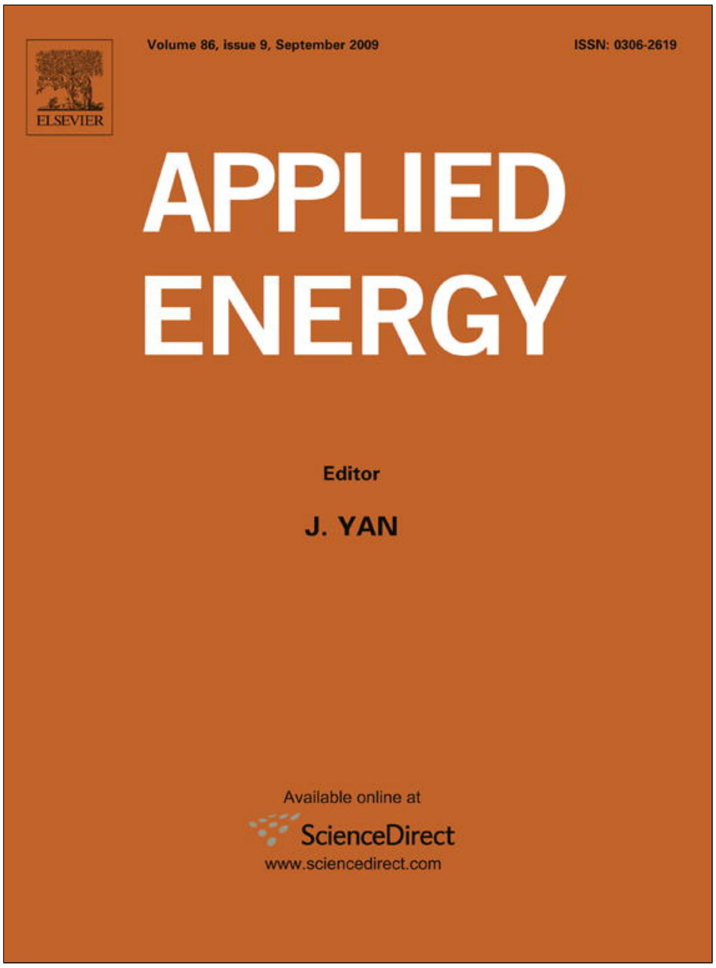

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NO_x emission and thermal efficiency of a 300 MWe utility boiler retrofitted by air staging

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ABSTRACT

Full-scale experiments were performed on a 300 MWe utility boiler retrofitted with air staging. In order to improve boiler thermal efficiency and to reduce NO_x emission, the influencing factors including the overall excessive air ratio, the secondary air distribution pattern, the damper openings of CCOFA and SOFA, and pulverized coal fineness were investigated. Through comprehensive combustion adjustment, NO_x emission decreased 182 ppm (NO_x reduction efficiency was 44%), and boiler heat efficiency merely decreased 0.21%. After combustion improvement, high efficiency and low NO_x emission was achieved in the utility coal-fired boiler retrofitted with air staging, and the unburned carbon in ash can maintain at a desired level where the utilization of fly-ash as byproducts was not influenced.

1. Introduction

In China, the requirements for environmental protection are increasingly strict, especially for coal-fired utility boiler. Coal remains the primary energy resource in China, and one of the major concerns associated with coal-fired power plants is the emission of pollutants, especially for NO_2 and NO (collectively referred to as NO_x). Today, NO_x emission is regulated and has become an important consideration in the design and modification of coal-fired utility boiler. Therefore, in order to reduce NO_x emission, many NO_x control techniques must be applied not only to new boilers but also to existing boilers.

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 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. Therefore, these low NO_x combustion techniques appear to be the most cost-effective reduction technologies for most types of boiler [5–7]. 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 or over-fire air (OFA), a combustion-related technology which can meet current NO_x emission reduction objectives, is discussed herein. In air staging system, the OFA nozzles are located in the windbox above the uppermost coal nozzles. Approximately 20% of the total combustion air is introduced through these OFA nozzles [8–10]. As a result, the combustion process is divided into two stages to complete: lower furnace (primary combustion zone) is at slightly sub-stoichiometric air conditions, upper furnace (burnout zone) is air-rich atmosphere area, where OFA permits the combustion process to go to completion. During air staging, in the primary combustion zone, since the air stoichiometric ratio is less than 1, the oxygen-deficient and relatively low combustion temperature reduce the formation of thermal-NO_x, and the fuel-rich environment makes these intermediate nitrogen compounds of fuel-N evolve to N_2, which reduces the formation of fuel-NO_x. In burnout zone, OFA is injected above the primary combustion zone to produce a relatively low-temperature zone, and this limits the formation of thermal-NO_x [11,12].

For coal-fired utility boiler, two types of OFA are used to reduce NO_x emissions. Close-coupled over-fire air (CCOFA) is OFA that is introduced immediately above the top coal nozzle using the main windbox. Separated over-fire air (SOFA) is OFA that is introduced through a windbox separated from the main windbox supplying the bulk of the combustion air [13].

The use of OFA in tangentially fired boiler (T-fired boiler) results in significant decrease of NO_x emission and is by far the most cost-effective technique for reducing NO_x emissions [5,13]. However,

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the NO_x reduction principle normally results in the incomplete combustion of the fuel and high levels of unburned carbon in the fly-ash thereby reducing boiler efficiency [14,15]. Sub-stoichiometric air condition in the primary combustion zone reduces pulverized coal combustion rate and results in high unburned carbon (UBC) in the fly-ash and high CO emission, and this makes boiler thermal efficiency decrease.

The conflict between low NO_x emission and high boiler thermal efficiency encounters, especially for existing coal-fired utility boilers retrofitted with combination CCOFA and SOFA due to the space restrictions of furnace. Although previous many researchers investigated the influences of low NO_x combustion technologies on unburned carbon in fly-ash and CO emission, they overstressed the reduction of NO_x emission [11,16]. The balance between boiler thermal efficiency and NO_x emission is important for existing coal-fired boilers retrofitted with air staging, and it is helpful for power plant designers and operators to perform clean and efficient utilization of coal. Therefore, the performance improvement of coal-fired utility boiler for low NO_x emission is indispensable. However, NO_x emission from utility boilers is a function of fuel properties and many boiler design and operating variables, and the applicability, ease of retrofit, NO_x reduction performance, and costs are very much influenced by site-specific factors.

In order to improve the performance of coal-fired utility boiler retrofitted by air staging, the paper concentrates on the balance between boiler thermal efficiency and NO_x emission. The paper dealt with the adjustment of boiler operating conditions including excessive air ratio, secondary air distribution pattern, OFA damper opening, and pulverized coal fineness. The experiments were performed on a 300-MWe, tangentially fired dry bottom boiler. The experimental results indicated that the relationship between of NO_x emission and boiler efficiency can be improved through the adjustment of operating conditions. Through comprehensive experiments, high efficiency and low NO_x emission can be achieved in the existing fired-coal utility boiler retrofitted with air staging, and the unburned carbon in ash can maintain at a desired level where the utilization of fly-ash as byproducts is not influenced.

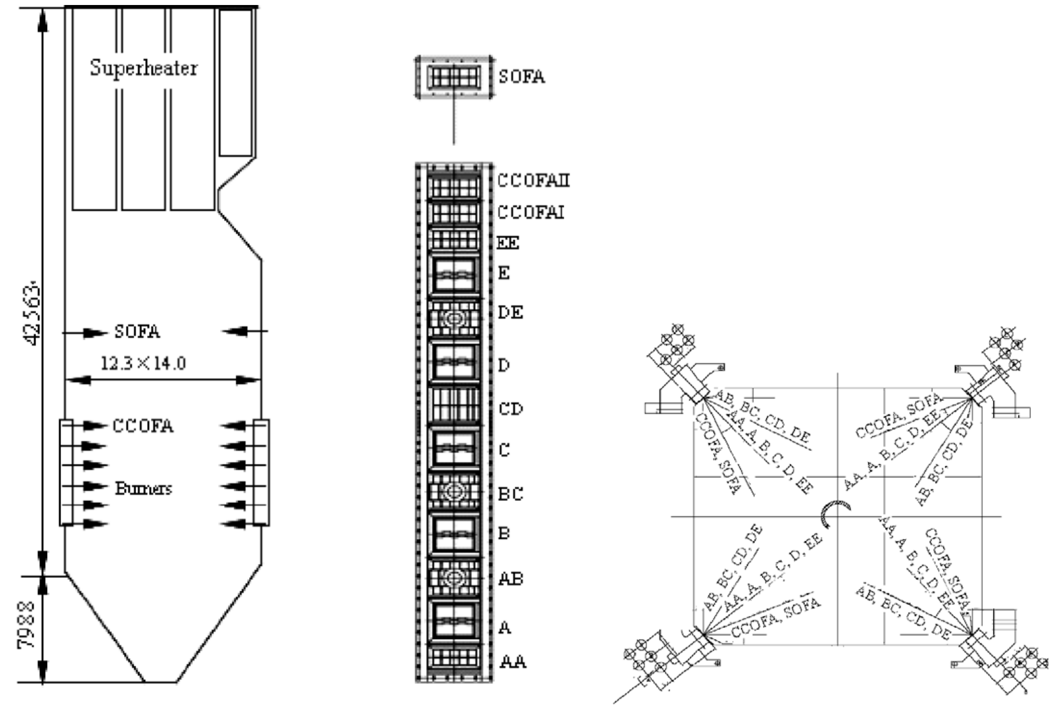
2. Experimental facilities and procedure

2.1. Experimental facilities

The experiments were performed on a 300 MWe, tangentially fired dry bottom boiler with a furnace of $14.0 \times 12.3\ m^2$ section and height of 50.5 m, as shown in Fig. 1. The maximum continuous rating (MCR) of the boiler is $1025\ t\ h^{-1}$ of superheated steam at 540 °C. The boiler had five levels of primary air nozzles (A, B, C, D, E) and six levels of secondary air nozzles (AA, AB, BC, CD, DE, EE). For primary air nozzles, four levels and five levels were put into operation under the rated load and the maximum load, respectively. Before low NO_x modification, NO_x emission was 413 ppm (at $O_2 = 6\%$), and boiler heat efficiency was 92.87%.

For NO_x emission reduction, the boiler was retrofitted with low NO_x burners and air staging by adding CCOFA and SOFA. Two levels of CCOFA nozzles and one level of SOFA nozzles were located in each corner of the retrofitted furnace, and the arrangements of the burners are illustrated in Fig. 1. Primary air nozzles are wide range (WR) burner, which are vertical bias combustion burners [17].

As seen in Fig. 1, concentric firing system (CFS) is employed in which the secondary air is directed away from the primary air towards the adjacent furnace wall. The primary air is directed to form a small imaginary circle while the secondary air is directed to form a larger imaginary circle. The outer concentric flow of air provides an air-rich atmosphere near the boiler wall surface, which protects from ash slagging for wall. The inner concentric zone is fuel-rich. Therefore, in the CFS, the mixture of fuel with air and combustion is delayed so as to reduce local peak temperature, and then thermal-NO_x formation is reduced [18]. At the meantime, The CFS provides the fuel-nitrogen compounds a longer residence



(a) Cross-sectional view of furnace (b) Front view of burners (c) Burner arrangement in furnace

Fig. 1. Schematic layout of utility boiler retrofitted with combination CCOFA and SOFA.

Table 1
Coal characteristics.

Moisture	Ash	Volatility	Fixed carbon	HHV ($kJ \cdot kg^{-1}$)
Proximate analysis, wt% (as air-dried)				
12.5	15.66	25.91	45.93	22,172
Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur
Ultimate analysis, wt% (as air-dried)				
58.46	3.28	8.68	0.98	0.44

time in the fuel-rich environment, thus fuel-NO_x formation is reduced.

More precise geometries and details of the burner arrangement were not available, due to the proprietary nature of the burners.

2.2. *Coal qualities*

Each level pulverized coal is supplied by one DTM350/600 pulverizer. The coal used in the experiment is a Chinese bituminous coal, and the proximate and ultimate analysis data are given in Table 1.

In pulverized coal combustion, oxidation of fuel-N is generally the major source of NO, and the split of nitrogen in the fuel into volatiles and char during devolatilization is important for NO_x formation [19]. The distribution of nitrogen between char and volatiles depends mainly on the fuel structure and the temperature. For the tested coal, at 800 °C, the distribution of char-N and volatile-N were 47% and 53%, respectively, at 1100 °C, the distribution of char-N and volatile-N were 30% and 70%, respectively.

2.3. *Test program*

Low NO_x modification by air staging resulted in the decrease of coal burning rate in primary combustion zone due to reducing atmosphere condition. At the same time, due to the space restrictions of the existing boiler furnace, the combustion residence time in furnace is fixed. Therefore, without improvement of operating conditions, the air staging system would produce high unburned carbon in fly-ash and CO emission, and boiler efficiency would decrease. Increasing unburned carbon in fly-ash would reduce the applicable value of fly-ash, and excessive amount of carbon in ash may render the fly-ash un-sellable for cement and concrete applications leaving costly land-filling.

In order to achieve low NO_x emission, high boiler thermal efficiency and moderate unburned carbon in fly-ash, the improvement of the operating conditions of the retrofitted boiler was performed. In the test, the influences of overall excessive air ratio on boiler thermal efficiency and NO_x emission were firstly investigated when keeping secondary air and OFA (CCOFA and SOFA) openings constant, and the optimum overall excessive air ratio was determined according to boiler high thermal efficiency and relatively low NO_x emission; subsequently, the influences of secondary air distribution pattern on NO_x emission and boiler thermal efficiency when keeping CCOFA and SOFA damper openings constant, and optimum air distribution pattern was determined according to low NO_x emission; under the optimum overall excessive air ratio and the optimum secondary air distribution pattern condition, lower low NO_x emission was achieved by combination adjustment of CCOFA and SOFA damper openings; finally, high boiler thermal efficiency was achieved by altering pulverized coal fineness. In the experiment, the primary air nozzles of E level and the secondary air nozzles of EE level were out of service, and other nozzles were in service. Fifteen cases were conducted under the rated load, as shown in Table 2. Air damper settings for each case are also given in Table 2. The damper opening indicated in Table 2 is the percentage opening of a butterfly valve across the area of the given inlet port. Field tests showed that the air was almost evenly distributed among the burners at the same level and the air flow was in proportion to the flow areas according to the percentage damper opening. Cases 1–6 were conducted to determine optimum overall excessive air ratio. At the optimum excessive air ratio, Cases 3 and 7–9 were conducted to investigate the effects of secondary air distribution pattern on NO_x emission and boiler thermal efficiency. At given optimum excessive air ratio and secondary air distribution pattern, Cases 9–13 were conducted to adjust OFA damper openings. Cases 11, 14 and 15 were conducted to investigate the effects of pulverized coal fineness on unburned carbon in fly-ash and boiler thermal efficiency.

Fly-ash was taken before electrostatic precipitator by isokinetic sampling system. The rectangular gas dust was divided 24 uniform sections, and the sampling point was located at the center of each uniform section. 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.

Gas concentrations in flue gas were measured by on-line analysers. Flue gas was taken before the air preheater 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

Table 2
The operating parameters of the tests.

Case	The secondary air burner damper opening (%)					OFA damper opening (%)			Excessive air ratio	Coal fineness R_{90} (μm)
	AA	AB	BC	CD	DE	CCOFA I	CCOFA II	SOFA		
1	75	75	75	75	75	10	10	10	1.15	14
2	75	75	75	75	75	10	10	10	1.19	14
3	75	75	75	75	75	10	10	10	1.22	14
4	75	75	75	75	75	10	10	10	1.25	14
5	75	75	75	75	75	10	10	10	1.31	14
6	75	75	75	75	75	10	10	10	1.37	14
7	60	60	70	80	90	10	10	10	1.22	14
8	100	75	60	75	100	10	10	10	1.22	14
9	100	100	50	50	25	10	10	10	1.22	14
10	100	100	50	50	25	10	10	50	1.22	14
11	100	100	50	50	25	20	20	50	1.22	14
12	100	100	50	50	25	30	30	50	1.22	14
13	100	100	50	50	25	30	30	100	1.22	14
14	100	100	50	50	25	20	20	50	1.22	11
15	100	100	50	50	25	20	20	50	1.22	9

Table 3
The total air flows of different excessive air ratios.

Excessive air ratio	1.15	1.19	1.22	1.25	1.31	1.37
Total air flow ($kg \cdot s^{-1}$)	336.8	348.5	357.3	366.1	383.6	401.2

accuracy is 0.01%; O_2 concentration is determined by MSI compact flue gas analyser, and the measurement accuracy is 0.3%.

In the experiment, the accuracies of UBC is ±0.05% Coal feeding rate was kept constant (39.2 kg/s), and primary and secondary air ratios were during the tests 20.8% and 74.1%. The total air flows of different excessive air ratios are shown in Table 3. The uncertainty in boiler thermal efficiency calculation is much important, the uncertainty analysis was provided in Table 4, and the uncertainty of boiler thermal efficiency calculation was 0.326%.

3. Results and discussions

3.1. The influences of overall excess air ratio on NO_x emission and boiler efficiency

Excess air ratio is an important operating parameter, which not only affects NO_x formation but also boiler thermal efficiency. Low excess air ratio reduces NO_x formation and tends to reduce stack and draft losses [20], but reduction of the excess air results in incomplete combustion of the fuel and high unburned carbon in the fly-ash, thereby reducing boiler efficiency. Air staging delays pulverized coal burnout, especially for the existing boiler retrofitted with air staging due to the limitation of combustion space. Therefore, for the existing utility boiler retrofitted with air staging, the determination of excessive air ratio is crucial to the boiler performance with high thermal efficiency and low pollutant emission.

The major boiler heat loss is the heat of the exit flue gas, namely, stack loss (q_2). Flue gas is the mixture of byproducts of vaporized combustibles and the total air supplied. Therefore, a reduction in excessive air can reduce the heat carried out through the stack. However, because of heterogeneous mixing of the combustible and oxygen molecules, an excess supply of air is provided to promote complete combustion of pulverized coal. Therefore, the optimum excess air ratio is a compromise between stack heat loss and incomplete combustion loss (q_{3+4}) as measured by unburned carbon in the ash and further indicated by CO emission.

Fig. 2 illustrates the effects of excessive air ratio on unburned carbon in ash and CO emission. Before low NO_x modification, the boiler optimum excessive air ratio was 1.19, and unburned carbon in fly-ash and CO emission concentration were 0.35% and 20 ppm, respectively. However, after low NO_x modification, when excessive air ratio was 1.19, the unburned carbon in fly and CO emission concentration increase to 2.6% and 210 ppm, respectively, as shown in Fig. 2. In order to reduce unburned carbon in fly-ash and CO emission, excessive air ratio was increased to intensify pulverized coal combustion. The experimental results show that increasing excessive air ratio makes unburned carbon in fly-ash and CO emission decrease. When excessive air ratio increased from 1.19 to 1.22, unburned carbon in fly-ash and CO emission significantly decrease, as shown in Fig. 2. However, stack heat loss (q_2) increases with excessive air ratio, as shown in Fig. 3. Increasing excessive air ratio makes the amount of excessive air in flue gas increase. Consequently, at a given stack temperature, increasing excessive air ratio

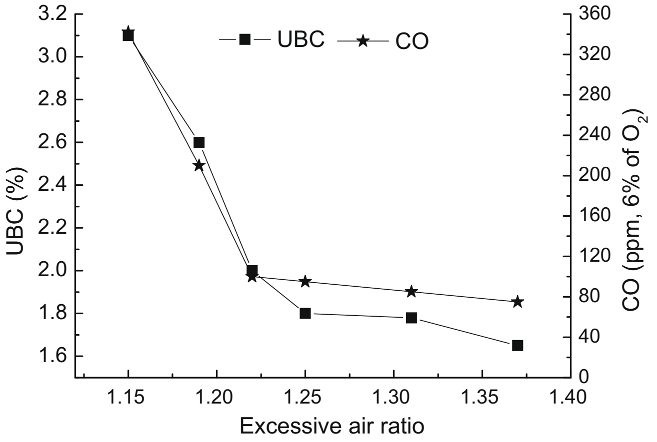


Fig. 2. The influences of excessive air ratio on unburned carbon and CO emission.

Table 4
Uncertainty analysis in boiler thermal efficiency calculation.

Variables	Absolute sensitivity coefficient (C_i)	Bias limit (u_i)	Result of bias limit ($c_i \times u_i$)
Coal flow rate	−0.0012	4.200	−0.00504
HHV	0.0030	21.7200	0.06516
Carbon analysis	−0.0350	7.5400	0.2639
Hydrogen analysis	−0.2230	0.7290	0.162567
Oxygen analysis	0.0270	0.0180	0.000486
Nitrogen analysis	0.0000	0.0000	0
Sulphur analysis	−0.0000	0.0005	0
Moisture analysis	−0.0004	0.0200	−0.000008
Ash analysis	−0.0250	0.8000	−0.0002
Oxygen analysis of flue gas	−0.0030	0.5000	0.0015
Ambient dry bulb temperature	0.0006	0.0700	0.000042
Wet bulb temperature at boiler inlet	−0.0020	0.0500	−0.0001
Outer wall surface temperature of boiler	−0.0017	0.1300	−0.000221
Air temperature of outer boiler	0.0011	0.1400	0.00000154
Ash analysis of slag	−0.0130	1.3000	−0.0169
Ash analysis of fly-ash	−0.1000	0.1000	−0.01
Carbon analysis of slag	−0.100	−0.1600	−0.016
Carbon analysis of fly-ash	−0.079	0.0840	−0.006636
Slag temperature	−0.0000	0.0000	0
Fly-ash temperature	−0.0007	0.1400	−0.000098
Flue temperature	−0.0520	1.3300	−0.06916
Drum Pressure	−0.0180	0.4000	−0.0072
atmospheric pressure	0.0010	0.1000	0.0001
Primary air temperature	0.0013	0.2200	0.000286
Total uncertainty (U)		$U = \sqrt{\sum (c_i \times u(x_i))^2} = 0.326$	

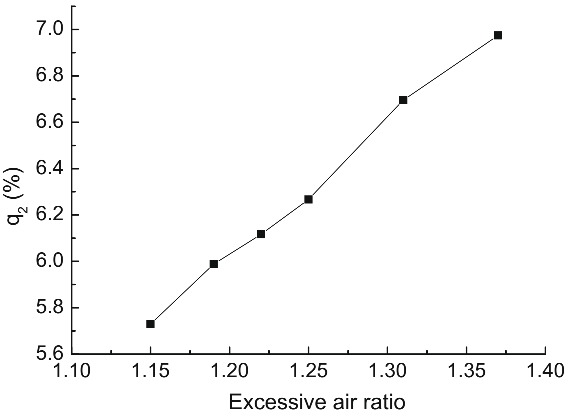


Fig. 3. The influence of excessive air ratio on stack heat loss.

makes the increase of heat loss carried out by flue gas through the stack, and this results in the increase of stack heat loss.

Fig. 4 illustrates the influences of excessive air ratio on NO_x emission and the sum of the stack heat loss and the incomplete combustion loss. The experimental results indicate the optimum excessive air ratio is 1.22, where the sum of stack heat loss and incomplete combustion loss is minimum in the test range. Meanwhile, experimental results also indicate that NO_x emission increases monotonically with excessive air ratio. Since increasing excessive air abates the reducing atmosphere in primary combustion zone during air staging, NO_x formation increases.

Under the optimum excessive air ratio, boiler thermal efficiency is highest (92.55%) in the test range, The increase of NO_x emission is not notable when excessive air ratio increases from 1.15 to 1.22.

3.2. *The influences of secondary air distribution pattern on NO_x emission and boiler efficiency*

Cases 3 and 7–9 were conducted to investigate the influences of the secondary air distribution pattern on NO_x emission and combustion performances. Based on above tests, here the excessive ratio remained 1.22. In Case 3, secondary air is evenly distributed among secondary air nozzles; in Case 7, the supply of the secondary air gradually increases along furnace height; in Case 8, the supply of secondary air first decreases, later increases along furnace height; in Case 9, the supply of secondary air gradually decreases along furnace height.

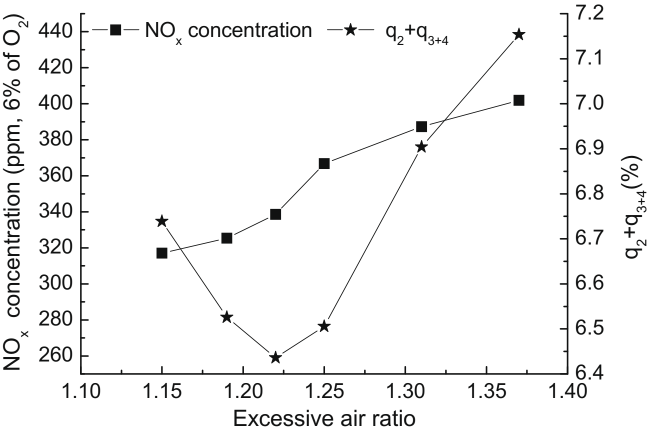


Fig. 4. The influences of excessive air ratio on NO_x emission and boiler losses.

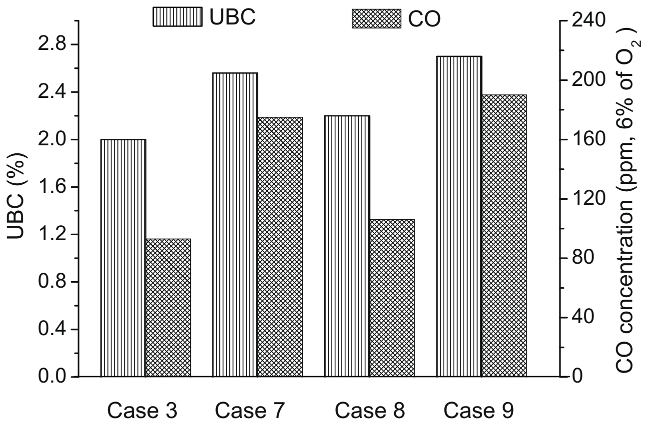


Fig. 5. The influences of secondary air distribution pattern on unburned carbon in fly-ash and CO emission.

The experimental results are shown in Figs. 5 and 6. The results indicate that the even distribution of secondary air is conducive to combustion (unburned carbon in fly-ash and CO emission are minimal, and boiler efficiency is highest in the test range), but NO_x emission is highest. Lowest NO_x emission is achieved in Case 9, but it is accompanied with lowest boiler efficiency.

Experimental results indicate that the secondary air distribution pattern along furnace has great influences on NO_x formation and pulverized coal burnout. The reasons are as follows: low NO_x combustion technology is based on controlling and delaying the mixing of fuel and air in the furnace, and it is strongly dependent on providing the local proper air-to-fuel ratio in furnace. Firstly adjustment of secondary air distribution influences the mixing of fuel and air, and then it influences NO_x formation. Reducing atmosphere (fuel-rich) is conducive to reduce NO_x formation, but it reduces burning rate of pulverized coal and produces high unburned carbon in fly-ash and CO emission finally.

In Case 9, since air is sufficient in lower primary combustion zone, pulverized coal combusts intensively, and a large amount of fuel-N in coal is released to form NO_x. Increasing NO_x concentration entering upper furnace is conducive to increase NO_x reduction efficiency in reducing atmosphere of upper primary combustion zone where the supply amount of secondary air is relatively low. Therefore, lowest NO_x emission is achieved in Case 9, as shown in Fig. 6.

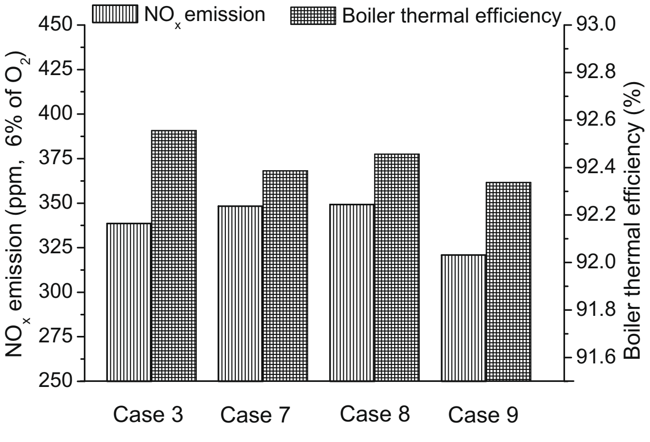


Fig. 6. The influences of secondary air distribution pattern on NO_x emission and boiler efficiency.

3.3. The influences of the OFA damper openings on NO_x emission and boiler thermal efficiency

In above experiments, the damper openings of CCOFA and SOFA were kept constant. In practice, at given excessive air ratio, the damper openings of CCOFA and SOFA determine the air distribution between primary combustion zone and burnout zone during air staging. Increasing the damper openings of CCOFA and SOFA can increase the air supply of burnout zone, and the air supply of primary combustion zone decreases. Therefore, adjustment of the damper openings of CCOFA and SOFA influences the reducing atmosphere in primary combustion and controls NO_x formation during air staging.

Based on above experimental results, here the excessive air ratio remained 1.22, and the secondary air distribution pattern is like as Case 9.

Fig. 7 illustrates the influences of the damper openings of CCOFA and SOFA on NO_x emission and boiler thermal efficiency. Experimental results show that the adjustment of damper openings of CCOFA and SOFA has noticeable influence on NO_x emission. Appropriately increasing damper openings of CCOFA and SOFA makes NO_x emission decrease noticeably, such as in Cases 11 and 12. However, excessively increasing damper openings of CCOFA and SOFA results the increase of NO_x emission, such as in Case 13.

At the given excessive air ratio, increasing damper openings of CCOFA and SOFA can increase air staging degree and strengthen the reducing atmosphere in primary combustion zone, and it is conducive to NO_x reduction. However, excessively increasing the damper openings of CCOFA and SOFA makes oxygen severely deficient in primary combustion zone, a large amount of char enters burnout zone, and large char-N is released to form NO_x in oxidizing atmosphere of burnout zone, which finally results in the increase of NO_x emission.

In the test range, lowest NO_x emission (231 ppm) is achieved in Case 11, and the boiler thermal efficiency is 92.27%. NO_x reduction efficiency is 44%, but boiler thermal efficiency decreases 0.59%. In Case 11, unburned carbon in fly-ash is 3.2%.

3.4. The influences of pulverized coal fineness on unburned carbon in fly-ash and boiler thermal efficiency

Through above experiments, though NO_x emission reduced noticeably, the increase of unburned carbon in ash reduced the applicable value of ash and resulted in the decrease of boiler thermal efficiency. In order to reduce the unburned carbon in fly-ash, pulverized coal fineness was decreased by adjusting the pulverizer classifier. Decreasing pulverized coal size can obtain high combustion efficiency, but grinding the particles finer requires additional power consumption at coal pulverized equipment. Therefore, here R_{90} of the lowest pulverized coal fineness is 9 μm.

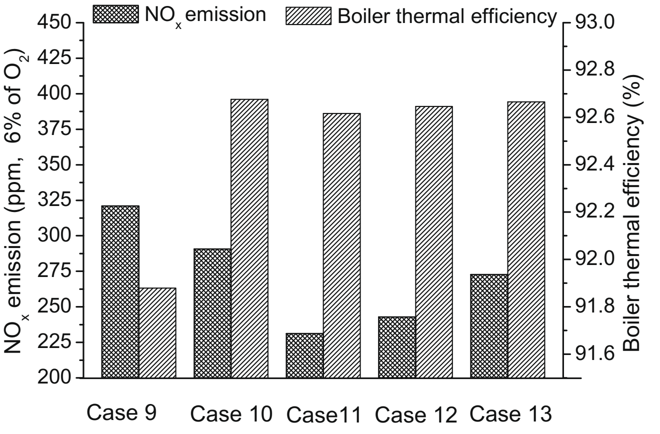


Fig. 7. The influences of the damper openings of CCOFA and SOFA on NO_x emission and boiler thermal efficiency.

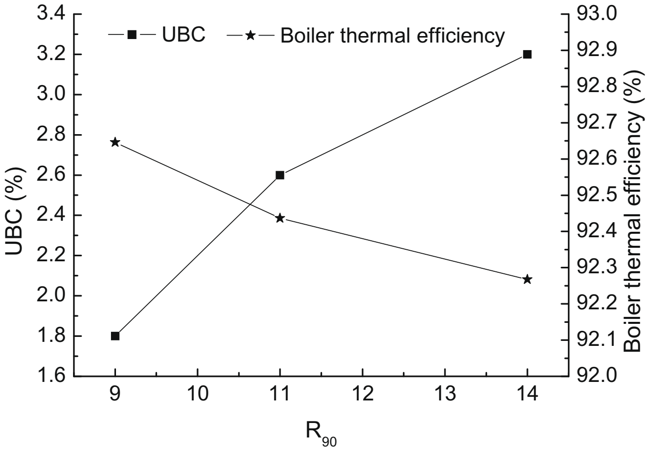


Fig. 8. The influences of pulverized coal fineness on unburned carbon in fly-ash and boiler thermal efficiency.

Based on above experimental results, here the excessive air ratio remained 1.22, the secondary air distribution pattern was like as Case 9, and the damper openings of CCOFAI, CCOFAII and SOFA were 20%, 20% and 50%, respectively.

In Cases 11, 14 and 15, NO_x emission was 229 ppm or so. The experimental results showed that the influence of pulverized coal fineness on NO_x emission was negligible, and thus it is not discussed here. Fig. 8 illustrates the influences of pulverized coal fineness on unburned carbon in fly-ash and boiler thermal efficiency. With the decrease of coal particle size, the entire reactive surface is enlarged, and the diffusive resistance also decreases. Therefore, the burnout rate increase significantly, and unburned carbon in fly-ash decrease noticeably, as shown in Fig. 8. When R_{90} of pulverized coal is 9 μm, unburned carbon in fly-ash and boiler thermal efficiency are 1.8% and 92.65%, respectively. The boiler efficiency merely decreased 0.21%, and unburned carbon in fly-ash was 1.8% compared with that before low NO_x modification.

4. Conclusions

The balance between boiler thermal efficiency and NO_x emission is important for existing coal-fired boilers retrofitted with air staging. The experiments of boiler thermal efficiency and NO_x emission were carried out in a 300 MWe utility boiler retrofitted by adding CCOFA and SOFA, and some important conclusions are as follows:

(1) After air staging modification of an existing coal-fire utility boiler, excessive air ratio must be adjusted to avoid noticeable decrease of boiler thermal efficiency. Experimental results show that boiler thermal efficiency is high and NO_x emission is relatively low at the optimum excessive air ratio (1.22).
(2) The secondary air distribution pattern has great influences on NO_x emission and boiler thermal efficiency, and there is an optimum distribution pattern. Under the optimum distribution pattern, boiler thermal efficiency is high and NO_x emission is relatively low.
(3) The combinative adjustment of CCOFA and SOFA damper openings has noticeable influence on NO_x emission. There is an appropriate damper opening of CCOFA and SOFA which makes NO_x emission decrease noticeably.

(4) The influence of pulverized coal fineness on NO_x emission was negligible. After series of combustion improvement, NO_x reduction efficiency is 44%, the boiler thermal efficiency merely decreases 0.21% compared with that before low NO_x modification.

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