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Optimization of air staging in a 1 MW tangentially fired pulverized coal furnace

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ABSTRACT

This paper deals with an experimental study of air staging in a 1 MW (heat input power) tangentially fired pulverized coal furnace. The influences of several variables associated with air staging on NO_x reduction efficiency and unburned carbon in fly ash were investigated, and these variables included the air stoichiometric ratio of primary combustion zone (SR_1), the locations of over-fire air nozzles along furnace height, and the ratio of coal concentration of the fuel-rich stream to that of the fuel-lean one (RRL) in primary air nozzle. The experimental results indicate that SR_1 and RRL have optimum values for NO_x reduction, and the two optimum values are 0.85 and 3:1, respectively. NO_x reduction efficiency monotonically increases with the increase of OFA nozzle location along furnace height. On the optimized operating conditions of air staging, NO_x reduction efficiency can attain 47%. Although air staging can effectively reduce NO_x emission, the increase of unburned carbon in fly ash should be noticed.

1. Introduction

Coal is the major energy resources to meet the demand of electricity in China, and one of the major concerns associated with coal-fired power plants is the pollutant emissions of flue gas, especially nitrogen oxides (NO_x). With more stringent regulation on NO_x emission, NO_x emission control becomes an important consideration in the design and modification of coal-fired utility boiler.

NO_x emission reduction is generally achieved using two approaches: combustion controls and post-combustion controls [1–4]. Combustion-controls reduce NO_x emissions by altering or modifying the firing conditions, and post-combustion controls reduce NO_x emissions by introducing a reagent into the flue gas stream to selectively react with NO_x. For coal-fired boilers, combustion system modifications are generally less costly and may independently result in NO_x emission reduction that satisfies regulatory requirements. Moreover, even when stringent regulations pertain to NO_x emission, an integrated solution that combines combustion and post-combustion technologies is frequently less costly than a post-combustion system alone. Air staging, a combustion-related technology which can meet current NO_x emission reduction objectives, discussed herein.

Many researchers have reported air staging as a means to reduce NO_x emission [5–10]. In-furnace air staging technology is that the combustion air is separated into primary air and over-fire air (OFA) flows. 70–90% of the combustion air as the primary air is mixed with the fuel producing a fuel-rich primary combustion zone, and the 10–30% of the combustion air as OFA is injected burnout zone which is above the primary combustion zone. Since the primary combustion zone where the ratio of the air amount supplied in the fist zone to the stoichiometric amount of air (SR_1) is less than 1, the primary air and fuel produce a relatively low-temperature, oxygen-deficient, fuel-rich environment in the combustion zone which reduces the formation of thermal-NO_x and fuel-NO_x.

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OFA is injected above the primary combustion zone to produce a relatively low-temperature burnout zone that limits the formation of thermal-NO_x.

Air staging in tangentially fired boiler (T-fired boiler) can effectively reduce NO_x emissions, and it is by far the most cost-effective technique for reducing NO_x emission. NO_x reduction efficiency of air staging ranges from 20% to 50%, and it depends on a boiler's initial NO_x level, fuel combustion equipment design, and fuel type [3,11].

The success of air staged combustion technique primarily depends on the location of OFA injection and the air stoichiometric ratio of primary combustion zone. Up to now, although the experiments of coal air staged combustion have been conducted, most experiments were conducted in drop-tube furnaces and single burner furnaces without combination with other low NO_x combustion technologies. The objective of the paper is to optimize the influencing factors of air staging for NO_x reduction. A 1 MW tangentially fired coal furnace with low NO_x burners (LNB) and low NO_x concentric firing system of biased primary air (CFS) is used to investigate NO_x reduction. Several variables associated with the air staging system were investigated in the experiment, and these variables included the air

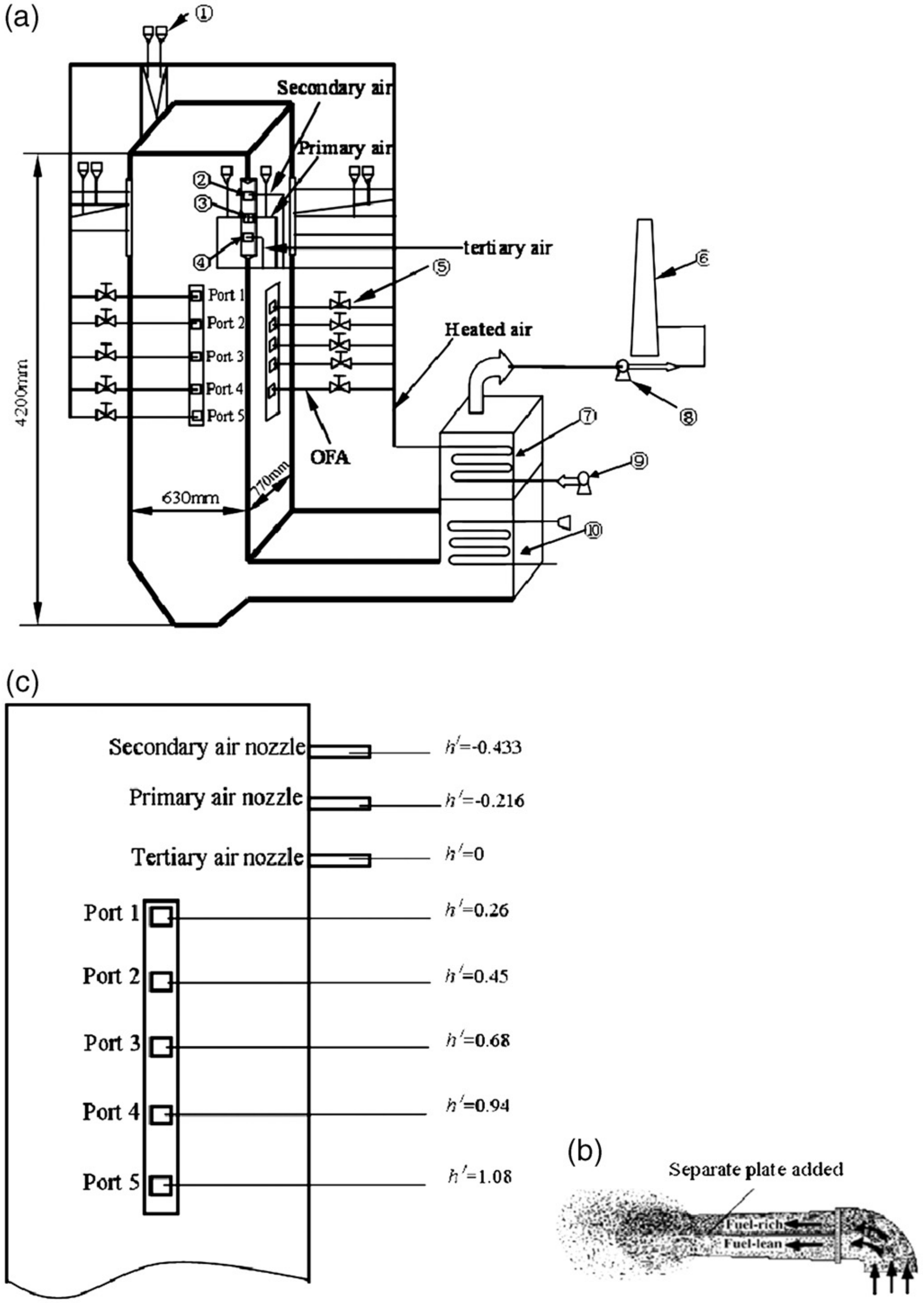

Fig. 1 – Schematic of the test facility system for a 1 MW PC furnace.

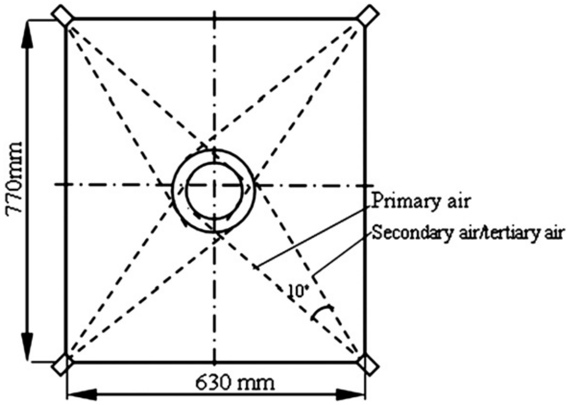

Fig. 2 – The concentric firing system of biased primary air (CFS).

stoichiometric ratio in primary combustion zone, the locations of OFA ports, and the ratio of coal concentration of the fuel-rich stream to that of the fuel-lean one of primary burner.

2. Experimental facilities and test coal quality

2.1. Test facility

Fig. 1 is the scheme of the test facility for a 1 MW (heat input power) pulverized coal (PC) furnace. The test facility is a T-fired furnace which is 4.2 m in height, 0.77 m in width and 0.63 m in depth.

The burners were separated into two groups. The top group of burners was arranged on each corner of the furnace including one secondary air, one tertiary air and one primary air, as shown in Fig. 1. The primary air was separated into two streams by a plate added in the PC pipe which was horizontal bias combustion burner, and thus primary burner is low NO_x burner (LNB), as shown in Fig. 1(b). The ratio of coal concentration of the fuel-rich stream to that of the fuel-lean one (RRL) in primary air nozzle was investigated in the experiment. The bottom group of burners was arranged on somewhere near the middle of furnace wall including five OFA nozzles (port1, port2, port3, port4 and port5).

The relative locations of burner nozzles including OFA injection ports (h') and the relative furnace height (z') are defined respectively, as shown in Eqs. (1) and (2):

$$h' = h/D_h \tag{1}$$

$$z' = z/D_h \tag{2}$$

where h is the length (height) of OFA nozzle from the location of tertiary air burner (where, $h=0$); z is the furnace height of a furnace section from the location of tertiary air burner (where, $h=0$); D_h is the hydraulic diameter of furnace cross-section, and it can be expressed as:

$$D_h = 2ab/(a+b) \tag{3}$$

where a and b are the width and the length of furnace cross-section, respectively. The relative heights of the five ports are 0.26, 0.45, 0.68, 0.94 and 1.08, respectively. The relative locations of burner nozzles are shown in Fig. 1(c).

The primary air, secondary air and tertiary air were injected from burners located in the four corners into the furnace to form imaginary circles in the furnace center, as shown in Fig. 2. Primary air nozzles, secondary air nozzles and tertiary air nozzles were laid out at different offset angles, and the combustion systems is called CFS (concentric firing system of biased primary air). The CFS provides two effects: (1) The imaginary circle diameter of secondary air and tertiary air is larger than that of primary air, and thus the outer concentric flow of air provides an oxidizing atmosphere near the boiler wall surface. In oxidizing atmosphere, the existing form of Fe is Fe_2O_3 in ash, and ash melting temperature does not decrease. In the meantime, the outer concentric flow of air can prevent combusting coal particles from scouring furnace wall surface. Therefore, the CFS can prevent furnace wall from slagging. (2) The inner concentric zone and outer concentric zone of furnace cross-section are in fuel-rich atmosphere and air-rich atmosphere, respectively. The mixing of fuel with air and combustion is delayed so as to reduce local peak temperature, and then thermal-NO_x formation is abated. In the meantime, the CFS can provide the fuel-nitrogen compounds a greater residence time in fuel-rich atmosphere, and thus fuel-NO_x formation is reduced [12].

The location of the injection ports and mixing of OFA are critical to maintain efficient combustion. In the experiment, OFA injection forms the wall tangentially-firing system (WTFS), as shown in Fig. 3. In WTFS, OFA easily enters furnace center zone and mixes with the flue gas entering from primary combustion zone, and then unburned fuel continue to burn out. In the meantime, there is sufficient air near the middle region of furnace wall so as to prevent furnace wall from slagging and fouling [13].

Two pulverized coal feeders were installed in each corner, which fed two pulverized coal streams into the primary air separately to form horizontal bias combustion. The eight feeders were calibrated using the measuring weight method for various operating conditions and the pulverized coal feeding rate had an accuracy of ±3.5% of the measured value.

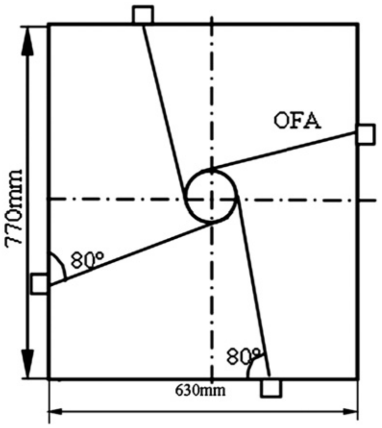

Fig. 3 – The scheme of the wall tangentially-firing system (WTFS).

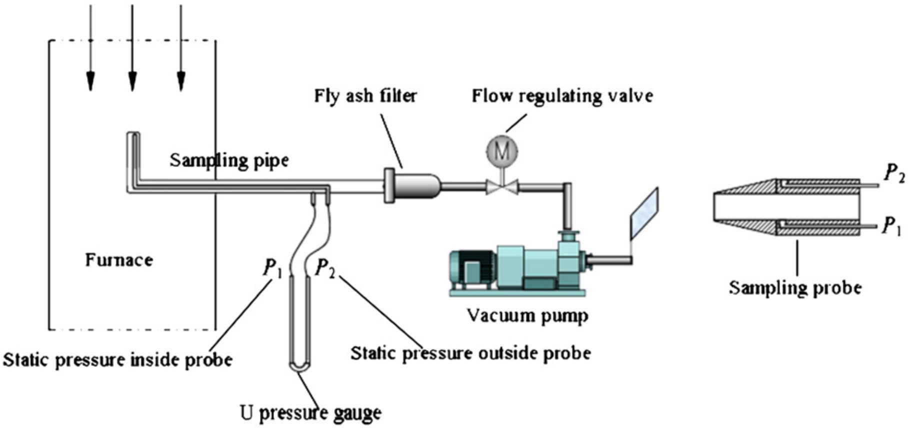

Fig. 4 – Schematic of the isokinetic sampling of fly ash system.

The furnace temperatures along the height were measured by water-cooled platinum–rhodium thermocouples. The measurement accuracy of platinum–rhodium thermocouple is ±1.5 °C at 0–1600 °C.

Fly ash was taken from the furnace exit by isokinetic sampling system, as shown in Fig. 4. In order to achieve isokinetic sampling, adjusting flow valve ensures the static pressure inside sampling probe is equal to that inside sampling probe. Fly ash is collected by filter.

The flue gas sampling system is shown in Fig. 5. Flue gas was taken from the exit of the furnace using water-cooled stainless probe, and the temperature of flue gas sample entering analyser was 180 °C or so, which was above the dew-point temperature of flue gas. The concentrations of gases (NO, NO_2, CO, CO_2, SO_2, H_2O, etc.) were continuously determined by GASMET FTIR Dx4000 flue gas analyser, and the measurement accuracy is 0.01%; O_2 concentration is determined by MSI compact flue gas analyser, and the measurement accuracy is 0.3%.

In the experiments, based on test coal compositions, flue gases concentration monitored and unburned carbon in fly ash, the total mass balance and carbon balance under various air staging condition were calculated by mass balance method [14], and the results indicated that the experiment facility and measurement system were credible.

2.2. *Test coal quality*

In the experiment, test coal is ShenMu coal, a Chinese bituminous coal. The proximate and ultimate analysis data are given in Table 1. The particle size distribution of pulverized coal were determined with a Malvern particle analyser, as given in Table 2, and coal median diameter is 53.69 μm.

3. Results and discussion of experiments

3.1. *The effects of SR_1 and the location of OFA on NO_x emission and unburned carbon in fly ash during air staging*

In order to compare the effectiveness of NO_x reductions by air staging, the test of non-air staging and keeping RRL 1:1 is taken as the baseline, and NO_x reduction efficiency of air staging is defined by:

$$\eta_{NO_x} = \frac{(NO_x)_{baseline} - (NO_x)_{air\ staging}}{(NO_x)_{baseline}} \times 100\% \qquad (4)$$

where, $(NO_x)_{baseline}$ and $(NO_x)_{air\ staging}$ are the NO_x concentrations under baseline operating condition and under air staging condition at O_2=6%, respectively.

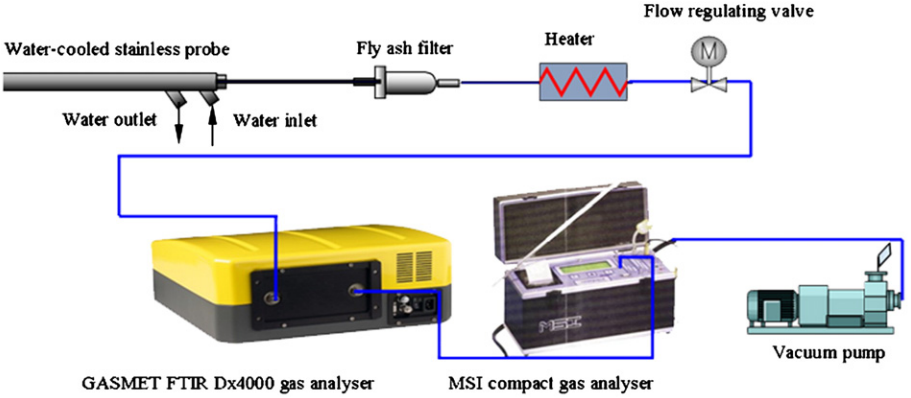

Fig. 5 – Flue gas sampling and on-line measurement system.

The relative unburned carbon in fly ash is expressed as follows:

$$\theta = \frac{(\mathrm{UBC})_{\text{air staging}}}{(\mathrm{UBC})_{\text{baseline}}} \tag{5}$$

where, $(\mathrm{UBC})_{\text{baseline}}$ and $(\mathrm{UBC})_{\text{air staging}}$ are the percentage of unburned carbon in fly ash under baseline operating condition and under air staging condition, respectively.

During the air staging experiments, overall air stoichiometric ratio at the furnace exit is 1.15. Three air stoichiometric ratios in the primary combustion zone, $SR_1=0.75$, 0.85 and 0.95, were principally used in the experiment. At $SR_1=0.85$ and 0.95, there is one layer of OFA nozzles, and the locations of OFA nozzles are changed among port 1, port 2, port 3 and port 4, as shown in Fig. 1. Since the amount of OFA at $SR_1=0.75$ is larger than that at $SR_1=0.85$ and 0.95, there are two layers of OFA nozzles, and locations of the two layer OFA nozzles are changed among port1 and port2, port2 and port3, port3 and port4, port4 and port5.

During investigation of the influences of SR_1 and the locations of OFA nozzles on NO_x reduction efficiency, unburned carbon in fly ash, CO emission and furnace temperature, RRL maintained 1:1. The experimental results are shown in Fig. 6–9. At $SR_1=0.75$, the relative height of the two layers of OFA nozzle is expressed by average relative height.

Fig. 6 shows the relationship of the locations of OFA nozzles and NO_x reduction efficiency. The NO_x reduction efficiency doesn't increase with the decrease of SR_1 ($SR_1=0.75$–0.95). The NO_x reduction efficiency at $SR_1=0.85$ is the highest in the test range of SR_1.

In the process of pulverized coal combustion, fuel-bound nitrogen accounts for 75 to 95% of the total NO_x generated, while thermal-NO_x and prompt-NO_x account for the balance [15]. For coal, it is assumed that fuel-bound nitrogen is distributed between the volatiles and the char during coal combustion. High temperature char-N content is the main factor limiting NO_x emission reductions by deep air staging [9]. The split of nitrogen in the fuel into volatiles and char during combustion depends on the fuel type, the temperature, and the residence time. At low-temperature, fuel-bound nitrogen is preferentially retained in the char [16–20]. Previous experiments showed that the char-N of ShenMu coal increased with the decrease of temperature during coal pyrolysis [18]. In Figs. 7 and 8, the experimental results show that: at $SR_1=0.75$, the temperature distribution in primary combustion zone ($h'<0.5$) is lowest, and unburned carbon in fly ash and CO concentration are highest in the test range of SR_1. Foresaid results indicate that strongly reducing atmosphere in primary combustion zone restrain coal combustion, and large amount of unburned char enters burnout zone. In the meantime, due to low furnace temperature in primary combustion zone at $SR_1=0.75$, fuel-N doesn't release sufficiently, and unburned char entering burnout zone had high char-N. Although NO_x formation may decrease in primary combustion zone at $SR_1=0.75$ where reducing atmosphere is conducive to NO_x reduction, large amount of unburned char with high char-N enters burnout zone where oxygen is sufficient, char-N releases to form more NO_x, and this finally results in large amount of NO_x emission. Hartmut Spliethoff also demonstrated that excessive char-N entering from fuel-rich zone resulted in a noticeable increase in NO_x emission during air staging [21]. LU Jie carried out an experiment of air staged combustion using ShenHua coal (a Chinese bituminous coal) which was similar to ShenMu coal, and he also found that NO_x emission increased when SR_1 was too low [22]. Therefore, too low SR_1 may result in low NO_x reduction efficiency

Table 1 – Proximate analysis and ultimate analysis of dry coal

Proximate analysis, wt.% (as air-dry)				
Moisture	Ash	Volatility	Fixed carbon	Net heating, kJ kg^{-1})
2.6	6.56	32.76	58.08	28,370
Ultimate analysis, wt.% (as air-dry)				
Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur
73.63	4.54	11.38	0.95	0.34

Table 2 – Cumulative particle size distribution of coal

Particle diameter, μm	11.4	15.6	21.0	37.8	43.8	51.0	68.4	106.2	160.7
Cumulative distribution, vol.%	15.7	22.1	31.1	51.8	60.5	68.1	76.9	94.2	100

At $SR_1=0.95$, oxygen is relative sufficient in the primary combustion zone as compared to that at $SR_1=0.75$ and 0.85, and it is conducive to coal combustion. Therefore, at $SR_1=0.95$, the furnace temperature in the primary combustion zone is high, and unburned carbon in fly ash and CO emission at furnace exit are lowest in the test range of SR_1, as shown in Figs. 7–9. However, at $SR_1=0.95$, the relative sufficient oxygen in the primary combustion zone abates NO_x reduction, and this results in low NO_x reduction efficiency, as shown in Fig. 6.

Therefore, too low or too high SR_1 will result in the decrease of NO_x reduction efficiency, and thus there will be an optimum SR_1 when keeping other variables constant. The optimum SR_1 is 0.85 as being in the range of 0.75–0.95, as shown in Fig. 6.

In Fig. 6, with the increase of the locations of OFA, the NO_x reduction efficiency greatly increases at the beginning of $SR_1=0.85$, and then the NO_x reduction efficiency slightly increases when h' is greater than 0.79. The phenomenon

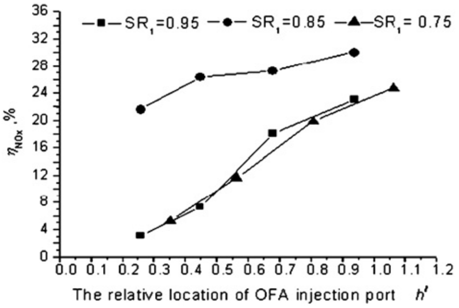

Fig. 6 – The influences of SR_1 and the location of OFA nozzles on NO_x reduction efficiency.

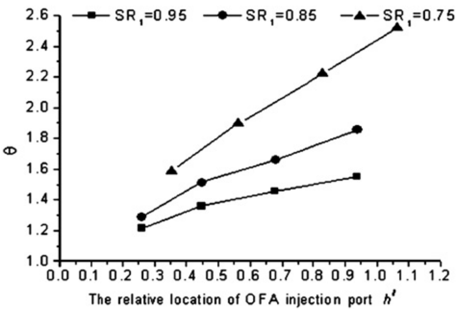

Fig. 7 – The influences of SR_1 and the location of OFA on unburned carbon in fly ash.

may be explained as follows: the residence time of flue gas in primary combustion zone increases with the location of OFA nozzles, and this increases the time of NO_x reduction in reducing atmosphere and results in significant NO_x reduction at the beginning; however, the NO_x concentration and the temperature of flue gas decrease with the further rise of flue gas in primary combustion zone, the capability of NO_x reduction weakens, and then NO_x reduction efficiency increases slightly with the further increase of location of OFA nozzles at the end of $SR_1=0.85$.

Figs. 7 and 8 show the influences of the locations of OFA nozzles on unburned carbon in fly ash and CO emission at furnace exit. The experimental results indicate that the unburned carbon in fly ash and CO emission increase with the increase of the locations of OFA nozzles.

According to the principle of coal combustion, the total burning rate is determined not only by the rate of chemical reactions but also by the intensity of oxygen supply in the reaction zone. The total reaction rate of coal particle (according to the diffusive-kinetic theory of fuel combustion) is given by the expression [23]:

$$K_S = \frac{C^b_{O_2}}{\frac{1}{\alpha_d}+\frac{1}{k}} \tag{6}$$

Where, K_S is the total reaction rate of coal particle; $C_{O_2}{}^b$ is the oxygen concentration near the coal particle surface; α_d is the mass-transfer coefficient; k is the reaction rate constant.

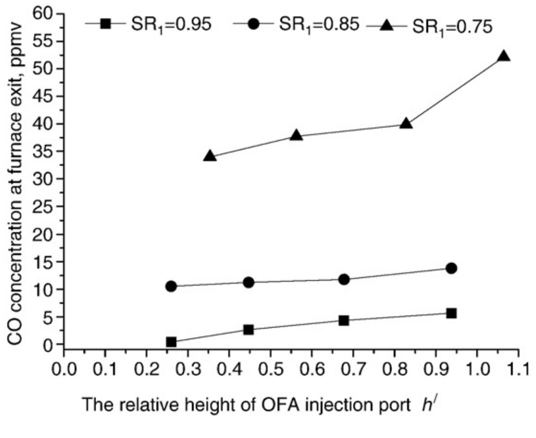

Fig. 8 – The influences of SR_1 and the location of OFA nozzles on CO concentration at the exit of furnace.

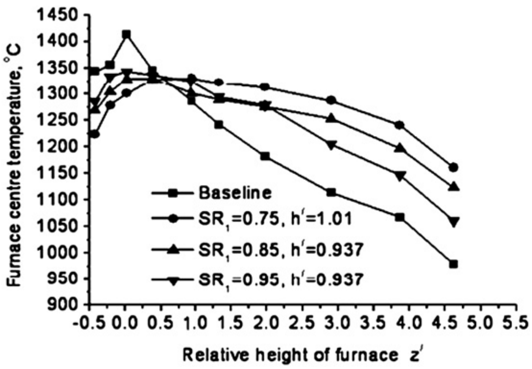

Fig. 9 – The influences of SR_1 on furnace temperature distribution.

Most of combustible matters of fuel are combusted and release majority of heat in primary combustion zone. Therefore, the temperature in primary combustion zone is high, and the reaction rate constant ($k \propto e^{-E/RT}$) is great, which is conducive to coal burnout. However, in primary combustion zone, oxygen is deficient ($C_{O_2}{}^b$ is low), and then coal combustion is delayed. With the increase of the location of OFA ports, the residual concentration of oxygen turns out to be rather low at the end of primary combustion zone, and then the reaction rate of pulverized coal decreases. Therefore, a large amount of unburned fuel enters burnout zone with the increase of the location of OFA ports, and then unburned carbon in fly ash and CO emission increase with the increase of the location of OFA ports, as shown in Figs. 7 and 8.

Figs. 7 and 8 also show that unburned carbon in fly ash and CO emission decrease with the increase of SR_1. The reason can be explained as follows: the concentration of oxygen increases with the increase of SR_1 in primary combustion zone, the total reaction rate of coal particle, K_S enhances, and thus this is conducive to coal burnout.

3.2. *The effects of RRL on NO_x reduction efficiency and unburned carbon in fly ash*

Based on above experimental results, we also investigated the effect of RRL on NO_x reduction efficiency and unburned carbon in fly ash. Here, SR_1 and h' maintain 0.85 and 0.937, respectively in the following experiments. The RRL varies from 1 to 4. The experimental results are shown in Fig. 10.

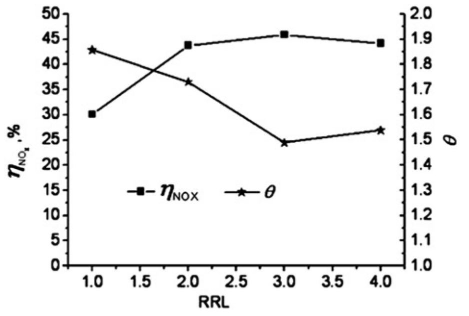

Fig. 10 – The influences of RRL on NO_x reduction efficiency and unburned carbon in fly ash.

Fig. 10 shows that NO_x reduction efficiency increases with RRL at the beginning, then NO_x reduction efficiency reaches a maximum value at RRL=3, and NO_x reduction efficiency declines slightly at the end. In the horizontal bias combustion burner, the pulverized coal combustion with rich/lean streams may have a great influence on NO_x reduction [24]. The less air supply inhibits fuel-NO_x formation in the rich stream of pulverized coal, and, and thermal-NO_x formation is also limited because of the low temperature in the coal lean stream of pulverized coal. Therefore, the capability of NO_x reduction increases with RRL. However, when RRL is too large, the mixing of air and pulverized coal may become too bad to support ignition, and a large amount of unburned carbon with high char-N enters burnout zone to combust and form much NO_x.

Fig. 10 also shows that unburned carbon in fly ash apparently decreases with the increase of RRL at the beginning, then unburned carbon in fly ash reaches a minimum value at RRL=3, and unburned carbon in fly ash increases slightly at the end. The reason is as follows: with the increase of RRL, the pulverized coal concentration in rich stream of LNB increases, the need of ignition heat in the stream decreases so that the ignition of pulverized coal advances, and thus coal combustion can be reinforced, which is conducive to pulverized coal burnout; however, when RRL is too large, the mixing of air and pulverized coal may become too bad to support ignition, and thus this results in the increase of unburned carbon in fly ash.

4. Conclusions

NO_x emission in air staged combustion system are studied in a 1 MW tangentially fired furnace. In the meantime, unburned carbon in fly ash and CO emission are investigated. The following conclusions can be drawn from the experimental results:

NO_x reduction efficiency monotonically increases with the increase of the relative location of OFA ports, there is an optimum SR_1 when keeping other variables constant, and the optimum SR_1 is 0.85 as being in the range of the air staged combustion experiments.

Increasing the location of OFA injection ports is conducive to reduce NO_x emission, but the unburned carbon in fly ash and CO emission monotonically increase.

For the horizontal bias combustion burner, the ratio of coal concentration of the fuel-rich stream to that of the fuel-lean one (RRL) has an optimum value, and NO_x reduction efficiency is highest and unburned carbon in fly ash is low. The optimum value of RRL is 3:1 in the experiment.

On the optimized operating conditions of air staging, NO_x reduction efficiency can achieve 47%. Although air staging can reduce NO_x emission, unburned carbon in fly ash should be noticed.

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REFERENCES

[1] B.J. Zhong, W.W. Shi, W.B. Fu, Effects of fuel characteristics on the NO reduction during the reburning with coals, Fuel Process. Technol. 79 (2002) 93–106.
[2] L.D. Smoot, S.C. Hill, H. Xu, NO_x control through coal reburning, Prog. Energy Combust. Sci. 24 (1998) 385–408.
[3] S.A. Benson, J.D. Laumb, C.R. Crocker, J.H. Pavlish, SCR catalyst performance in flue gases derived from subbituminous and lignite coals, Fuel Process. Technol. 86 (2005) 577–613.
[4] S. Li, T.M. Xu, Q.L. Zhou, H.Z. Tan, S.E. Hui, H.L. Hu, Optimization of coal reburning in a 1 MW tangentially fired furnace, Fuel 86 (2007) 1169–1175.
[5] EPA, Summary of NO_x Control Technologies and Their Availability and Extent of Application, US Environmental Protection Agency, EPA-450/3-92-004, 1992, pp. 8–12.
[6] H. Spliethoff, U. Greul, H. Rüdiger, R.S. Klaus, Basic effects on NO_x emissions in air staging and reburning at a bench-scale test facility, Fuel 75 (1995) 560–564.
[7] W.J. Ma, W.J. Fan, M.Y. Hou, M.L. Yang, Influences of air staged proportion on combustion and exhaust emissions, J. Combust. Sci. Technol. 10 (2004) 345–349 (in Chinese).
[8] B. Coda, F. Kluger, D. Förtsch, H. Spliethoff, Coal–nitrogen release and NO_x evolution in air-staged combustion, Energy Fuels 12 (1998) 1322–1327.
[9] C.K. Mana, J.R. Gibbins, J.G. Witkampb, J. Zhang, Coal characterisation for NO_x prediction in air-staged combustion of pulverised coals, Fuel 84 (2005) 2190–2195.
[10] R.I. Backreedy, J.M. Jones, L. Ma, M. Pourkashanian, A. Williams, A. Arenillas, et al., Prediction of unburned carbon and NO_x in a tangentially fired power station using single coals and blends, Fuel 84 (2005) 2196–2203.
[11] E.C. Zabetta, M.H.K. Saviharju, Reducing NO_x emissions using fuel staging, air staging, and selective noncatalytic, reduction in synergy, Ind. Eng. Chem. Res. 44 (2005) 4552–4561.
[12] DOE/NETL, The Advanced Tangentially Fired Combustion Techniques for the Reduction of Nitrogen Oxides (NO_x) Emissions from Coal-Fired Boilers Demonstration Project, US Department of Energy and Nation Energy Technology Laboratory, DOE/NETL-2000/1122, 2000.
[13] H.Z. Tan, T.M. Xu, Z.Y. Yu, S.E. Hui, The experiment study of heat flux distribution in wall tangentially flame, J. Eng. Thermophys. 21 (2000) 525–528 (in Chinese).
[14] F. Wilfrid, M.C. Peters, Fuels and Fuel Technology, 2nd ed, Pergamon Press, New York, 1980, pp. 93–94.
[15] B.G. Miller, Coal Energy Systems, Elsevier Academic Press, Boston, 2005, pp. 322–323.
[16] S. Kambara, T. Takarada, Y. Yamamoto, K. Kato, Relation between functional forms of coal nitrogen and formation of NO_x precursors during rapid pyrolysis, Energy Fuels 7 (1993) 1013–1020.
[17] C.W. Lau, S. Niksa, The impact of soot on the combustion characteristics of coal particles of various types, Combust. Flame 95 (1993) 1–21.
[18] P. Glarborg, A.D. Jensen, J.E. Johnsson, Fuel nitrogen conversion in solid fuel fired systems, Prog. Energy Combust. Sci. 29 (2003) 89–113.
[19] W.C. Xu, M. Kumagai, Nitrogen evolution during rapid dropyrolysis of coal, Fuel 81 (7) (2002) 2325–2334.
[20] X. Yan, D.F. Che, T.M. Xu, Experimental investigation on char nitrogen conversion during coal pyrolysis, J. Xi'an Jiaotong Univ. 38 (9) (2004) 980–984 (In Chinese).

[21] H. Spliethoff, U. Greul, H. Rüdiger, K.R.G. Hein, Basic effects on NO_x emissions in air staging and reburning at a bench-scale test facility, Fuel 75 (1996) 560–564.
[22] J. Lu, J.W. Xie, W.G. Fan, M.C. Zhang, Size effect of pulverized Shenhua coal particles on NO_x emission in combustion with air staging, J. Power Eng. 27 (2007) 949–953 (in Chinese).
[23] K.F. Cen, Q. Yao, Z.Y. Luo, X.T. Li, Advanced Combustion Theory, Zhejiang University Press, Hangzhou, 2000, p. 308, (in Chinese).
[24] X.L. Wei, T.M. Xu, S.E. Hui, Burning low volatile fuel in tangentially fired furnaces with fuel rich/lean burners, Energy Convers. Manag. 45 (2004) 725–729.