Industrial Experiment on NO\textsubscript{x} Reduction by Urea Solution Injection in the Fuel-Rich Zone of a 330 MW Tangentially Pulverized Coal-Fired Boiler

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ABSTRACT: The effects of various factors on NO\textsubscript{x} reduction by urea solution injection in the fuel-rich zone (UIFR) under a reducing atmosphere at high temperature were experimentally investigated in a 330 MW tangentially pulverized coal-fired boiler. The experimental results indicated that the NO\textsubscript{x} emission of the boiler could be effectively reduced by using the UIFR method, and the NO\textsubscript{x} reduction efficiency was mostly affected by the operating load of the boiler, the air distribution condition, and the boiler operating oxygen content (BOOC). The higher the load was, the larger the optimal normalized stoichiometric ratio (NSR) and the lower the NO\textsubscript{x} reduction efficiency became. As compared with the condition of conventional air distribution mode, the reducing atmosphere in the combustion zone could be enhanced under the condition of limiting air distribution (LAD) mode, which thus increased the NO\textsubscript{x} reduction efficiency of UIFR and reduced the optimal NSR value. A low BOOC could further increase the NO\textsubscript{x} reduction efficiency of UIFR. When the BOOC was, respectively, reduced to 1.71 and 1.85 vol % under 210 and 240 MW loads, the corresponding NO\textsubscript{x} reduction efficiencies of UIFR reached 45.3 and 41.3% in the LAD mode, respectively. However, the low BOOC increased the CO emission concentration, which could be avoided by the combined use of UIFR and high-velocity over-fire air. These experimental results can provide guidance for the ultra-low NO\textsubscript{x} emission of coal-fired boilers.

1. INTRODUCTION

The nitrogen oxide (NO\textsubscript{x}) emissions caused by a large amount of coal combustion are one of the main sources of NO\textsubscript{x} pollution in China. Therefore, the higher efficiency and the lower NO\textsubscript{x} emission of coal combustion is increasingly becoming one of the most important developing directions of high efficiency coal-fired power generation technology in China. In 2014, China enacted new requirements for the ultra-low emissions of coal-fired boilers, where the emissions of NO\textsubscript{x} should be controlled to below 50 mg/m\textsuperscript{3} (6% O\textsubscript{2}).\textsuperscript{1} With the increasingly stringent NO\textsubscript{x} emission requirements, power units are facing the dual pressure of ultra-low NO\textsubscript{x} emissions and economic operation. The traditional low-NO\textsubscript{x} combustion technologies for power plant unit boilers, including various low-NO\textsubscript{x} burner technologies, air or fuel-staging combustion technologies, and so forth, can no longer meet the requirement of a lower 50 mg/m\textsuperscript{3} (6% O\textsubscript{2}).\textsuperscript{2−5} Therefore, most power plant unit boilers have to adopt the combined use of low-NO\textsubscript{x} combustion technologies and flue gas post-treatment technologies, such as selective noncatalytic reduction (SNCR) technology and selective catalytic reduction (SCR) technology in China.\textsuperscript{6−7} Although the ultra-low emissions of NO\textsubscript{x} can be achieved to a certain extent, there are still some shortcomings, such as the narrow reaction temperature window and relative lower NO\textsubscript{x} reduction efficiency for SNCR, easy deactivation of the catalyst, and relative higher investment and operating costs for SCR.\textsuperscript{9−11} Therefore, it is crucial to break through the existing technical bottlenecks and develop new technology to achieve a significant NO\textsubscript{x} emission reduction.

Around 70−90% of the total NO\textsubscript{x} generated during the pulverized coal combustion process in utility boilers comes from fuel NO\textsubscript{x}.\textsuperscript{12,13} Previous studies have shown that fuel NO\textsubscript{x} is mainly formed by the thermal decomposition of nitrogen compounds in coal: volatile-N and char-N.\textsuperscript{14,15} In an oxidizing atmosphere, nitrogen-containing compounds in coal: volatile-N and char-N can be further oxidized to form NO. In a reducing atmosphere, HCN and NH\textsubscript{3} can be transformed into
NHi radicals, which thus react with the generated NO to form N2. It seems that by creating a fuel-rich and oxygen-lean zone, more intermediate products can be converted into NHi to reduce NOx. Bose et al. studied the formation and reduction mechanisms of NO, HCN, and NH3 in the fuel-rich zone on a bench-scale platform. It was found that when pulverized coal was burned in a reducing atmosphere, the higher the concentration of the intermediate product NH3, the faster the reduction rate of NOx in the fuel-rich zone. However, for low volatile coals, the concentrations of intermediate products (HCN and NH3) are lower, and the generated NO cannot be easily reduced in a reducing atmosphere. Thus, whether it is possible to further enhance NO reduction by increasing the concentration of NH3 in the fuel-rich zone needs further study.

Hasegawa and Sato experimentally investigated the effects of oxygen concentration on NH3 conversion in a flow reactor at 1100 °C, and the results showed that the lower the oxygen concentration was, the less NH3 was consumed, and NH3 was not consumed in the absence of oxygen. Through the analysis of the reaction kinetic mechanism of NH3/NO/O2, Javed et al. found that under the conditions of high temperature and a strong reducing atmosphere, NH3-based reagents (urea or ammonia solution) can reduce NOx in flue gas to N2 without self-oxidation reaction. Spliethoff et al. studied the effects of the atmosphere and temperature on NH3/NO reduction reactions in an electric heating furnace system, and the results indicated that the stronger the reducing atmosphere and the higher the temperature were, the more favorable it was for the NH3/NO reduction reaction. Those studies revealed that the injection of ammonia cannot be oxidized in an oxygen-lean
Table 1. Properties of Dongsheng Lignite Coal

| fixed carbon | volatile | ash | moisture | C    | H    | O    | N    | S    | LHV at (MJ/kg) |
|--------------|----------|-----|---------|------|------|------|------|------|----------------|
| 34.24        | 21.82    | 16.94 | 27.0    | 43.31| 2.00 | 0.63 | 0.54 | 0.58 | 15.76          |

atmosphere, and high temperatures can also promote the \( \text{NH}_3/\text{NO} \) reduction reaction rate. Therefore, an ultra-low NO\(_x\) reduction combustion technology was proposed. This technology first establishes an area with a high-temperature and oxygen-lean atmosphere in the furnace by adjusting the pulverized coal combustion process, and then through the injection of a certain amount of an NH\(_3\)-based reducing agent (urea or ammonia solution) into this area to further improve the NO\(_x\) reduction efficiency by enhancing the content of NH\(_3\) in the high-temperature reduction area in the furnace.

Some researchers have studied the application of this technology. Yue et al.\(^{24}\) studied the effect of NH\(_3\) on the \( \text{NO}_x \) reduction characteristics of pulverized coal combustion in a one-dimensional drop-tube furnace system. The results indicated that the low stoichiometric ratio in the fuel-rich zone allows the urea solution to reduce NO\(_x\) more effectively, with a maximum NO\(_x\) reduction efficiency of 94.1\% in the temperature range from 1200 to 1400 °C. Bi et al.\(^{25}\) found that the optimal stoichiometric ratio in the fuel-rich zone was 0.85, and the normalized stoichiometric ratio (NSR) of the urea solution injected was 2. Through the establishment of a mechanistic model of the ammonia-injected denitrification in a high-temperature reduction zone, Lu et al.\(^{26}\) found that the reaction temperature window of NO\(_x\) reduction with an NH\(_3\) reagent injected at high temperatures was from 1200 to 1600 °C and the O\(_2\) concentration in the flow gas should be less than 1 vol \%. The technology of injecting reagents into the fuel-rich zone for NO\(_x\) reduction has been first applied to utility boilers by the REI Company in the United States, where the technology was called rich reagent injection (RRI).\(^{27-29}\) Based on the test of two existing cyclone-fired utility boilers equipped with overfire air (OFA), that is, a single wall-fired 130 MW unit (B.L. England Unit 1) and an opposed wall-fired 500 MW unit (Sioux Unit 1), RRI was demonstrated to achieve 30% NO\(_x\) reduction. Full-load NO\(_x\) emissions of 0.39 and 0.27 lb/Mbtu were obtained for BLE1 and Sioux Unit 1, respectively, using OFA and RRI. Apart from this, the applicability of RRI in the 205 and 330 MW opposed wall-fired cyclone units was predicted using computational fluid dynamics simulations,\(^{30}\) which indicated that the NO\(_x\) reduction efficiency of RRI may exceed 50\% in certain cyclone-fired units.

At present, research studies on the technology of injecting reagents into the fuel-rich zone are mainly at the laboratory bench-scale test stage, and its application in power plant boilers is concentrated on wall-fired cyclone units, while its application in tangentially pulverized coal-fired boilers is rarely reported. Bi et al.\(^{31}\) conducted industrial trials on the reduction of NO\(_x\) by urea solution injection in the fuel-rich zone (UIFR) technology in a 50 MW tangentially pulverized coal-fired boiler, which successfully demonstrated the high NO\(_x\) reduction efficiency (approximately 90\%), and the NO\(_x\) concentration in the flue gas at the outlet of the boiler had been achieved at 68 mg/m\(^3\) (O\(_2\) = 6\%) through the hybrid applications of UIFR and SNCR. However, there is still some information lacking when using that technology in utility tangentially pulverized coal-fired boilers, such as the optimal NSR, the effects of air distribution modes, and boiler operation oxygen contents (BOOCs), that is, the O\(_2\) volume fraction at the outlet of the boiler.

In this paper, the characteristics of UIFR technology were tested and analyzed in a 330 MW corner-tangentially pulverized coal-fired boiler, and the effects of NSR, air distribution modes, BOOCs, and high-velocity OFA (HVOFA) on NO\(_x\) emission characteristics were analyzed in detail. These findings clarify some critical features of UIFR technology in large capacity boilers and can provide good guidance for the reduction of NO\(_x\) emissions in coal-fired boilers.

2. EXPERIMENTAL SECTION

2.1. Experimental Facility. As depicted in Figure 1, the studied boiler was a 17.5 MPa/541 °C/540 °C subcritical corner-tangentially pulverized coal-fired boiler, with a single-furnace chamber of 61,000 mm in height and a cross-sectional area of 14,022 × 13,640 mm. In the primary combustion zone, five coal burners and seven secondary air nozzles are installed alternately on the four corners, and a layer of closed-coupled OFA nozzles is set above the uppermost secondary air nozzle. In addition, two groups of separated OFA (SOFA) nozzles were mounted at 3830 and 7500 mm above the primary combustion zone to reduce NO\(_x\) emissions. The detailed installation information for the burners and air nozzles is shown in Figure 1b. The boiler adopted a positive-pressure direct-firing pulverizing system with five medium speed coal mills (A–E). Under boiler maximum continuous rating conditions, four mills were put into use, each of which controlled one layer of coal burners, and one mill was kept for spare use. Dongsheng lignite coal was used, and its properties are listed in Table 1.

The retrofit with UIFR technology was conducted on the boiler, where the NH\(_3\) reagent was injected into the fuel-rich reducing atmosphere in the primary combustion zone, which was created by deep air staging. In this process, a certain amount of the urea solution with a 10\% mass concentration was injected into the fuel-rich zone in the furnace through 16 urea solution injectors to reduce NO\(_x\) (see Figure 1a). As shown in Figure 1c, the 16 injectors were divided into one injector on each corner (four) and three on each wall (twelve). To quantitatively evaluate the economic operating effect, the NSR, which represents the ratio of the molar concentration of the injected urea solution to NO\(_x\), was used and defined as follows:

\[
\text{NSR} = 2 \times \frac{n(\text{CO(NH}_2)_2)}{n(\text{NO})}
\]

(1)
the lower group of SOFA-I nozzles. The velocity of HVOFA was designed at 80 m/s, with a proportion of 5% of the total amount of combustion air. The schematic diagram of HVOFA nozzles and their installation is depicted in Figure 2.

![Figure 2. Schematic of HVOFA arrangement schemes.](image)

### 2.2. Experimental Method

The experiments were carried out at 210 MW, 240 MW, and 300 MW, respectively, and the cases investigated are summarized in Table 2. Under each operating load condition, the conventional air distribution (CAD) model was considered as a reference air distribution operating load condition, the conventional air distribution (LAD) mode. Finally, the in

Table 2. Design of Investigated Cases

| boiler load/(MW) | NSR  | air distribution mode | BOOC/(vol %) | HVOFA |
|------------------|------|-----------------------|--------------|-------|
| 210              | 0−5  | conventional air distribution | 3.19, 1.71  | off   |
|                  |      | limiting air distribution | on (in use) |       |
| 240              |      | conventional air distribution | 3.21, 1.85  | off   |
|                  |      | limiting air distribution | on (in use) |       |
| 300              |      | conventional air distribution | 3.15       | off   |

Operating load/(MW) NSR air distribution mode BOOC/(vol %) HVOFA

SCR system were obtained through the preserved hole to measure the gas components at the furnace exit. The monitoring point of the BOOC was also arranged at the inlet of the SCR system, which was measured online using a zirconia oxygen analyzer. The measurement accuracy of the platinum-rhodium thermocouples was ±1.5 °C at 0−1600 °C. The gas species components were recorded online using a Testo 350 gas analyzer, where O2, CO, and NOx could be measured with accuracies of ±0.2%, ±10, and ±5 ppm, respectively. For the convenience of comparison between cases, the NOx values presented below have been normalized to 6% oxygen content.

### 3. RESULTS AND DISCUSSION

#### 3.1. Effect of the NSR on NOx Reduction by Urea Solution Injection in the Fuel-Rich Zone (UIFR)

Figure 4 shows the effects of the NSR on NOx reduction under CAD mode conditions. The NOx concentrations showed parabolic variations with the continuous increase of the NSR. Under the conditions of 210 MW load and 3.19 vol % BOOC, the NOx concentration decreased rapidly with the increase of the NSR when it was below 3.5, and then the NOx content re-increased slightly when the NSR exceeded 3.5. Similar trends were also found under 240 MW and 300 MW loads. This phenomenon can be explained by the following reactions that occurred during the combustion process.

During the experiments, the flue gas temperature and gas species concentration in the fuel-rich zone and at the inlet of the SCR system were measured. By inserting thermocouples and a gas sampling gun into the furnace from the opened holes for urea solution injectors, the parameters in the fuel-rich zone were measured. Similarly, parameters before the inlet of the SCR system were obtained through the preserved hole to measure the gas components at the furnace exit. The monitoring point of the BOOC was also arranged at the inlet of the SCR system, which was measured online using a zirconia oxygen analyzer. The measurement accuracy of the platinum-rhodium thermocouples was ±1.5 °C at 0−1600 °C. The gas species components were recorded online using a Testo 350 gas analyzer, where O2, CO, and NOx could be measured with accuracies of ±0.2%, ±10, and ±5 ppm, respectively. For the convenience of comparison between cases, the NOx values presented below have been normalized to 6% oxygen content.

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After being injected into the fuel-rich zone, the urea solution first undergoes hydrolysis and decomposition at high temperature conditions to produce NH3. The reaction is shown as follows

\[
\text{CO}(\text{NH}_2)_2 \rightarrow \text{NH}_3 + \text{HNCO} \quad (2)
\]

\[
\text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2 \quad (3)
\]

Thereafter, NH3 reacted with OH and H radicals, which were generated in the primary combustion zone at high temperature, to form NH2,\textsuperscript{2,3,5,6} This process is thought to be the basis of the NH3/NO reduction. The relative chemical reactions are shown as follows

\[
\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} \quad (4)
\]

\[
\text{H} + \text{H}_2\text{O} \rightarrow \text{OH} + \text{H}_2 \quad (5)
\]

\[
\text{NH}_3 + \text{OH} \rightarrow \text{NH}_2 + \text{H}_2\text{O} \quad (6)
\]
Meanwhile, the reducing atmosphere helped to inhibit the oxidation of NH₂ due to the lean of oxygen, so that the generated NH₂ tended to selectively react with the generated NO through the following pathways to reduce NO₂5,37

\[ \text{NH}_3 + \text{H} \rightarrow \text{NH}_2 + \text{H}_2 \]  

\[ \text{NH}_2 + \text{NO} \rightarrow \text{N}_2 + \text{H}_2\text{O} \]  

\[ \text{NH}_2 + \text{NO} \rightarrow \text{NNH} + \text{OH} \]  

\[ \text{NNH} \rightarrow \text{N}_2 + \text{H} \]  

With the increase of the NSR, the amount of urea solution injected into the fuel-rich zone increased and thus promoted the subsequent NOₓ reduction process, causing NOₓ concentration to decrease rapidly when the NSR was increased from 0 to 3.5. However, when NH₃/NO reduction reactions reached the chemical equilibrium state after the NSR was increased to a certain level, the further increase of the NSR no longer promoted the reduction process. In contrast, the extra urea solution (NH₃) injected into the furnace moved upward with the flue gas and then became oxidized in the high-temperature and oxygen-rich SOFA zone. Thus, the NOₓ concentration increased when the NSR exceeded the optimal value.

Table 4 presents the concentrations of the NH₃ slip at the outlet of the boiler. As it can be seen from Table 4, the NH₃ slip was less than 2.0 mg/m³ under all the experimental conditions. This is attributed to the fact that NH₃ not completely consumed in the fuel-rich zone could be oxidized in the SOFA region by the fresh injected oxygen, so that no significant NH₃ slip was detected. The UIFR has advantages over traditional SNCR or SCR technologies in controlling the NH₃ slip.

### Table 3. Detailed Operating Parameters of the Boiler

| boiler load/(MW) | BOOC/(vol %) | coal feeding rate/(t/h) | mass flow rate of total air/(t/h) | primary air rate/(%) | temperature of fuel-rich zone/(°C) |
|-----------------|-------------|------------------------|----------------------------------|----------------------|----------------------------------|
| 210             | 3.19        | 118                    | 732.1                            | 26                   | 1150–1600                        |
|                 | 1.71        |                        | 675.9                            |                      |                                  |
| 240             | 3.21        | 134                    | 831.9                            | 1150–1650            |                                  |
|                 | 1.85        |                        | 773.2                            |                      |                                  |
| 300             | 3.15        | 185                    | 1145.4                           | 1200–1700            |                                  |
|                 |             |                        |                                  |                      |                                  |

**Figure 4.** Effect of the NSR on NOₓ reduction under the CAD scenarios.

**Table 4.** NH₃ Slip for Different NSRs under Three Loads (mg/m³)

| NSR load (MW) | 210 | 240 | 300 |
|---------------|-----|-----|-----|
| 210           | 0.73| 0.82| 0.95|
| 240           | 0.84| 1.21| 1.42|
| 300           | 1.27| 1.65| 1.73|

### 3.2. Effect of Air Distribution Mode on NOₓ Reduction by UIFR.

Figure 5 presents the distribution profiles of combustion temperature along the axis of urea injection ports, and the profiles of the concentration of O₂ and CO are shown in Figure 6. The temperature level under the CAD mode was higher than that under the LAD mode, which could be attributed to the fact that the coal combustion process is successive when air nozzles DD to OFA were operating under residence time of the urea solution in the reducing zone. On the other hand, the flue gas swirling momentum increased correspondingly due to its increased velocity and flow rate, so the atomized urea solution injected into the furnace had difficulty penetrating the flue gas and reacting with the generated NOₓ. Furthermore, the distance between the combustion air nozzles and the urea solution injectors decreased when the D mill was put into use, which increases the oxygen content in the reducing zone. Therefore, instead of being reduced, part of the injected urea solution is likely to be oxidized into NOₓ. Thus, the NOₓ concentration in the case of 300 MW was significantly higher when using the D mill.

![Figure 4](http://pubs.acs.org/journal/acsodf)

![Figure 5](http://pubs.acs.org/journal/acsodf)
the CAD mode. In contrast, the coal combustion process was separated into two disconnected parts under the LAD mode when these air nozzles were shut down. When the measuring point was more than 1 m from the urea solution injection ports, the combustion temperature values were higher than 1200 °C under the two air distribution modes, thus meeting the urea solution injection requirements of UIFR technology.

As shown in Figure 6, the O₂ concentration near the furnace wall region (X < 0.5 m) was still higher than 1.5 vol % under both air distribution modes, indicating that an oxygen-rich condition existed in this region, even though air-staging technology was applied. However, it can be found that the reducing atmosphere was much stronger under the LAD mode, where the O₂ concentration decreased to below 1.0 vol % when X > 1.5 m and the CO concentration increased to 10,000 µL/L. In comparison, these conditions could only be reached when X > 2.5 m in the CAD mode. This suggests that the LAD mode helps to increase the size of the oxygen-lean area in the urea solution injection zone, which thus strengthens the reducing atmosphere.

Figure 7 shows the profiles of the NOₓ concentration and its reduction efficiency under both air distribution modes.

Compared with the value of 210 mg/m³ under the CAD mode, the initial NOₓ concentration without urea solution injection slightly decreased to 206 mg/m³ under the LAD mode, meaning that the increase in the size of the reducing area caused by the LAD mode had no significant effect on the overall NOₓ reduction efficiency by itself. However, the optimal NSR value was 3.2 under the LAD mode, which was smaller than that under the CAD mode, and the corresponding NOₓ reduction efficiency also increased from 32.9 to 37.9%. This fully demonstrated that the combination of the LAD mode and the injection of the urea solution can effectively reduce NOₓ emissions in boilers. The reasons for this are presented as follows.

Although deep air-staging technology was applied to create an overall reduced atmosphere in the primary combustion zone, an oxygen-rich area still existed in the primary combustion zone due to the swirling and fluctuations of the flue gas, especially in the near-wall region. Therefore, under the CAD mode, the injected urea solution could undergo the following oxidation process in the local oxygen-rich zone:

\[ \text{NH}_2 + \text{O} \rightarrow \text{NH} + \text{OH} \]  \hspace{1cm} (11)

\[ \text{NH}_2 + \text{O} \rightarrow \text{HNO} + \text{H} \]  \hspace{1cm} (12)

\[ \text{NH} + \text{OH} \rightarrow \text{HNO} + \text{H} \]  \hspace{1cm} (13)

\[ \text{NH} + \text{O}_2 \rightarrow \text{HNO} + \text{O} \]  \hspace{1cm} (14)

\[ \text{HNO} + \text{OH} \rightarrow \text{H}_2\text{O} + \text{NO} \]  \hspace{1cm} (15)

This also explains why the required amount of urea solution in practical boiler operation is larger than that in laboratory facilities where the combustion atmosphere is much more uniform. In contrast, the reducing atmosphere is stronger and the appearance of local oxygen-rich zones can be avoided under the LAD mode, so that the injected urea solution is more likely to react with generated NOₓ, thus increasing the NOₓ reduction efficiency.

In summary, local oxygen-lean and oxygen-rich areas coexist in the high-temperature fuel-rich reducing zone, and the injected urea solution will undergo two competitive pathways, that is, NH₃/NOₓ reduction reactions and NH₃/O₂ oxidation reactions. Therefore, the NOₓ reduction efficiency of UIFR technology is largely dependent on the local combustion atmosphere of the urea solution injection area. The stronger the reducing atmosphere is, the larger the size of the reducing area is, and the higher the NOₓ reduction efficiency will be.

3.3. Effect of Boiler Operating Oxygen Content on NOₓ Reduction by UIFR

The BOOC, that is, the boiler outlet O₂ volume fraction, is thought to have a significant influence on the coal combustion process and NOₓ transformation characteristics. To explore this, Figure 8 plots the effects of the BOOC on the NOₓ emission concentration under various experimental cases. The variation trends of the NOₓ concentration were basically the same under the 210 MW and 240 MW conditions. Taking the 210 MW condition as an example, when the BOOC was decreased from 3.19 to 1.71 vol %, NOₓ emissions under the CAD mode were reduced by 13.3%. Similarly, the NOₓ concentration could also be decreased from 189 to 161 mg/m³ under the LAD mode. This indicated that decreasing the BOOC could create a reducing atmosphere for the combustion process, promoting the reduction of N-intermediates and thus lowering the initial amount of NOₓ generation.

Furthermore, the decrease in the BOOC could amplify the NOₓ reduction effect of UIFR technology. Figure 8a shows that when the urea solution was injected into the fuel-rich zone under a 3.19 vol % BOOC condition, the NOₓ concentrations were reduced by 32.8 and 38.5%, respectively, under the CAD mode and LAD mode. Comparatively, when the urea solution

Figure 6. O₃ and CO concentration distributions along the axis of the urea injection port.
was injected into the furnace under a 1.71 vol % BOOC condition, the NO\textsubscript{x} reduction efficiencies increased to 38.4 and 45.3%, respectively. This was because the reducing atmosphere was stronger when the BOOC was decreased, which was conducive to maximizing the utilization efficiency of the injected urea solution, thereby promoting the reduction reactions along with NH\textsubscript{3}, N-intermediates, and generated NO\textsubscript{x}. Moreover, the volumetric flow rate of the flue gas also decreased under low BOOC conditions. As a result, the increase in residence time for the urea solution in the reducing zone can ensure a sufficient NH\textsubscript{3}/NO reduction reaction. Therefore, the NO\textsubscript{x} reduction efficiency of UIFR technology can be increased under low BOOC conditions.

### 3.4. Cooperative Control of NO\textsubscript{x} and CO by UIFR and HVOFA

Figure 9 presents the concentration of O\textsubscript{2}, CO, and NO\textsubscript{x} under various conditions with 210 and 240 MW boiler loads. The NO\textsubscript{x} emissions concentration was high under regular BOCC conditions, and then it decreased significantly when the BOCC decreased for UIFR. However, the CO concentration increased significantly at the same time, from 83 and 62 to 786 and 665 μL/L under 210 and 240 MW conditions, respectively. The CO concentration at the outlet of the boiler reflects the combustion efficiency in the furnace. Thus, although a low BOCC value could effectively reduce NO\textsubscript{x} emissions, it could also cause adverse effects on combustion efficiency. To reduce the unfavorable effects of low BOCC conditions on the coal combustion process, HVOFA was introduced into the boiler system.

When HVOFA was introduced under the “LAD + UIFR” condition, the CO concentrations were significantly lowered under two boiler operating load conditions, although they were still slightly higher than those under regular BOOC conditions. The mechanism through which the HVOFA reduced the CO emissions can be explained as follows. First, the introduction of 5% HVOFA extracted from high-temperature primary air tubes increased the oxygen content in the burnout zone, which was indicated by the boiler outlet oxygen content that increased by 0.1 vol % under the 210 MW condition. Second, HVOFA nozzles were embedded into the SOFA nozzles, so the high-velocity and strong-rigidity of HVOFA air flow helped to strengthen the overall rigidity of SOFA airflow, thereby promoting the mixing between fresh combustion air and flue gas (incompletely consumed combustibles). Thus, the application of HVOFA not only enhanced the air-staging degree in the primary combustion zone but also strengthened the mixing and continuous combustion process in the burnout zone. Thus, the purpose of reducing NO\textsubscript{x} emissions while maintaining combustion efficiency could be achieved simultaneously. According to the analysis of the fly ash content, the unburned carbon contents in fly ash were 0.96 and 0.65% when HVOFA was applied under 210 and 240 MW conditions, which were not significantly higher than those of 0.82 and 0.49% under the regular BOCC conditions. Therefore, under
low BOOC conditions, the combined use of HVOFA and UIFR could effectively reduce the NO\textsubscript{x} emissions and prevent the significant decrease in the burnout rate.

4. CONCLUSIONS

The characteristics of UIFR technology were applied and studied in a 330 MW corner-tangentially pulverized coal-fired boiler, and the effects of some critical factors on NO\textsubscript{x} reduction efficiency were tested and analyzed in detail. The following conclusions were reached:

(1) During conventional boiler operation, NO\textsubscript{x} could be effectively removed by injecting the urea solution into the fuel-rich zone. The higher the load was, the larger the NSR and the lower the NO\textsubscript{x} reduction efficiency became. Under 210 MW, 240 MW, and 300 MW loads, the optimal NSRs were 3.5, 3.7, and 4.0, respectively, and the corresponding NO\textsubscript{x} reduction efficiencies were 35.4, 32.9, and 23.3\%, respectively.

(2) Compared with the CAD mode, the LAD mode could increase the size of the reducing area and enhance the reducing atmosphere in the zone for urea solution injection. The combination use of the LAD mode amplifies the NO\textsubscript{x} reduction effect of UIFR, which greatly improves its NO\textsubscript{x} reduction efficiency and reduces the optimal NSR at the same time.

(3) Under the same NSR conditions, UIFR could achieve a higher NO\textsubscript{x} reduction efficiency by reducing the BOOC. When the BOOC was reduced to 1.71 and 1.85 vol\% under 210 MW and 240 MW loads, respectively, the corresponding NO\textsubscript{x} reduction efficiencies of the UIFR reached 45.3 and 41.3\% in the LAD mode, respectively.

(4) HVOFA airflow could enhance the overall rigidity of SOFA airflow, promote the mixing of fresh combustion air and flue gas in the burnout zone, and thus reduce the CO concentration at the outlet of the boiler. Under a low BOOC condition, the combined use of HVOFA and UIFR could effectively reduce the NO\textsubscript{x} emissions while preventing a significant decrease in the burnout rate.

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Notes
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