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Numerical Simulation of the NO_x Emissions in a 1000 MW Tangentially Fired Pulverized-Coal Boiler: Influence of the Multi-group Arrangement of the Separated over Fire Air

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ABSTRACT: Computational fluid dynamics (CFD) investigations have been carried out to understand the combustion and NO_x emission characteristics in a 1000 MW pulverized-coal boiler, which is equipped with a dual-circular tangential-firing system in a single furnace. One group of separated over fire air (SOFA) nozzles has been widely studied and used in controlling the NO_x emissions in a pulverized-coal boiler. In this work, a multi-group of SOFA nozzle arrangement is investigated for the NO_x control and reduction. The predicted results agree well with the measured information from the full-scale boiler. The flow field, temperature distribution, species concentration, and char burnout are discussed. The relationship between the NO_x formation and the SOFA arrangement are analyzed. The numerical results show that the multi-group of SOFA nozzle arrangement is an efficient method to control the NO_x emissions in the pulverized-coal boiler, with few unfavorable effects on the coal burnout. The arrangement of the two-group of SOFA nozzles being in service presents better ability than the one-group arrangement in reducing the NO_x emissions. The distance between the two groups of the SOFA nozzles should be longer for a better result of NO_x reduction. The technology of air-staging combustion presented in this work is good to enhance the understanding of the NO_x formation characteristics and useful for the NO_x control and reduction in pulverized-coal boilers.

1. INTRODUCTION

NO_x emissions during coal combustion in pulverized-coal boilers have caused an international concern, because of their unfavorable impact on the environment. Restrictive regulation legislation against the NO_x emissions from pulverized-coal boilers has been established by concerned organizations and local governments around the world.[1] To reduce the NO_x emissions in coal-fired boilers, several technologies have been employed, such as the use of the horizontal fuel-rich/lean burner[2] and enhanced ignition dual-register burner,[3] over fire air (OFA) technique,[4,5] and reburning.[6−9]

Pulverized-coal boilers have been developed toward large capacity, taking the advantages of higher efficiency and less pollutant emissions. In China, several 1000 MW ultra-supercritical (USC) pulverized-coal-fired boilers have been put into commercial operations since 2006 and hundreds of USC boilers are under construction. Tangentially fired pulverized-coal boilers have been widely used in industrial power generation, especially in China.[10] Dual-circle tangential-firing single-furnace systems are employed in large-capacity boilers, with the benefits of steady combustion and uniform temperature distribution.[11,12]

Many numerical investigations have been reported on flow, combustion, heat transfer, and pollutant formation in coal-fired boilers.[13−17] These studies focus on the combustion process, temperature deviation, and NO_x emissions. One of the efficient methods to reduce the NO_x emissions during the combustion process is the employment of OFA.[5,18] Under the OFA operation, the temperature of the burner zone will be reduced and NO_x can be changed to N_2 in the fuel-rich region in the furnace.[19,20] Liu et al.[11] investigated the influence of the OFA position on the NO_x emissions. They found that the NO_x emissions can be greatly reduced with less influence on combustion efficiency by adjusting the OFA position. Huang et al.[21] studied various OFA parameters and analyzed the effect of OFA on the NO_x emissions for a 670 tons/h wall-fired boiler. The above studies focus on one group of separated over fire air (SOFA) nozzles in controlling the NO_x emissions in a pulverized-coal boiler. However, there are few studies that focus on the influence of multi-group SOFA nozzle arrangements on the combustion characteristics and NO_x emissions. A deep understanding of the effect of multi-group SOFA arrangement on NO_x formation could be useful for NO_x control, high combustion efficiency, design, and operation of a pulverized-coal boiler.

In this work, a 1000 MW USC pulverized-coal boiler with a dual-circle tangential-firing system in a single furnace is studied by numerical simulation. The characteristics of the flow, combustion, temperature, and pollutant emissions in the furnace are obtained. The predicted results are compared to measured information obtained from the full-scale industrial utility-boiler furnace. Three cases of SOFA arrangements are studied to investigate the influence of multi-group SOFA nozzles on NO_x emissions and burnout.

2. 1000 MW PULVERIZED-COAL BOILER

Figure 1 shows the schematic configurations of the 1000 MW tangentially pulverized-coal boiler with a dual-circle tangential-firing single-furnace system. The boiler investigated in this work includes ash hopper, burner zone, SOFA zone, and outlet. The height of the boiler is about 65 m, and the cross-section of the furnace is a rectangle with a width of 34 m and a depth of 15 m. Figure 2 presents the arrangement for the burners in a horizontal cross-section. There are eight burners installed in the cross-section, and every burner is located with an inclination angle

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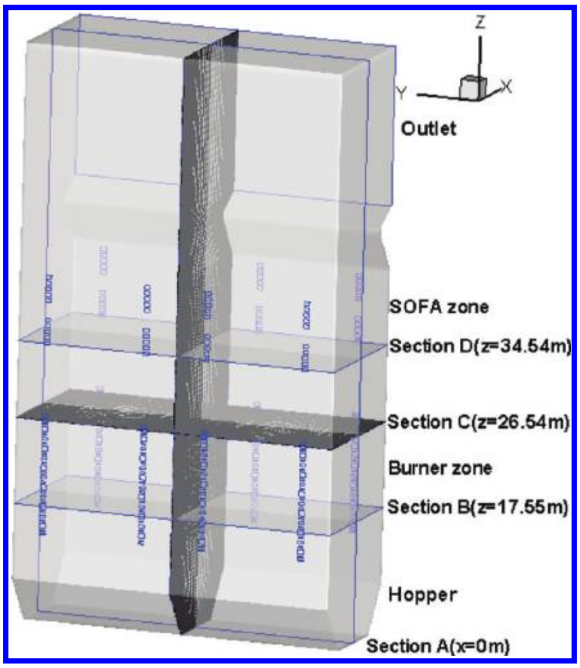

Figure 1. Schematic configurations of the 1000 MW pulverized-coal boiler.

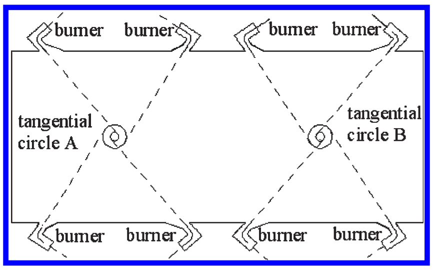

Figure 2. Horizontal arrangement for the burners in a 1000 MW tangentially fired boiler.

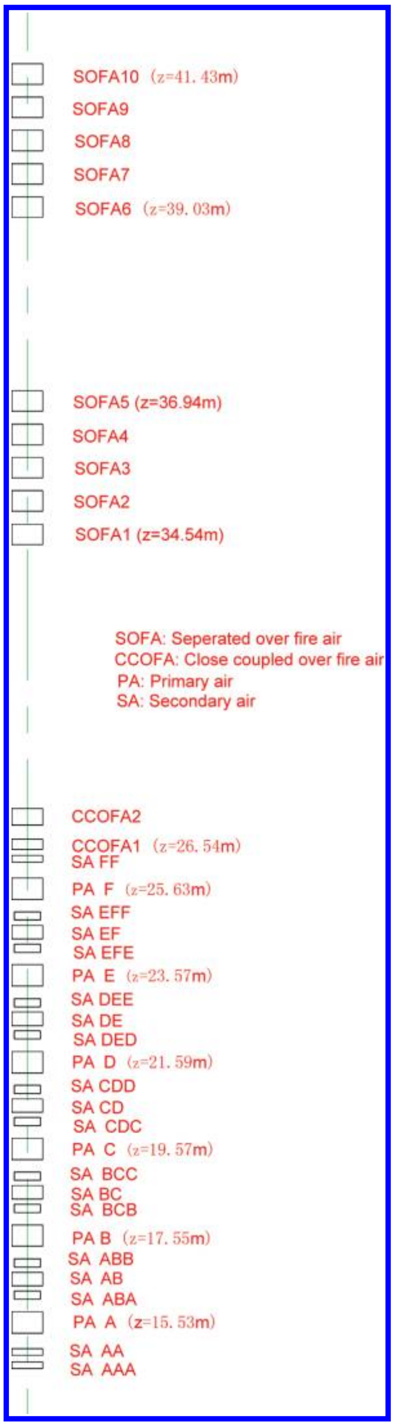

Figure 3. Burner nozzle distribution at various elevations of the furnace.

between the burner axis and the furnace diagonal. Four burners at the left side form a tangential circle, while the other four burners at the right side form the other tangential circle. The burner nozzle distribution at various levels of the furnace is illustrated in Figure 3. There are six primary air (PC) nozzles numbered from A to F. The pulverized coal is injected into the furnace along with the primary air. Between two primary nozzles, there are three secondary air (SC) nozzles. Two narrow secondary nozzles are installed at both the bottom and top of the burner assemble. At the top of the burner zone, there are two close coupled over fire air (CCOFA) nozzles. Under the operation of the design capacity, only five primary air nozzles of A−E are put into use. The primary air nozzle of F and two secondary air nozzles of EF and EFF are out of service.

Two groups of the SOFA nozzles are located above the burner zone. There are five nozzles in each group, and there are 10 SOFA nozzles in total for the two groups. When the boiler is operated for its design capacity, only five SOFA nozzles in the two groups are put into operation, while the other five nozzles are not employed. In this work, the optimal arrangement of the SOFA nozzles being in service is investigated by adjusting the organization of the employed SOFA nozzles during the operation. Three cases with a different arrangement of five employed SOFA nozzles are numerically studied, as shown in Figure 4. Case 1 is studied as the base case, with all of the five employed nozzles in group 1. In cases 2 and 3, the nozzles that are employed are divided into two groups and the second group shows an increasing elevation from case 2 to case 3. The first group of SOFA nozzles includes nozzles of 1−3 in cases 2 and 3. However, the second group of the SOFA nozzles includes nozzles of 6−7 and 9−10 for cases 2 and 3, respectively. The influence of the multi-group SOFA nozzle arrangement on the NO_x emissions is numerically investigated. The coal characteristics and the operating information of the boiler are listed in Tables 1 and 2, respectively.

3. NUMERICAL ANALYSIS

The turbulent flow, species concentration, combustion temperature, particle motion, and pollutant emissions in the boiler are numerically simulated by the commercial computational fluid dynamics (CFD) software of FLUENT in this work. Before the case studies, grid dependence tests are carried out. A total of 940 167 and 1 596 103 cells are employed in the grid tests, and no noticeable change in the simulation results is obtained with finer meshes with in a trial. Finally, 940 167 hexahedral cells are employed in the computational zone. The numerical simulations are carried out in a workstation with dual Xeon 5520 CPUs and 16 GB random access memory, and it takes about 100 h to simulate each case.

The conservation equations for mass, species, momentum, and energy in the Reynolds-averaged forms are solved. In this work, the turbulent flow is closed by a realizable $\kappa-\varepsilon$ model.[22] The discrete ordinate (DO) radiation model is used to calculate radiation heat transfer.[23]

The coal particle motion is calculated by Newton's second law in the scheme of the Lagrangian method. The particle motion is influenced by the drag force[24] in this work, while the other forces, such as the Saffman lift force and the Basset force, are neglected. During the coal particle combustion, the volatile matter releases from the coal particle into the gas phase, and the remainder is char and ash in the particle. Therefore, there are two kinds of reactions in the furnace: the homogeneous reaction of volatile matter and the heterogeneous reaction of char particles. The process of volatile matter releasing from the coal particle can be modeled by one- and two-step models. In this work, the coal devolatilization is modeled by the widely used two-competing-rate model reported by Kobayashi et al.[25] The volatile matter homogeneous combustion happens in the gas phase. A mixture fraction equation can be solved in a non-premixed model instead of individual species equations. The fuel species and oxidant species cannot exist in the same place, otherwise they will converse to products. Therefore, the individual species mass fraction can be determined by the mean mixture fraction and the fraction variables. The influence of the turbulence on the gas chemistry reactions can be taken into account by the β probability density function (PDF), as reported by Sivathanu et al.[26] The char combustion can be calculated by the model presented by Field et al.[27]

NO_x formation simulation is carried out as a post-processing procedure, the NO_x emission calculation is based on the flow field, temperature distribution, and species concentration. In this work, the prompt NO_x formation is not considered because it is not significant in the pulverized-coal boiler. Only the thermal NO_x and fuel NO_x are calculated. To describe and model the formation of the thermal NO_x, the mechanism presented by Zeldovich in 1946[28] is widely employed. In this work, the thermal NO_x formation is modeled by the extended Zeldovich mechanism[29] as follows:

$$O + N_2 \underset{K_{-1}}{\overset{K_{+1}}{\rightleftarrows}} N + NO \tag{1}$$

$$N + O_2 \underset{K_{-2}}{\overset{K_{+2}}{\rightleftarrows}} O + NO \tag{2}$$

$$N + OH \underset{K_{-3}}{\overset{K_{+3}}{\rightleftarrows}} H + NO \tag{3}$$

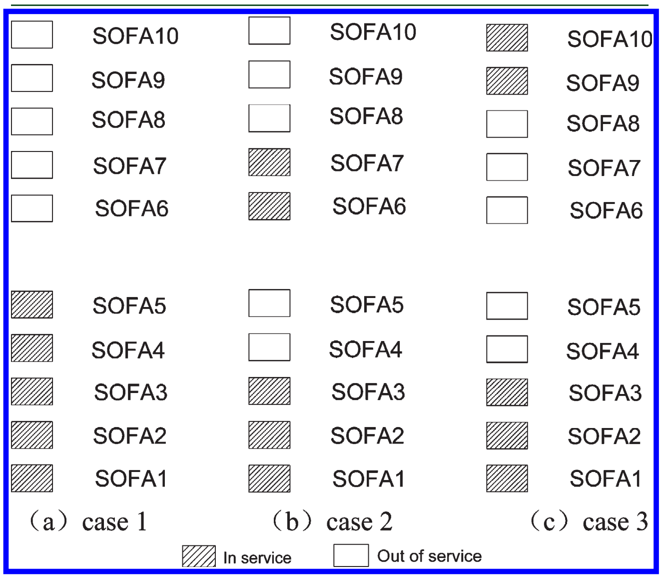

Figure 4. SOFA nozzle arrangement for three cases.

Table 2. Operating Information of the Pulverized-Coal Boiler

air flow rates for each nozzle (kg/s)	PA (nozzle: A, B, C, D, and E)	8.085
	SA (nozzle: AA and AAA)	2.66
	SA (nozzle: ABA, ABB, BCB, BCC, CDC, CDD, DED, DEE, and EFE)	2.722
	SA (nozzle: AB, BC, CD, DE, and EF)	5.445
	CCOFA (nozzle: CCOFA1 and CCOFA2)	6.743
	SOFA (nozzle in service)	8.209
air inlet temperature (K)	primary air	348
	secondary air	607
	CCOFA	607
	SOFA	607
furnace wall temperature (K)	700	
coal mass flow rate (kg/s)	100	
excess air coefficient	1.18	

Table 1. Proximate and Ultimate Analyses and Diameter Distribution of the Pulverized Coal

proximate analysis (%, dry basis)	volatile matter						41.13				
	fixed carbon						48.45				
	ash						10.42				
ultimate analysis (%, dry and ash-free basis)	carbon						57.92				
	hydrogen						3.68				
	oxygen						8.65				
	nitrogen						1.12				
	sulfur						0.6				
net heating value (kJ/kg, as received)	heating value						23442				
coal diameter distribution	diameter (μm)	1	23	45	67	89	112	134	156	178	200
	mass fraction (%)	3.6	28.3	22.3	15.9	11	7.6	4.8	3.2	2	1.3

Table 3. Information at the Outlet of Four Cases

	case 1 (measured)	case 1 (predicted)	case 2 (predicted)	case 3 (predicted)
NO_x concentration (mg N^{-1} m^{-3}, at 6% O_2)	272	269.6	229.9	214.4
burnout (%)	99.87	98.82	98.57	98.56
average temperature (K)		1426.8	1432.1	1434.8

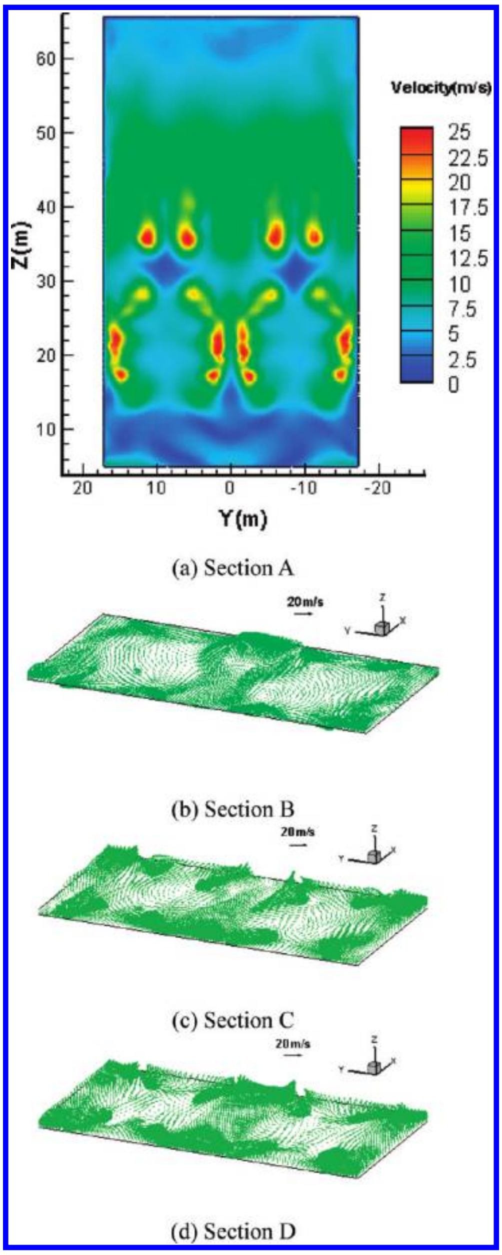

Figure 5. Gas velocity distribution and velocity vectors.

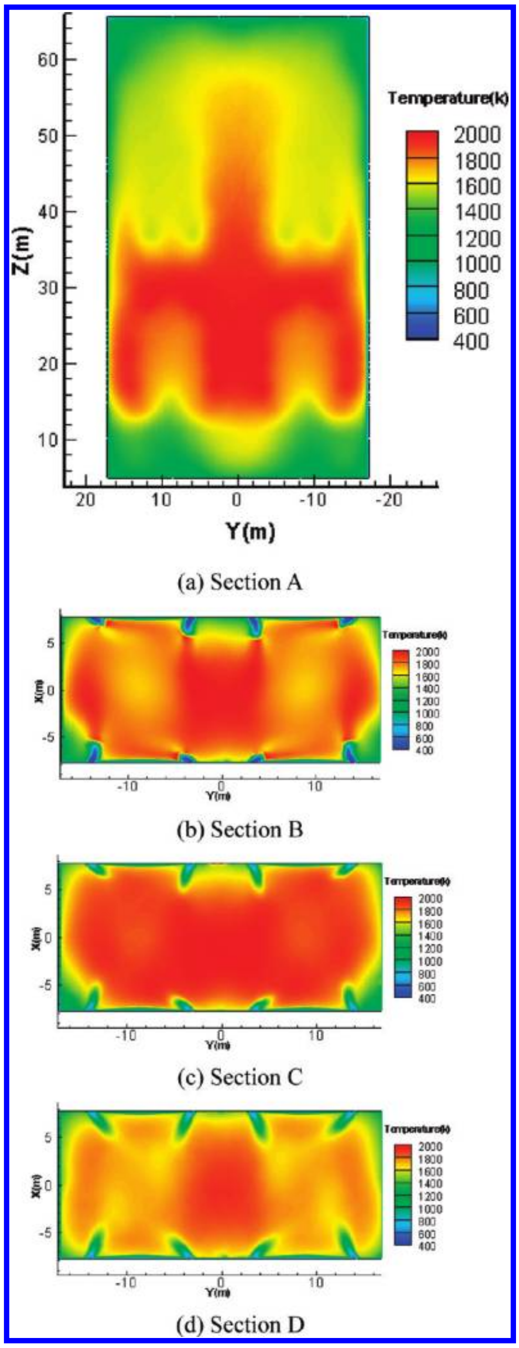

Figure 6. Temperature distributions.

where K_i ($i = \pm1$, 2, and 3) are the reaction rates, and they can be determined according to Hanson et al.[29] Then, the net reaction rate of the NO formation is calculated from

$$\frac{\mathrm{d}[\mathrm{NO}]}{\mathrm{d}t} = K_1[\mathrm{O}][\mathrm{N_2}] + K_2[\mathrm{N}][\mathrm{O_2}] + K_3[\mathrm{N}][\mathrm{OH}] - K_{-1}[\mathrm{NO}][\mathrm{N}] - K_{-2}[\mathrm{NO}][\mathrm{O}] - K_{-3}[\mathrm{NO}][\mathrm{H}] \quad (4)$$

Fuel NO_x is generated because of the nitrogen deriving from the volatile matter and the char in the coal particle. In this work, HCN is assumed to be the only intermediate species in the process of the fuel NO_x formation, and HCN is generated via the volatile matter. HCN can be converted partially to NO, and all char N converted to NO directly.[30] NO can be reduced by a heterogeneous reaction on the char surface, modeled according to Levy et al.[31]

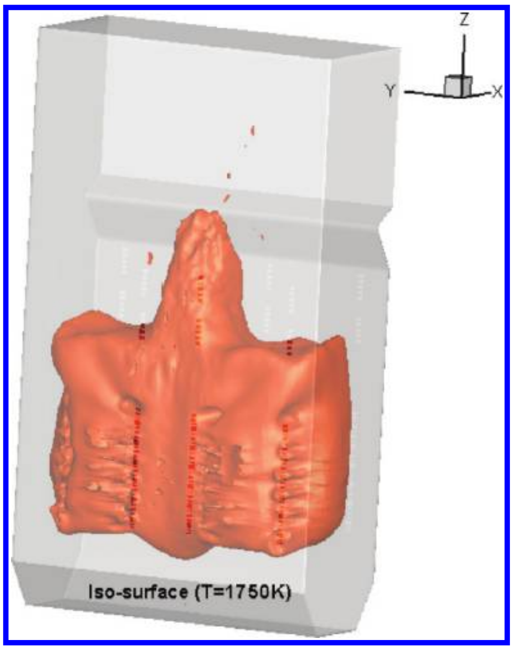

Figure 7. Iso-surface at a temperature of 1750 K.

4. RESULTS AND DISCUSSION

The predicted flow fields, temperature distributions, species distributions, and particle trajectories obtained from the calculation of case 1 will be presented and discussed in sections 4.1−4.3. Then, a comparison of the cases 1−3 in the NO_x emission, burnout rate, and temperature of the furnace will be made in section 4.4, to investigate the influence of the multi-group SOFA nozzle arrangement on the combustion characteristics and NO_x emissions.

Validation of the simulation results with measured NO_x in the 1000 MW pulverized-coal boiler of a power plant is also shown in Table 3. The NO_x emissions and the burnout of case 1 are compared to the measured information from the full-scale boiler. The difference of the NO_x emissions and burnout between the measured and predicted values is 0.88 and 1.05%, respectively. The calculation models of the flow, combustion, and NO_x formation employed in this work are reasonable and acceptable.

4.1. Flow Fields and Velocity Distributions. Figure 5a shows the contours of the gas velocity magnitude along the vertical cross-section of the furnace, while panels b−d of Figure 5 show velocity vector distributions in horizontal cross-sections of B−D. The results indicate that high-velocity regions are close to the burner zone, while the other zone, such as the hopper and the upper region of the boiler, show low-velocity magnitude. As can be seen, the gas flow has high velocity along the burner axis and there are two tangential circles in the flow field. Because of the symmetrical design and the burner arrangement, the double-tangential circular flow field is symmetrical in the cross-sections. The left tangential circle shows clockwise swirling flow, while the right tangential circle shows counterclockwise swirling flow. Recirculating zones appear between each burner and the water walls. These zones produce a favorable effect on the heat transfer from the furnace to the water wall.

4.2. Temperature Distributions. The temperature distributions along the vertical cross-section are shown in Figure 6a.

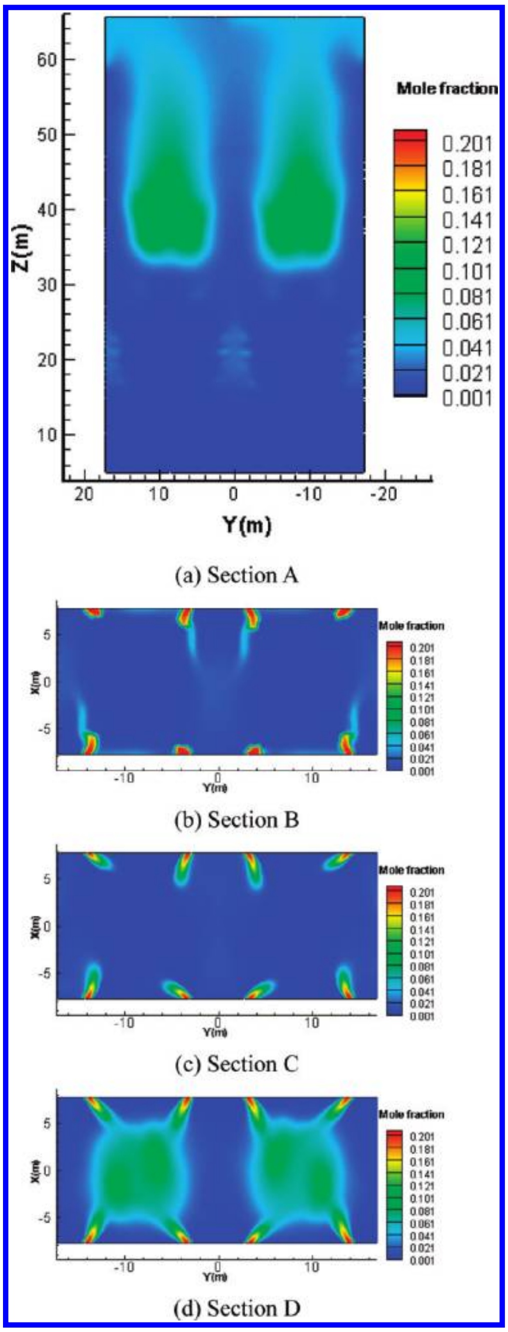

Figure 8. Mole fraction distributions of O_2.

Clear patterns of the temperature change along the height can be seen. The burner zone shows a relatively high temperature because the coal combustion mainly takes place in these regions. The temperature increases from the hopper to the burner zone, but it decreases when the flue gas flows upward in the furnace. Panels b−d of Figure 6 present the temperature distribution in the horizontal cross-sections. From the cross-sections of B−D, the temperature increases. In the cross-section of C, the temperature increases up to the maximum temperature of about 2000 K in the furnace and an outstanding high temperature distribution is obtained. However, with the increase of the furnace height, the temperature begins to decrease, because of the coal burnout and heat transfer by radiation and convection between the flue gas and water walls. Figure 7 shows the iso-surface at a temperature

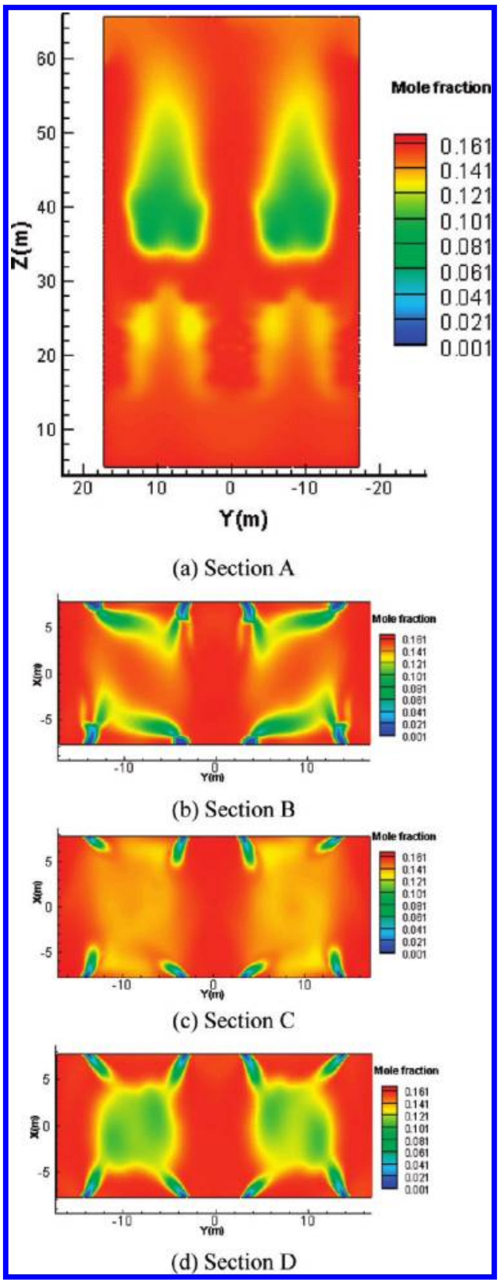

Figure 9. Mole fraction distributions of CO_2.

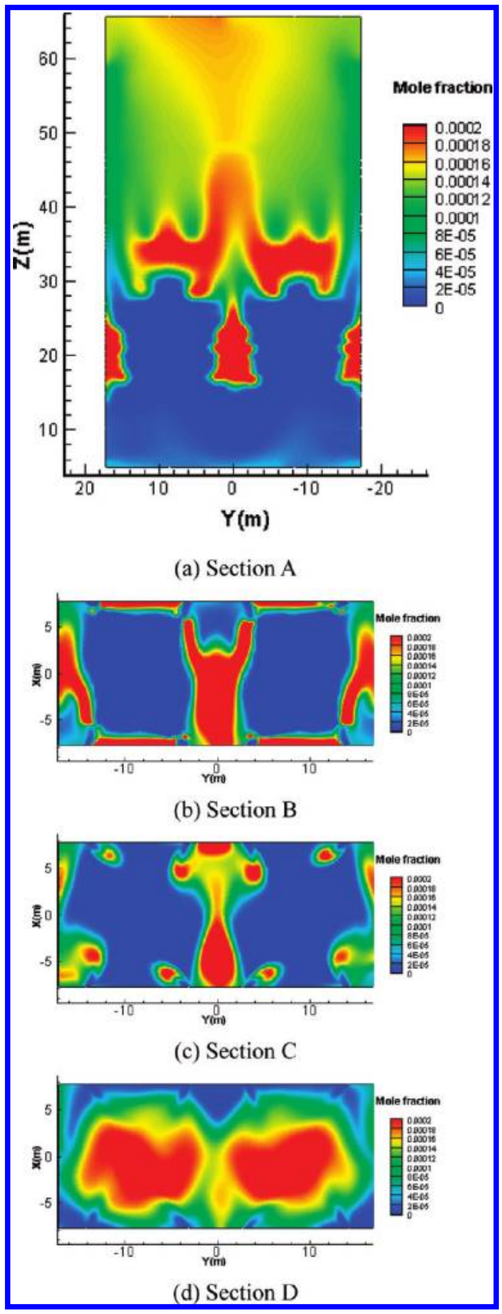

Figure 10. Mole fraction distributions of NO_x.

of 1750 K, and we can clearly see the dual-circle tangential firing in the furnace and the high temperature distributions at the burner zone and central furnace.

4.3. Species Concentrations. Figures 8 and 9 depict the mole fraction distribution of O_2 and CO_2, respectively. There are two peaks of the O_2 concentration in the vertical cross-section A. In sections B and C, the O_2 concentration near the burner outlet is relatively higher but decreases rapidly in the central furnace because it is consumed during the coal combustion. The CO_2 concentration is relatively low in the central zone with the fuel-rich atmosphere. However, with the process of the coal combustion and the SOFA injected, the O_2 concentration becomes higher and the CO_2 concentration decreases significantly in the furnace center. Therefore, in the cross-section of D, the O_2 concentration is higher and the CO_2 concentration becomes lower than in the cross-sections of B and C. The NO_x concentration contour is shown in Figure 10. The NO_x concentration in cross-section A is similar to the distribution of the temperature. The zone with a high temperature appears with a high NO_x concentration. In sections B and C, the two tangential circle centers show a very low NO_x concentration, while in section D, high NO_x concentration distributions appear in the central furnace.

4.4. Comparison between Different Cases. Figure 11 shows the temperature distribution in the horizontal cross-section along the furnace height for cases 1−3. In the burner zone, the temperature distributions of both of the three cases are similar because of the same operating parameters. The furnace temperature increases up to the maximum temperature of 1830 K at the height

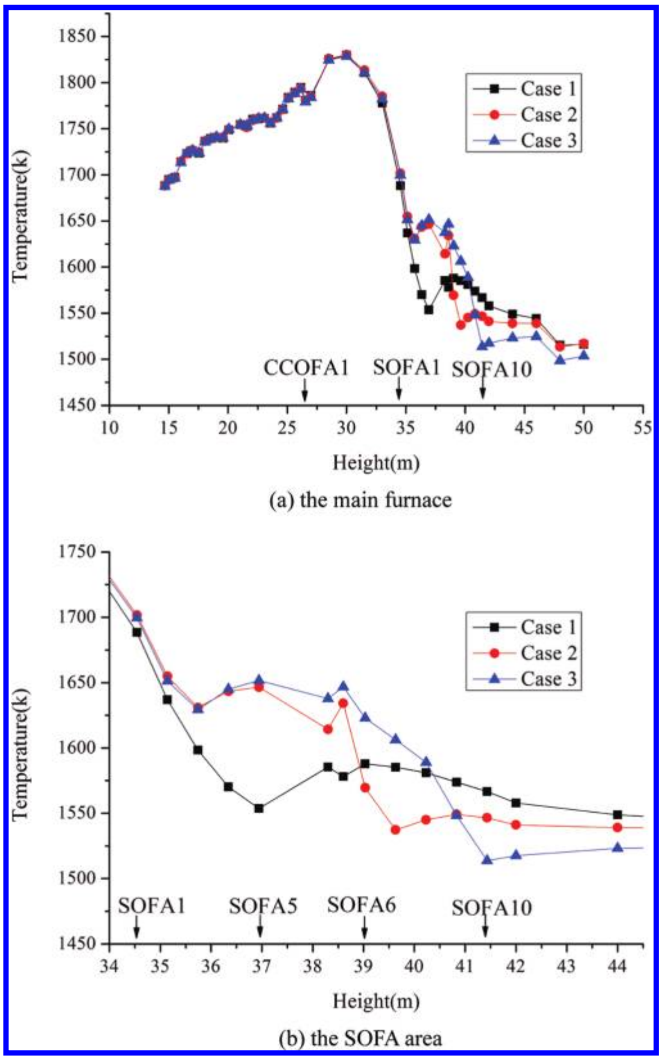

Figure 11. Average temperature in each horizontal cross-section along the furnace height for three cases.

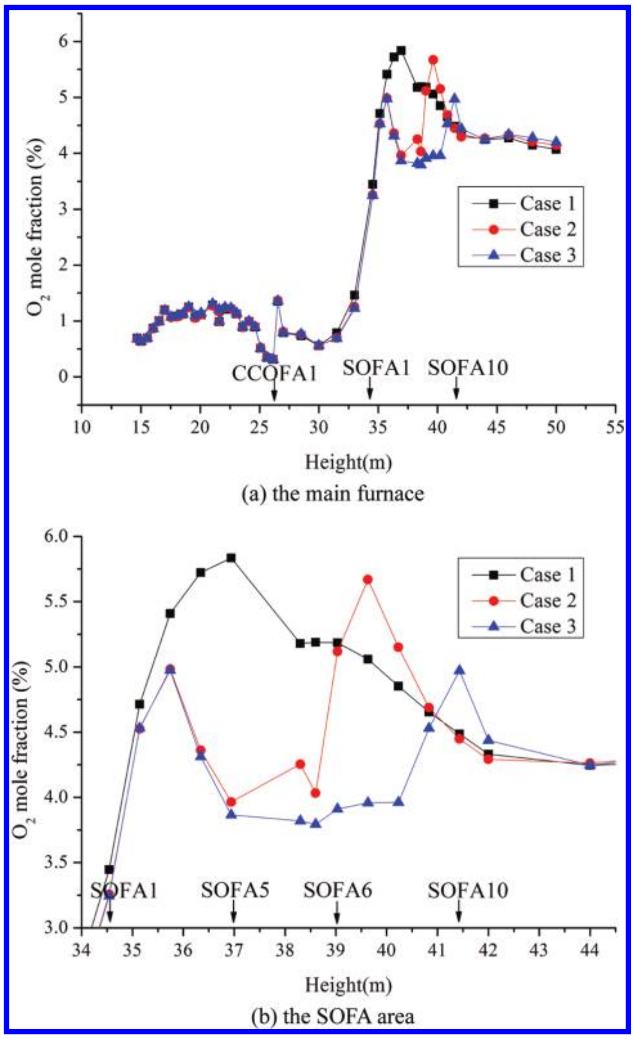

Figure 12. Average O_2 concentration in each horizontal cross-section along the furnace height for three cases.

of 30 m. When the height increases to the SOFA zone, the furnace temperature begins to decrease rapidly. For different cases, the temperature decreases at different rates. In case 1, the temperature decreases rapidly from the height of 30 to 37 m, because the SOFA is injected intensively at one group of the SOFA nozzles. However, in cases 2 and 3, the SOFA is divided into two groups. As a result, the temperature decreases strategically. After the first group of the SOFA being injected into the furnace, the coal particle burned out further, resulting in the furnace temperature increasing again. In case 3, the second group of the SOFA nozzles being in service is arranged at a different height. The change of the furnace temperature is more active than case 2 after the second group of SOFA is injected into the furnace.

Figure 12 shows the mean O_2 mole fraction distribution along the furnace height. The O_2 concentration is very low at the primary combustion zone, with the fuel-rich atmosphere. When the furnace height increases to the SOFA zone, the O_2 concentration increases rapidly, as a result of the SOFA injected into the furnace. For case 1, the O_2 concentration increases up to the peak value of 5.6%, resulting from the SOFA being injected into the furnace intensively. However, for cases 2 and 3, there are two peaks as the O_2 concentration increased, because there are two groups of the SOFA nozzles being in service. At the same time, these O_2 concentration peaks of the cases 2 and 3 are smaller than the O_2 concentration peak in case 1. Because coal particles burn out further, O_2 is consumed and the O_2 concentration decreases with the increase of the furnace height. However, the O_2 concentrations at the furnace outlet are almost the same for the three cases.

The mean NO_x mole fraction in various horizontal cross-sections along the furnace height for cases 1−3 is shown in Figure 13. As can be seen, the NO_x concentrations at the burner zone of the three cases are almost the same and the NO_x concentration is less than 90 ppm, because the burner zone is the fuel-rich region. Because of the SOFA being injected into the furnace and the higher O_2 concentration, char nitrogen and the intermediate species are oxidized to converse to NO_x. Then, the NO_x concentration increases rapidly. For case 1, the SOFA is injected at one group of the SOFA nozzles, the O_2 concentration increases up to a high level, and then the NO_x concentration increases greatly. For cases 2 and 3, because of the multi-group SOFA arrangement, the O_2 concentration increases strategically and, after the second group of the SOFA is injected, the NO_x concentration increases to lower levels. With the increasing

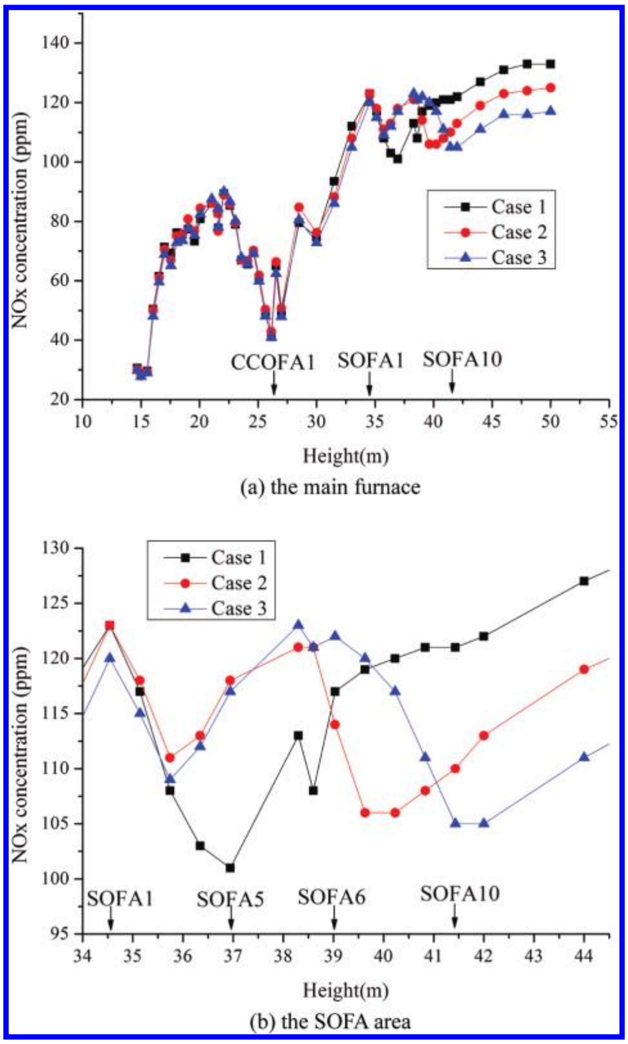

Figure 13. Average NO_x concentration in each horizontal cross-section along the furnace height for three cases.

height of the furnace, the coal particle burned out further and the O_2 concentration decreases, while the NO_x concentration was kept at a certain level. The results show that the low O_2 concentration can restrain the formation of NO_x in the furnace. The arrangement of the multi-group of SOFA nozzles produces a favorable effect on the NO_x control.

To investigate the degree of carbon burnout, which is an important operating characteristic of full-scale pulverized-coal combustion systems, the burnout of the coal particle is calculated. Figure 14 shows the burnout of the coal particle along the furnace height for the three cases. The burnout increases along the furnace height. In the SOFA region, the burnout increases rapidly, because the coal combustion was carried out further. For case 1, the SOFA is injected into the furnace intensively; therefore, the coal combustion will be carried out further at the SOFA region. In addition, the char combustion showed high conversion, and the burnout is outstanding. In cases 2 and 3, because of the multi-group SOFA arrangement and the O_2 concentration increasing strategically in the SOFA region, the char burnout is a little smaller than that of case 1. The burnout increases with the increase of the furnace height.

Table 3 shows the O_2 mole fraction, NO_x emission, burnout, and average temperature at the outlet of the furnace. The average

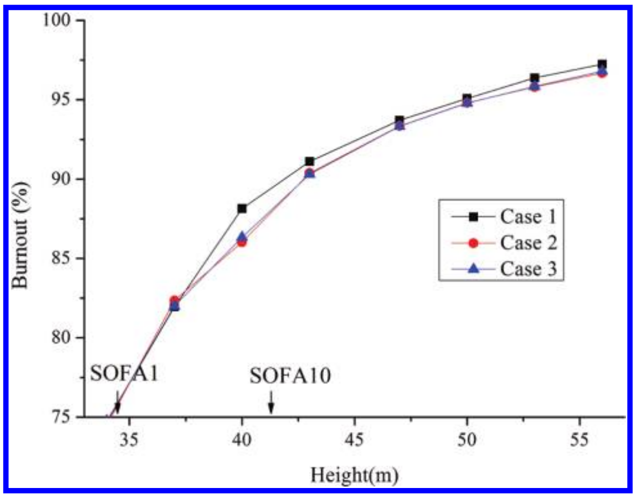

Figure 14. Burnout along the furnace height for three cases.

outlet temperatures are 1426.8, 1432.1, and 1434.8 K for cases 1−3, respectively. The burnout is 98.82, 98.57, and 98.56% for cases 1−3, respectively. The various SOFA arrangements have a few effects on the average outlet temperature and burnout. The burnout in cases 2 and 3 is a little lower than case 1. However, the NO_x information showed a large difference between the three cases. The NO_x concentrations are 269.6, 229.9, and 214.4 mg N^{-1} m^{-3} (6% O_2) at the outlet for cases 1−3, respectively. For cases 2 and 3, with two groups of SOFA nozzles, the NO_x concentration is lower than that of case 1. The NO_x emission of case 3 is lower than that of case 2, because the second group of the SOFA nozzles locate at a higher elevation in case 3. The NO_x emissions in the boiler are reduced by 14.7 and 20.5% in cases 2 and 3, respectively. These results show that the multi-group SOFA nozzle arrangement produces an advantageous influence on the NO_x control and reduction and has few unfavorable effects on the combustion characteristics.

5. CONCLUSION

The gas flow, species concentration, temperature distribution, NO_x emissions, and char burnout are simulated in a 1000 MW tangentially coal-fired boiler. The predicted results are validated by comparing to the measurements from the full-scale boiler. In this work, the influence of the SOFA on the char burnout and NO_x emissions is numerically investigated. Three cases with different SOFA arrangements are carried out, and the optical case is obtained.

The results show that the O_2 concentrations and furnace temperature have a remarkable effect on the NO_x formation. The O_2 concentrations will increase rapidly up to a maximum level under the condition of the SOFA being injected into the furnace intensively, and then NO_x will be formed quickly. With the arrangement of multi-group SOFA nozzles, the O_2 concentrations increase strategically and the NO_x formation can be restrained. The arrangement of multi-group SOFA nozzles provides an efficient way to reduce the NO_x emissions in the coal-fired burner. The technology of air-staging combustion presented in this work promotes the full understanding of the NO_x formation characteristics and is helpful for the NO_x control and reduction in pulverized-coal boilers.

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NOMENCLATURE

CFD = computational fluid dynamics
PDF = probability density function
USC = ultra-supercritical
PA = primary air
SA = secondary air
OFA = over fire air
SOFA = separated over fire air
CCOFA = close coupled over fire air

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