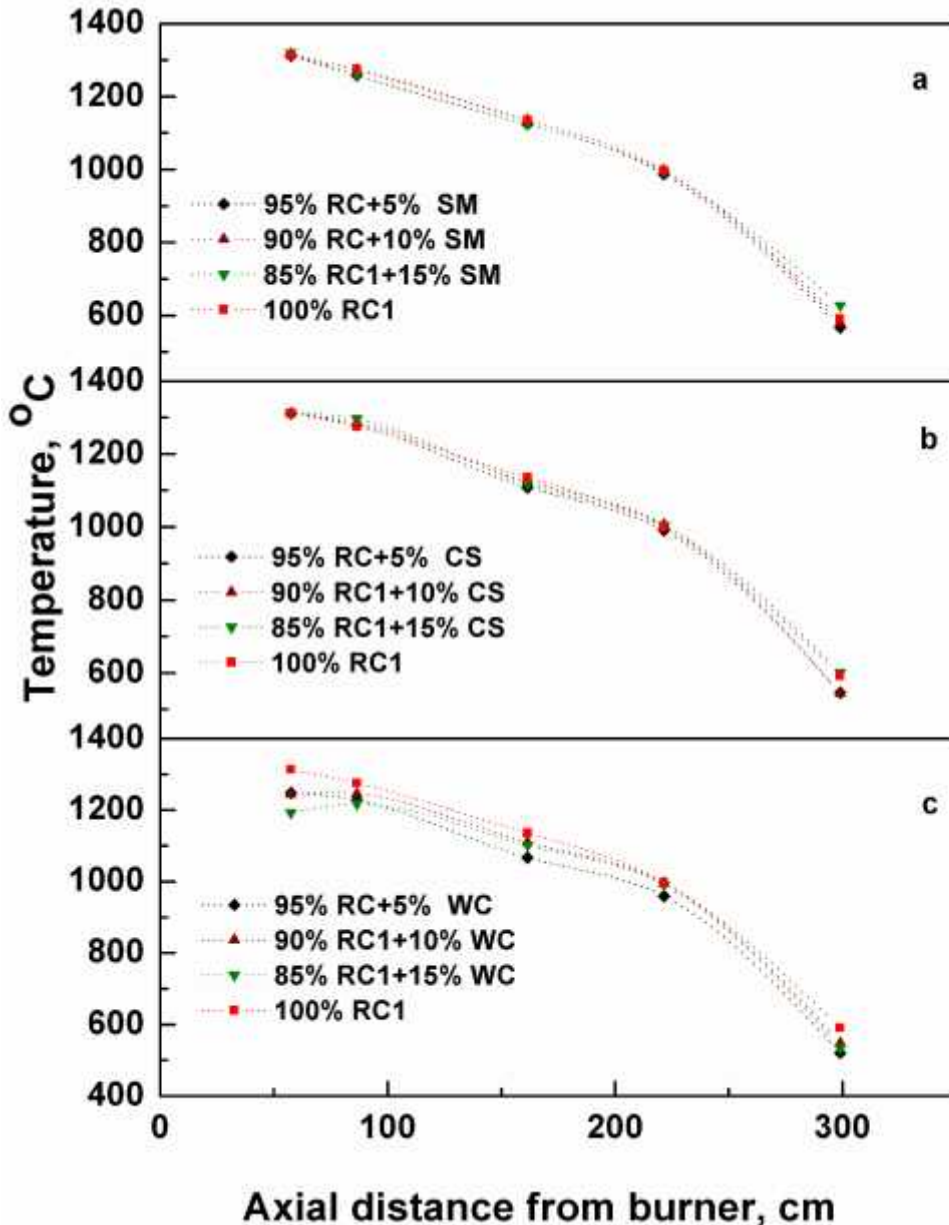


Figure: 9 Temperature profile of pure RC and RC-biomass blends with different thermal BBR at  $SR_1=0.9$



#### 4. Biomass staged co-combustion

A series of experiments were conducted to evaluate the suitability of biomass as reburn fuel. Three delineated physical combustion zones named primary zone, reburn zone, and burnout zone were created inside the combustor to implement the reburning process scheme. In the primary zone, the primary/main fuel (RC)

was burnt under fuel lean conditions ( $SR_1=1.05$ ). In the subsequent Reburn zone, biomass was injected as secondary fuel/reburn fuel using  $N_2$  as carrier (116.5cm down from the burner) to create fuel rich reducing atmosphere producing hydrocarbon radicals. As biomasses contain higher volatile matter, they are well suited for  $NO_x$  reburning process. A greater amount of  $CH_i$  radical release from the devolatilization may enhance the NO reduction mechanism under fuel rich conditions. The major reaction path is the formation of HCN via the chemical pathway (Salzmann and Nussbaumer, 2001):



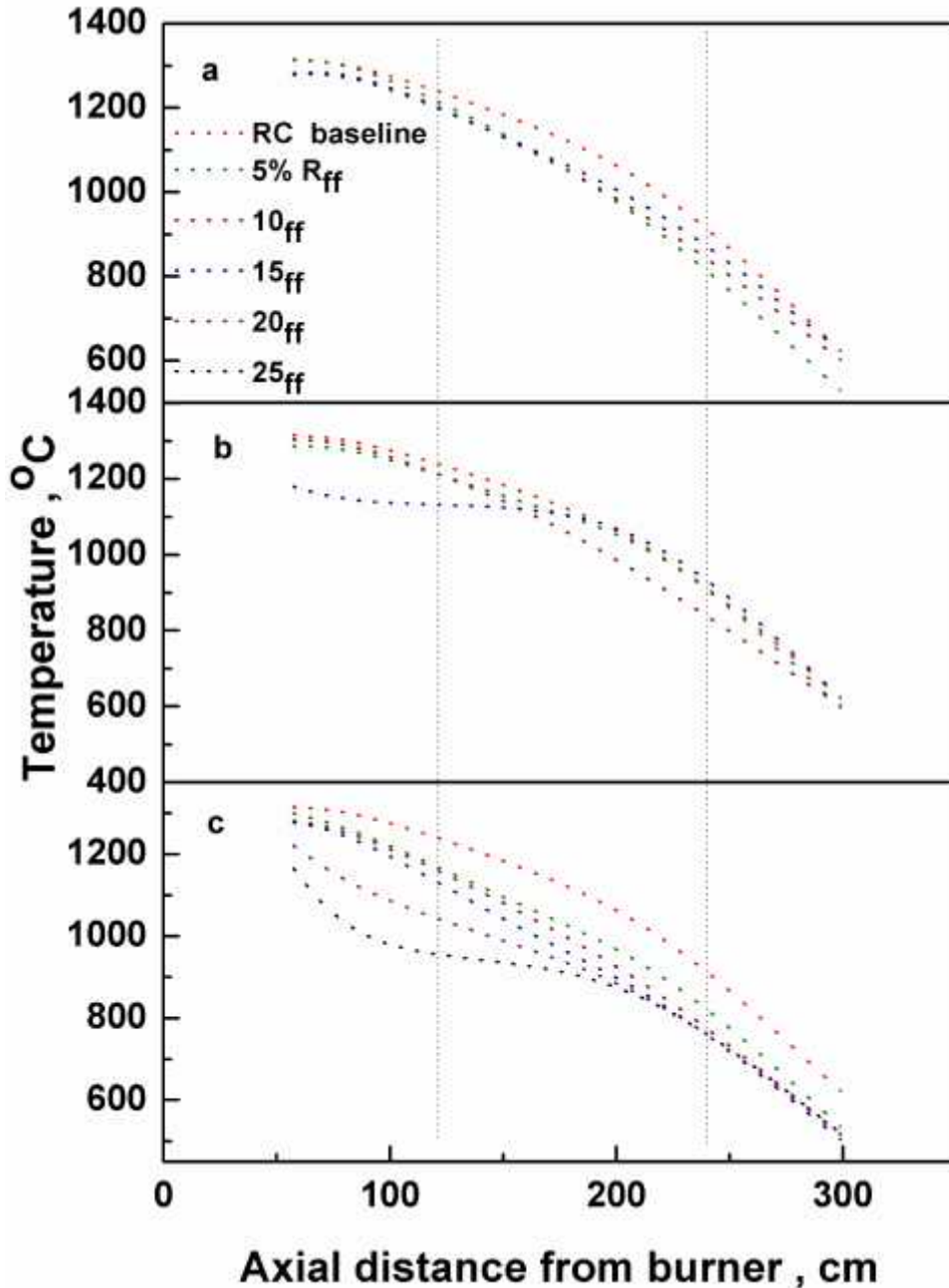
Nitrogen content in the biomasses is beneficial since it leads to the additional reducing species (Salzmann and Nussbaumer, 2001):



At the end of reburn zone, (at 236.5 cm down from the burner), fuel lean burnout zone started in which additional air was introduced to complete the combustion process at overall  $SR_3=1.16$ .



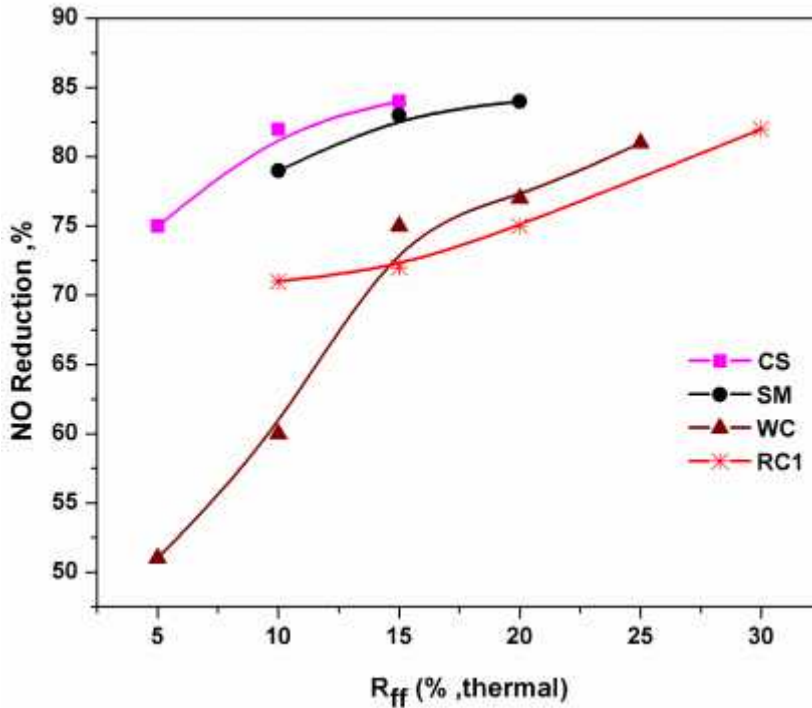
Figure 10: Temperature profile comparison of pure RC with different thermal  $R_{ff}$  of (a) CS (b) SM (c) WC



A general decrease in temperature in the reburn zone with reference to baseline (Figure 10) could further reduce the formation of thermal  $\text{NO}_x$ . The mean temperature in the fuel rich reburn zone was  $1100^\circ\text{C}$  for SM,  $1080^\circ\text{C}$  for CS and  $1020^\circ\text{C}$  for WC the mean temperature in the fuel rich primary zone was above

1300°C which means an average temperature difference of more than 250°C in the fuel rich zones of air and fuel staging methods. To evaluate the performance of biomasses, RC was used as reburn fuel with the primary coal RC. It was found that an increase in thermal  $R_{ff}$  yields higher NO reduction efficiency. This could be due to higher concentration of HC release from volatiles in reducing environment in the reburn zone. The results obtained are plotted in *Figure 11*.

The NO reduction achieved with biomasses was significantly higher compared to coal when used as reburn fuel for the same thermal fuel fraction. A 5%  $R_{ff}$  for CS gave an NO reduction of 75% compared to 71% NO reduction with two times higher  $R_{ff}$  for RC. NO reduction of 75, 82 and 84% was obtained with thermal  $R_{ff}$  of 5, 10 and 15% of CS. A similar trend was found with SM where NO reduction of 79, 83 and 84% was recorded with thermal  $R_{ff}$  of 10, 15 and 20%. The maximum NO reduction was obtained at 20%  $R_{ff}$ . The addition of 5% thermal SM to obtain 1% extra NO reduction is not a favourable option because of the potential risk of slagging and fouling as SM ash is rich in alkaline earth metals (*Table 5*). SM at 20%  $R_{ff}$  yielded NO reduction of 84% at  $SR_2=0.76$  which is not an attractive option (*Figure 14*). Therefore, 15%  $R_{ff}$  was considered to be the optimum  $R_{ff}$  for both CS and SM. Moreover, NO reductions of 51, 60, 75, 77 and 81% were obtained with 5, 10, 15, 20 and 25 %  $R_{ff}$  of WC. At the same time, it is clear from *Figure 12* that beyond 15% WC  $R_{ff}$ , carbon burnout begins to level off. Keeping in view the NO reduction and carbon burnout, 15 %  $R_{ff}$  was considered an optimum  $R_{ff}$ . The residence time of the gases in the reburn zone was calculated and found 1.38 sec for CS and 1.35 sec. *Figure 14* revealed that the higher is the value of  $R_{ff}$ , the lower is the value of  $SR_2$  resulting in lower oxygen availability and higher NO reduction. *Figure 11* showed that different levels of NO reduction were obtained by biomasses and coal for the same value of  $R_{ff}$ . It could be due to the volatility difference, as biomasses have 2 to 2.3 times higher VM compared to coal (*Table 1*). The levels of NO recorded in the flue gas (corrected at 6%  $O_2$ ) were 215, 155 and 144 ppm for 5, 10 and 15% thermal CS  $R_{ff}$ . The NO levels for SM were found to be 176, 144 and 136 ppm (corrected at 6%  $O_2$ ) for 10, 15 and 20%  $R_{ff}$  of SM. Similarly, NO levels for 5, 10, 15, 20 and 25%  $R_{ff}$  for WC were found to be 416, 339, 216, 194 and 158 ppm.

Figure 11: Effect of thermal  $R_{ff}$  on NO reduction

The most influential parameter in biomass reburning process is the reburn zone stoichiometry (Harding and Adams 2000). Reburn zone stoichiometry  $SR_2$  was varied between 0.66 to 0.97 (Figure 13 and Figure 14). The optimum values of reburn zone stoichiometry ( $SR_2$ ) corresponding to an optimum thermal  $R_{ff}$  of 15% and optimum NO reduction efficiencies (CS = 84%, SM = 83%, WC = 75%) were found to be 0.82, 0.83 and 0.8 for CS, SM and WC (Figure 11 and Figure 14). Maximum NO reduction efficiency exhibited by coal was 82% at 30%  $R_{ff}$  and  $SR_2 = 0.73$ . Moreover, the RC  $R_{ff}$  consumed was two times higher than SM and CS  $R_{ff}$  under much stronger reducing environment which could result in lower carbon burnout.

Figure 12: Effect of  $R_{ff}$  on Carbon burnout

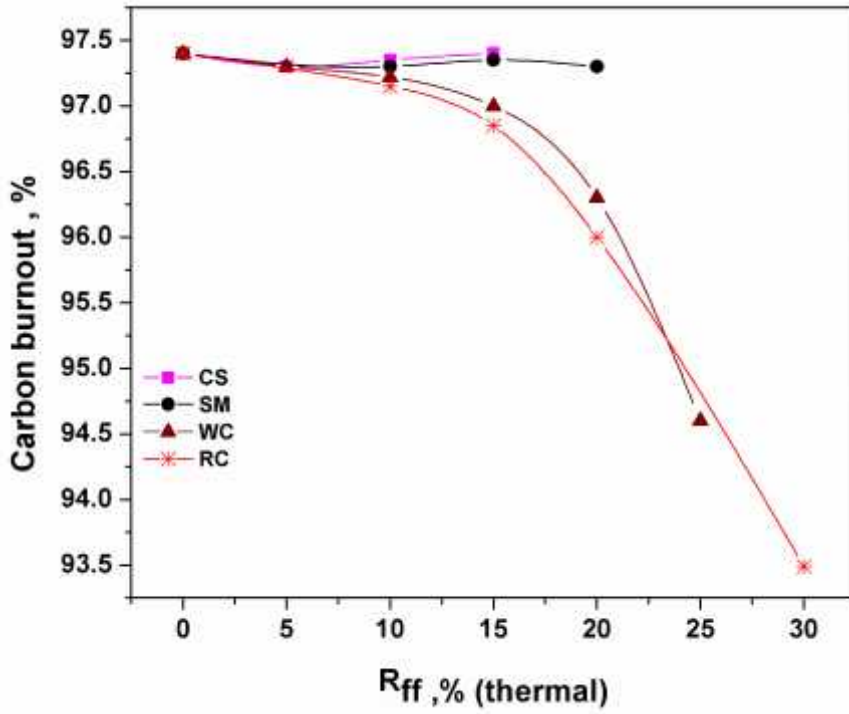


Figure 13: Effect of Reburn zone Stoichiometry on NO

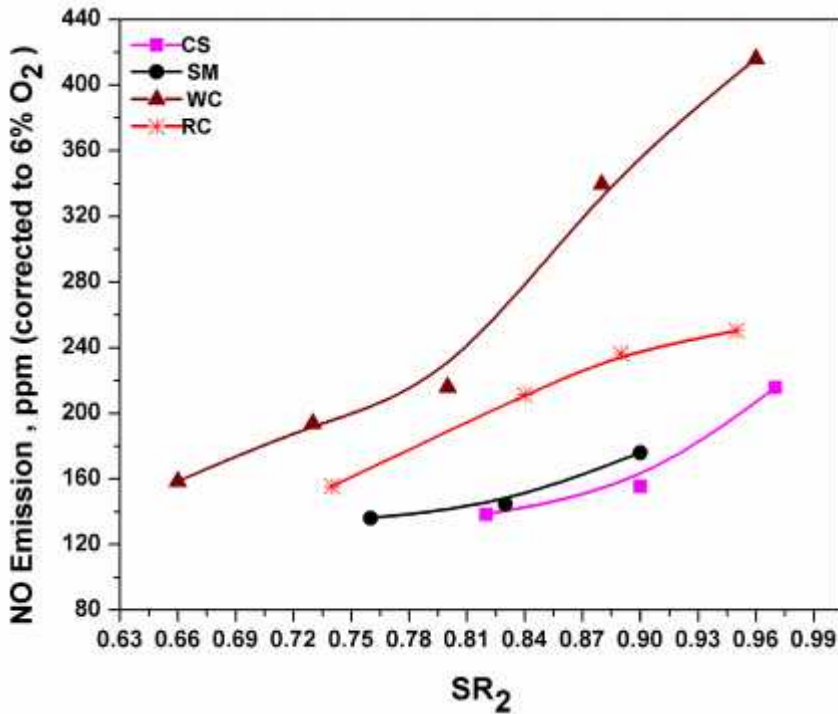
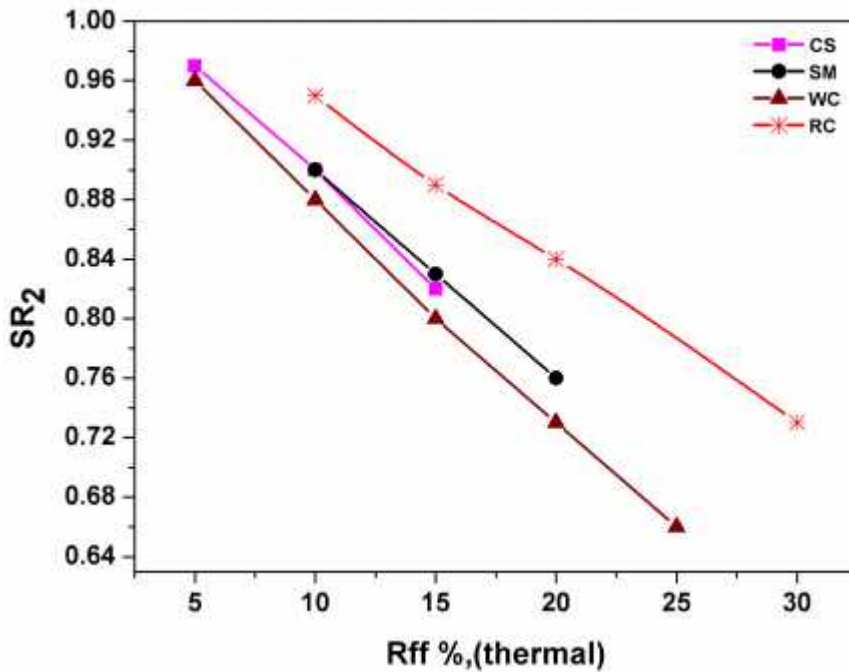
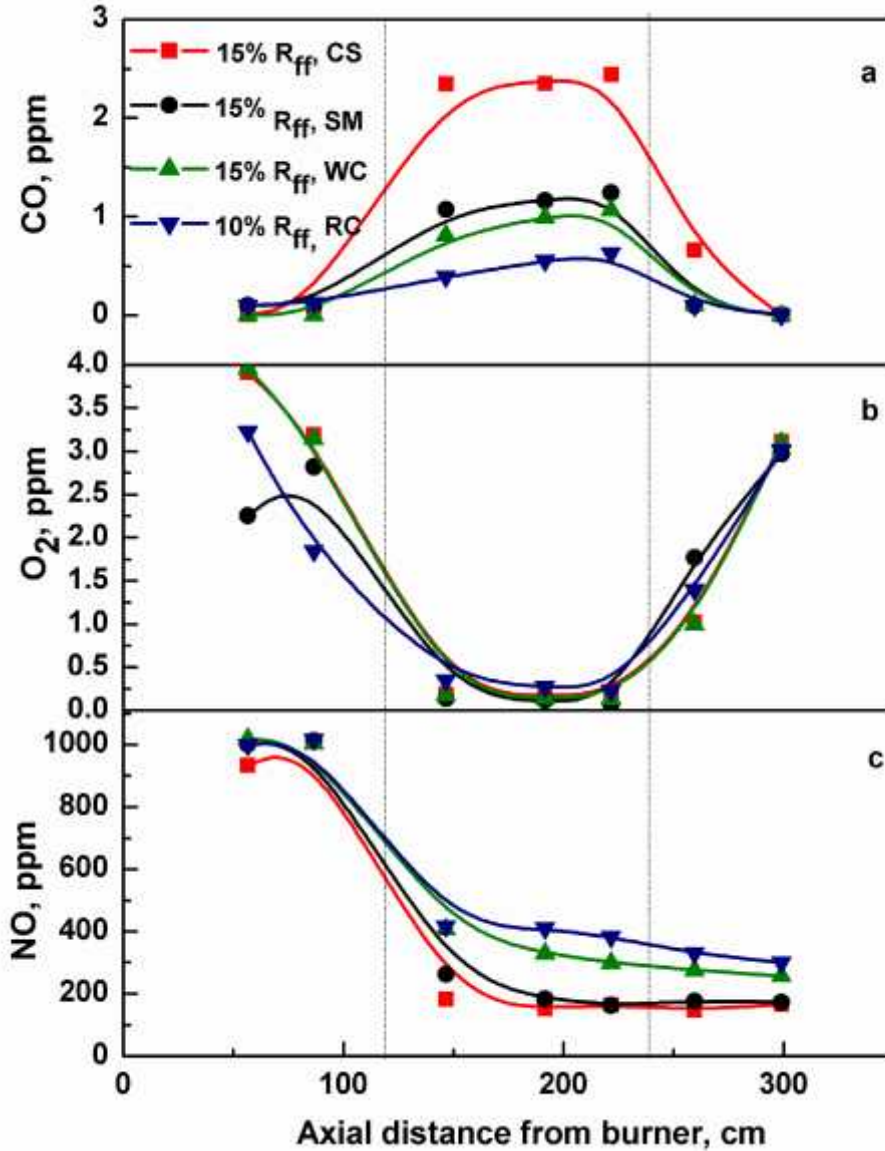


Figure 14: Effect of thermal  $R_{ff}$  on  $SR_2$ 

The axial distribution of gases in three distinct zones is presented in *Figure 15*. The dotted lines in *Figure 15* represent the  $R_{ff}$  injection location 116.5 cm and burnout air injected at 236.5 cm from the burner. The area before the injection of  $R_{ff}$  until 116.5 cm (before first dotted line) is a fuel lean zone and the area between dotted lines represents the reburning zone. Whereas the area after the second dotted line (after the injection of burnout air) represents burnout zone. The axial gases profiles given in *Figure 15* revealed that combustor was operated in well defined fuel lean, fuel rich and fuel lean zones. The oxygen concentrations were found below 0.2% for 15%  $R_{ff}$  of each of the studied biomass samples (*Figure 15*). The bowl-shaped oxygen curves with flat base and bell shaped CO peaks in the reburn zone are an indication of well established fuel rich oxygen deficient zone. While co-firing SM, CS and WC as reburn fuels, the CO concentration measured in the reburn zone were found to be significantly higher than RC for the same level of thermal  $R_{ff}$  of 15% (*Figure 15*). Similarly, for the same level of 15%  $R_{ff}$ , the value of  $SR_2$  was found to be 0.8~0.83 for biomasses and 0.89 for coal while keeping  $SR_1=1.05$  fixed. It could be due to the fact that SM, CS and WC have significantly higher VM than RC (*Table 1*) and the main gas species of VM for biomass are CO and low grade HC (*Table 4*). Furthermore, volatiles in biomass have the propensity to evolve easily even at low temperatures (Gani et. al., 2005). As a result of biomass fragmentation in the reburn zone, a greater volatiles release of  $CH_i$  radicals and

NH<sub>i</sub> species from biomass nitrogen content could lead to NO destruction yielding molecular nitrogen.

Figure 15: Axial distribution of (a) CO (b) O<sub>2</sub> (c) NO, in the Combustor, SR<sub>1</sub>=1.05, R<sub>ff</sub>=15%



### 5. Slagging and Fouling

Slagging and fouling reduces heat transfer and causes corrosion and erosion problems, which reduce the life time of the equipment. (Sami et. al., 2001). The major elements including alkali metals (K, Na), alkaline earth metals (Ca, Mg), silicon, chlorine and sulphur are involved in reactions leading to ash slagging and fouling (Jenkins et al., 1998; Pronobis, 2005). Mixing of ash from biomass

fuels during co-combustion can enhance slagging and fouling propensity because of the typically lower ash melting temperature for biomass ash as biomass ashes are rich in alkali and alkaline earth metals. A comparison of the studied biomasses and coal ash is given in *Table 5*. The most commonly used traditional Slagging and Fouling Indices are given in *Table 6*.

It is evident from *Table 8* that the values of calculated Slagging Indices and Fouling Indices for SM and CS fall in the severe slagging and fouling propensity range. Similarly, the values of slagging viscosity index, and  $R_{(B/A)}$  are in high range for SM and CS (*Table 8*). For WC, the estimated values of Slagging viscosity Index and B/A(+P) were found to be in medium slagging propensity (*Table 8 and Table 6*). The co-fired ash under air staged configuration for 10% BBR displayed quite different mineralogical mix compared to pure biomass. A dominance of silica and alumina is evident in co-fired ash samples under air staged co-combustion (*Table 7*). The ash mineralogy was close to coal ash. It was in agreement with the findings of Heinzl et al. (1998). Co-combustion of coal with biomass for 10% BBR showed synergistic effect with respect to slagging and fouling compared to pure biomass combustion. All the values of relationships traditionally used to predict slagging and fouling propensity under co-firing configurations studied were found in the range associated for low slagging and fouling inclination (*Table 8*).

**Table 5: A comparison of the biomass ash composition with coal ash**

<b>Components (%)</b>	<b>CS</b>	<b>SM</b>	<b>WC</b>	<b>RC</b>
<b>Na<sub>2</sub>O</b>	1.90		3.64	0.247
<b>MgO</b>	2.50	3.67	3.79	1.225
<b>Al<sub>2</sub>O<sub>3</sub></b>	2.09	2.60	14.9	23.169
<b>SiO<sub>2</sub></b>	8.96	10.47	46.29	63.695
<b>P<sub>2</sub>O<sub>5</sub></b>	5.61	7.55	2.43	0.463
<b>SO<sub>3</sub></b>		13.94	1.95	0.046
<b>K<sub>2</sub>O</b>	34.57	42.49	4.79	2.229
<b>CaO</b>	18.15	6.92	8.43	1.333
<b>TiO<sub>2</sub></b>		0.27	2.41	0.970
<b>MnO</b>		0.23	0.68	0.085
<b>Fe<sub>2</sub>O<sub>3</sub></b>	2.41	7.66	10.4	5.527
<b>NiO</b>				0.003
<b>CuO</b>	0.11	0.14		0.031
<b>ZnO</b>	0.17	0.70		0.083
<b>Rb<sub>2</sub>O</b>	0.11	0.41		
<b>SrO</b>	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

Table 6: 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>	$R_s = \frac{B}{A} \times S^d$ <p><math>S^d = \% \text{ of } S \text{ on dry basis}</math></p>	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 7: Air staged ( $SR_1=0.9$ ) co-fired ash composition for 10% BBR of different blends**

Components (%)	RC	RC + SM	RC + CS	RC + WC
Na <sub>2</sub> O	0.35	0.32	0.36	0.36
MgO	1.386	1.68	1.7	1.36
Al <sub>2</sub> O <sub>3</sub>	23.07	21.57	22.77	22.98
SiO <sub>2</sub>	63.35	60.98	59.9	63.27
P <sub>2</sub> O <sub>5</sub>	0.444	0.7	0.58	0.49
K <sub>2</sub> O	2.18	2.5	2.83	2.28
CaO	1.5	2.69	2.27	1.55
TiO <sub>2</sub>	0.995	0.9	0.965	0.998
Fe <sub>2</sub> O <sub>3</sub>	5.75	6.78	5.6	5.74
SO <sub>3</sub>	0.058	0.223	0.06	0.06
*Others				






\*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<sub>2</sub>

The chemical composition of the ash for optimum R<sub>ff</sub> fuel staged co-combustion experiments along with slagging and fouling indices is given in Table 9. The evaluated S & F Indices for the optimum R<sub>ff</sub> blends (Table 9) were found to be in the range attributed to lower inclination of S & F (Table 9).

**Table 8: Predicted slagging and fouling behaviour (based on fusibility correlations) of the studied fuels and biomasses-coal blends under unstaged and air-staged conditions** (Propensity indication key:  - Severe,  - High,  - Medium,  - Low,  - Extremely low)

Fuel	R <sub>b</sub>	B/A	B/A(+P)	R <sub>(B/A)</sub>	R <sub>S</sub>	Fu	S <sub>R</sub>
SM	60.75	4.55	5.119	1.397	0.455	193.47	36.44
CS	59.54	5.387	5.89	2.087	0.00	196.49	27.98
WC	31.05	0.488	0.526	0.3696	0.059	4.116	67.17
RC, SR=1.16	10.561	0.12	0.1255	0.093	0.0409	0.2977	88.736
RC, SR <sub>1</sub> =0.9	11.166	0.1277	0.1328	0.0999	0.043	0.323	88.00
90%RC+10%SM, SR <sub>1</sub> =0.9	13.97	0.1674	0.17579	0.13507	0.0508	0.472	84.54
90%RC+10%CS, SR <sub>1</sub> =0.9	12.76	0.15257	0.1595	0.11576	0.043	0.4867	86.22
90%RC+10%WC, SR <sub>1</sub> =0.9	11.29	0.1294	0.135	0.1003	0.039	0.3416	87.97

**Table 9: Ash chemical composition of optimum  $R_{ff}$  blends with their S&F Indices under fuel staged conditions**

(Propensity indication key:  - Severe,  - High,  - Medium,  - Low,  - Extremely low)

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

\*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<sub>2</sub>

## 6 .Conclusion

Co-combustion characteristics of the coal and biomass have been studied through a series of extensive experimentation in a 20 kW down fired combustor to monitor NO<sub>x</sub> behaviour and combustion efficiency using air staging and fuel staging configurations. Pre-blended unstaged co-combustion did not display convincing results with regard to NO reduction. The maximum NO reductions were found to be 7.16%, 9.74% and 9% with 15% thermal BBR of SM, CS and WC. NO reduction efficiencies were found to be significantly higher under air staged and fuel staged modes of operation for co-combustion than coal on coal air staging and reburning or alone co- firing.

Fuel staging (reburning) exhibited more attractive results for NO reduction compared to air staging. For air staged experiments, the optimum NO reductions were found to be 60%, 51% and 53% for CS, SM and WC corresponding to an

optimum BBR of 10%. For fuel staging (Reburning) the optimum NO reductions were found to be of 84%, 83% and 75% corresponding to an optimum 15%  $R_{ff}$  of CS, SM and WC. In both the methods of air and fuel staging  $NO_x$  formation kinetics were also linked with reductive power of hydrocarbons in the biomass. It was revealed the stoichiometry of the fuel rich zone has a direct impact on  $NO_x$  reduction. Lower the fuel rich zone stoichiometry the higher is the  $NO_x$  reduction. For air-staging, the fuel rich zone optimum stoichiometry ( $SR_1$ ) was 0.9. The optimum values of fuel rich zone stoichiometry ( $SR_2$ ) were found to be 0.83, 0.82 and 0.8 for SM, CS and WC in the case of fuel staging. Generally, the biomasses are low in nitrogen content but both SM and CS are high nitrogen content biomasses. SM contains higher fuel nitrogen more than coal. The results of this study are in agreement with the findings of Slazmann and Nussbaumer (2001) that fuel staging may be favourable for  $NO_x$  reduction for biomasses with high nitrogen content. Moreover, the addition of biomasses as secondary fuels was found to have synergistic effect on NO reduction and carbon burnout improvement.

According to the calculated traditional Slagging and Fouling Indices, the potential of Slagging and Fouling was found to be in high to severe range for CS and SM firing. Moreover, the slagging viscosity index value of WC was found to be in the range attributed for medium slagging propensity. The values of all the calculated Slagging and Fouling Indices for air and fuel staged co-combustion experiments (for optimum BBR and optimum  $R_{ff}$ ) were found in the range attributed for low Slagging and Fouling propensity. The addition of biomasses up to optimum thermal fractions of 10% and 15% under air and fuel staged configurations was found to have no adverse effect on Slagging and Fouling. It can be concluded that air and fuel staged co-combustion of coal with 10-15% thermal fraction of biomass is more attractive option than alone biomass firing or coal firing that can reduce NO significantly with improved burnout and without the risk of slagging and fouling.

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