Development of Subair Technique for Combustibility Enhancement and NOx Reduction in a Pulverized Coal-Fired Boiler

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ABSTRACT: In this work, subair injection was proposed to improve the combustibility and NOx emission in a 500 MW tangentially fired coal boiler. The location of injection ports was determined based on the coal particle trajectory and its effect was investigated numerically. The flow rate of subair was set to 0, 5, and 10% of the total combustion air. The secondary air flow rate was decreased appropriately to ensure that the total quantity of combustion air remained constant. The over-fire air was not adjusted to retain the effect of an air-staged combustion. The simulation results showed that the subair improved the combustibility of coal particles originating from burners A and B in the lower part of the furnace. Particles from other burners were not affected significantly. In addition, this method achieved reduction of NOx by 6.3 and 13.2% when the subair accounted for 5 and 10% of the combustion air, respectively. This reduction was attributed to the decrease in the peak temperature as a result of a wider combustion region. The proposed subair technique improved the coal combustibility and reduced the NOx emissions successfully in the furnace.

1. INTRODUCTION

In South Korea, thermal coal-fueled power generation is the second most utilized method of generating electricity right after nuclear power. In fact, this important and relatively cheap power source represents more than 38% of the annual energy production in South Korea. Nevertheless, power plants utilizing pulverized coal as the fuel are often regarded as one of the major sources of nitrogen oxide (NOx) pollution. Countries around the world have already started to focus on issues of emissions reduction, which is an important way to reach the environmental objectives. Therefore, the acceptable limits for the emission of these oxides are increasingly tightening all around the world. NOx emissions are known to contribute to global warming, acid rain, and photochemical smog formation, and they also pose a risk to human health. NOx emission can be controlled by the reaction of these oxides with ammonia through a selective catalytic reduction process, whose efficiency is sufficiently high to meet the regulation limits. However, the cost of ammonia consumption required to counteract the NOx pollution is directly related to the maintenance costs for this method of power generation. In contrast to sulfur oxide emissions, the NOx emissions from boilers can be reduced significantly by the modification of the combustion process. To date, several technologies directed at reducing NOx emissions such as air-staged combustion, reburning by gas fuel injection, and low-NOx burners have been studied and applied widely.

Tangentially fired coal boiler is one of the most commonly employed boilers in South Korea, as tangential combustion can guarantee stable combustion, wide coal adaptability, and efficient air staging for the control of NOx emissions. This boiler, which is the subject of this work, employs a separated over-fire air (SOFA) to generate air-staged combustion. The staged combustion consists of a primary oxygen-lean combustion zone and a secondary combustion zone where the fuel burnout is completed by over-fire air. The NOx emissions arising from the nitrogen-containing fuel in this setup can be decreased by lowering the peak temperature in the primary zone. Air staging (i.e., a two-stage combustion process) employing over-fire air is a fairly efficient method for reducing the NOx emission. However, such a reduction is usually in conflict with the complete combustion and can pose a risk of increased unburned carbon content in fly ash. Power plants in South Korea have expanded the range of coal employed as fuel and coals with poor reactivity can increase the content of unburned carbon despite other advantages of tangentially fired coal boilers. Therefore, it is essential to not only reduce NOx emissions but also to improve the burnout of coal particles in the furnace. To this end, researches have been conducted introduction of adjustments to the parameters under which coal boilers operate to optimize their performance. Furthermore, Sun et al. introduced the concept of horizontal bias combustion technology, which was developed to solve the problems of combustion efficiency, flame...
stabilization, slagging, corrosion, and NOx emissions. An horizontal bias combustion burner divides the primary air (PA) stream into two substreams, each with a different air–fuel ratio, which form a fuel-rich/fuel-lean region horizontally.24 Chen et al.25,26 reported the combustion characteristics and NOx emission for a down-fired boiler retrofitted with a new combustion system. This system involved the introduction of an over-fire air and a decrease in the flow areas of the inner and outer secondary air (SA) ducts of swirl burners. Using this system in industrial experiments, the authors demonstrated a significant reduction in NOx emission without increasing the content of unburned carbon in fly ash.

The numerical analysis performed herein aims to improve further the technology currently available for controlling NOx emissions by the supply of subair through ports located at the boiler bottom and, in particular, by reducing the burnout problem. This attempt is similar to the under-fire air (UFA) system, whose effect on the combustion efficiency was evaluated by Filkoski et al.27 With the implementation of UFA inlet ports in the lower part of the furnace, additional swirls are created near the burner regions, and the combustion efficiency improved as UFA flow rate was increased. However, the combustion chamber of the boiler was not a tangential firing system which is discussed in this work, and the effect on the NOx formation was not treated.

In numerical work on tangentially fired coal boilers, some of the coal particles supplied from burners A and B (lower burners) first move to the bottom of the boiler, which is followed by their movement to the upper furnace.28,29 These particles have a longer residence time than other particles supplied from burners C to E (upper burners). Nevertheless, burnout can be delayed under such circumstances as a result of oxygen deficiency in the inner swirling flow that particles from burners A and B pass by. Herein, therefore, a fraction of combustion air was supplied through the boiler throat to increase the concentration of oxygen in the bottom zone. A continuous burnout from the bottom burners is expected to decrease the rate of NOx formation by reducing the peak temperature. To examine this hypothesis, a numerical analysis implemented using a commercial code (ANSYS Fluent 16.1) is performed, with a particular focus on evaluating the effect of air supply from the bottom in terms of coal combustion characteristics and NOx formation.

2. METHODS

2.1. Boiler Specifications and Coal Properties. Figures 1 show schematic representations of a 500 MW tangentially fired coal boiler examined in this study. The boiler consists of a furnace, crossover pass, and rear pass. Pulverized coal and air are supplied through all corners of the furnace and the gas stream produces a swirling flow. As a result of the intense rotational speed and the low-pressure region at the center of the fireball in the furnace, the combustion particles and gases are attracted to the center of the furnace.30 The burner incorporates a primary air (PA) and secondary air (SA) that can be found in each of the six burner levels, A to F. Burner F, however, was not used in this study. PA supplies pulverized coal and air at a temperature of 340 K, whereas SA provides air at a temperature of 593 K. The over-fire air (OFA) located at the top of the furnace consists of two elements, namely, a close-coupled over-fire air (CCOFA) and a separated over-fire air (SOFA), both of which facilitate the combustion of unburned particles from the lower part of the furnace. The use of SOFA turns the lower furnace into a fuel-rich environment and contributes significantly to the reduction of NOx emissions. The heat generated from the combustion in the furnace is delivered to the water wall and tube bundles that consist of the superheater (SH), reheater (RH), and economizer located in the crossover pass and the rear pass. Some of the ash remaining after coal particles have burned flows out via the ash hopper positioned at the bottom of the boiler, whereas the fly ash moves through the heat-receiving part and comes out through the boiler exit. In this work, bituminous coal, which is commonly employed in thermal power plants, was selected as fuel. The coal properties are described in Table 1.

The computational grid was made up of 6.6 million hexahedral cells, many of which were used to represent the furnace to allow a more precise representation of the flow and combustion processes. To ensure the independence of the results, a test was conducted using other grid with 7.5 million cells. In the test, the gas temperature and x-velocity along the

Table 1. Properties of Bituminous Coal

|                  | proximate analysis (wt %), as received |
|------------------|---------------------------------------|
| volatile matter  | 34.0                                  |
| fixed carbon     | 47.1                                  |
| ash              | 9.3                                   |
| moisture         | 9.6                                   |

|                  | ultimate analysis (wt %), dry ash free |
|------------------|----------------------------------------|
| C                | 79.5                                   |
| H                | 5.1                                    |
| O                | 12.2                                   |
| N                | 2.4                                    |
| S                | 0.7                                    |
| calorific value  | $2.53 \times 10^7$                    |
y-direction lines \((x = 0\, \text{m}, \, y = -8 \, \text{to} \, 8\, \text{m}, \, z\) at the burner A and the lowest SOFA level) were compared (Figure 2). The variation of the results was small; therefore, the grid with 6.6 million cells was adopted to reduce computation cost.

2.2. Computational Models. The simulations performed in this work implemented the realizable \(k-\varepsilon\) model for turbulence. This model includes an alternative formulation for the turbulent viscosity and a modified transport equation for the dissipation rate. The realizable \(k-\varepsilon\) model was selected in particular because it provides substantial improvements over the standard \(k-\varepsilon\) model, where the flow features include strong streamline curvature, vortices, and rotation. \(^{31}\)

Radiation is a major form of heat transfer within the furnace. Recently, various reports describing the incorporation of radiation in furnace simulations have been introduced by Yin. \(^{32,33}\) In this work, the discrete ordinates (DO) model, offering satisfactory results over a wide range of optical thicknesses, is used to represent the particle and gas radiation. The DO model approximates the solution of the radiative-transfer equation by discretizing the entire solid angle into a finite number of solid angles. The weighted sum of gray gases model was applied in gas emissivity calculations. The particle emissivity of pulverized coal varies with the fraction of unburned char. \(^{33}\) Calculations performed here, however, employed the most commonly utilized emissivity constant of 0.9. The particle scattering factor was set to 0.6—\(a\) value that is indicative of forward scattering. \(^{34}\)

For the calculations of the reaction between homogeneous gaseous volatiles, the finite-rate/eddy-dissipation (FR/ED) model was applied using a simple two-step reaction mechanism that provides a reasonable compromise between accuracy and computational cost. The FR/ED model calculates both the reaction rates and the rate of production of species through the turbulence--chemistry interactions. The net reaction rate value was calculated using a minimum of two values of reaction rates.

The volatile release was described using the two competing rates model (the Kobayashi model). \(^{35}\) In this model, the competing rates control the devolatilization over both low- and high-temperature ranges and the required kinetic parameters were set to the default values. The kinetic/diffusion-limited model was selected for the char combustion. The char reaction rate is determined by both the diffusion of oxygen to the particle surface and the intrinsic chemical reaction kinetics. \(^{36,37}\)

The particle mass is calculated as

\[
\frac{\text{d}m_p}{\text{d}t} = -\pi d_p^2 \rho_{O_2} \frac{D_0 k}{D_0} + k
\]

where \(d_p\) is the particle diameter, \(\rho_{O_2}\) is the partial pressure of oxygen in the gas surrounding the particle, \(D_0\) is the bulk molecular diffusion rate, and \(k\) is the kinetic rate.

\(D_0\) and \(k\) can be calculated as

\[
D_0 = C_1 \left(\frac{T_p + T_g}{2}\right)^{0.75} \frac{d_p}{D_p}
\]

\[
k = A \exp \left(-\frac{E}{RT_p}\right)
\]

where \(C_1\) is the mass diffusion coefficient, \(T_p\) is the particle temperature, \(T_g\) is the gas temperature, \(A\) is the pre-exponential factor, \(E\) is the activation energy. The kinetic parameters of this model were obtained from a pressurized wire mesh heating reactor in Pusan Clean Coal Center. The pre-exponential factor is \(0.0043\, \text{kg/}(\text{m}^2\, \text{Pa}\, \text{s})\) and the activation energy is \(8.37 \times 10^7\, \text{J/kmol}\). The equipment and experimental procedures employed are provided in reference. \(^{38}\)

Since the NOx concentration in the flue gas is very low, NOx formation was determined by postprocessing after calculating the flow, temperature, and gas species concentration fields. NOx formation was calculated by taking into
NOx is described by the extended Zeldovich mechanism as reactions (6)
\[
\begin{align*}
O + N_2 & \rightleftharpoons N + NO \quad (4) \\
N + O_2 & \rightleftharpoons O + NO \quad (5) \\
N + OH & \rightleftharpoons H + NO \quad (6)
\end{align*}
\]
A third reaction contributes to the formation of thermal NOx, particularly at near-stoichiometric conditions and in fuel-rich mixtures.

A more detailed description of the computational models used can be found in the literature.

3. RESULTS AND DISCUSSION

3.1. Simulated Performance of a Tangentially Fired Coal Boiler Lacking Subair Ports. To assess the influence of subair supply through the bottom section of the boiler, it was first necessary to examine through simulations the performance of a boiler lacking the extra ports. These simulations were performed using values of flow rate, air temperature, and coal feed rate that were based on the operating conditions typical for power plants in South Korea. Under these conditions, the flow rate of PA, SA, and OFA (COCFA and SOFA) accounted respectively for about 24, 28, and 48% of the total combustion air and the excess air was 15%. The PA, SA, and OFA temperatures were set to 340, 593, and 593 K, respectively.

The temperature and oxygen concentration at the boiler exit were calculated as 604 K and 2.6%, respectively. The tube bundles exhibited a unified trend in terms of heat absorption; despite minor disparities between the individual components, the results displayed close correlation with the values expected based on the design conditions (Figure 3).

Based on the temperature distribution determined within the furnace (Figure 4), it was observed that the high-temperature region formed a ring around the low-temperature region located at the center. This phenomenon gives rise to an ascending swirl flow of coal particles and air supplied through the tangentially fired coal burner. The temperature measured at burner E and lower SOFA was greater than that of burner A or upper SOFA. Therefore, a considerable proportion of particles was combusted in these regions, as nearly half of the total air within the boiler is supplied by OFA located above burner E. Whereas a high concentration of oxygen was observed near the coal burners located in the lower part of the furnace, oxygen was virtually nonexistent in all other parts of the boiler. This observation could be explained by the distribution of combustion air—only half of coal particles were combusted in the lower furnace while the coal burners were located. This, in turn, created fuel-rich conditions that suppressed the production of NOx. Additionally, the air supplied from SOFA system, located in the upper section of the furnace, is used in the combustion of unburned carbon particles rising from the lower part of the furnace. It should be noted that the mass fraction of oxygen near the wall was found to be relatively high. Figure 5 shows the particle trajectory, where completely combusted particles are represented with transparent color for ease of comparison.

Figure 5 clearly demonstrates that some coal particles from burners A and B fall initially to the furnace bottom, where they concentrate at the center prior to rising again. Despite their long residence time, these particles undergo combustion at a lower rate, since the oxygen concentration in their trajectory is extremely low. In contrast, the particles coming from burners D and E exhibit shorter residence time—they do not fall to the bottom of the furnace and, instead, they ascend via a relatively wide swirling trajectory and exposed to high oxygen concentration in the SOFA region near the wall, which causes these particles to undergo rapid combustion. Thus, at a fixed OFA flow rate, the flow rate of SA was diverted only into the ash hopper, where a large fraction of particles from burners A and B were concentrated. Therefore, based on these observations, it was predicted that the combustion could be accelerated by the supply of air through ports located at the furnace bottom.

3.2. Simulated Subair Supply at the Bottom of Furnace. Preliminary numerical analysis was conducted to select the most appropriate method of supplying subair through the boiler throat. In the dry bottom ash removal system, which is part of 500 MW two-pass boilers currently employed in South Korea, a tiny amount of air enters the system through the boiler throat due to the internal negative pressure formed in the boiler during the course of opening the discharge doors to get rid of bottom ash. Furthermore, the built-in air valves allow the system to control the flow rate of air coming through the throat into the bottom part of the boiler. Therefore, an initial simulation was performed where 5% of the flow rate of total combustion air was supplied, whereas the entire boiler throat was set as the air inlet. In this situation, however, the bottom ash that needed to be discharged through the throat was constantly being blown upward by the air entering through the bottom. Hence, it was concluded that this method was not feasible, even if it could lead to improvements in combustion and reduced NOx emissions. To circumvent this problem, four arbitrarily sized ports capable of supplying subair in the vertical direction at a
temperature of 340 K were installed at the furnace throat (Figure 6). The cross section of the injection port was a rectangle with dimensions 0.74 m × 0.45 m and the port-to-port spacing was set to 2.8 m. Although these ports may also interfere with the discharge of bottom ash through the throat by creating an ascending flow along the furnace center, the results obtained showed improvements compared to those determined with the first method. Although the number and size of ports could potentially affect the outcomes of the analysis, these factors were not considered in great depth in this study and, instead, the focus was on examining the effect of air supply through the boiler bottom on fuel combustibility and NOx formation.

In the next step, simulations examining supply of subair through ports, set at 5 and 10% of the flow rate of total combustion air, were performed. The temperature and oxygen distributions determined in these simulations are shown in Figure 7. High temperature was detected at the bottom ash hopper as a result of coal combustion from burners A and B, and the temperature of the furnace center increased as the flow rate of the subair increased. Conversely, the gas temperature

Figure 4. Temperature and oxygen distribution in the boiler.

Figure 5. Particle trajectory determined for different burners, colored by char mass fraction.

Figure 6. Subair supply ports located at the boiler throat.
Along the fireball was found to decrease, thereby leading to a relatively even temperature distribution in the furnace. Analysis of the oxygen distribution in the 5% case revealed that there is a high concentration of oxygen at the furnace center—an observation that can be attributed to the fact that the subair joins the swirling flow rather quickly. In contrast, the stream of subair supplied in the 10% case was significantly faster, penetrating deeper into the furnace. Thus, the streams from each port did not merge together in the ash hopper. The oxygen distribution in the 10% case was less even than in the 5% case and determined from the position of ports.

Table 2 summarizes the temperature, the char conversion, and the mole fractions of oxygen and NOx at the boiler exit in the simulation results. Due to the constraints on the on-site collection of data inside the power plant furnace, these values are crucial for comparison. The lowest quantity of unburned carbon was observed when no subair was supplied. Nevertheless, it cannot be concluded that the subair hinders the coal combustion, as the char combusted in the boiler varied across the cases examined due to changes in the outflow rate of coal through the throat. Therefore, the initial mass of char discharged per exit was measured and multiplied by the conversion rate at the exit, confirming that coal combustion increased as the flow rate of subair increased. It could be confirmed by lower mole fraction of oxygen at the boiler exit in the 10% case. In addition, the results showed that the fraction of NOx at the exit decreased. To examine the influence of subair further, the combustibility and NOx inside the furnace were analyzed.

### Table 2. Results at the Boiler Exit in the Simulations

| subair (%) | 0 | 5  | 10 |
|------------|---|----|----|
| temperature (K) | 603.98 | 605.73 | 605.70 |
| char conversion (%) | 99.99 | 99.69 | 99.73 |
| initial mass of char discharged through exit (kg/s) | 24.51 | 24.73 | 24.82 |
| O₂ mole fraction (%) | 2.63 | 2.58 | 2.52 |
| NOx (ppm, 6% O₂ content) | 135.21 | 126.65 | 117.40 |

3.2.1. Combustion Characteristics. To investigate the effect of subair on the in-furnace combustibility of coal particles, particle residence time, particle mass, and burnout were analyzed. Figure 8 depicts the particle residence time determined for each burner level up to the boiler nose. As the flow rate of subair increased, the residence times of particles from burners A, B, and C tended to decrease. In contrast, the residence time of particles from burners D and E increased. These trends correlate with the gas velocity and for the ease of comparison, the x- and z-components of gas velocity along the lines are shown in Figure 9. The magnitude of the x-velocity decreased at both burner A and the lowest SOFA levels in the simulation employing subair ports. The increase in the residence time of the particles D and E despite the reduction of swirling velocity can be explained by the z-velocity, as shown in Figure 9c-d. The vertical component of gas velocity through the boiler center (y = 0 m) exhibits a positive correlation with the subair flow rate. The vertical gas velocity observed at the off-center region, with dense concentration of particles from burners D and E, on the other hand, tended to decrease as the flow rate of subair was increased. This change in behavior can be explained by the decrease in the SA flow rate, which subsequently resulted in a decrease in the vertical gas velocity at the off-center region. Overall, however, it was concluded that the changes in the residence time arising from subair were not significant, with the exception of burner A.

In general, the extent of particle combustion increases with increasing residence time, however, residence time on its own is not an accurate indicator of particle combustibility. Hence,
the mass distribution of the particles from each burner was expressed as a function of the furnace height (Figure 10). As observed for the residence time, the changes in the flow rate of subair affected predominantly the particles originating from burner A. The results showed that the mass of these particles in the region below burner A (including the ash hopper zone, \( z < 9 \) m) decreased as the subair flow rate was increased. The particle mass at the region above burner A was smaller and, therefore, it may be concluded that combustion took place significantly in the hopper. In addition, examination of the extent of burnout as a function of boiler height demonstrated that the supply of subair increased the burnout in the lower section of the furnace. The majority of particles that sunk to the hopper were found to originate from burner A, thereby confirming that the subair supply increases the combustibility of burner A particles. In contrast, virtually no changes were observed for burner B in the 5% case. When the proportion of subair was increased to 10%, however, the mass of these particles in the lower section of the boiler was found to decrease. Interestingly, at a furnace height of approximately \( z = 30 \) m, the particle mass was found to be largely similar, irrespective of the subair flow rate. In terms of the particles originating from burner E, the supply of subair seemed to hinder the combustion when the flow rate was set at 10%. As

Figure 9. Gas velocity in (a) \( x \)-direction and (c) \( z \)-direction of gas along the line (\( x = 0 \) m, \( y = -8 \) to 8 m, \( z \) at the burner A level) and (b) \( x \)-direction and (d) \( z \)-direction along the line (\( x = 0 \) m, \( y = -8 \) to 8 m, \( z \) at the lowest SOFA level).

Figure 10. Mass distribution of particles from each burner as a function of furnace height.
observed previously, there was no change in combustibility at $z = 30$ m. Thus, as determined for the residence time, no significant changes were observed at the top of furnace, with the exception of burner A.

Further analysis of the general changes in burnout across the furnace (Figure 11) showed that bulk of the combustion occurs around the burners and SOFA. In contrast, the combustion in the hopper zone was found to be negligible in the absence of subair. When the subair accounted for 5%, combustion took place up to a furnace height of <5 m and the peak burnout values decreased sharply in the burner zone. The zone with the relatively low burnout exhibited, on the other hand, an increase in burnout. When the proportion of subair was increased to 10%, the combustion in the hopper zone generally increased, with the exception of combustion below the furnace height of $z = 5$ m, where the extent of burnout decreased compared to the 5% case. These differences may be related to the residence time of particles originating from burner A, as these particles ascend more rapidly due to increased flow rate of subair. Additionally, the burnout fluctuations as a function of height were less noticeable in the burner zone, giving rise to a more even distribution of burnout. When subair was supplied, it was noted that the burnout was increased in SOFA zone as well as in burner zone as shown in accumulated burnout (see right of Figure 11). In summary, reducing SA and simultaneously supplying subair improved the burnout of particles originating from burners A and B, whereas the burnout of particles from burners C, D, and E decreased. Nevertheless, particles from burners C, D, and E could utilize the oxygen available near the wall in the SOFA zone more effectively than those from burners A and B, as they followed a swirling trajectory with a large radius. Thus, the flow rate of SOFA remained constant, however, the burnout increased when subair was employed. The increase in burnout observed when the subair flow rate was increased from 5 to 10% was negligible. The reason why the accumulated burnout was normalized arises from the fact that the quantities of particles discharged through the throat and exit change due to the subair. To show that the increase in burnout in the 10% case was not due to the decrease in the number of particles exiting through the boiler throat, accumulated burnout was divided by the initial mass of char discharged through the exit.

### 3.2.2. NOx Formation

Figure 12 illustrates the distribution of NOx determined as a function of subair flow rate. When the subair supply was fixed at 0%, the fraction of NOx observed at the furnace center was very low, and the burner zone exhibited a low concentration of NOx in general. The fraction of NOx in the SOFA zone was relatively high compared to other zones—an observation that can be attributed to the rapid formation of NOx as a result of the combustion of remaining unburned

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**Figure 11.** Burnout and normalized accumulated burnout as a function of furnace height.

**Figure 12.** NOx distribution within the boiler.
in turn, decreased the temperature of the remaining particles and resulted in combustion taking place in a scattered manner. Nevertheless, the accumulated burnout at the boiler exit and, therefore, the accumulated NOx formation rate was generally decreased but increased at the higher SOFA. In the cases employing subair, the fraction of NOx in the burner zone increased noticeably; however, the fraction of NOx in the upper parts of the boiler remained low as a result. To find an explanation for this result, the NOx formation rate with respect to furnace height was examined (Figure 13). Specifically, this analysis allowed the effect of subair on the formation of NOx to be assessed. Additionally, the right side of Figure 13 shows that the accumulated NOx formation rate was plotted to relate the NOx formation with the results obtained at the boiler exit. It should be noted that the units for the accumulated NOx formation rate are not equal to those of the NOx formation rate. Specifically, the subair increases the NOx rate at the hopper zone, whose cross-sectional area is different from that of the furnace above. The NOx formation rate was multiplied by the volume of the grid cell and then accumulated. The results showed that the NOx formation rate exhibits a distribution pattern similar to that determined for burnout. The differences in the influence of subair were most notable in the hopper zone and level E (at approximately \( z = 22 \) m). When subair was supplied, the SA flow rate was reduced and the temperature decreased, which led to a decrease in the NOx formation rate near level E. The NOx distribution shown in Figure 12 illustrates that NOx fraction near levels A–D increased with increasing proportion of subair. This can be explained by the fact that the formation of NOx at the center of the furnace as a result of the subair caused the overall fraction of NOx to increase, and not because the combustion reaction in front of the burners increased.

As the flow rate of subair was increased, the NOx formation rate in the hopper zone increased; however, the rate in the burner zone decreased. In the OFA zone, the NOx formation rate was generally decreased but increased at the higher SOFA. The results showed that subair reduces the NOx measured at the boiler exit and, therefore, the accumulated NOx formation rate was examined for comparison. At approximately \( z = 22 \) m, the accumulated NOx formation rate was found to be fairly same across all cases. Nevertheless, the accumulated burnout at \( z = 22 \) m was the highest in the 10% case. As a result of this significant observation, it can be concluded that the ratio of NOx formed at the burnout has a negative correlation with the flow rate of subair supplied. Under normal circumstances, particles are combusted along the fireball. The subair, however, resulted in combustion taking place in a scattered manner, which, in turn, decreased the temperature of fireball. As such, the remaining particles were combusted at a furnace height of \( z = 22 \) m and the accumulated NOx formation rate was reversed starting at that height. At approximately \( z = 35 \) m, the accumulated NOx formation rate determined in the 0 and 5% cases were equal; however, the 5% case exhibited greater burnout. Therefore, in the case employing no subair, the burnout processes continued and the NOx was slightly larger than in the 5% case—these outcomes are in agreement with the results measured at the boiler exit.

4. CONCLUSIONS

In the present study, subair was proposed to improve the combustibility of coal particles and reduce the NOx formation in a 500 MW tangentially fired coal boiler. The particles from the lower burners, especially burner A, first sink to the hopper before rising again. Based on this trajectory, subair was supplied vertically through the injection ports located at the bottom of ash hopper to promote the combustion of the particles. In addition, it was hypothesized that the combustion with subair would moderate the temperature, thus inhibiting NOx formation. This hypothesis was tested using computational analysis, with particular focus on combustion characteristics and NOx formation.

The analysis showed that increasing the proportion of subair increased the extent of burnout of particles A and B. The burnout of particles C, D, and E did not deteriorate although the SA diverted to subair. This is because those particles could consume oxygen effectively near the wall in the SOFA zone. In addition, the results showed a 6% and 13% decrease in NOx emissions at the boiler exit when the proportion of subair was set to 5 and 10%, respectively, even though the amount of burnout in the furnace was increased. Although the supply of subair resulted in the formation of NOx in the hopper zone, a smaller quantity of NOx was formed in the burner zone as a result of lower peak temperature and even temperature distribution.

In summary, although the use of subair exerted a positive impact in terms of combustion characteristics and NOx formation, it also caused a reduction in the bottom ash discharged via the boiler throat. As the size and number of ports used in this study were selected arbitrarily, further work should be performed to minimize the impact of ports on the discharge of bottom ash.

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Notes
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ABBREVIATIONS
CCOFA, close-coupled over-fire air; DO, discrete ordinates; FR/ED, finite-rate/eddy-dissipation; NOx, nitrogen oxides; OFA, over-fire air; PA, primary air; RH, reheater; SA, secondary air; SH, superintendent; SOFA, separated over-fire air

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