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Analysis of Emissions and Furnace Exit Gas Temperature for a Biomass Co-firing Coal Power Generation System

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ABSTRACT

The effect of biomass co-firing on the furnace exit gas temperature and the gaseous emissions of CO₂, NO_x and SO_x is examined for a biomass co-firing based pulverized coal power generation system. We consider four biomass fuels (rice husk, sawdust, chicken litter and refused derived fuel) and two coals (bituminous coal and lignite). The results generated through simulation illustrate that increasing biomass proportion in the mixture decreases the furnace exit gas temperature for all fuel combinations. The net CO₂ emissions reduce significantly with increasing biomass for all types of selected biomass while there is an increase in gross CO₂ emissions for all blends except bituminous coal/refuse derived fuel, lignite/chicken litter and lignite/refuse derived fuel. The reductions in NO_x and SO_x emissions are dependent on the nitrogen and sulphur contents, respectively of the biomass fuel.

Key words: Biomass, coal, co-firing, co-combustion, emissions

INTRODUCTION

Biomass is a renewable energy source derived from plants and animals and is a CO₂-neutral fuel since it releases no net CO₂ emissions, if carefully managed. The CO₂ released from biomass combustion is absorbed by plants during photosynthesis. The use of biomass as a clean fuel has gained great interest in recent years.

Various technologies are available to convert biomass into useful energy through thermochemical and biochemical processes (Van Loo and Koppejan, 2008; Zhang *et al.*, 2010). Among these, biomass co-firing with coal is the most common method and has the greatest potential for fostering large-scale biomass utilization in the near future (Lian *et al.*, 2010; Hughes and Tillman, 1998).

Numerous studies (Hughes and Tillman, 1998; Spliethoff and Hein, 1998; Kruczek *et al.*, 2006; Kwong *et al.*, 2007; Casaca and Costa, 2003; Demirbas, 2007; Abbas *et al.*, 1994; Backreedy *et al.*, 2005; Ghenai and Janajreh, 2010; Huang *et al.*, 2006) have been reported on co-firing of biomass with coal. Experimental studies focus on the effects of co-firing on factors such as boiler performance, combustion characteristics and gaseous and particulate emissions. However, there are few modeling studies on biomass co-firing with coal. Abbas *et al.* (1994) develop a numerical model for sawdust co-firing with coal in a 0.5 MW pulverized coal boiler. Backreedy *et al.* (2005) model the co-firing of pulverized coal and pinewood in a 1 MW combustor using a commercially available Computational Fluid Dynamics (CFD) code (Fluent version 6). Ghenai and Janajreh (2010) apply

Computational Fluid Dynamics (CFD) to a co-pulverized coal/wheat straw furnace to investigate the effects of co-firing on flow field, gas and particle temperature distributions, particle trajectories and gas emissions.

Biomass co-firing based on a conventional pulverized coal power plant is modeled and assessed in this study, with the aim of improving understanding. The impacts of biomass co-firing on the furnace exit gas temperature and the gaseous emissions of CO₂, NO_x and SO_x is investigated by considering various combinations of fuels and co-firing conditions and using Engineering Equation Solver (EES).

CHARACTERISTICS OF FUELS

The analysis considers four biomass fuels: Rice husk, pine sawdust, chicken litter and refuse derived fuel, as well as two coals: bituminous coal and lignite. Information about these feedstocks is presented in Table 1. The Higher Heating Value (HHV) of biomass and the Lower Heating Value (LHV) of coal are calculated as follows (Van Loo and Koppejan, 2008; Ghamarian and Cambel, 1982):

$$HHV_b = 0.3491C_b + 1.178H_b + 1.005S_b + 0.0151N_b - 0.1034O_b - 0.0211A_b \quad (1)$$

$$LHV_b = 427.0382n_c + 90.88110n_H + 207.46424n_o + 297.0116n_s \quad (2)$$

Table 1: Characteristics of selected solid fuels

Parameter	Chicken litter ¹	Pine sawdust ¹	Refuse derived fuel ¹	Rice husk ²	Bituminous coal ³	Lignite ³
Proximate analysis (wt.%, as received)						
Fixed carbon	13.10	14.20	0.50	20.10	53.90	35.00
Volatile matter	43.00	70.40	70.30	55.60	28.20	44.50
Moisture	9.30	15.30	4.20	10.30	7.80	12.40
Ash	34.30	0.10	25.00	14.00	10.10	8.10
Ultimate analysis (wt.%, as received)						
Hydrogen	3.80	5.00	5.50	4.50	3.90	4.10
Carbon	34.10	43.20	38.10	38.00	70.30	51.00
Oxygen	14.40	36.30	26.10	32.40	6.40	23.80
Nitrogen	3.50	0.08	0.78	0.69	1.07	0.40
Sulphur	0.67	-	0.33	0.06	0.41	0.16
Ash analysis (wt.%)						
SiO ₂	5.77	9.71	38.67	94.48	51.67	46.15
Al ₂ O ₃	1.01	2.34	14.54	0.24	29.15	20.91
Fe ₂ O ₃	0.45	0.10	6.26	0.22	10.73	6.77
CaO	56.85	46.88	26.81	0.97	3.72	12.54
SO ₃	3.59	2.22	3.01	0.92	1.47	8.00
MgO	4.11	13.80	6.45	0.19	1.41	2.35
K ₂ O	12.19	14.38	0.23	2.29	0.29	1.49
TiO ₂	0.03	0.14	1.90	0.02	1.24	0.77
Na ₂ O	0.60	0.35	1.36	0.16	0.31	0.73
P ₂ O ₅	15.40	6.08	0.77	0.54	-	0.29
Heating value (kJ kg⁻¹)⁴						
Higher heating value	14,240	17,280	16,620	14,980	28,330	20,070
Lower heating value	13,410	16,180	15,410	13,990	27,340	19,070

¹Vassilev *et al.* (2010). ²Madhiyanon *et al.* (2009). ³Vassilev and Vassileva (2009). ⁴Calculated from equations 1-3

In Eq. 1, subscript b denotes biomass while C, H, S, N, O and A are the carbon, hydrogen, sulphur, nitrogen, oxygen and ash contents of biomass in wt.%. In Eq. 2, subscript c denotes coal and n is the number of moles of the respective constituent.

For a given substance, the higher and lower heating values are related as:

$$HHV = LHV + 21.978n_H \quad (3)$$

System description: Figure 1 shows a schematic of the co-firing based power plant, modeled for the analysis. A direct co-firing configuration which is the most commonly applied co-firing configuration (Al-Mansour and Zuwala, 2010) is employed. Pulverized biomass mixes with pulverized coal in the fuel transport lines before the burners because co-firing at elevated ratios can be achieved by this type of mixing (Van Loo and Koppejan, 2008). Both air and the fuels enter the boiler at the environment temperature (8°C) and pressure (1.013 bar). Combustion occurs in the combustion chamber and the flue gases, after exchanging heat with the feedwater, exit through the stack. Superheated steam enters the high pressure turbine. Some of the steam is extracted from the turbine after expansion through the first turbine and routed to the open feedwater heater while the remaining is reheated to original temperature and expands through the low pressure turbine to the condenser pressure. The reheat pressure is 1/4 of the original pressure. The steam and

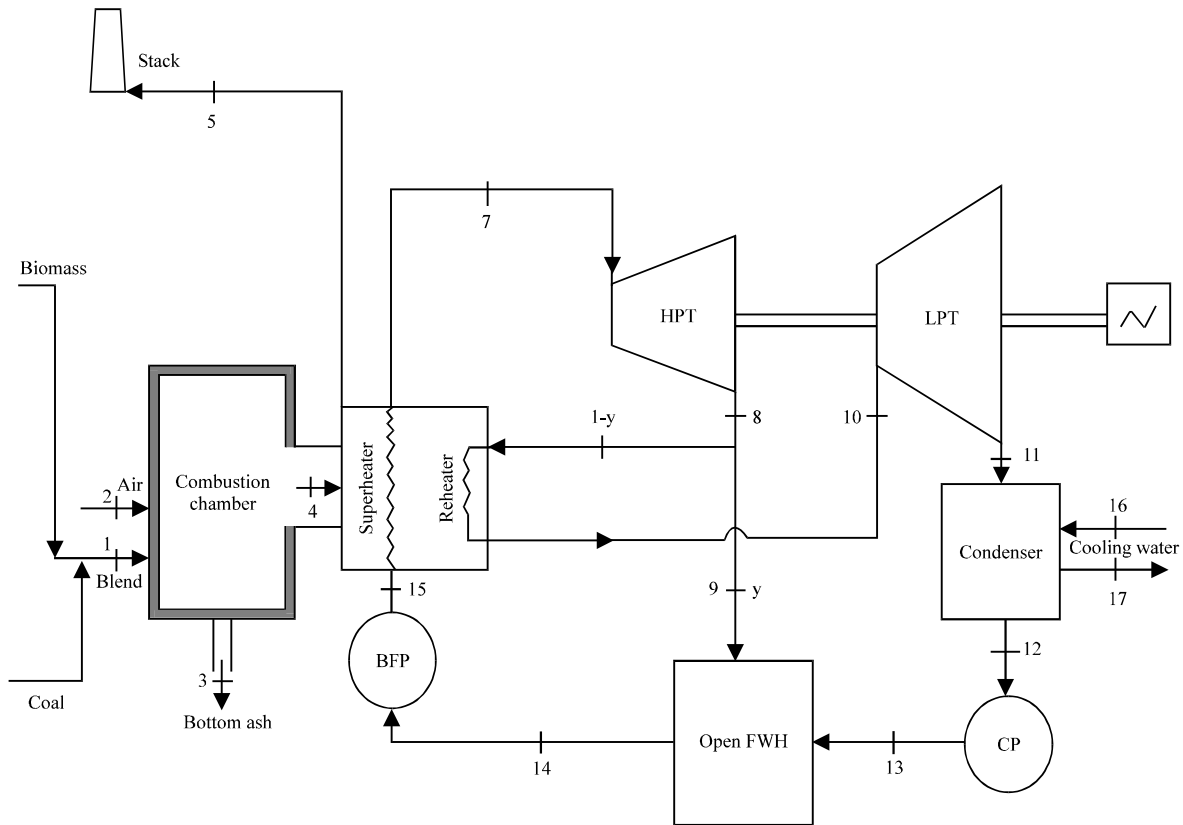


Fig. 1: Diagram of simulated co-firing power plant. Devices are identified as HPT: High pressure turbine, LPT: Low pressure turbine, CP: Condensate pump, FWH: Feedwater heater, BFP: Boiler feed pump

Table 2: Stream data for 100% coal-fired power plant

Stream	For 100% bituminous coal				For 100% lignite			
	Mass flow rate (kg sec ⁻¹)	Temperature (°C)	Pressure (bar)	Energy rate (MW)	Mass flow rate (kg sec ⁻¹)	Temperature (°C)	Pressure (bar)	Energy rate (MW)
1	1.00	8	1.013	28.33	1.00	8	1.013	20.07
2	2.31	8	1.013	0.00	2.31	8	1.013	0.00
3	0.002	600	1.013	0.01	0.001	600	1.013	0.009
4	11.87	1886	1.013	26.22	8.40	1734	1.013	18.12
5	11.87	150	1.013	2.867	8.40	150	1.013	3.086
6 ¹	0.08	150	1.013	0.009	0.06	150	1.013	0.007
7	8.44	600	120	30.46	5.82	600	120	21.00
8	8.44	395.9	30	27.20	5.82	395.9	30	18.75
9	2.35	395.9	30	7.57	1.62	395.9	30	5.22
10	6.09	600	30	22.44	4.24	600	30	15.47
11	6.09	36.17	0.06	15.35	4.24	36.17	0.06	10.58
12	6.09	36.17	0.06	0.92	4.24	36.17	0.06	0.64
13	6.09	36.35	3	0.94	4.24	36.35	3	0.65
14	8.44	233.9	3	8.51	5.82	233.9	3	5.87
15	8.44	236.2	120	8.62	5.82	236.2	120	5.94
16	596.4	8.00	1.013	20.10	411.3	8	1.013	13.86
17	596.4	16	1.013	40.07	411.3	16	1.013	27.63

¹6 (not shown in Fig. 1) represents fly ash carried with flue gases through stack

condensate exit the feedwater heater as a saturated liquid at the extraction pressure. The condensate leaving the condenser mixes with the feedwater leaving the feedwater heater and is then pumped to the boiler pressure. Table 2 contains stream data for all components for both base coals (100% coal).

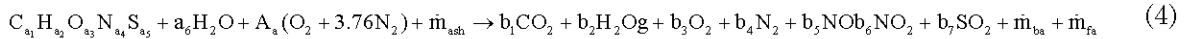
ANALYSIS

The boiler is divided into two subsystems: Combustor and heat exchangers (superheaters and reheater). All components operate at steady state conditions. All gases are ideal and ambient air is considered as 79% nitrogen and 21% oxygen on a volume basis and the excess air is fixed at 20%, as recommended for the pulverized boilers (Basu *et al.*, 2000). The stack gas temperature is 150°C (Basu *et al.*, 2000). Radiation and convective heat losses through large boilers and unburned losses due to combustibles in the ash are each 1.5% of the fuel energy input (Basu *et al.*, 2000; De Souza-Santos, 2010). The 20% of the ash in the fuel is collected as bottom ash while 80% exits as fly ash (Drbal *et al.*, 1996). The ash is inert and the bottom ash temperature is 600°C, based on values reported for pulverized boilers with dry bottoms (Basu *et al.*, 2000). Each steam turbine has the isentropic efficiency of 85% and each pump has an isentropic efficiency of 88% (Drbal *et al.*, 1996). The mechanical efficiency of each turbine and the generator efficiency are 99 and 98%, respectively (Drbal *et al.*, 1996; Suresh *et al.*, 2010; Aljundi, 2009). All components of the steam cycle have adiabatic boundaries and kinetic and potential energy effects are neglected.

In the analysis, the fuel flow rate remains the same and the calculations are on the basis of a unit fuel flow rate. The mass flow rate of coal at one particular co-firing condition for all combinations of fuels remains constant. The mass flow rate of coal is decreased from 1-0.75 kg sec⁻¹ in intervals of 0.05 kg sec⁻¹ and that of biomass is increased from 0-0.30 kg sec⁻¹. For all co-firing conditions, the operating temperature and pressure of all steam cycle components remain fixed.

However, the mass flow rate of the steam produced varies at different co-firing conditions due to the changing feeding rate to the boiler which consequently changes the energy flows at the inlet and outlet of all components.

The following general chemical reaction, accounting for reactants entering and products leaving the combustion chamber, can be written:



In Eq. 4-11, a_1 to a_6 are the molar flow rate of carbon, hydrogen, oxygen, nitrogen, sulphur and moisture, respectively. b_1 to b_6 are the molar flow rates of the respective flue gases exiting the chamber. A_a , \dot{m}_{ba} and \dot{m}_{fa} are the molar flow rate of air, the mass flow rate of bottom ash and the mass flow rate of fly ash, respectively. The subscripts c and b denote coal and biomass while the letters P and M represent the percent share of co-firing and molecular weight, respectively.

The mass flow rate of all reactants excluding air is found from the ultimate analysis as:

$$a_1 = \frac{P_c C_c + P_b C_b}{M_c} \quad (5)$$

$$a_2 = \frac{P_c H_c + P_b H_b}{M_H} \quad (6)$$

$$a_3 = \frac{P_c O_c + P_b O_b}{M_O} \quad (7)$$

$$a_4 = \frac{P_c N_c + P_b N_b}{M_N} \quad (8)$$

$$a_5 = \frac{P_c S_c + P_b S_b}{M_S} \quad (9)$$

$$a_6 = \frac{P_c w_c + P_b w_b}{M_w} \quad (10)$$

The calculations for the ash are done on a mass basis. The mass flow rate of ash is expressible as:

$$\dot{m}_{ash} = P_c \dot{m}_{ash,c} + P_b \dot{m}_{ash,b} \quad (11)$$

The molar flow rate of hot products and air are found by element balances. All carbon in the fuel is converted to CO_2 . For pulverized coal boilers, the incomplete combustion loss is zero (Basu *et al.*, 2000; Bellhouse and Whittington, 1996). Moreover, the addition of biomass in the blend enhances the combustion characteristics because of its high volatile content. So, the carbon balance is:

$$b_1 = a_1 \quad (12)$$

Balancing hydrogen in the reactants and products gives the following relation:

$$b_2 + a_6 = 2b_2 \quad (13)$$

The oxygen balance is:

$$a_3 + a_6 + 2A_a = 2b_1 + b_2 + 2b_3 + b_5 \quad (14)$$

The balance for nitrogen is:

$$a_5 + 7.52A_a = 2b_4 + b_5 + b_6 \quad (15)$$

NO_x emissions from the combustion process are predominantly NO with a small fraction of NO₂, usually less than 5% (Bellhouse and Whittington, 1996; Sarofim and Flagan, 1976; Phong-Anant *et al.*, 1985; Miller and Bowman, 1989). It is assumed that 96% of NO_x emissions are through the formation of NO and 4% are through NO₂ formation. 10-50% of the fuel nitrogen is normally converted to NO (Sarofim and Flagan, 1976; Phong-Anant *et al.*, 1985). 30% of the fuel nitrogen is assumed to convert to NO here. For a typical pulverized coal system, approximately 80% of NO emissions are due to fuel bound nitrogen (24) and NO emission through prompt mechanism is less than 5% (Phong-Anant *et al.*, 1985). The formation of NO emissions through prompt, thermal and fuel bound paths are assumed to be 4, 16 and 80% of the total NO emissions formed, respectively. Using these assumptions, the balance for nitrogen oxide can be written as:

$$b_5 = 0.3a_4 + 3.76a_a + \beta \quad (16)$$

where, the first, second and third (β) terms on the right hand side represent the formation of nitrogen oxide through fuel-bound nitrogen, thermal and prompt paths, respectively. Since, 30% of fuel nitrogen is assumed converted to nitrogen oxide, a_4 is multiplied by 0.3. The balances for thermal and prompt NO are:

$$3.76a_a = 0.16b_5 \quad (17)$$

$$\beta = 0.04b_5 \quad (18)$$

In Eq. 15, b_6 is the molar rate of NO₂, for which a balance can be written as:

$$b_6 = 0.04(b_5 + b_6) \quad (19)$$

All sulphur in the fuel is oxidized to SO₂. This is the only source of SO_x emissions. SO_x emissions are due to formation of SO₂ and SO₃. However, sulphur trioxide (SO₃) only constitutes 10% of SO_x emissions (Bellhouse and Whittington, 1996). Both biomass and coal contain negligible amount of sulphur. So, if any traces of SO₃ are produced, they would be so small that they can be neglected. Therefore, the sulphur balance is:

$$a_5 = b_7 \quad (20)$$

About 80% of the ash in coal being fired is assumed to carry as fly ash. The other 20% gets collected as bottom ash. So, the ash balance can be written as:

$$\dot{m}_{ash} = 0.2\dot{m}_{ba} + 0.8\dot{m}_{fa} \quad (21)$$

RESULTS AND DISCUSSION

The effect of co-firing on furnace exit gas temperature and various gaseous emissions is described. Two types of emission factors that represent normalized mass emissions are used to describe the effect of co-firing on emissions. The emission factors are in energy-based ($\text{g kW}^{-1} \text{h}^{-1}$) and mass-based (kg mg^{-1}) units. The energy-based factor represents the mass of emission per unit output (1 kW h) of electrical energy from the overall plant while the mass-based factor represents the mass of emission per unit mass of fuel input (1 mg) to the overall plant. For CO_2 emissions, gross (total) and net emissions are considered. The gross emissions include all material exiting the plant stack while the net emissions are discounted by the CO_2 used in growing biomass and thus take into account the fact that biomass is relatively CO_2 neutral.

In the results described here, abbreviations used for the name of a fuel blend are based on the first letter of the coal and first and last letters of the biomass. For example, the abbreviation for the bituminous and rice husk blend is B/RH. The co-firing share of coal (P_c) and the co-firing share of biomass, also named as co-firing ratio (P_b) are defined as:

$$P_c = \frac{(m)_c}{m_c + m_b} \times 100 \tag{22}$$

$$P_b = \frac{(m)_b}{m_c + m_b} \times 100 \tag{23}$$

Here, m_c and m_b , respectively represent mass flow rate of coal and mass flow rate of biomass.

Effect of co-firing on furnace exit gas temperature: The furnace exit gas temperature is an important performance measure for the boiler as heat transfer between the furnace exit gas and feedwater depends on it. Figure 2 shows that the furnace exit gas temperature decreases with increasing biomass content for all blends. The extent of decrease in the furnace exit gas temperature depends on the heating value, moisture content and ash content of biomass fuels. Biomass with a low heating value provides little energy input. A high biomass moisture content requires part of the heat supplied to be used to vaporize the moisture. A high ash content results in more sensible heat leaving the combustion chamber with solid waste. These factors lower the furnace exit gas temperature. Among the considered biomass types, chicken litter has the lowest

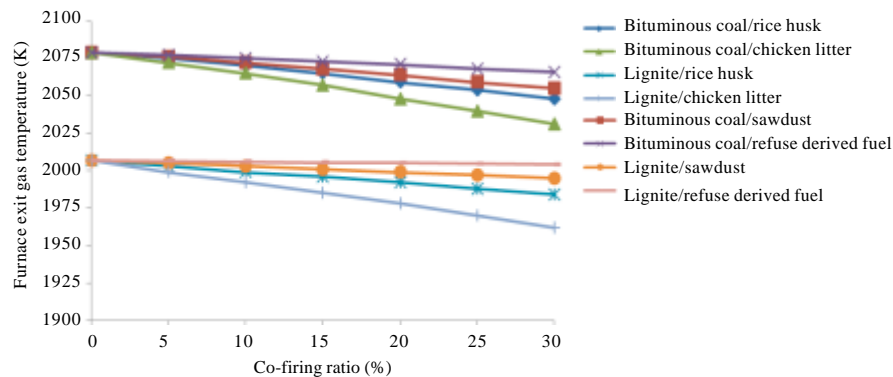


Fig. 2: Effect of co-firing on furnace exit gas temperature

calorific value and the highest ash content. It also contains more moisture than bituminous coal. Therefore, the largest reductions in furnace exit gas temperature are observed for the bituminous coal/chicken litter and lignite/chicken litter blends. When the co-firing ratio increases from 0-30%, for instance, the furnace exit gas temperature decreases from 2079-2031 K for the bituminous coal/chicken litter blend and from 2007-1962 K for the lignite/chicken litter blend.

It is also found that the moisture content of biomass has a much more significant effect than ash content on the reduction of furnace exit gas temperature. Refuse derived fuel has much higher ash content than sawdust which has a much higher moisture content than refuse derived fuel. The higher moisture content of sawdust requires more heat to be supplied for the latent heat of vaporization during its combustion compared to refuse derived fuel. Hence, a more pronounced decrease in furnace exit gas temperature is observed for the bituminous coal/sawdust blend than for the bituminous coal/refuse derived fuel blend. Similarly, lignite has higher calorific value and lower ash content than that of refuse derived fuel but contains about 8% more moisture. Much more heat is needed to vaporize the moisture of lignite than of refuse derived fuel, diminishing the difference between heating values of these two fuels. Thus, the furnace exit gas temperature decreases the least for the lignite/refuse derived fuel blend compared to all other blends. With respect to base coal, the furnace exit gas temperature decreases to 2066 and 2004 K, respectively for blends of bituminous coal/refuse derived fuel and lignite/refuse derived fuel, at a 30% co-firing ratio.

Mass-based emission factors: Table 3 shows the mass-based emission factors for all the blends (with the listing for CO₂ representing gross emissions). The mass-based CO₂ emission factors (kg mg⁻¹) found in all cases are less than CO₂ emission factors (3125 kg mg⁻¹ for bituminous coal and 2300 kg mg⁻¹ for lignite), suggested by the US Environmental Protection Agency (USEPA, 1995). Since, biomass fuels have lower carbon content than coals, the mass-based CO₂ emission factors decrease for all blends as the biomass proportion increases in the blend. The most advantageous biomass in terms of CO₂ emissions reduction is chicken litter because it has the lowest carbon content of the considered biomass fuels. The mass-based CO₂ emission factor decreases by 15.43 and 9.94%, respectively for the blends of bituminous coal/chicken litter and lignite/chicken litter when the co-firing ratio increases from 0-30%.

In all cases, except for chicken litter blends at high co-firing ratios (<20%), the mass-based NO_x emission factor is also less than NO_x emission factors (15.5 kg mg⁻¹ for bituminous coal and 7.5 kg mg⁻¹ for lignite) proposed by the US Environmental Protection Agency (USEPA, 1995). The mass-based NO_x emission factor decreases for all bituminous coal/biomass blends except bituminous coal/chicken litter. This is due to the fact that all considered biomass fuels except chicken litter have lower nitrogen concentrations than bituminous coal. Similarly, since all considered biomass fuels except sawdust contain more nitrogen than lignite, the mass-based NO_x emission factor increases for all lignite/biomass blends except lignite/sawdust. Sawdust is the most beneficial biomass for reducing NO_x emissions because of its small nitrogen content. At a 30% co-firing ratio, the mass-based NO_x emission factor declines by 27.78% for the bituminous coal/sawdust blend and by 24.14% for the lignite/sawdust blend.

Regarding mass-based SO_x emissions, in case of bituminous coal/biomass blends, the mass-based SO_x emission factor at all co-firing ratios is less than mass-based SO_x emission factor (around 13 kg mg⁻¹ for bituminous coal) suggested by the US Environmental Protection Agency (28). However, in case of lignite/biomass blends, the mass-based SO_x emission factor is less than proposed emissions factor (around 5 kg mg⁻¹ for lignite) by the US Environmental Protection Agency (USEPA, 1995) for rice husk and sawdust only. For bituminous coal and biomass co-firing, this

Table 3: Mass-based emission factors for blends of bituminous coal/biomass and lignite/biomass

Fuel blend	For bituminous coal/biomass blends					For lignite/biomass blends					
	Co-firing share (%)		Emission factor (kg mg ⁻¹)			Co-firing share (%)		Emission factor (kg mg ⁻¹)			
	P _c	P _b	CO ₂	NO _x	SO _x	Fuel blend	P _c	P _b	CO ₂	NO _x	So _x
Base ¹	100	0	2839	10.08	9.03	Base ¹	100	0	2062	3.77	3.52
B/RH	95	5	2773	9.90	8.64	L/RH	95	5	2036	3.91	3.41
	90	10	2708	9.72	8.26		90	10	2009	4.04	3.30
	85	15	2643	9.54	7.87		85	15	1983	4.18	3.19
	80	20	2578	9.36	7.49		80	20	1957	4.31	3.08
	75	25	2513	9.18	7.10		75	25	1930	4.45	2.97
	70	30	2447	9.00	6.72		70	30	1904	4.59	2.86
B/SD	95	5	2784	9.61	8.58	L/SD	95	5	2046	3.62	3.35
	90	10	2729	9.15	8.13		90	10	2030	3.47	3.17
	85	15	2675	8.68	7.68		85	15	2014	3.32	3.00
	80	20	2620	8.22	7.22		80	20	1998	3.17	2.82
	75	25	2565	7.75	6.77		75	25	1982	3.01	2.64
	70	30	2510	7.28	6.32		70	30	1966	2.86	2.47
B/CL	95	5	2766	11.23	9.31	L/CL	95	5	2027	5.23	4.09
	90	10	2693	12.37	9.60		90	10	1993	6.69	4.65
	85	15	2620	13.52	9.89		85	15	1959	8.15	5.21
	80	20	2547	14.66	10.18		80	20	1925	9.61	5.77
	75	25	2474	15.80	10.46		75	25	1891	11.07	6.33
	70	30	2401	16.95	10.75		70	30	1857	12.53	6.89
B/RDF	95	5	2774	9.94	8.94	L/RDF	95	5	2036	3.95	3.71
	90	10	2709	9.81	8.86		90	10	2009	4.13	3.90
	85	15	2644	9.67	8.76		85	15	1983	4.31	4.09
	80	20	2579	9.53	8.68		80	20	1957	4.48	4.27
	75	25	2514	9.40	8.59		75	25	1931	4.66	4.46
	70	30	2449	9.26	8.50		70	30	1905	4.84	4.65

¹B/RH, B/SD, B/CL, B/RFD, L/RH, L/SD, L/CL and L/RFD denote respectively bituminous coal/rice husk, bituminous coal/sawdust, bituminous coal/chicken litter, bituminous coal/refuse derived fuel, lignite/rice husk, lignite/sawdust, lignite/chicken litter and lignite/refuse derived fuel

factor decreases for all blends except bituminous coal/chicken litter because all selected biomass fuels except chicken litter have less sulphur content than bituminous coal. However, for lignite and biomass co-firing, the mass-based SO_x emission factor decreases for the blends of lignite/rice husk and lignite/sawdust while this factor increases for the blends of lignite/chicken litter and lignite/refuse derived fuel. Sawdust is the most beneficial biomass in terms of SO_x reduction. The mass-based SO_x emission factor decreases at a 30% co-firing ratio by 30.01 and 29.83%, respectively for the blends of bituminous coal/sawdust and lignite/sawdust.

Energy-based emission factors: Figure 3 illustrates the impact of co-firing on total (gross) CO₂ emissions in terms of energy-based emission factors. The gross CO₂ energy-based emission factor increases with co-firing ratio for all bituminous coal/biomass blends except bituminous coal/refuse derived fuel. In case of lignite/biomass blends, the gross CO₂ energy-based emission factor decreases with co-firing ratio for blends of lignite/chicken litter and lignite/refuse derived fuel and increases for blends of lignite/rice husk and lignite/sawdust.

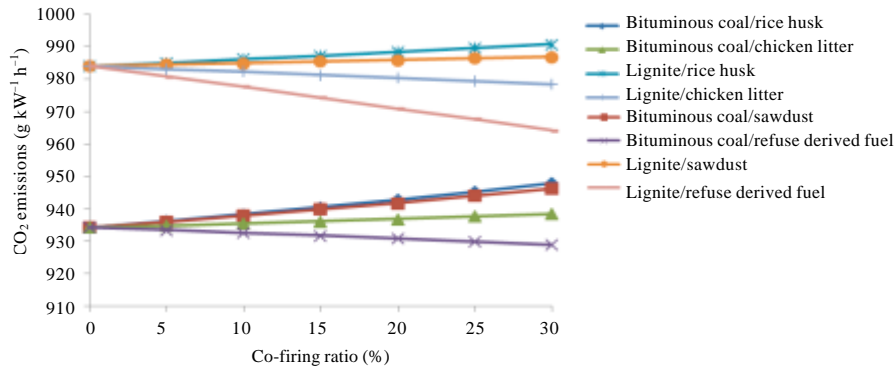


Fig. 3: Effect of co-firing on gross CO₂ emissions

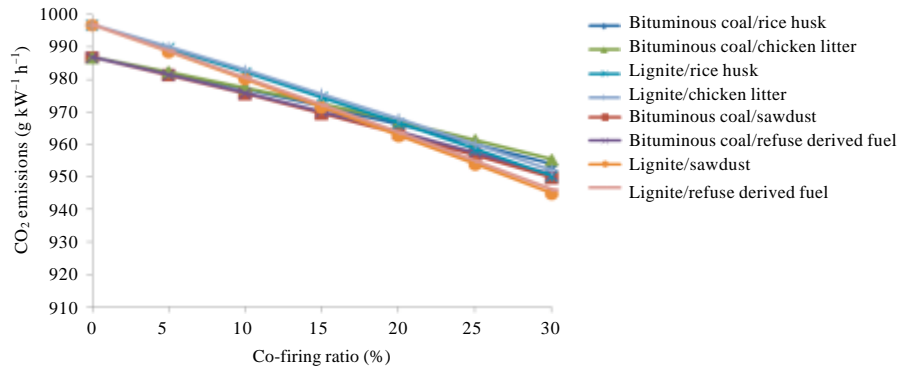


Fig. 4: Effect of co-firing on net CO₂ emissions

The increase in gross CO₂ emissions is due to the decrease in net work output with increasing co-firing ratio which generally yields higher emissions compared with 100% coal. The decrease in CO₂ emissions with co-firing ratio for blends of bituminous coal/refuse derived fuel, lignite/refuse derived fuel and lignite/chicken litter is due to the relatively low carbon content of refuse derived fuel and chicken litter which diminishes the work output reduction. The energy-based CO₂ emission factors at a 30% co-firing ratio are 948.1, 946.3, 936.6 and 929 g kW⁻¹ h⁻¹, respectively for blends of bituminous coal/rice husk, bituminous coal/sawdust, bituminous coal/chicken litter and bituminous coal/refuse derived fuel. The corresponding CO₂ emissions factors are 990.8, 986.9, 978.5 and 964.2 g kW⁻¹ h⁻¹ for blends of lignite/rice husk, lignite/sawdust, lignite/chicken litter and lignite/refuse derived fuel, respectively.

When the net CO₂ emissions to the environment are calculated, i.e. accounting for the fact that biomass is considered to be CO₂ neutral, the co-firing process exhibits a much lower level of CO₂ emissions, as shown in Fig. 4.

With reference to base coal, net CO₂ emissions decrease from 934.3-769.8, 749.2, 776.9 and 753.9 g kW⁻¹ h⁻¹, respectively for the blends of bituminous coal/rice husk, bituminous coal/sawdust, bituminous coal/chicken litter and bituminous coal/refuse derived fuel, at a 30% co-firing ratio. The corresponding net CO₂ emissions for blends of lignite/rice husk, lignite/sawdust, lignite/chicken litter and lignite/refuse derived fuel at a 30% co-firing ratio are 751.2, 724.5, 760.5 and 730.5 g kW⁻¹ h⁻¹, respectively. It is evident that the most suitable biomass in terms of CO₂ reduction is sawdust due to it having the highest carbon content among the considered biomass fuels.

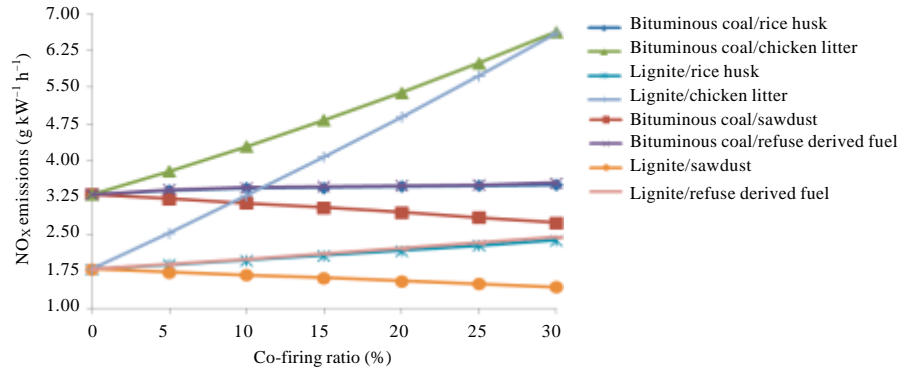


Fig. 5: Effect of co-firing on NO_x emissions

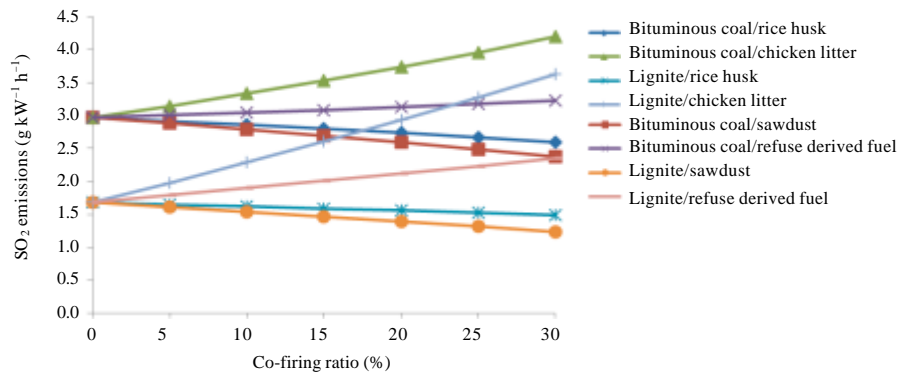


Fig. 6: Effect of co-firing on SO_x emissions

The trends found in this study for energy-based CO₂ emission factor agree with those of Kwong *et al.* (2007) and Huang *et al.* (2006).

The effect of co-firing on NO_x emissions is illustrated in Fig. 5. Since, all biomass fuels except chicken litter have higher concentrations of nitrogen than lignite, NO_x emissions increase with co-firing ratio for all lignite/biomass blends except lignite/sawdust. For bituminous coal/biomass blends, however, regardless of the lower nitrogen concentrations of both rice husk and refuse derived fuel relative to bituminous coal, NO_x emissions increase slightly with co-firing ratio for blends of bituminous coal/rice husk and bituminous coal/refuse derived fuel. The increase in NO_x emissions is due to the decrease in net work output with increasing co-firing ratio. It is also evident that the most advantageous biomass in terms of NO_x reduction is sawdust because of its low nitrogen content. NO_x emissions decrease from 3.32-2.75 g kW⁻¹ h⁻¹ for the bituminous coal/sawdust blend and from 1.80-1.44 g kW⁻¹ h⁻¹ for the lignite/sawdust blend, as the co-firing ratio increases from 0-30%. The findings and observations regarding NO_x emissions found in this study agree with those of Spliethoff and Hein (1998), Kruczek *et al.* (2006), Kwong *et al.* (2007) and Huang *et al.* (2006).

The sulphur content in fuel has a direct effect on the generation of sulphur dioxide during combustion. Among the chosen biomass, rice husk and sawdust have negligible sulphur content. So, their addition to a fuel mixture results in an overall reduction in SO_x emissions with co-firing ratio, as illustrated in Fig. 6. Since, chicken litter has much higher sulphur content than

bituminous coal and lignite, the SO_x emission factor increases with co-firing ratio for blends of bituminous coal/chicken litter and lignite/chicken litter. The sulphur concentration of refuse derived fuel is slightly lower than that of bituminous coal. The SO_x emission factor increases with co-firing ratio for the bituminous coal/refuse derived fuel blend due to a decrease in the work output.

CONCLUSION

Biomass co-firing with coal results in significantly reduced CO₂ emissions if biomass is considered to be CO₂ neutral. The gross (total) CO₂ emissions are lower if the carbon content of the biomass is relatively low; this characteristic also diminishes the work output reduction caused by biomass addition to a fuel blend. Moreover, reductions in NO_x and SO_x emissions are also achieved with biomass co-firing with coal if the selected biomass has less nitrogen and sulphur than coal. Therefore biomass co-firing can lead to substantial benefits in terms of CO₂, NO_x and SO_x emissions reduction. Hence, co-firing of biomass with coal has significant environmental benefits and fosters an increased use of renewable energy.

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