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 CO$_2$, 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 CO$_2$ emissions reduce significantly with increasing biomass for all types of selected biomass while there is an increase in gross CO$_2$ 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 CO$_2$-neutral fuel since it releases no net CO$_2$ emissions, if carefully managed. The CO$_2$ 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 Leeu 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; Kruczak et al., 2006; Kwong et al., 2007; Casaca and Costa, 2003; Demirbas, 2007; Abbas et al., 1994; Backreedy et al., 2005; Ghanaï 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 pine wood in a 1 MW combustor using a commercially available Computational Fluid Dynamics (CFD) code (Fluent version 6). Ghanaï 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, NOₓ and SO₂ 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; Gharianian and Cambel, 1982):

\[
\text{HHV}_b = 0.3491C + 1.178H_c + 1.005S_c + 0.0151N_c - 0.1034O_c - 0.0211A_c
\]

\[
\text{LHV}_b = 427.0382n_c + 90.88110n_{sh} + 207.46424n_{j} + 297.0116n_{s}
\]

<table>
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<tr>
<th>Parameter</th>
<th>Chicken litter¹</th>
<th>Pine sawdust¹</th>
<th>Refuse derived fuel¹</th>
<th>Rice husk²</th>
<th>Bituminous coal³</th>
<th>Lignite³</th>
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<tr>
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<td>6.08</td>
<td>0.77</td>
<td>0.54</td>
<td>-</td>
<td>0.29</td>
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</tbody>
</table>

| Heating value (kJ kg⁻¹)⁴  |                 |               |                      |            |                  |         |

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:

\[
HHV = LHV + 21.978n_H
\]  

(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 re heater pressure is \( 1/4 \) of the original pressure. The steam and

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**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.
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., 1995). 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., 1995). 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 1.075 kg sec\(^{-1}\) in intervals of 0.05 kg sec\(^{-1}\) and that of biomass is increased from 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:

$$C_{n+}H_{m}O_{p}N_{q}S_{r} + a_{i}H_{2}O + A_{i}(O_{i} + 3.76N_{i}) + m_{a} \rightarrow b_{i}CO_{2} + b_{i}H_{2}Og + b_{i}O_{i} + b_{i}N_{i} + b_{i}NO_{x} + b_{i}SO_{2} + m_{as} + m_{a} \quad (4)$$

In Eq. 4-11, $a_{i}$ to $a_{5}$ are the molar flow rate of carbon, hydrogen, oxygen, nitrogen, sulphur and moisture, respectively. $b_{i}$ to $b_{5}$ are the molar flow rates of the respective flue gases exiting the chamber. $A_{i}$, $m_{as}$ and $m_{a}$ 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:

$$a_{i} = \frac{P_{i}C_{c} + P_{i}C_{b}}{M_{c}} \quad (5)$$

$$a_{i} = \frac{P_{i}H_{c} + P_{i}H_{b}}{M_{h}} \quad (6)$$

$$a_{i} = \frac{P_{i}O_{c} + P_{i}O_{b}}{M_{o}} \quad (7)$$

$$a_{i} = \frac{P_{i}N_{c} + P_{i}N_{b}}{M_{n}} \quad (8)$$

$$a_{i} = \frac{P_{i}S_{c} + P_{i}S_{b}}{M_{s}} \quad (9)$$

$$a_{i} = \frac{P_{i}W_{c} + P_{i}W_{b}}{M_{w}} \quad (10)$$

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

$$m_{as} = P_{i}m_{as,c} + P_{i}m_{as,b} \quad (11)$$

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:

$$b_{i} = a_{i} \quad (12)$$

Balancing hydrogen in the reactants and products gives the following relation:
The oxygen balance is:

\[ a_o + 2a_s = 2b_2 \]  \hspace{1cm} (13)

The balance for nitrogen is:

\[ a_s + 7.52A_s = 2b_4 + b_2 + b_6 \]  \hspace{1cm} (14)

\[ a_3 + 7.52A_3 = 2b_4 + b_2 + b_6 \]  \hspace{1cm} (15)

\( \text{No}_x \) emissions from the combustion process are predominantly NO with a small fraction of \( \text{NO}_2 \); usually less than 5% (Bellhouse and Whittington, 1996; Sarofim and Flagan, 1978; Phong-Anant et al., 1985; Miller and Bowman, 1989). It is assumed that 96% of \( \text{NO}_x \) emissions are through the formation of NO and 4% are through \( \text{NO}_2 \) formation. 10-50% of the fuel nitrogen is normally converted to NO (Sarofim and Flagan, 1978; 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:

\[ b_3 = 0.3a_3 + 3.76a_3 \beta - b_3 \]  \hspace{1cm} (16)

where, the first, second and third (\( \beta \)) 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, \( a_3 \) is multiplied by 0.3. The balances for thermal and prompt NO are:

\[ 3.76a_3 = 0.16b_3 \]  \hspace{1cm} (17)

\[ \beta = 0.04b_3 \]  \hspace{1cm} (18)

In Eq. 15, \( b_6 \) is the molar rate of \( \text{NO}_2 \), for which a balance can be written as:

\[ b_6 = 0.04(b_6 + b_6) \]  \hspace{1cm} (19)

All sulphur in the fuel is oxidized to \( \text{SO}_2 \). This is the only source of \( \text{SO}_2 \) emissions. \( \text{SO}_2 \) emissions are due to formation of \( \text{SO}_2 \) and \( \text{SO}_3 \). However, sulphur trioxide (\( \text{SO}_3 \)) only constitutes 10% of \( \text{SO}_2 \) emissions (Bellhouse and Whittington, 1996). Both biomass and coal contain negligible amount of sulphur. So, if any traces of \( \text{SO}_3 \) are produced, they would be so small that they can be neglected. Therefore, the sulphur balance is:

\[ a_5 = b_7 \]  \hspace{1cm} (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:

\[ \dot{m}_{ash} = 0.2\dot{m}_{as} + 0.8\dot{m}_{ba} \]  \hspace{1cm} (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 (g kW⁻¹ 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 CO₂ 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 CO₂ used in growing biomass and thus take into account the fact that biomass is relatively CO₂ 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 BRH. 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:

\[
P_c = \frac{(m)_c}{(m)_c + (m)_b} \times 100
\]

\[
P_b = \frac{(m)_b}{(m)_c + (m)_b} \times 100
\]

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](image_url)
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 NOₓ emission factor is also less than NOₓ 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 NOₓ 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 NOₓ emission factor increases for all lignite/biomass blends except lignite/sawdust. Sawdust is the most beneficial biomass for reducing NOₓ emissions because of its small nitrogen content. At a 30% co-firing ratio, the mass-based NOₓ emission factor declines by 27.78% for the bituminous coal/sawdust blend and by 24.14% for the lignite/sawdust blend.

Regarding mass-based SO₂ emissions, in case of bituminous coal/biomass blends, the mass-based SO₂ emission factor at all co-firing ratios is less than mass-based SO₂ 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 SO₂ 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
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) $CO_2$ emissions in terms of energy-based emission factors. The gross $CO_2$ 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 $CO_2$ 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 CO\textsubscript{2} emissions

Fig. 4: Effect of co-firing on net CO\textsubscript{2} emissions

The increase in gross CO\textsubscript{2} 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 CO\textsubscript{2} 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 CO\textsubscript{2} emission factors at a 30% co-firing ratio are 948.1, 946.3, 936.6 and 929 g kW\textsuperscript{-1} h\textsuperscript{-1}, respectively for blends of bituminous coal/rice husk, bituminous coal/sawdust, bituminous coal/chicken litter and bituminous coal/refuse derived fuel. The corresponding CO\textsubscript{2} emissions factors are 990.8, 986.9, 978.5 and 964.2 g kW\textsuperscript{-1} h\textsuperscript{-1} for blends of lignite/rice husk, lignite/sawdust, lignite/chicken litter and lignite/refuse derived fuel, respectively.

When the net CO\textsubscript{2} emissions to the environment are calculated, i.e. accounting for the fact that biomass is considered to be CO\textsubscript{2} neutral, the co-firing process exhibits a much lower level of CO\textsubscript{2} emissions, as shown in Fig. 4.

With reference to base coal, net CO\textsubscript{2} emissions decrease from 934.3-769.8, 749.2, 776.9 and 753.9 g kW\textsuperscript{-1} h\textsuperscript{-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 CO\textsubscript{2} 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\textsuperscript{-1} h\textsuperscript{-1}, respectively. It is evident that the most suitable biomass in terms of CO\textsubscript{2} 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 CO$_2$ emission factors 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 Splethoff 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$_2$ 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$_2$ 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 CO$_2$ emissions if biomass is considered to be CO$_2$ neutral. The gross (total) CO$_2$ 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$_2$ 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 CO$_2$, NO$_x$ and SO$_2$ 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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