Effects of the outer secondary air cone length on the combustion characteristics and NO\textsubscript{x} emissions of the swirl burner in a 0.5 MW pilot-scale facility during air-staged combustion

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HIGHLIGHTS

- Effect of outer secondary air cone length on burner performance was determined.
- The size of central recirculation zone increases with increasing the length.
- NO\textsubscript{x} emissions and unburned carbon in fly ash decrease with increasing the length.
- Considering NO\textsubscript{x} emissions and burnout rate, a length of 49 mm is advisable.

ABSTRACT

Cold air experiments using a centrally fuel-rich pulverized-coal swirl burner model were performed within a laboratory-scale facility to study the effects of the outer secondary air cone length on the aerodynamic fields. The divergent angle of the air jet and the size of the central recirculation zone were found to increase with increasing outer secondary air cone lengths. The 0.5 MW pilot-scale facility was also used to optimize the length of the outer secondary air cone by measuring the flue gas temperature, and O\textsubscript{2}, CO and NO\textsubscript{x} concentrations, at different cone lengths. As the cone length was varied from 0 to 49 mm, the NO\textsubscript{x} emissions rapidly fell from 778 to 458 mg/m\textsuperscript{3} (O\textsubscript{2} 6%), while the unburned carbon content in the fly ash decreased from 5.83% to 3.51%, and CO concentration decreased from 1355 mg/m\textsuperscript{3} (O\textsubscript{2} 6%) to 99 mg/m\textsuperscript{3} (O\textsubscript{2} 6%). Based on these results, the optimum length of the outer secondary air cone was determined to be 49 mm.

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1. Introduction

In recent years, environmental protection regulations in China have become increasingly stringent, especially for coal-fired utility boilers. A new Chinese air pollutants emissions standard for thermal power plants was announced in 2011, in which the NO\textsubscript{x} emissions limit was reduced from 450 to 100 mg/m\textsuperscript{3} (O\textsubscript{2} 6%) [1]. In addition, some provinces, such as Guangdong and Zhejiang, announced new environmental targets in 2014, with a future NO\textsubscript{x} emissions limit of 50 mg/m\textsuperscript{3} (O\textsubscript{2} 6%). The primary methods for controlling NO\textsubscript{x} emissions include using a low NO\textsubscript{x} burner, over fire air, and selective catalytic reduction. However, the NO\textsubscript{x} reduction for each technique is about 50–70% [2]. As a result, multiple techniques are typically combined to achieve greater reductions. The most widely used techniques are low NO\textsubscript{x} burners, over fire air technology and selective catalytic reduction. This study focused on the application of a low NO\textsubscript{x} burner when employing over fire air technology.

Admittedly, problems such as late ignition and poor combustion stability [3], heavy slagging [4], poor burnout [5–7] and high NO\textsubscript{x} emissions [8], are generally present in practical operations of low NO\textsubscript{x} swirl burners when employing overfire air technology. Many studies on low NO\textsubscript{x} burner technologies have been performed with air staging. Kurose et al. studied the effects of the fuel ratio on the combustion characteristics and NO\textsubscript{x} emissions of a 760 kW test facility incorporating a swirl burner. The results showed that, with an increasing fuel ratio, NO\textsubscript{x} emissions were reduced while the unburned carbon content in the fly ash (denoted by C\textsubscript{fa}) increased [9]. Xue et al. investigated the effect of the outer secondary air ratio on NO\textsubscript{x} emissions and C\textsubscript{fa} from a radially biased swirl burner in a 1
MWe laboratory scale furnace. The results showed that NO\textsubscript{x} emissions decreased and C\textsubscript{B} increased as the outer secondary air ratio varied from 49 to 54 % [10]. Li et al. examined the influence of air temperature and particle concentration in the primary air duct on NO\textsubscript{x} emissions from the swirl burner in a 0.5 MW large-scale laboratory furnace with air staging. They concluded that the NO\textsubscript{x} emissions and C\textsubscript{B} were reduced as the air temperature and pulverized-coal concentration increased [11,12]. The effect of the swirl number of the burner on NO\textsubscript{x} emissions was investigated experimentally by Abbas [13] and Corrêa da Silva [14,15]. These studies showed that NO\textsubscript{x} emissions decreased initially but then increased with an increasing swirl number. Daood et al. [16] varied the over-fire air location to investigate NO\textsubscript{x} emissions from a one-dimensional furnace with multi-path air inlets and found that NO\textsubscript{x} emissions decreased with increasing distance between the over-fire air (OFA) and the burner nozzle. According to Costa et al. [5–7], industrial experiments performed on a 300 MW front-wall-fired furnace suggested that adopting the air staging technology decreased NO\textsubscript{x} emissions from 1405 to 620 mg/m\textsuperscript{3} (at 6% O\textsubscript{2}), but unfortunately, raised C\textsubscript{B} from 3.2 to 4.0%.

Swirl burners mainly use high-speed swirl secondary air (located at its periphery burner outlet zone) to form a recirculation zone filled with high-temperature and lean-oxygen recirculating gas, thereby igniting the pulverized coal. This swirl burner operational principle means that reducing the current high NO\textsubscript{x} emissions to acceptable levels by forming deep air staging conditions but without increasing C\textsubscript{B} has been a huge challenge. Again, poor combustion stability and heavy slagging in these furnaces compound difficulties in the NO\textsubscript{x} reduction. To resolve these problems, Li and co-workers proposed a new low NO\textsubscript{x} swirl burner, i.e., the so-called centrally fuel-rich (CFR) swirl burner [17]. The published work revealed the excellent CFR burner performance characterized by weak slagging tendency, low NO\textsubscript{x} emissions, good burnout, and combustion stability present in a 300 MW front-wall-fired boiler [17]. However, NO\textsubscript{x} emissions were still a little high, and could not meet the latest air pollutant emission standards (specially for the NO\textsubscript{x} emission limit of 100 mg/m\textsuperscript{3} at 6% O\textsubscript{2}). This means that it is necessary to extend the CFR burner performance study under air-staging conditions specially established for further lowering NO\textsubscript{x} emissions. The low-NO\textsubscript{x} burner performance is affected not only by the operating parameters but also by the burner geometry [18]. Some researchers have investigated the influence of the structure of the primary air [17,19–24], the location of the swirl generator [20], and swirl angle [3,26,27] on combustion and the NO\textsubscript{x} emissions. According to Zhou et al. [19], employing an optimized primary air pipe structure decreased NO\textsubscript{x} emissions from 462 to 304 mg/m\textsuperscript{3} (at 6% O\textsubscript{2}), compared with the initial emission data obtained from a prototype swirl burner. Luo et al. proposed a novel burner which contained dual-gear rings and double conical flaring in the primary air outlet. The novel burner organizes a more stable temperature field and better ignition conditions than a conventional burner [22,23]. Komarek et al. studied the swirl generator location effect on the flame response of a perfectly premixed swirl burner and found that the location of the swirl generator significantly affected the dynamic flame response [25]. According to Jing et al. [26], both the NO\textsubscript{x} concentration at the moderate outer secondary air vane angle of 30° and 35° were less than those for the sharp angles of 25° and 40° in a 300 MW boiler fired by swirl burners. Xue et al. found that within a radially-biased swirl burner, NO\textsubscript{x} emissions increased while C\textsubscript{B} decreased with the swirl intensity [27]. These studies are obviously confined to various parameters related to the primary air structure, swirl generator location, and swirl angle effects on the burner performance. Few studies have been reported on other important low-NO\textsubscript{x} burner parameters under air-staging conditions, for example, the outer secondary air cone length presented in this study, in which the air staging technology was adopted and the secondary air mass flow rate of the burner decreased with an increasing OFA ratio. As a result, the aerodynamic field changed considerably, which directly influenced the combustion and NO\textsubscript{x} formation characteristics [13]. Results in this study can therefore enrich the understanding of the effect of the outer secondary air cone length on the burner performance under air-staging conditions. In this work, cold air experiments were performed using a CFR swirl burner with varying outer secondary air cone lengths. A 0.5 MW pilot-scale facility was employed to investigate the effect of the outer secondary air cone length of the CFR burner on the combustion characteristics and NO\textsubscript{x} emissions.

2. Experimental method

2.1. Cold air experimental systems

Cold air experiments were performed using a CFR model burner one-fourth the size of the designed prototype of a 600 MW utility boiler. The test system consisted of wind boxes, valves, rotameters, a burner model and a coordinate frame, positioned downstream of the burner outlet. Each grid of the frame had a thin piece of cloth tied to it, to allow an observer to assess the direction of the central recirculation zone boundary and the divergent angle of the air jet. A more detailed description of the experimental apparatus was published previously [17]. The schematic diagram of the CFR burner is shown in Fig. 1, in which L\textsubscript{c(osa)} is the outer secondary air cone length applied in the model burner during cold air flow experiments. The cold air flow trials were performed with L\textsubscript{c(osa)} = 0.49 and 98 mm. The other experimental parameters (all in kg/s) were: primary air mass flow rate of 0.260, inner secondary air mass flow rate of 0.161 and outer secondary air mass flow rate of 0.248. In addition, an OFA ratio of 25% was applied.

2.2. 0.5 MW pilot-scale facility experimental systems

Fig. 2 presents a scheme of the 0.5 MW pilot-scale furnace. The combustion chamber was a cylindrical furnace made of steel with an internal diameter of 800 mm and 5760 mm long. The roof section and inside wall of the furnace were lined with a refractory layer and a cooling layer was located between the refractory and insulating layers. Thirty ports were mounted on the furnace sidewall of the OFA system to allow for the measurement of the concentrations and temperatures of the gas species, and eight furnace windows were situated along the top of the furnace to enable viewing of the flame. A more detailed description of the experimental apparatus was published previously [11,12]. In the present work, the air-flue system was retrofitted and divided into
primary and secondary air boxes. The primary air, secondary air and OFA flows were measured using rotameters. The gas measurement systems consisted of a water-cooled stainless steel probe and a Testo 350 M-type gas analyzer. The accuracy of this analyzer was as follows: O2 accuracy $\pm$0.8% over the range of 0.0–25 vol%, CO accuracy $\pm$10.0 ppm over the range of 0.0–99.0 ppm and $\pm$5.0% over 100.0–2000.0 ppm or $\pm$10.0% over 2001 to 10,000 ppm and NO accuracy $\pm$5.0 ppm over 0.0–99.0 ppm and $\pm$5.0% over 100.0–2000.0 ppm. The analyzer was calibrated prior to performing measurements. The flue gas temperatures were measured with a thermocouple with an accuracy of $\pm$0.25% over a range of 0–1600 °C.

Fig. 3 shows a schematic of the three model burners, each of which was one-eighth the size of the design prototype for a 600 MW pulverized coal utility boiler. $L_{\text{o}(\text{rea})}$ is defined as the outer secondary air cone length of the model burner used for the reacting
flow experiments, and the experimental trials were performed with \( L_{r(osa)} = 0, 24.5 \) and 49 mm. Coal was used in all trials with an average pulverized coal particle size of 39.94 \( \mu \)m. The characteristics of the coal are given in Table 1 and the experimental parameters are given in Table 2. The stoichiometric ratio in the primary combustion zone was approximately 0.9.

3. Results and discussion

3.1. Cold air experiments

Fig. 4 presents the jet borders and central recirculation zone boundaries obtained with \( L_{r(osa)} \). In this figure, the distance to the burner outlet along the axial direction and the distance to the burner axis along the radial direction are defined as \( x \) and \( r \). As \( L_{r(osa)} \) decreased, the divergent angle of the air jet and the diameter and length of the central recirculation zone were seen to decrease. When \( L_{r(osa)} = 0 \) mm, an annular recirculation zone appeared at the exit of the burner and the divergent angle of the jet was only 43.52°. This occurred because of the increasing delay in the mixing of the primary air and secondary air in the burner, with decreasing values of \( L_{r(osa)} \).

3.2. Experiments using the 0.5 MW pilot-scale facility

Fig. 5 presents different profiles of gas temperature and \( \text{O}_2 \), CO and \( \text{NO}_x \) concentrations in the primary combustion zone with different \( L_{r(osa)} \). Here, \( d \) is the diameter of the outer secondary air cone. The initial stage of pulverized coal combustion was affected noticeably by the aerodynamic fields generated at each \( L_{r(osa)} \) value.

At a gas temperature of 750 °C, the \( \text{O}_2 \) concentration decreased from 21 to 18%, indicating that the pulverized coal had ignited. At the cross-section located at \( x = 80 \) mm, the reaction zone radius exhibited \( r/d \) values ranging from 0.1 to 0.4 at \( L_{r(osa)} = 49 \) mm, and the zone was thus wider under these conditions than at \( L_{r(osa)} = 0 \) or 24.5 mm. These results clearly show that the ignition of the pulverized coal at \( L_{r(osa)} = 49 \) mm was superior to that obtained at \( L_{r(osa)} = 24.5 \) or 0 mm. This observation is consistent with the central recirculation zone data provided in Fig. 4. The size of the central recirculation zone decreased as \( L_{r(osa)} \) decreased, and an annular recirculation zone appeared at the burner exit at \( L_{r(osa)} = 0 \) mm, because the furnace could not draw more high-temperature flue gas to ignite the pulverized coal. Compared with \( L_{r(osa)} = 24.5 \) and 0 mm, the \( \text{O}_2 \) concentration at \( L_{r(osa)} = 49 \) mm was low and the gas temperature was high in the region defined by \( x = 80 \) mm.

In the cross-section at \( x = 80 \) mm, the \( \text{NO}_x \) concentration decreased with increasing \( L_{r(osa)} \) values and a single peak appeared in the secondary air flow zone. As shown in Fig. 4, an annular recirculation zone was generated at \( L_{r(osa)} = 0 \) mm, with a large amount of particle penetration between the two zones. The particle residence time inside the recirculation zones consequently decreased, resulting in higher \( \text{NO}_x \) concentrations. The trends observed at \( L_{r(osa)} = 24.5 \) mm were similar to those obtained at \( L_{r(osa)} = 0 \) mm. Compared with the results at \( L_{r(osa)} = 0 \) and 24.5 mm, the data acquired at \( L_{r(osa)} = 49 \) mm showed that the pulverized coal was ignited in a timely manner, and that devolatilization occurred primarily in the central recirculation zone, where an elevated CO concentration (above 4000 ppm) prevented the formation of excessive amounts of \( \text{NO}_x \). For all \( L_{r(osa)} \) values, the reaction zone was wider in the cross-section at \( x = 240 \) mm than at \( x = 80 \) mm, leading to a rapid increase in the CO concentration around the primary air boundary, with a concurrent rapid decrease in the \( \text{O}_2 \) concentration. A highly reducing atmosphere was thus formed, and this decreased the \( \text{NO}_x \) concentration around the primary air boundary at each \( L_{r(osa)} \).

Fig. 6 shows the profiles of the gas temperatures and \( \text{O}_2 \), CO and \( \text{NO}_x \) concentrations in the burnout zone at different \( L_{r(osa)} \) values. The gas temperature decreased with decreasing \( L_{r(osa)} \) in the cross-section at \( x = 1200 \) mm. In the region following the second OFA nozzle, the differences induced by varying the \( L_{r(osa)} \) were reduced, although the gas temperature at \( L_{r(osa)} = 0 \) mm was lower than the other two cases near the inside wall in the three cross-sections from \( x = 1200–2000 \) mm, indicating that the reaction zone was slowly extending.

In the three cross-sections situated from \( x = 1200–2000 \) mm, the \( \text{O}_2 \) and CO concentrations increased when \( L_{r(osa)} \) varied from 0 to 49 mm. After the first OFA nozzle, the CO concentrations decreased with increasing values of \( x \) at each \( L_{r(osa)} \); the CO concentrations at \( L_{r(osa)} = 0 \) and 24.5 mm were above 4000 ppm after the second OFA nozzle, while the CO concentration at \( L_{r(osa)} = 49 \) mm was about 1000 ppm. Fig. 7 shows plots of the unburned carbon content of the fly ash as measured at \( x = 1200, 1680 \), and 2000 mm at different \( L_{r(osa)} \) values. The unburned carbon levels increased with decreasing \( L_{r(osa)} \), indicating that the influence of \( L_{r(osa)} \) on combustion performance was not negligible.

### Table 1

Characteristics of coal used in the experimental trials.

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<td>V</td>
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<td>M</td>
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<td>Ultimate analysis (as received, wt.%)</td>
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<tr>
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<td>H</td>
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<td>66.12</td>
<td>3.89</td>
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<td>Ash fusion (°C)</td>
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<td>ST</td>
<td>FT</td>
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<td>1218</td>
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### Table 2

Experimental parameters.

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<td>Length of the outer secondary air cone (mm)</td>
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<td>Primary air temperature (°C)</td>
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<td>Secondary air temperature (°C)</td>
<td>300</td>
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<td>Primary air mass flow rate (kg/h)</td>
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<td>Mass flow rate of inner secondary air (kg/h)</td>
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<td>Mass flow rate of outer secondary air (kg/h)</td>
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<td>Mass flow rate of OFA (kg/h)</td>
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<td>Feed rate of pulverized-coal (kg/h)</td>
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<td>Overall excess air (%)</td>
<td>20</td>
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<tr>
<td>NO(_x) emissions (mg/m(^3) @ (\text{O}_2) 6%)</td>
<td>778</td>
<td>736</td>
<td>458</td>
</tr>
<tr>
<td>CO emissions (mg/m(^3) @ (\text{O}_2) 6%)</td>
<td>1355</td>
<td>981</td>
<td>99</td>
</tr>
<tr>
<td>(C_p) measured at (x = 2000) mm (%)</td>
<td>5.83</td>
<td>5.41</td>
<td>3.51</td>
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Fig. 4. Jet border and central recirculation zone boundary profiles at \( L_{r(osa)} = 0 \) (×), 49 (△) and 98 mm (○).
The reduction in NO\textsubscript{x} concentration primarily depended on the primary combustion zone. When the flue gas arrived at the burnout zone the NO\textsubscript{x} concentrations were observed to increase for different $L_{\text{t(osa)}}$. The mean NO\textsubscript{x} concentration increased in the cross-section at $x = 2000$ mm when compared with that in the cross-section at $x = 1200$ mm, with $L_{\text{t(osa)}}$ values of 0, 24.5 and 49 providing increases of 110, 64 and 33 mg/m\textsuperscript{3} (O\textsubscript{2} 6%). The difference in NO\textsubscript{x} concentrations when changing from 0 to 24.5 mm was minimal. NO\textsubscript{x} concentrations were above 600 mg/m\textsuperscript{3} (O\textsubscript{2} 6%) at each $L_{\text{t(osa)}}$ in the three cross-sections from $x = 1200$ to 2000 mm, while the NO\textsubscript{x} concentration at $L_{\text{t(osa)}} = 49$ mm was below 450 mg/m\textsuperscript{3} (O\textsubscript{2} 6%) in the three cross-sections from $x = 1200$ to 2000 mm.

As shown in Figs. 5 and 6, the gas temperatures near the side wall in the primary combustion zone and burnout zone were lower than the softening temperature (1248 °C) and the O\textsubscript{2} concentrations were above 8%. These conditions were effective at preventing high temperature corrosion and slagging at each different $L_{\text{t(osa)}}$.

Fig. 8 shows profiles of the gas temperatures and O\textsubscript{2}, CO and NO\textsubscript{x} concentrations along the furnace centerline at different values of $L_{\text{t(osa)}}$. Comparing the data obtained at $L_{\text{t(osa)}} = 0$ and 24.5 mm, the gas temperature at $L_{\text{t(osa)}} = 49$ mm was higher in the region defined by $x < 3360$ mm and lower in the region $x > 3360$ mm, indicating that the flame center in the furnace moved backwards at $L_{\text{t(osa)}} = 0$ and 24.5 mm.

In the region $80 \leq x \leq 400$ mm, the O\textsubscript{2} concentration decreased rapidly while the CO concentration and temperature increased around the furnace centerline, indicating that pulverized coal underwent ignition and consumed a large amount of O\textsubscript{2} at each $L_{\text{t(osa)}}$. In the zone $400 < x \leq 1200$ mm, the O\textsubscript{2} concentration was constant.
but increased with decreasing $L_{\text{osa}}$. This can be attributed to the fact that the pulverized coal ignition was reduced with decreasing $L_{\text{osa}}$, such that a significant proportion of the O$_2$ was not consumed. After the second OFA nozzle, the O$_2$ concentration was observed to have increased, following which, as the combustion progressed further, the O$_2$ concentration began to decrease and eventually plateaued. At each $L_{\text{osa}}$, the CO concentration increased rapidly in the primary combustion zone and then decreased near the burnout zone, before reaching a constant value after the burnout zone. The CO concentrations at $L_{\text{osa}} = 0$, 24.5 and 49 mm were higher than the value obtained at $L_{\text{osa}} = 49$ mm after the second OFA nozzle.

Fig. 8 shows that the NO$_x$ concentration fluctuated widely at $x = 80$ mm, owing to ignition of the pulverized coal. The extent of NO$_x$ formation was sensitive to the O$_2$ concentration and the NO$_x$ concentration decreased rapidly in the region defined by $80 < x < 1200$ mm, because the O$_2$ concentration also decreased rapidly in this zone. At $L_{\text{osa}} = 0$, 24.5 and 49 mm, the NO$_x$ concentrations at $x = 1200$ mm (the region in front of the first OFA nozzle) were 623.39, 644.12 and 398.38 mg/m$^3$, respectively. This trend resulted from the decrease in O$_2$ concentration with increasing values of $L_{\text{osa}}$. In the zone defined by $80 < x < 1200$ mm, the mean O$_2$ concentrations at $L_{\text{osa}} = 0$, 24.5 and 49 mm were 3.8, 2.5 and 0.6%. A lower O$_2$ concentration
indicated a more highly reducing atmosphere, which was beneficial in terms of limiting NO\textsubscript{x} formation. At \( L_{\text{r(osa)}} = 0, 24.5 \text{ and } 49 \text{ mm}, \) the NO\textsubscript{x} concentrations at \( x = 2000 \text{ mm} \) (behind the second OFA nozzle) were 707.45, 681.64 and 429.27 mg/m\textsuperscript{3}, respectively. As shown in Fig. 7, at \( L_{\text{r(osa)}} = 0, 24.5 \text{ and } 49 \text{ mm}, \) the unburned carbon contents in the fly ash at \( x = 1200 \text{ mm} \) were 38.83, 34.00 and 28.50\%, respectively. The reduction in \( C_{\text{fa}} \) within the burnout zone decreased about 1.73\% when \( L_{\text{r(osa)}} \) varied from 0 to 49 mm. From Fig. 8, the NO\textsubscript{x} levels produced in the burnout zone were 84.06, 37.64 and 30.89 mg/m\textsuperscript{3}.

Table 2 summarizes the gas temperatures, CO concentrations, NO\textsubscript{x} concentrations and \( C_{\text{fa}} \) at the furnace exit. The NO\textsubscript{x} concentration decreased about 42 mg/m\textsuperscript{3} (O\textsubscript{2} 6\%) when \( L_{\text{r(osa)}} \) varied from 0 to 24.5 mm. Meanwhile, the CO concentration decreased from 1355 to 981 mg/m\textsuperscript{3} (O\textsubscript{2} 6\%) and the \( C_{\text{fa}} \) fell from 5.83 to 5.41\%. These data indicated that the pulverized coal burnout performance improved with increasing \( L_{\text{r(osa)}} \) values. As shown in Table 2, the NO\textsubscript{x} concentration decreased about 278 mg/m\textsuperscript{3} (O\textsubscript{2} 6\%) when \( L_{\text{r(osa)}} \) varied from 24.5 to 49 mm, while the \( C_{\text{fa}} \) and the CO concentration also underwent obvious decreases. Based on an evaluation of the overall pulverized coal combustion characteristics and NO\textsubscript{x} emissions, an \( L_{\text{r(osa)}} \) value of 49 mm is optimal.

### 4. Conclusions

The flow and combustion characteristics of a CFR burner were investigated in a single-phase facility in a 0.5 MWe pilot-scale facility, applying different outer secondary air cone lengths. The conclusions drawn are as follows:

1. The size of the central recirculation zone increases with increasing \( L_{\text{r(osa)}} \).
2. Both the ignition and burnout performance of the CFR burner are affected by \( L_{\text{r(osa)}} \), such that pulverized coal ignition occurs sooner at \( L_{\text{r(osa)}} = 49 \text{ mm} \) than at \( L_{\text{r(osa)}} = 0 \text{ and } 24.5 \text{ mm}. \) The \( C_{\text{fa}} \) and the CO concentration at the furnace exit both decrease with increasing \( L_{\text{r(osa)}} \); when \( L_{\text{r(osa)}} \) varies from 0 to 49 mm, the \( C_{\text{fa}} \) decreases from 5.83 to 3.51\% while the CO concentration decreases from 1355 to 99 mg/m\textsuperscript{3} (O\textsubscript{2} 6\%).
3. The NO\textsubscript{x} emissions decrease with increasing \( L_{\text{r(osa)}} \); when \( L_{\text{r(osa)}} \) varies from 0 to 49 mm, the NO\textsubscript{x} emissions measured at \( x = 5600 \text{ mm} \) decrease from 778 to 458 mg/m\textsuperscript{3} (O\textsubscript{2} 6\%).
4. Based on an evaluation of ignition and burnout performance and NO\textsubscript{x} emissions, the optimum value of \( L_{\text{r(osa)}} \) is 49 mm.

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### Nomenclature

**Abbreviations**

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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>A</td>
<td>ash</td>
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<tr>
<td>CFR</td>
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<td>nitrogen</td>
</tr>
</tbody>
</table>
Symbols

- $C_{fa}$: unburned carbon content in the fly ash
- $d$: the diameter of the outer secondary air cone of the model burner in the 0.5 MW pilot-scale facility
- $L_{r(osa)}$: the length of the outer secondary air cone of the model burner in cold flow experiments
- $L_{r(osa)}$: the length of the outer secondary air cone of the model burner in the 0.5 MW pilot-scale facility
- $r$: the distance to the burner axis
- $x$: the distance to the burner exit along the jet flow direction

References