NO Emissions and Combustion Efficiency during Biomass Co-firing and Air-staging

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Experiments were carried out in a drop tube furnace to investigate the effects of biomass/coal co-firing and air staging on NO emission and combustion efficiency. NO and CO emissions along the height of the furnace were monitored by a gas analyzer, and the content of unburned carbon (UBC) in fly ash was also tested. Results showed that NO emission from straw or wood combustion only account for 1/3 or 1/2 that from coal combustion, respectively. Under the conditions of biomass co-firing, the increase in blending ratio had a positive effect on the reduction of NO emission and combustion efficiency. Moreover, results of air-staging combustion showed that for coal combustion, air staging notably reduced NO emission and combustion efficiency. For biomass combustion, the effect was slight. Synergetic analysis indicated that there was an optimum biomass co-firing ratio around 0.4, when the positive synergetic effects on reducing NO emission and UBC were the most significant. When the co-firing ratio exceeded this optimum value, further increasing the co-firing ratio had little influence on NO emission and combustion efficiency. After air staging was adopted, the degree of synergetic effect on NO emissions was reduced while that of UBC was increased.

Keywords: Biomass; Co-firing; Air staging; NO; Unburned carbon

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INTRODUCTION

Biomass is regarded as CO_2-neutral, and its utilization is attracting more and more attention with the aggravation caused by the greenhouse effect (Martinot and Sawin 2009; Munir *et al.* 2011; Wang *et al.* 2011). However, large amounts of alkali and chlorine in biomass fuels, which are greater than in fossil fuels, result in severe problems of slagging, fouling, and corrosion in heat exchangers of biomass-fired furnaces (Michelsen *et al.* 1998; Demirbas 2005; Davidsson *et al.* 2008; Hansson *et al.* 2009; Kazagic and Smajevic 2009). This is a serious hazard in furnace operations. Consequently, it has been suggested that biomass be co-fired with fossil fuels to alleviate fouling (Baxter 2005; Pisa and Lazaroiu 2012). Co-firing is generally viewed as the most effective approach to biomass utilization for the electric utility industry (Spliethoff and Hein 1998; Tillman 2000).

Moreover, the Chinese government recently announced a strict standard for NOx emissions, 50 to 100 mg/Nm^3, and is encouraging the adoption of low-NOx combustion and NOx removal technologies (air staging, fuel staging, SNCR, and SCR); air staging is mostly widely applied here because of its low cost (Han *et al.* 2012; Daood *et al*. 2013). The content of nitrogen in biomass is lower than in coal, and if air staging and biomass co-firing are combined, a higher NOx reduction could be achieved. The high amount of alkali in biomass would also improve the NOx reduction (García-García *et al.* 1999; Zhong and Tang 2007). Consequently, some recent works have focused on the combining of biomass co-firing and air staging to reduce NOx emission.

Biomass was co-fired with coal in specially designed co-firing burners, and it was found that biomass co-firing reduced NOx emission and that the reduction on NOx emission was related to burner type (Pedersen *et al.* 1997). Spliethoff and Hein (1998) measured gas emission from biomass co-firing in a 0.5 MW semi-industrial pulverized coal furnace. It was found that SO_2 emission was reduced linearly with the increase in biomass co-firing ratio; however, NO reduction percentage was less, and NO emission could be very high at a high air ratio. Shen *et al.* (2003) investigated the effect of temperature and blending ratio on NOx emission in a laboratory-scale bubbling fluidized bed, indicating that co-combustion of biomass and coal was effective in lowering NOx emission. Lawrence *et al.* (2009) reported a lower NOx emission when dairy biomass (DB) was co-fired with coal in a 29 kW furnace, even though DB fuels are higher in moisture, nitrogen, sulfur, and ash. Wang *et al.* (2011) conducted a full-scale biomass co-firing test in a 300 MW pulverized coal fired furnace, and the results showed that both NOx and SO_2 emissions were reduced.

As to another effective and low-cost technology to reduce NOx, air staging has been widely used. Fan *et al.* (2008; 2010) investigated the effect of air staging on the NOx emission of anthracite and lignite at 1300 °C in a multi-path air inlet one-dimensional furnace. It was observed that the air-staging ratio had a great effect on NOx formation, and NOx emission decreased with the decrease in stoichiometric ratio of 1.5 to 1.0. Wei *et al.* (2011) simulated the pollutant emissions in an entrained flow reactor and compared with the experimental results, and it was shown that the reduction of pollutant emissions was proportional to the blending ratio of biomass. Daood *et al.* (2013) compared the NOx emission after selective non-catalytic reduction (SNCR) with and without biomass co-firing, which indicated that combining SNCR and biomass-co-firing resulted in lower NOx emission. Bai *et al.* (2014) studied the effect of the reducing zone temperature and air-staging ratio on NOx emissions. A similar result was also found in that the air-staging ratio greatly affected the NOx reduction, and NOx emission decreased with the increase in reducing zone temperature.

There have indeed been many separate studies of biomass co-firing or air-staging for coal combustion. However, study of the effect of air-staging on biomass combustion has been little, and the coupled evaluation of both biomass co-firing and air-staging has been rarely considered. In the present study, biomass co-firing with coal, air staging combustion, and the combination of the two were investigated in a drop tube furnace. NO and CO concentration along the height of the furnace was monitored by an on-line gas analyzer, and the content of unburned carbon in fly ashes was also tested. We were aiming to obtain the NO emission and combustion efficiency under the combined effects from biomass co-firing and air-staging together. The synergetic effect from biomass co-firing was also compared under air-staging and non-air staging conditions.

EXPERIMENTAL

Drop Tube Furnace

The drop tube furnace (DTF) system has been widely used in investigations of biomass and coal combustion. It is the most commonly used lab-scale continuous reaction system for fundamental study at high temperatures in the area of combustion science. The basic data obtained from DTF should be reasonably instructive for different kinds of furnace, including grate furnaces, fluidized bed furnaces, and pulverized furnaces. A schematic diagram of a DTF is shown in Fig. 1.

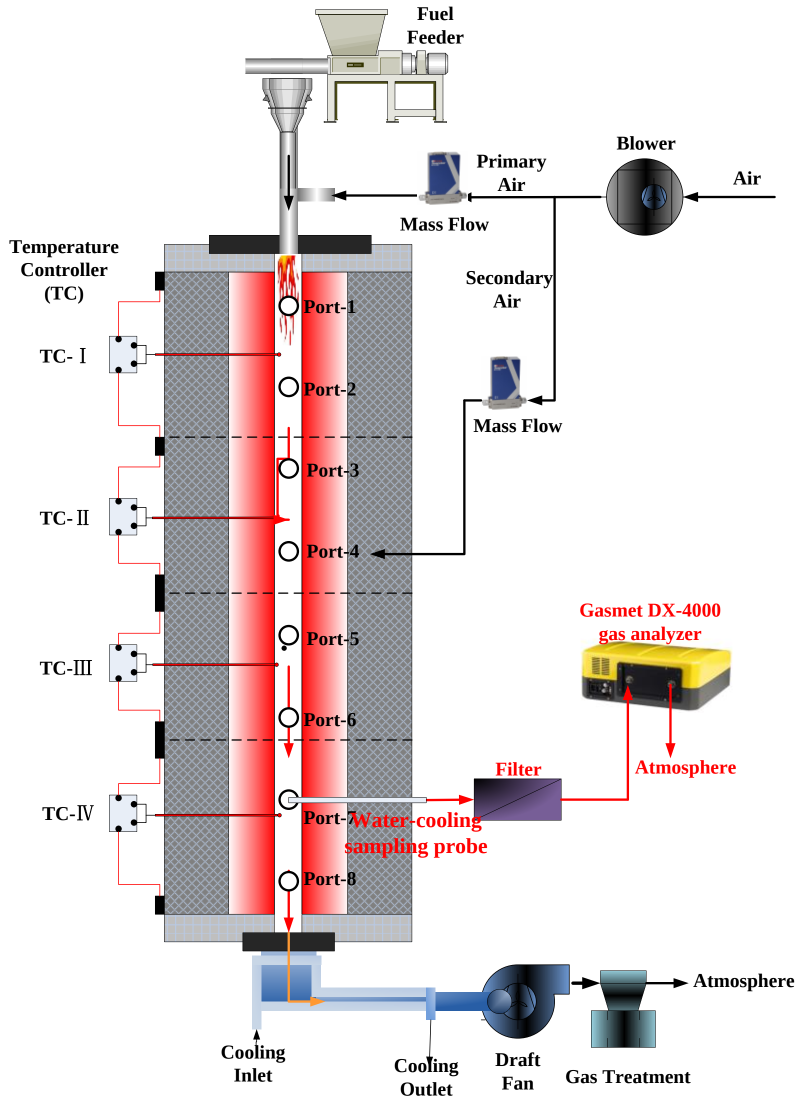


Fig. 1. Experimental system of drop tube furnace

The furnace is heated by using molybdenum silicide heating elements. Four Pt-Rh-Pt thermocouples (accuracy ±1 °C) are used to measure the temperature, ensuring a constant temperature. The inner corundum tube is 100 mm in diameter and 2600 mm in length. Eight measuring ports along the furnace height are arranged for gas sampling. An air compressor and draft blower are employed to transport the fuels and adjust the pressure in the furnace to reduce air leakage. The fuels are fed by a micro-scale spiral feeder with a stable feeding rate in the range of 8 to 20 g•min^{-1}. The main temperature is maintained at 1100 °C, and the air ratio is kept constant at 1.15.

A water-cooling sampling probe was adopted to collect the flue gas at high temperature 1100 ^{o}C to avoid the gas composition change during the sampling process. A GASMET DX-4000 Fourier transform infrared (FTIR) gas analyzer (Temet Instruments

Oy, Helsinki, Finland) was used to record the concentration of NOx and CO from the sampling ports along the furnace height. The connection pipes were always heated and accurately controlled at 180 °C. The measurement accuracy was ±1 ppm, and before we started our experiments, we always used the standard gas to check the measurement accuracy to make sure the equipment was running well.

The fly ash was also collected through the water-cooling sampling probe, captured by the filter, and then removed from the filter to be measured. The duration time for each test is one hour under stable conditions to collect enough fly ash for UBC measurement. The UBC in fly ash was examined by a Netzsch simultaneous thermal analyzer (STA 409 PC, Netzsch, Germany).10 mg fly ash was used for the UBC measurement, with a heating rate of 10 °C.min^{-1} from 20 °C to 1200 °C and with a carrier gas flow 100 ml· min^{-1} in air atmosphere.

Fuel Properties

Two kinds of biomass (wheat straw and wood) from Shaanxi Province in China were adopted to be co-fired with Huating bituminous coals. The proximate and ultimate analysis of the fuels is shown in Table 1. The seizing distribution of pulverized coal from a power plant is R_{90}=23%, while the diameter of biomass after grinding and seizing was below 1 mm. All the fuels were dried at 105 °C for 24 h before use.

Table 1. Proximate and Ultimate Analysis of Biomass and Coal Used

Fuel	Lower Heating Value (MJ/kg)	Proximate Analysis (wt%)				Ultimate Analysis (wt%)					
	$Q_{net,d}$	M_{ad}	A_d	V_{daf}	FC_{ad}	C_d	H_d	N_d	O_d	S_d	Cl_d
Straw	18.09	10.09	6.5	79.33	17.38	44.70	3.43	0.81	44.22	0.3	0.218
Wood	19.31	11.43	0.7	82.63	15.51	50.65	4.46	0.26	43.8	0.14	0.054
Coal	23.03	7.88	20.65	38.13	45.23	66.06	3.12	0.69	8.98	0.51	0.013

Note: d- dry basis; ad-air dry basis; daf-dry and ash free basis

RESULTS AND DISCUSSION

Comparison of Biomass and Coal Combustion

A comparison of CO concentration profiles along the furnace height for different fuel types is shown in Fig. 2 (Wang *et al.* 2014). In all tests of biomass (straw and wood) combustion, CO concentration decreased along the furnace height, while for coal combustion, there was a maximum CO concentration at the second measuring port. The difference in CO emission for biomass and coal combustion was mainly due to the ignition and burnout properties of the volatile content in biomass, which is much higher than that in coal. The formation of CO is mainly dominated by de-volatilization and further oxidation of char to CO (Werther *et al.* 2000; Permchart and Kouprianov 2004). Biomass is much easier to ignite because of higher volatile content, and large amounts of volatiles released from biomass and combustion result in a regional lack of oxygen, leading an extreme CO concentration at the very beginning of combustion. However, in coal combustion, because the volatile content of coal is much lower, and CO comes mainly from the oxidation of the char component. As is well known, the heterogeneous reaction rate of the char-oxidation reaction is much slower than the gas reaction rate of volatile oxidation. Consequently, the dominated slow char-oxidation reaction delayed the release of CO, thus the maximum CO concentration appears at the second sampling port.

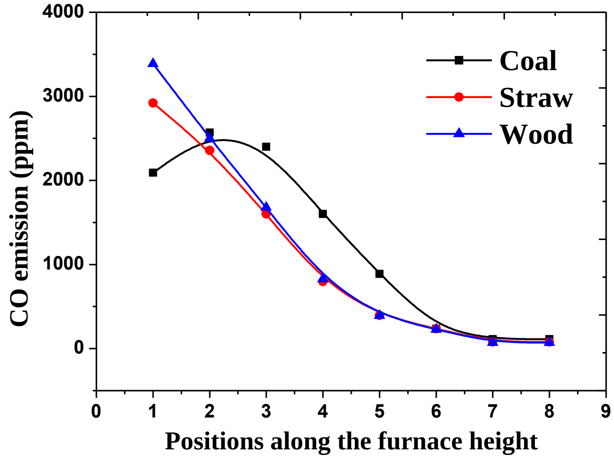


Fig. 2. Axial CO concentration profiles of coal/straw/wood combustion

NO emission along the furnace height for the three kinds of tested fuels was compared in Fig. 3 (Wang *et al.* 2014). It is apparent that NO concentration was the highest at the second sampling port. NO concentration in straw and wood combustion was much lower than that in coal combustion, only accounting for about 1/3 or 1/2, respectively.

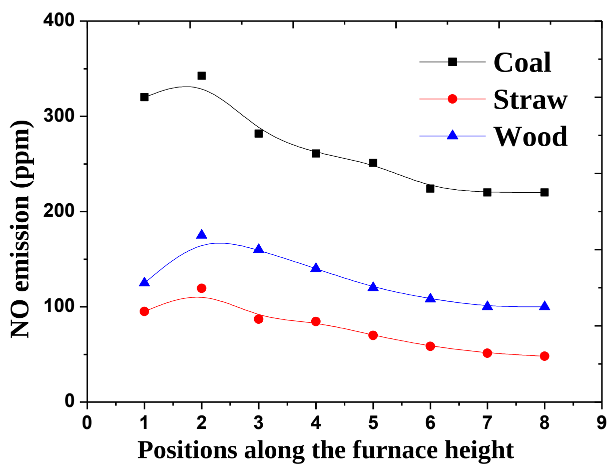


Fig. 3. Axial NO concentration profiles of coal/straw/wood combustion

From Table 1 one can see that the content of nitrogen in straw was even higher than that in coal, which indicated that NO emissions were not closely dependent on the nitrogen content in fuels. The reason for that should be ascribed to the different ignition process in biomass and coal combustion. The volatile content in biomass is much higher, and biomass is much more easily ignited. In the starting stage of biomass combustion, a large amount of oxygen was consumed, producing a reducing atmosphere, which was very efficient to control NO formation. Moreover, due to the high content of volatiles in biomass, radicals like CH_i were produced in large amounts, and these radicals were highly efficient at transforming NO into N_2.

Effect of Biomass Co-Firing

NO emission

Three co-firing mass ratios (20%, 40%, and 80%) of straw with coal were tested in the present study. A calculated NO emission under biomass co-firing was obtained by mass averaging of the NO emission value in coal and biomass combustion alone. The calculated values were compared with the experimental ones shown in Fig. 4. It can be observed that with the increase in biomass co-firing ratio, NO emission decreased. The experimentally measured NO emission was lower than the expected NO concentrations based on mass averaging calculations, which indicated a positive synergetic effect on NO reduction by biomass co-firing. It was also noted that the synergetic effect or the difference degree of calculated and experimental value was most significant when the co-firing ratio was 40%. It seems there should be an optimum co-firing ratio corresponding to the most positive synergetic effect on NO reduction.

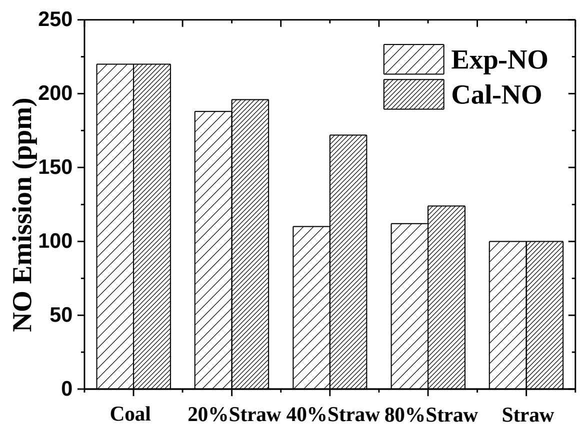


Fig. 4. Effect of biomass co-firing ratio on NO emission

Combustion efficiency

The unburned carbon content (UBC) in fly ash under different biomass co-firing ratios was analyzed by using TGA, and the results are shown in Fig. 5. Similar to NO emission, UBC also decreased with the increase in the straw co-firing ratio, and the experimental UBC values were also lower than the calculated ones.

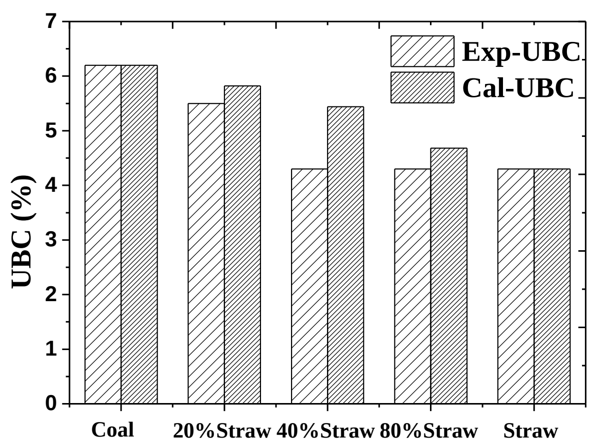


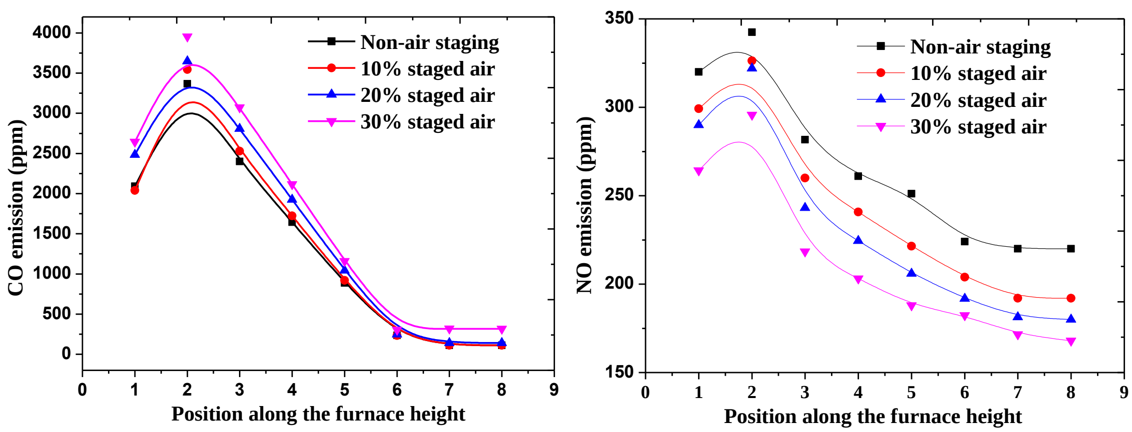
Fig. 5. Effect of biomass co-firing ratio on UBC

The results shown in Fig. 5 indicated that biomass co-firing also produced a positive synergetic effect on burnout properties or combustion efficiency. A similar synergetic effect was also confirmed by other tests in a single burner furnace and in a fluidized bed furnace for co-firing in the previous works (Molcan *et al.* 2009; Sun *et al.* 2013). It is believed that the advanced biomass combustion played a promotion on the ignition and burnout of coal, because the ignition temperature of bituminous coal was usually more than two hundredths of a centigrade higher than that of biomass (Wang *et al.* 2012). The synergetic effect degree of biomass co-firing on combustion efficiency was also the most significant at the co-firing ratio of 40%. This indicated again that 40% should be a good co-firing ratio both on NO reduction and combustion efficiency.

Effect of Air-Staging

Coal

The effect of air staging ratio on CO and NO emission in coal combustion was investigated. The staged air was introduced into the furnace through Port-4, as shown in Fig. 1. CO and NO concentrations along the furnace height under different air staging ratios are shown in Fig. 6. It can be seen that for all the tests on coal combustion with and without air staging, both CO and NO concentrations showed a peak at the second sampling point. Along the flue gas direction, CO and NO concentration increased to the peak value at Port-2 and then decreased.



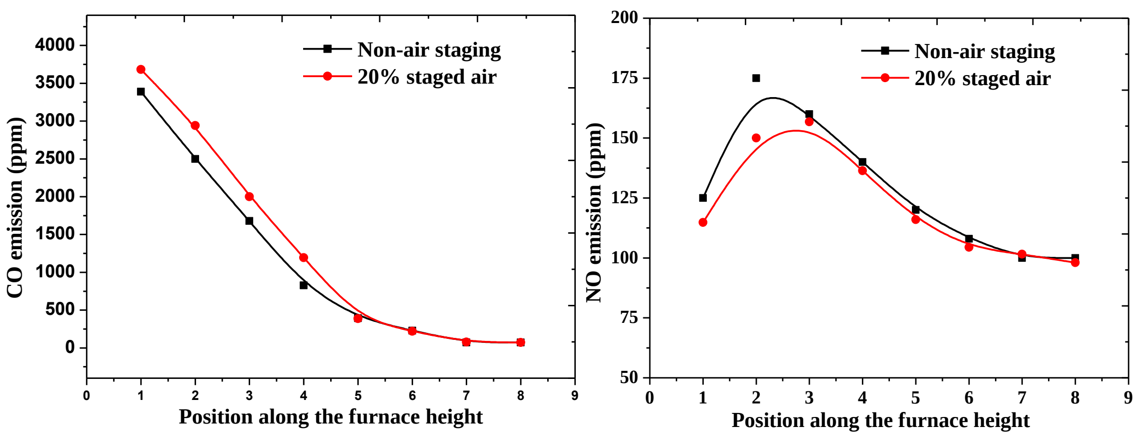
(a) CO emission (b) NO emission

Fig. 6. Effect of air staging ratio on CO and NO emission in coal combustion

In Fig. 6(a), with the increase in staged air ratio, the overall CO emission before the staged air injection Port-4 increased, while after the supplement of the residual staged air, the effect of staged air ratio on outlet CO emission was slight when the staged air ratio was below 20%. In the present work, only when the staged air ratio exceeded 30% was the effect of air staging on combustion efficiency significant. In Fig. 6(b) (Wang *et al.* 2014), the overall distribution of NO along the furnace is similar when the staged air ratio was changed. Under the condition of 10% staged air, outlet NO emission decreased from 220 ppm to 192 ppm. When the staged air ratio further increased to 20% and 30%, NO emission decreased to 180 ppm and 168 ppm. This indicated that the staged air ratio should be controlled below 20% when NO emission was reduced by 18%, while the combustion efficiency was little affected.

Biomass

The CO and NO emissions in biomass combustion were compared without and with 20% staged air. The results are shown in Fig. 7, which shows that the effect of air staging on biomass combustion mainly appeared before staged air injection, and that air staging increased CO emission but reduced NO emission. However, for the sampling positions after the staged air injection, from Fig. 7 it can be seen that the emission curves for non-air staging and 20% staged air almost coincided both for CO and NO emission after Port-5. This indicated that the adopting of air staging took very little effect on the combustion efficiency and NO emission, because biomass was much easier to ignite and burn out than coal.

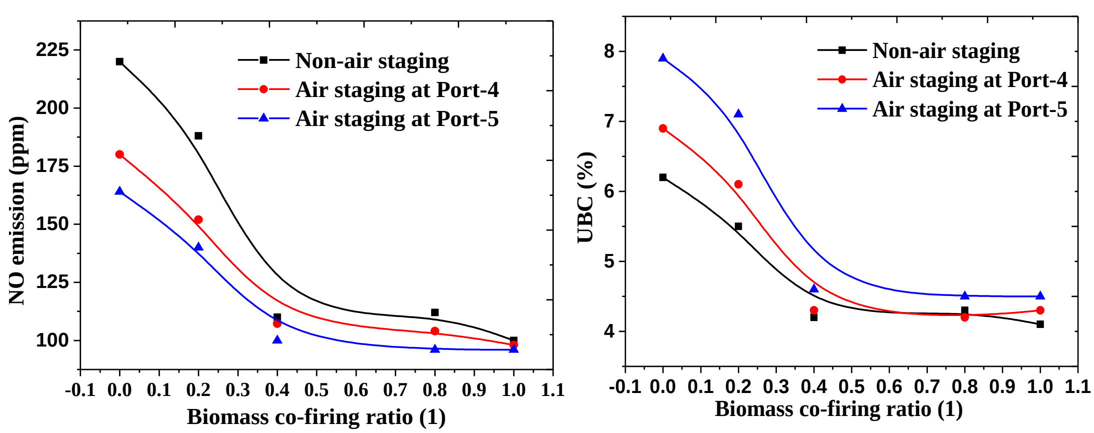


(a) CO emission (b) NO emission

Fig. 7. Effect of air staging ratio on CO and NO emission in straw combustion

Combination of Biomass Co-Firing and Air Staging

Based on the results of air staging on single fuel combustion alone, air staging was also conducted for biomass/coal co-firing. NO emission and UBC were measured for the conditions of non-air staging and 20% air staging at port-4 and at port-5. The results are shown in Fig. 8, showing that under both non-air staging and air staging conditions, with an increase of the biomass co-firing ratio from 0% to 40%, both NO emission and UBC decreased remarkably. However, when the co-firing ratio was higher than 40%, the further decrease in NO and UBC were not significant.



(a) NO emission (b) UBC

Fig. 8. Effect of co-firing ratio on NO emission and UBC with 20% air staging

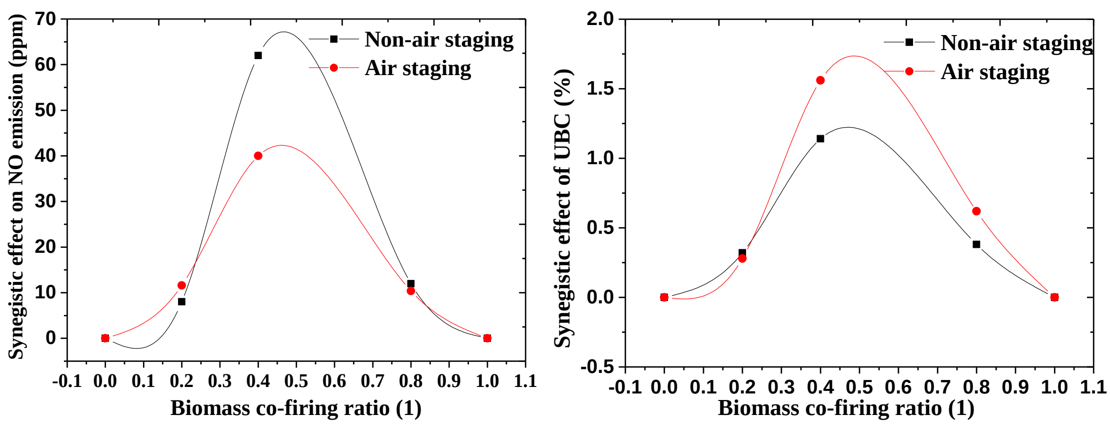
From Fig. 8 it also can be seen that with the increase in the co-firing ratio, the difference of NO emissions between non-air staging and air staging became smaller. For coal combustion alone, when air staging was adopted at port-4, NO emission decreased by 40 ppm and UBC increased by 0.7%; however, for biomass co-firing of 40%, NO emission only decreased by <10 ppm and UBC increased by <0.2%. This indicated that with the increasing of the biomass co-firing ratio, the effect from air staging was weakened because of the significant improvement on ignition properties. That also suggested that under the conditions with biomass co-firing ratios higher than 40%, the effect of air staging on NO emission and combustion efficiency could be negligible.

The emission and combustion efficiency were also compared when changing the staged air injection port. When the staged air injection position was moved down from port-4 to port-5, the overall NO emission decreased while UBC increased. This was because the delays on the supplement of staged air prolonged the residence time of fuel particles in a lean (fuel-poor) atmosphere.

Analysis of the Synergetic Effect of Biomass Co-Firing

Figures 4 and 5 have clearly shown that there was a positive synergetic effect on NO emission and combustion efficiency by biomass co-firing. To demonstrate the synergetic effect of biomass co-firing quantitatively, the synergetic effect can be defined as the difference between the measured value and the mass-averaging value by co-firing ratios.

The effects of co-firing ratio and air staging on the synergetic effect degree of NO and combustion efficiency are compared in Fig. 9. As the biomass co-firing ratio increased, both for NO emission and for UBC, regardless of air staging, the synergetic effect first increased and then decreased, and the synergetic degree was the greatest at the biomass co-firing ratio of 40%. At such an optimum co-firing ratio, the synergetic effect degree on NO emission and UBC was in the range of 38 to 62 ppm and 1.1 to 1.6 %, respectively.



(a) NO emission (b) UBC

Fig. 9. Effect of biomass co-firing ratio on the synergetic effect

The effect of air staging on the degree of synergetic effect depended on the co-firing ratio. When the co-firing ratio was below 20% or above 80%, the synergetic effect differences between NO emission and UBC were not remarkable. In the co-firing ratio region of 20 to 80%, the effect of air staging on the synergetic effect degree for NO emission and UBC was the opposite. With air staging, the synergetic effect degree of NO emission was lower while that of UBC was higher. This was because after air staging, the basis quota of NO emission decreased but the basis quota of UBC increased.

CONCLUSIONS

1. Along the height of the furnace, NO concentration increased first and then decreased slowly for all the fuels, and NO emission from straw or wood combustion only accounted for about 1/3 or 1/2 of that from coal combustion, respectively. With the increase in air staging ratio, CO emission of coal combustion increased; however, the effect of air staging on the outlet CO emission of biomass combustion was little in the range of tested air staging ratio.
2. Increasing the biomass co-firing ratio reduced NO emission but increased combustion efficiency, and it showed a synergetic effect on biomass co-firing. For coal combustion, air staging notably reduced NO emission and combustion efficiency, while for biomass combustion the effect of air staging was less significant
3. There was an optimum biomass co-firing ratio around 0.4, when the positive synergetic effects on reducing NO emission and UBC were the most significant. When the co-firing ratio exceeded this optimum value, a further increase of co-firing ratio had little influence on NO emission and combustion efficiency. After air staging was adopted, the synergetic effect degree of NO emission was reduced, while that of UBC was increased.

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