Effect of slot wall jet on combustion process in a 660 MW opposed wall fired pulverized coal boiler

Yong Zhang*[1,3], Yao Fang[1], Baosheng Jin[1], Youwei Zhang[2], Chunlei Zhou[2], FarooqSher[3]

[1]*Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing, 210096, China*

[2]*Jiangsu Frontier Electric Technology Co., Ltd, Nanjing, 211100, China*

[3]*Department of Chemical and Environmental Engineering, Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, UK*

Abstract

Numerical investigations of an anti-corrosion design and the combustion process (original conditions and optimal conditions) were conducted for a 660 MW opposed wall fired boiler. In order to solve high-temperature corrosion of the side wall, a scheme is proposed: slotting in the side wall and introducing air (closing-to-wall air) from the secondary air. The effect of anti-corrosion was disclosed in detail by varying the structures of slotting, gas velocities from nozzles and jet inclination angles. The temperature and NOx distribution in the furnace at optimized conditions were compared with those at the original operating conditions. Simulation results showed that the structures of the slot and gas velocities from the nozzles have a marked effect on anti-corrosion of the side wall. When the gas velocity was 4 m/s, an inclination angle of the gas velocity was not conducive to anti-corrosion of the side wall. When

*Corresponding author. Tel.: +86-25-83794744; Fax: +86-25-83795508.
E-mail address: zyong@seu.edu.cn (Y. Zhang). Farooq.Sher@Coventry.ac.uk (F. Sher).

the gas velocity increases at the middle and bottom of the side wall, the anti-corrosion effect increases significantly. When the optimal scheme is adopted, the corrosion area of the side wall decreases obviously, but the furnace temperature and the NOx emission increase slightly. The detailed results of this work promote a full understanding of closing-to-wall air and could help to reduce the corrosive area in pulverized-coal furnaces or boilers.

Keywords: Coal combustion, Pulverized coal boiler, High-temperature corrosion, Slotting, Closing-to-wall air and NOx emissions.

1 Introduction

At present, China relies on coal to meet 70% of its total energy needs and the coal production as a major energy resource in China is expected to increase in the near future. However, the use of a large number of coal-fired resources will exacerbate the air pollution (Mohr and Evans 2009) (Li, Zhuang et al. 2012) (Klein, Andren et al. 1975). As the aggravation of environment, the standard of NOx emission is becoming more and more rigorous. The government and organizations responsible for environmental protection have established stringent regulations and legislation for controlling NOx emissions from pulverized-coal furnaces (Zhou, Yang et al. 2014). The available methods of reducing the NOx emission in pulverized coal boilers are mainly low-NOx combustion technology and tail gas treatment. Selective catalytic reduction (SCR) (Wang, Zheng et al. 2017) and selective non-catalytic reduction (SNCR) (Qiong, Yuxin et al. 2013) of the tail gas treatment are very effective methods for controlling the discharged NOx, but these methods are costly and uneconomical. The suitable low NOx combustion technology could frequently control NOx emissions more economically (Ti, Chen et al. 2016), however, the application of low NOx combustion technology causes high-temperature corrosion issues in the furnaces and boilers (Zhang 2011) (Liang, Lei et al. 2009).

At present, water wall tube's high-temperature corrosion is increasingly prominent in large-scale utility boilers, which has seriously affected the safe and economic operation of the boilers. According to a statistics, high-temperature corrosion has been found in more than 80% large-scale power plant boilers in China and resulted in enormous loss (Xiu-Qing and Zeng 2001) (Zhou, Pei et al. 2015) (Jiang, Liu et al. 2014). Therefore, it is one of the most urgent problems to be resolved in the field of heat and power generation to reduce the corrosion and NOx emission simultaneously. Previous research showed that the near wall reducing atmosphere is considered to be the important cause of high-temperature corrosion in boilers (Zhou, Pei et al. 2015) (Han, Chun-Mei et al. 2004). There are several methods to resolve the high corrosion of water wall problem among them: the closing-to-wall air technology is in engineering practice due to its simple and reliable advantages (Wu, Zhuang et al. 2005). The closing-to-wall air can increase the local O_2 concentration in the high-temperature corrosion zone. It fundamentally destroys the reducing atmosphere required for the occurrence of corrosion reactions. The reduction of reducing atmosphere improves the high-temperature corrosion effectively. When the O_2 concentration is greater than 2%, it is not producing high-temperature corrosion (Zhou, Pei et al. 2015). In addition, when the proportion of the air volume rate to the total airflow is less than 5%, it has a negligible effect on the ignition of pulverized coal and the combustion stability (Zhou, Pei et al. 2015) (Lu, Chen et al. 2015) (Chen, Lu et al. 2015).

Many researchers have proposed different methods to solve the problem of high-temperature corrosion of water wall. (Zhang Zhixiang, Cheng Dingnan et al. 2011) proposed a new type of wall attachment device for preventing the high-temperature corrosion of the tangentially fired boiler's water walls. The wall air is ejected along the axial direction of the water wall. The results revealed that the utility device has the advantages of good effect, obvious reduction in the amount of the closing-to-wall air and the reduction of the nozzle temperature. (Qiu Jihua, Liming et al. 1999) attained combustion process of a 300 MW front and rear wall opposed coal-fired boiler by computer numerical simulation under different working conditions. The results showed that the temperature drop near the water wall is not obvious with the change in the position of the closing-to-wall air on the front and rear wall. While on the side wall, the high-temperature corrosion of water wall can be effectively reduced. During solving a problem of high temperature corrosion of the water wall of the side wall in a 660 MW front and rear wall opposed coal-fired boiler. (Chen, Lu et al. 2015) found that it can achieve good effect of oxygen supplementation in the area around the nozzles along the furnace depth direction by using less vertical closing-to-wall air. But with the diffusion range of closing-to-wall along the high direction of the furnace wall is limited, resulting in a considerable part of the high temperature corrosion area cannot get O_2 supply. (Yang, You et al. 2017) found that the concentration of CO and H_2S near the side wall was significantly reduced and the reducing atmosphere on the side wall was reduced by 40% by the injection of near-wall air.

Some researchers have concluded that the closing-to-wall air can improve the anti-corrosion situation of the furnace, but there is no detailed study on how the closing-to-wall air affects the combustion behaviour in the furnace from the perspective of jet and mixing. In the present study, the mixing mechanism of closing-to-wall air entering the furnace is analyzed emphatically from the jet and mixing perspective. An in-depth analysis is made on how to improve the corrosion resistance of the furnace by closing-to-wall air. The study provides a detailed reference for the mechanism of closing-to-wall air to improve the anti-corrosion. Furthermore, structure arrangements, gas velocities from nozzles and jet inclination angles are simulated under different conditions. The combustion process (original and optimal conditions) of the furnace is also simulated and analyzed in detail. Previous studies have shown that the high temperature corrosion is mainly caused by the reducing atmosphere near the side wall, while the distribution of O_2 concentration is contrary to that of CO and H_2S. The corrosive area ratio (the area of O_2 concentration less than 2% accounted for the percentage of total corrosion area) is an indicator of the effectiveness of the corrosion protection is also discussed. Based on the analysis of these different conditions, the anti-corrosion performance of the side wall is explained in depth.

2 Materials and experimental methods

2.1 Materials

The coal quality analysis is shown in

Table **1**. The sulfur content of the coal used in the boiler is very high. Higher the sulfur content of the coal used in boiler, the more serious is the boiler corrosion. The value of pulverized coal fineness is R90 = 16%. The particle size has a Rosin-Rammer (R-R) distribution (He, Qi et al. 2015) ranging from 10 to 200 μm with an average particle size of 51.5 μm.

Table 1. Ultimate and proximate analysis of the coal.

Ultimate analysis wt% (as received)					**Proximate analysis** wt% (as received)			**Net heating** value (MJ/kg)
Carbon	Hydrogen	Oxygen	Nitrogen	Surfer	Moisture	Ash	Volatile matter	
47.60	2.84	1.69	0.65	4.51	7.67	35.04	28.70	18.52

2.2 Boiler configurations and operating conditions

Fig. 1 shows the schematic configuration of the 660 MW opposed wall fired pulverized coal boiler with swirl burners. It is a supercritical once-through boiler. The boiler investigated in this study includes a hopper, burner zone, over fire air (OFA), side over fire air (SOFA) and outlet. The total height of the boiler is 66 m. The height of the hopper is 10.5 m, while the height of the other part of the boiler is 55.5 m. The cross-section of the boiler is a rectangle with a width of 22.2 m and a depth is 15.5 m. The boiler adopts the rich/lean burner and the distribution of the burner is divided into primary air, secondary air and central air, of which secondary air is a swirling flow.

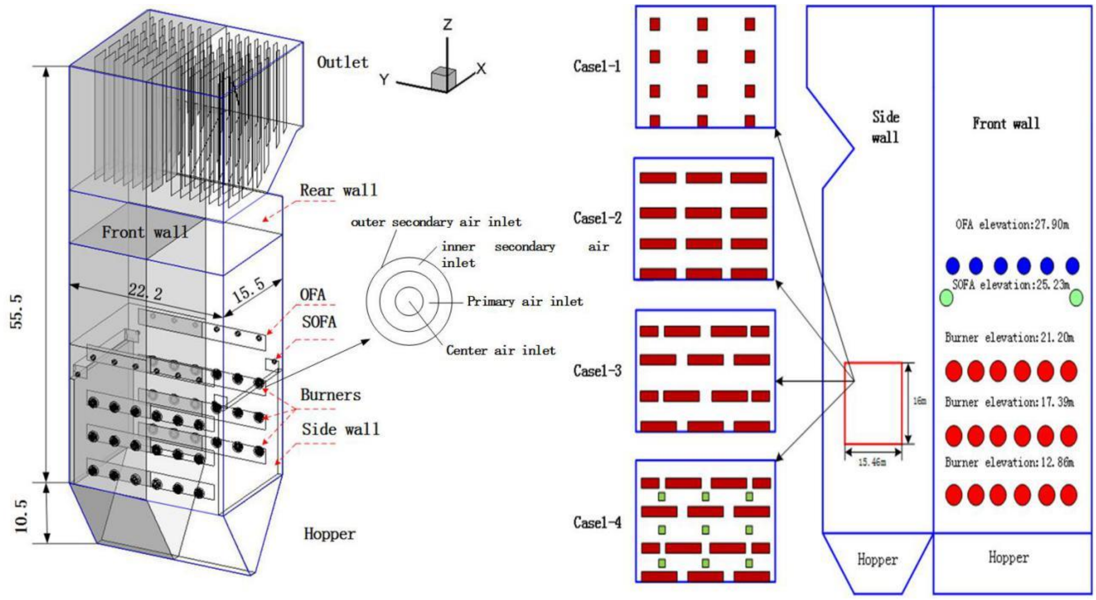


Fig. 1. The schematic configurations of 660 MW pulverized coal boiler along with the arrangements for slotting on the side wall.

There are 36 burners in total, 18 burners at the front wall, while the other 18 burners at the rear wall. The burner nozzles' distribution is at three levels of the furnace height. Under the operation of design conditions, only 30 burners are put into use. The burners at the top of the rear wall are out of service. Four SOFA nozzles are located above the burner zone. The top nozzles of the furnace are OFA ports. The original operating conditions of 660 MWe pulverized coal boiler at the power plant are given in Table 2.

Table 2. The original operation data of 660 MWe pulverized coal boiler.

Electrical power block (MWe)	660
Total coal feed rate (kg/s)	85.62
Primary air velocity (m/s)	18.93
Primary air temperature (K)	368
Center air velocity (m/s)	15.20
Center air temperature (K)	573
Inner secondary air velocity (m/s)	8.60
Outer secondary air velocity (m/s)	5.61
Secondary air temperature (K)	573
OFA velocity (m/s)	54.80
OFA temperature (K)	573
SOFA velocity (m/s)	56.87
SOFA temperature (K)	573
Total ratio of OFA and SOFA（%）	25

The closing-to-wall air comes from OFA and SOFA, and the proportion of the closing-to-wall air is controlled below 5% of the total air volume. After the initial trial calculations, it is determined that the numbers of layers of the slots are mainly four and finally the optimization is carried out on the base of the four layers. Fig. 1 also represents the arrangements of slotting on the side wall. In simulation, the data on the side wall is taken from a plane 150 mm away from the side wall and the plane was defined as the near side wall plane. Overall, there are four different structures. The slot of each working condition is evenly arranged and four cases with different arrangements are first numerically studied, then the optimal condition is chosen from these four structures to study the anticorrosion under different operating conditions. The required slotting area is determined according to the size of the corrosion zone, the calculated parameters with different structures and slot arrangements are given in Table 3.

Table 3. The calculated parameters with different structures and slot arrangements.

Structure parameters	Case 1-1	Case 1-2	Case 1-3	Case 1-4
L (mm)	670	4500	4500/2500	4500/2500
H (mm)	670	100	100	80
W (mm)	4430	600	600/300	600/300
S (mm)	3330	3900	3900	1810
D (mm)	2293	378	378	378
N	4	4	4	8

Where L and H represent the length and height of each slot respectively. W represents the horizontal distance between two slots. S represents the distance between the two slots in the vertical direction. D stands for the horizontal distance between the outermost slot and the wall. N represents layers of slots. If the volume of closing-to-wall air is not exceeding 5% of the total air volume, it will not have a bad effect on the burning of pulverized coal and the steady combustion in the boiler (Chen, Lu et al. 2015). Therefore, the volume of closing-to-wall air should not exceed 5% under different conditions of gas velocity from nozzles. Based on the above consideration, the side wall closing-to-wall air is chosen and four kinds of working conditions are simulated. The specific calculated parameters with different gas velocities are given in Table 4.

Table 4. Calculated parameters with different gas velocities.

Parameters	Case 2-1	Case 2-2	Case 2-3	Case 2-4	Case 2-5
Velocity (m/s)	1	2	3	4	5
Jet flux ratio (%)	1.00	2.10	3.13	4.18	5.22
Air temperature (K)	573	573	573	573	573

(Min, Li et al. 2014) investigated the effect of over fire air angles on flow characteristics within a small-scale model. The results show that an optimal setting of 40° was found for the OFA angle. Considering an effect of the angle of the gas jet on the mixing, five different operating conditions ranging from 0° to 80° are studied. The specific calculated parameters with different jet inclination angle are presented in Table 5.

Table 5. Calculated parameters with the different jet inclination angles.

Parameters	Case 3-1	Case 3-2	Case 3-3	Case 3-4	Case 3-5
Jet inclination angle (°)	0	20	40	60	80
Velocity (m/s)	4	4	4	4	4

Based on the results of gas velocity and inclination angle conditions, three different combinations are studied and finally, an optimal condition is obtained. The specific combinations of calculated parameters with different gas velocities and inclination angles are given in Table 6. The setting of original boundary conditions is listed in Table 2 according to the actual operation data of the boiler. The gas velocity of the side wall nozzle is determined according to the simulated working conditions in tables. The turbulence specification method is intensity and hydraulic diameter.

Table 6. The combinations of calculated parameters with different gas velocities and inclination angles.

Parameters	Case A	Case B	Case C	Arrangements	
	6	6	6 /30°	1	
	6	6	6	2	Slots
Velocity (m/s)	5	5 /6	5 /6	3	
	5	4 /5.5	4 /5.5	4	
	2 /1	2 /1	2 /1	Square nozzles	
Air volume rate (%)	4.9	4.9	4.9		

2.3 Description of numerical models

The numerical simulations are conducted on the basis of a computational fluid dynamics (CFD) coding. According to specific characteristics of the front and rear walls of the coal-fired boiler, a three-dimensional mathematical model is established to simulate the combustion process in the boiler. The area calculations of the boiler include ash hopper, furnace (Including swirling burner, OFA, SOFA) and tail flue. The simulation of swirling burner is performed by separate calculations due to its complex structure. After the flow field calculations, the results of swirling burner are taken as boundary conditions of the combustion process. Due to complex structural characteristics and flow symmetry of the boiler and in order to divide the grid more precisely half of the pulverized boiler structure was selected as the numerical simulation object. The method of drawing mesh in different domains is used to reduce the pseudo diffusion. It specifically shows that proper encryption of the mesh in the swirl burner and furnace burner region. After meshing, the independence of the grid is analyzed, and the total number of grids in the coal-fired boiler is about 4 million.

The combustion in pulverized coal boiler is a complex physical and chemical process involving chemical reactions, multiphase flows, heat and mass transfer operations. The corresponding governing equations of CFD are continuity equation, momentum conservation equation and energy conservation equation. Based on the computational fluid dynamics platform and using gas-solid two-phase flow model (Euler-Lagrange method) (A. Kohli and D. G. Bogard 1997) (Belosevic, Srdjan et al. 2012), the flow field of the entire boiler is numerically calculated. The combustion and heat transfer process in the furnace is numerically calculated using combustion heat transfer module of the fluent. Realizable K- epsilon model (Zhou, Mo et al. 2011) is used to simulate the turbulence in the boiler, it can accurately predict the diffusion of circular jet-flow, rotational flow and secondary flow. For the combustion of the gas phase, non-premixed combustion model is used because this model allows the prediction of intermediate component, dissolving effect and rigorous turbulence chemical coupling.

For solid phase, the movement of pulverized coal particles in the furnace is a gas-solid two-phase flow with a chemical in a turbulent flow. The volume fraction of pulverized coal particles is very small (<10%) relative to the continuous phase, hence, discrete phase model is used to calculate the motion of particles. The coal particles are considered as discrete particles, which track the trajectories of pulverized coal particles and calculates the heat and mass transfer caused by pulverized coal. The process of pulverized coal combustion can be defined as the precipitation of volatiles and the combustion of coke. Both of the processes are carried out at the same time and could affect each other. Dual-competitive reaction model is used to simulate the precipitation of pulverized coal volatiles in this study.

The burning of coke is a complex process. It is assumed that the reaction rate of coke is affected by the rate of oxygen diffusion to the surface of coke and the reaction rate of coke surface at the same time. Therefore, the kinetic/ diffusion control rate response model is adopted. Because of the high temperature in the furnace, radiation heat transfer is also considered. The p-1 model (Hu, Liu et al. 2013) was taken as it is relatively simple and widely used in the radiation heat transfer in the furnace. In the simulation, the velocity inlet and pressure outlet are taken as boundary conditions. Overall three-dimensional steady state calculations are adopted. The standard wall function is used to deal with the near wall turbulent flow in swirl combustion, the finite-difference methods are used to solve the differential equations, the simple algorithm and the first-order upwind format are used to solve the governing equations (Hu, Liu et al. 2013). The post-processing method is used for the prediction of NOx concentration, and later on, the generation law of nitrogen oxides is applied. A CFD work is completed in three stages: pre-processing, solver and post-processing. The gambit is used in pre-processing. The fluent 6.3.26 is applied to solve all conservation equations. The numerical solution post-processing is gathered with the tecplot 360 2010 and origin 2015. Every condition requires an iteration of 30000 steps to converge.

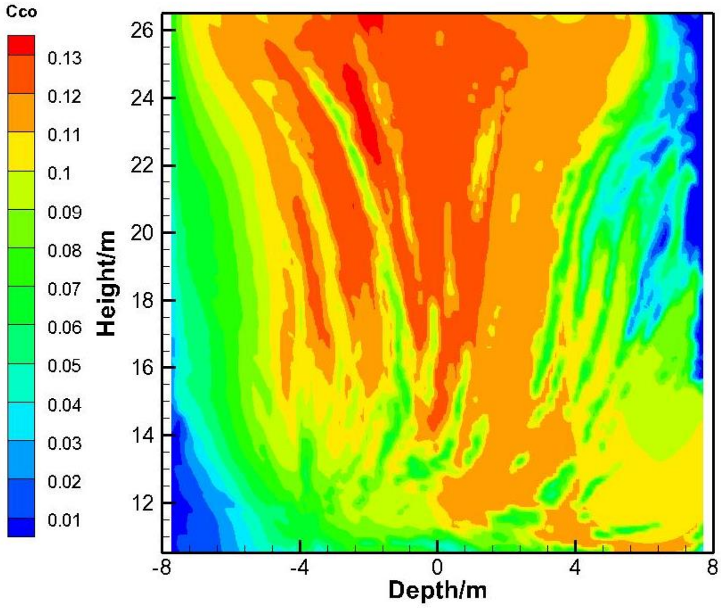
3 Results and discussion

3.1 Validation of the model

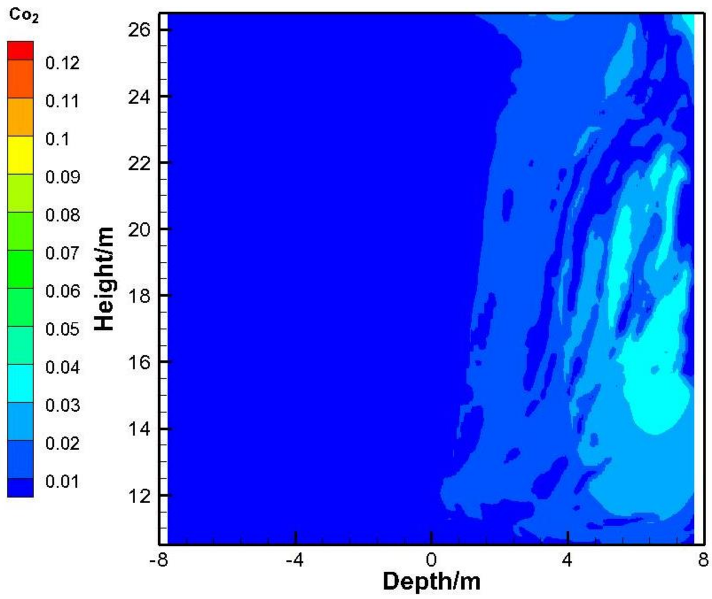
To validate the methodologies used in this study, the CFD simulation results are compared with experimental data of actual operation (Lu, Chen et al. 2015). The boiler modelling, meshing and model selection is based on the actual situation. Therefore, if the simulation and calculation methods are correct， the simulation results should be consistent with the experimental data of actual operation. The comparison of results is listed in Table 7.

Table 7. Comparison of average parameters of furnace outlet temperature and O_2 concentration (Lu, Chen et al. 2015).

Parameters	Predictions	Original condition	Relative errors
Furnace outlet temperature (K)	1358	1317	3.11%
Furnace O_2 concentration（%）	2.55	3.00	15.00%



(a) CO concentration distribution



(b) O_2 concentration distribution

Fig. 2. O_2 and CO concentration distribution in the near side wall

The simulated data shows that the average temperature of the furnace outlet section is 1358 K. The average concentration (mole fraction) of oxygen in the furnace outlet section is 2.55%, the actual mean temperature of the furnace outlet is 1317 K and the actual oxygen concentration in the furnace outlet is 3%. It can be seen that the simulation predictions are very close to the actual conditions. And the relative errors are comparatively small. Fig. 2 shows the distribution of CO and O_2 concentration distribution near the side wall. Fig. 2(a) shows a high concentration of CO near the side wall, whereas the distribution of O_2 is the opposite in Fig. 2(b). It is consistent with the corrosion area found in boiler shutdown detection. Then it shows that the simulation methodologies adopted are justified and it can give reliable and accurate predictions for the 660 MW front and rear wall opposed fired boiler.

3.2 Effect of slot structure parameters

Fig. shows the distribution of O_2 concentration in four schemes. It can be clearly seen the change of O_2 concentration in the near side wall. When the rate of closing-to-wall air is same, the O_2 coverage area of case1-1 is the smallest, case1-3 and case1-4 are larger than the others. Comparison of case1-1 and case1-2 in the corrosion zone, the O_2 concentration is relatively high with the narrow slots. This is because the airflow of the narrow slot has a longer coverage area when the flow is in the mainstream. So the coverage performance of O_2 with narrow slots is better than that with square slots in the near side wall.

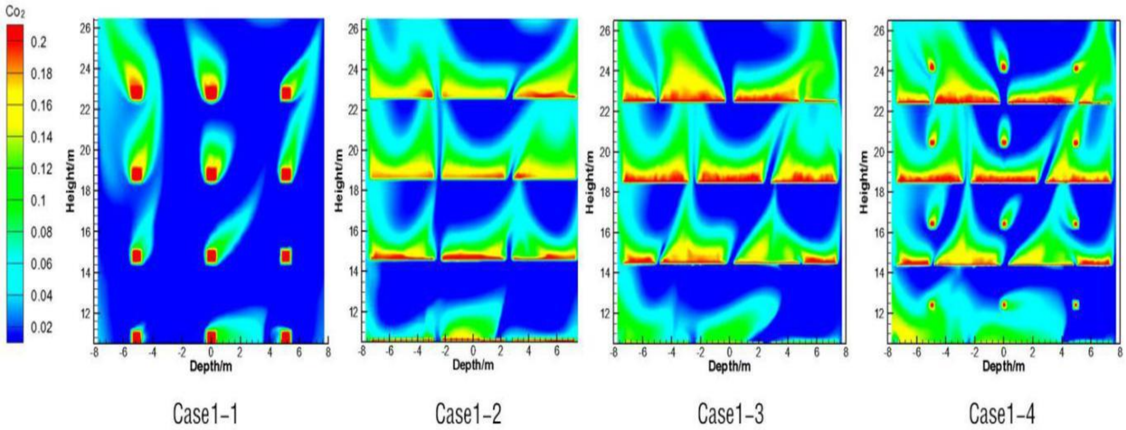


Fig. 3. The O_2 concentration contour of the different structures and arrangements in the near side wall.

Fig. shows the corrosive area ratio (the area of O_2 concentration less than 2% accounted for the percentage of total corrosion area) of in the near side wall under different conditions. It can be clearly seen the changes in the data of the four schemes. In case1-2 and case1-3, the narrow slots are divided into two types. As a result, the distribution of O_2 concentration of the latter is more uniform than the former. This is due to its staggered arrangement. It makes the gap area to get a good airflow cover. Subsequently, a stagger arrangement of slots is better than in aligned arrangement.

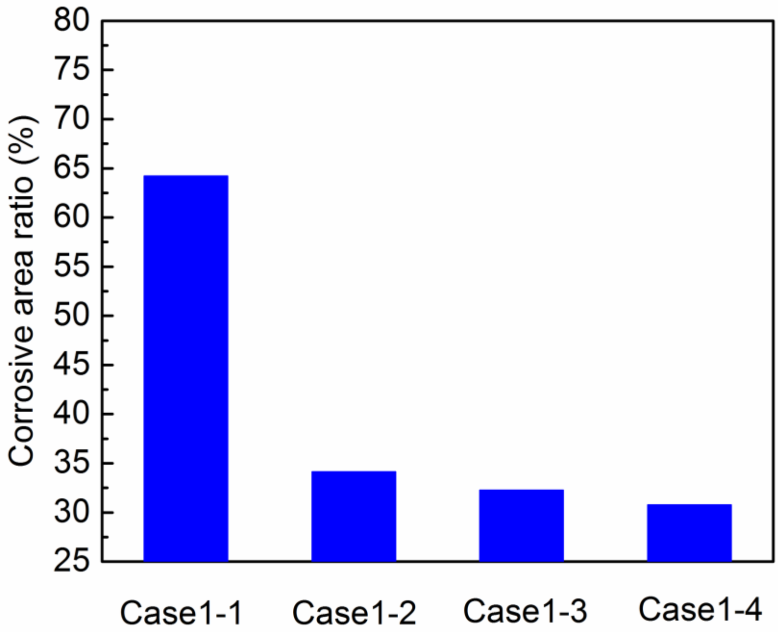


Fig. 4. The corrosive area ratio of the side wall under different conditions.

For case1-4, the mean O_2 concentration increases up to the maximum value, resulting from the closing-to-wall air being injected into the furnace evenly. Comparison of four conditions, arrangement of case1-4 has the best antiseptic effect under the current working conditions. In the latter calculations, slot structures and arrangements are considered as case1-4. Furthermore, the comparison of case1-1 with the others shows that the O_2 coverage in the middle of the corrosion zone is poor than others. Although the overall coverage effect of case1-1 is poor, the coverage of the top of the nozzles is larger than that of other cases. This is because the gas velocity in the middle of the opposed wall firing boiler is larger than the two sides, square slots have more gas flow than other cases. Accordingly, there is still more gas in the near wall area when it is mixed with the mainstream.

3.3 Effect of gas velocity from nozzles

The results of corrosive area ratio and the jet flux ratio of pulverized coal boiler are shown in Fig. . It can be seen that with the increase of velocity, the jet flux ratio of the closing-to-wall air increases linearly. This is due to the fact that other conditions are constant, while the increase in velocity is bound to increase the amount of closing-to-wall air, which increases the proportion of closing-to-wall air in the total air volume.

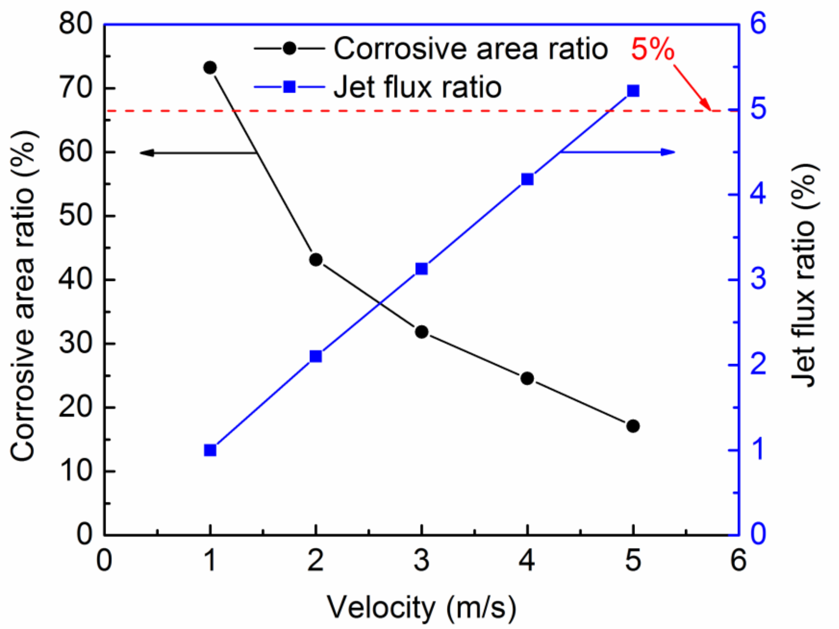


Fig. 5. The corrosive area ratio and jet flux ratio in different cross-sections with the jet velocities.

On the other hand, the corrosive area ratio on the left shows a downward trend in general. This can be interpreted as when closing-to-wall air volume increases, relative to the hot flue gas of the pulverized coal boiler, low-temperature closing-to-wall air reduces the corrosion zone temperature, and a large amount of air is ejected from the side wall. Therefore, the reductive atmosphere near the furnace wall can be improved, and this effect is better with the increase of air flow. When the velocity increases from 1 to 3 m/s, the corrosive area ratio dropped from 73.22 to 31.85%, this reduction of the corrosion area is very clear. When the velocity increases from 3 to 5 m/s, the corrosive area ratio decreases almost linearly, but the decline is slightly slower than that in the front. Consequently, it is very effective and important to select the reasonable gas velocity of closing-to-wall air to reduce the furnace corrosion area. The larger is the gas velocity, the more air enters means more O_2 it will have to destroy the reducing atmosphere required for the occurrence of corrosion reactions. The smaller area of corrosion is caused by reducing atmosphere. However, there are some restrictions on the volume of closing-to-wall air. When the closing-to-wall air velocity is 5 m/s, the required wall air volume is too large to exceed the value as seen at the red dotted line in the Fig. . Therefore, it is observed that the best antiseptic effect can be achieved at the velocity 4 m/s under the current working conditions.

3.4 Effect of jet inclination angle

Fig. shows the variation of O2 concentration in the near side wall under different injection angles. Overall, under the condition of 4.18% jet flux ratio, the trend of corrosive area ratio curve decreases with an increase of jet inclination angle. The results are not the same as the small hole jet and gas film cooling (Liu 2007) (A. Kohli and D. G. Bogard 1997). For the small hole jet, when the direction of the jet is perpendicular to the direction of the mainstream, there is more vigorous interaction and mixing of the jet with flue gas. In this study, the air jet velocity is smaller than the mainstream because of the limitation of the closing-to-wall air volume. The rigidity of the jet is weaker, and when the closing-to-wall air enters it could be easily diluted by the flue gas in the furnace which is not very effective for O_2 coverage on the side wall. However, the jet also has a blocking effect on the mainstream which is effective for O_2 coverage. Secondly, due to the design and layout of the swirling burner, the flow in the opposed wall firing boiler furnace is complex, which is different from the general single direction flow.

The curve in Fig. indicates that as the jet inclination angle increases, the O_2 coverage rate becomes lower, it achieves a worse anti-corrosive effect. This is because that the closing-to-wall air is injected into the furnace from the side wall which has a blocking effect on the mainstream flue gas coming from the lower part. When the air enters into the furnace vertically, it has the largest blocking effect on the mainstream near the side wall. Thus, it is difficult for the mainstream flue gas to reach the side wall, as a result, the reducing atmosphere near the side wall also reduces. Although the jet flow has a certain angle, the interaction between the mainstream and the jet flow is enhanced. The jet flow has a greater blocking effect on the mainstream. So the corrosive area ratio is the least when the jet inclination angle is 0°.

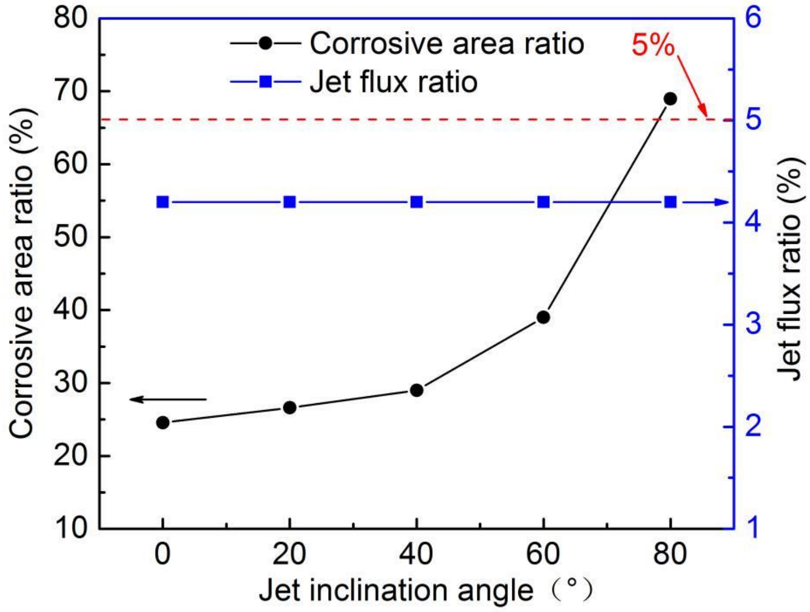


Fig. 6. The corrosive area ratio and jet flux ratio in different cross-sections with the jet inclination angle.

When jet inclination angle increases, the angle between the jet flow and the mainstream becomes smaller. As a result, the ability of the jet flow to block the flow of the mainstream becomes weaker. Moreover, when jet inclination angle exceeds 40°, the corrosive area ratio increases significantly. As the jet inclination angle reaches 80°, the direction of the closing-to-wall air velocity is almost parallel to the direction of the mainstream velocity and the corrosive area ratio is almost 70%. At this moment, the jet has the weakest barrier to the mainstream. The mixing of the jet and the mainstream is also the weakest. But the blocking effect is the main factor in O_2 coverage on the side wall. The reducing atmosphere has not been effectively improved, so the corrosive area ratio is the largest.

3.5 The optimal strategy

Fig. shows the O2 concentration contour of three different conditions in the near side wall when the jet flux ratio is 4.9% (<5%). The O_2 distribution in three cases is almost similar. The O_2 coverage of the case C is the larger than the others, therefore the reducing atmosphere of the case C can improve more effectively than other cases. It can be concluded that the arrangement of the case C is best for anti-corrosion in these three schemes. The difference among them in O_2 distribution is mainly in the middle and bottom of the side wall.

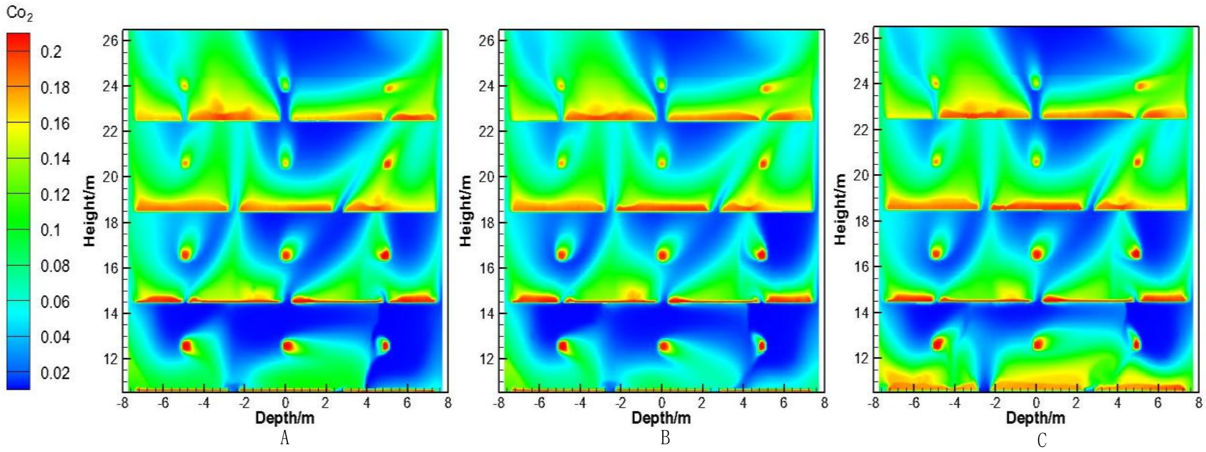


Fig. 7. The O2 concentration contour of three different conditions in the near side wall.

The O_2 concentration near to slots is very high. Then it is quickly reduced through dilution along the furnace height. In a comparison of case A and case B, the O_2 concentration of case B is slightly higher than that of case A in the middle of the side wall. The cause behind this phenomenon is mainly due to the relatively large mainstream velocity in the middle of the side wall. The mainstream velocity in the middle of the side wall is much greater than that on both sides in the opposed wall firing boiler. The decrease in gas jet velocity at both sides of the wall has a few effects on O_2 coverage. Therefore, with an increase of the gas jet velocity in the middle of the side wall, the O_2 coverage performance increases significantly. In a comparison of case B and case C, the most obvious difference is at the bottom of the side wall, O_2 coverage at the bottom of case C is apparently larger than that of case B. The air jet direction at the bottom of the side wall of case C has an inclination of 30°. This arrangement is mainly due to the small amount of flue gas produced at the bottom of the side wall and the smaller mainstream velocity. After that, the air jet flow easily enters the middle of the furnace and is quickly diluted with the mainstream. Therefore, when the air jet flow of the lowest layer has a certain angle of injection, the O_2 concentration of the side wall is greater. The reductive atmosphere is more effectively improved and anti-corrosion performance is far better. Different positions of the side wall require a different arrangement of the air jet, for less flue gas at the bottom, it is necessary to use air jet with a certain inclination angle. This makes the sprayed air more able to stick to the wall. For a large amount of flue gas and higher velocity in the middle of the side wall, a larger air jet velocity is required to improve the reducing atmosphere of the side wall.

3.6 Effect of the closing-to-wall air on combustion and pollutant emission

Fig. shows the average temperature distribution of flue gas in different cross-sections along the furnace height. Drawing a comparison between the original conditions and the optimized conditions, it can be seen that the general trend of the closing-to-wall air's curve is consistent with the original conditions. At the very start, when the original condition is at the height of 10 meters, the average temperature of the furnace is about 1300 K, while the temperature of closing-to-wall air condition is about 1400 K, with the increase of furnace height, the fuel was correspondingly increased. The combustion became more and more intense. Therefore, the temperature keeps going up. When the original condition is at the height of 20 meters, the average temperature of the furnace is about 1600 K, while the temperature of closing-to-wall air condition is about 1700 K.

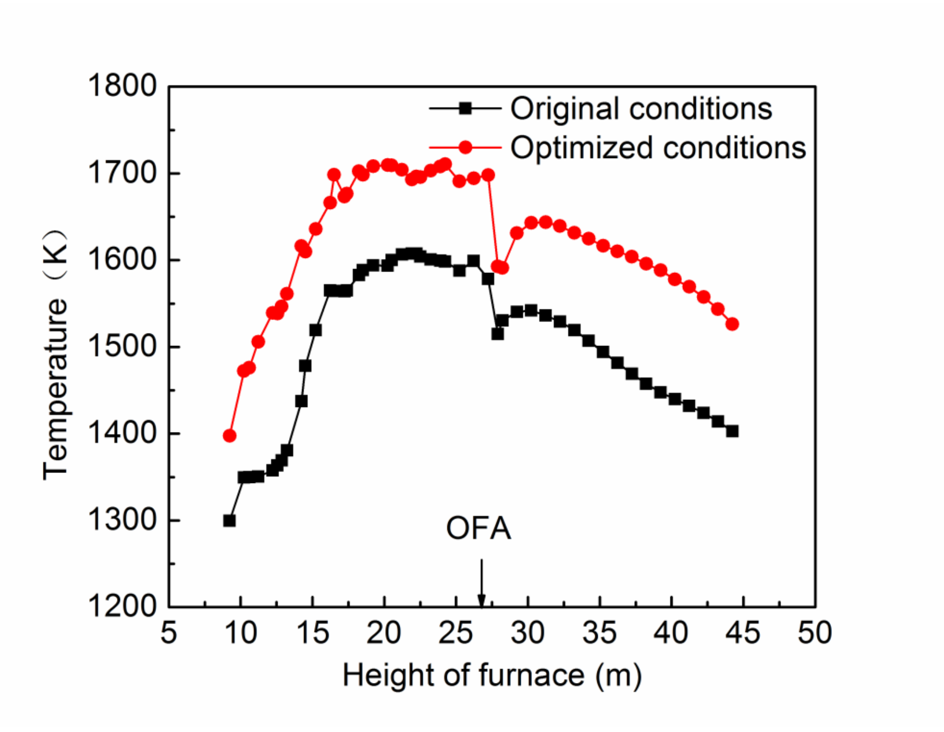


Fig. 8. The average temperature distribution along the furnace height.

When the furnace height is higher than the top burner, the fuel quantity is no longer changing, and the combustion is in a relatively stable period. The temperature of the two conditions remained relatively stable. However, when it reaches the OFA nozzle, the temperature of the furnace is rapidly decreased due to the introduction of a large amount of OFA. The temperature of the original conditions is reduced to 1515 K, while the temperature of the optimized conditions is reduced to 1593 K. With the burning of pulverized coal, the temperature of the furnace increases again. Finally, with the burnout of pulverized coal the temperature decreases slowly. Due to the introduction of the closing-to-wall air, the furnace temperature increased about 70K generally in the most zone, however, it can be seen from table 8 that there is no obvious effect on the burnout rate of furnace outlet.

Table 8. Burned carbon rate at the furnace outlet.

Parameters	**Original condition**	**Optimized condition**
Burned carbon rate (%)	99.40	99.38

The temperature in the original case is lower than the optimum temperature in the furnace. This is due to the introduction of the closing-to-wall air that has two effects. One is due to the introduction of cold air which has the effect of reducing the temperature of the furnace flue gas and the other is the introduction of air which provides a large amount of oxygen, causes the pulverized coal to further burn and release heat. The heat released by combustion is greater than the heat consumed by the cold air, consequently, the overall temperature of the furnace is slightly higher than the original conditions (Lu, Chen et al. 2015).

Fig. shows the distributions of NOx concentration along the height of the furnace. It can be seen that NOx concentration distribution of both of the two cases is almost similar. In between the burners, the concentration of NOx is high because the O_2 concentration is higher than that in the vicinity of the burner, as a result, the generated NOx exist in large quantities without being reduced. These findings agree with those of (Lu, Chen et al. 2015) and (ZhengqiLi, LingyanZeng et al. 2011). Furthermore, at the furnace height of 10 meters, the NOx concentration of the original conditions is 330 mg/m³ . Whereas, the NOx concentration of the closing-to-wall air conditions is twice as high as that in the original conditions. This is because the introduction of closing-to-wall air has increased the oxygen concentration in the fuel area so that air classification effect of the original boiler is weakened.

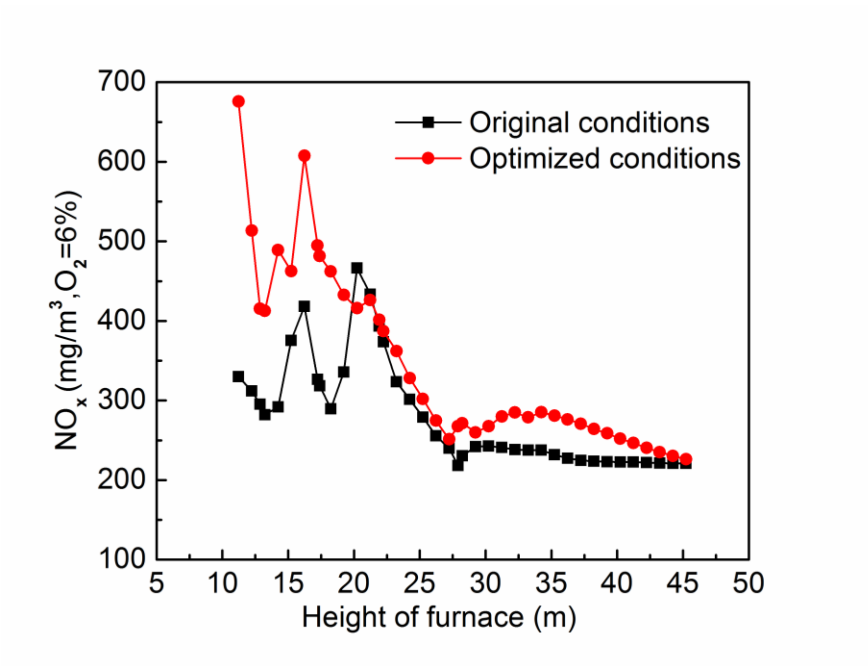


Fig. 9. Distribution of the average NOx concentration along the furnace height.

When the furnace height increases to the OFA zone, The NOx concentration of the original conditions and optimized conditions increases significantly. However, the NOx concentration at the optimized conditions increases to higher levels. This is related to the temperature of the furnace. The furnace temperature of the optimized conditions is higher than that of the original conditions and the time of fuel burning becomes shorter. Therefore, in a short time, the NOx concentration increase more obviously when closing-to-wall air conditions are applied. But with the rapid burn out of the fuel, it eventually reaches a stable value. While the burning of the original conditions have been kept at a slow speed. It can be found that the NOx concentration in the original conditions is 220 mg/m^3 in the vicinity of the furnace outlet, while the NOx concentration in the closing-to-wall air conditions is 226 mg/m^3 which is only a little higher than that in the original conditions. By introducing the closing-to-wall air from the over fire air on the side wall, the concentration of NOx in the bottom of the furnace increase dramatically. However, the concentration of NOx is only slightly higher than that in the original conditions as combustion continues. Therefore, it is also a very effective way to reduce the corrosion of the furnace without considering the NOx emission.

4 Conclusions

To reduce the high temperature corrosion of water wall of side wall of 660 MW coal fired boiler in a power plant, the scheme of slotting in the side wall was proposed. A numerical investigation was performed to clarify the effect of anti-corrosion in detail by varying the structure of slotting, gas velocity from nozzles and jet inclination angles. Through the investigation of different working conditions in 660 MW opposed wall firing boiler, the following conclusions could be drawn:

(1) In terms of influences of the structure and the layout, the coverage performance of O_2 with narrow slots is better than that with square slots in the near side wall. A stagger arrangement

of slots is better than in aligned arrangement. The more slots deployed, the better covered effect of O_2 will be.

(2) In the case of constant slot configuration, the velocity of closing-to-wall air has a marked effect on O_2 coverage in the near side wall. The greater velocity of gas injection, the better effect of O_2 coverage. Moreover, with the increase of the mainstream velocity, a greater gas jet velocity will be required correspondingly. The required air volume will increase significantly and the entrance of heavy cold air will easily affect the combustion process of the furnace.

(3) When the gas jet velocity is 6 m/s, the O_2 coverage performance with gas inclination angle 30° is better than that with 0° at the bottom of the side wall. When the gas jet velocity is 4 m/s. The angle increases with the horizontal direction, the performance of O_2 coverage becomes worse on the entire side wall.

(4) When the air volume ratio is 4.9 %, the optimum scheme can effectively reduce the area of the corrosion zone. There is no significant change of burned carbon rate at the furnace outlet. However, owing to the introduction of closing-to-wall air, the temperature of the furnace and the NOx emissions are slightly increased.

Acknowledgement

The authors gratefully acknowledge financial support from the National Key Research and Development Program of China (Grant No. 2018YFB0605102), A Foundation for the Author of National Excellent Doctoral Dissertation of PR China (201440) and the Fundamental Research Funds for the Central Universities.

References

A. Kohli and D. G. Bogard. 1997. "Adiabatic Effectiveness, Thermal Fields, and Velocity Fields for Film Cooling With Large Angle Injection." Journal of Turbomachinery 119(2): 352-358.

Belosevic, Srdjan, Beljanski, Vladimir, Tomanovic, Ivan, Crnomarkovic, Nenad, Tucakovic and Dragan. 2012. "Numerical Analysis of NOx Control by Combustion Modifications in Pulverized Coal Utility Boiler." Energy Fuels 26(1): 425-442.

Chen, T., Y. Lu, J. Liu, Q. Huang, G. Chen, B. Jin and Z. Yong. 2015. "Numerical Simulation on the Optimization of Closing-to-wall Air in a 660 MW Front and Rear Wall Opposed Coal-fired Boiler." Proceedings of the Csee.

Han, K. H., L. U. Chun-Mei, L. I. Guan-Peng and J. Liu. 2004. "Current Situation and Discussion About Preventive Measure to the High Temperature Corrosion of Water-wall Tubes in Large Boilers." Power System Engineering.

He, Z., H. Qi, Y. Yao and L. Ruan. 2015. "Inverse estimation of the particle size distribution using the Fruit Fly Optimization Algorithm." Applied Thermal Engineering 88: 306-314.

Hu, L., Y. Liu, G. Yi, N. Li and D. Che. 2013. "Effects of Air Staging Conditions on the Combustion and NOx Emission Characteristics in a 600 MW Wall Fired Utility Boiler Using Lean Coal." Energy & Fuels 27(10): 5831-5840.

Jiang, B., F. G. Liu, K. Liu and H. J. Liu. 2014. "Experimental Research on High Temperature Corrosion Prevention Technology for Water Wall of Opposed Wall Fired Ultra Supercritical Boiler." Applied Mechanics & Materials 654: 69-73.

Klein, D. H., A. W. Andren, J. A. Carter, J. F. Emery, C. Feldman, W. Fulkerson, W. S. Lyon, J. C. Ogle and Y. Talmi. 1975. "Pathways of thirty-seven trace elements through coal-fired power plant." Environmental Science & Technology 9(10).

Li, J., X. Zhuang, X. Querol, O. Font, N. Moreno and J. Zhou. 2012. "Environmental geochemistry of the feed coals and their combustion by-products from two coal-fired power plants in Xinjiang Province, Northwest China." Fuel 95(95): 446-456.

Liang, S. H., H. Lei and E. X. Zhang. 2009. "Study on On-line Monitoring Technology for High Temperature Corrosion of Boilers." Journal of Power Engineering.

Liu, J. 2007. "Expermental Research on Flat Plate Film Cooling Effectiveness at Different Injection Angles." Journal of Engineering Thermophysics 28(3): 409-411.

Lu, Y., T. Chen, J. Liu, Q. Huang, G. Chen, B. Jin and Z. Yong. 2015. "Influence of closing-to-wall air on combustion process in 660MW opposed firing boiler." Journal of Southeast University 45(1): 85-90.

Min, K., Z. Li, Z. Ling, X. Jing and Q. Zhu. 2014. "Effect of overfire air angle on flow characteristics within a small-scale model for a deep-air-staging down-fired furnace." Energy Conversion & Management 79(79): 367-376.

Mohr, S. H. and G. M. Evans. 2009. "Forecasting coal production until 2100." Fuel 88(11): 2059-2067.

Qiong, L. I., W. U. Yuxin, H. Yang and L. Junfu. 2013. "Simulation and optimization of SNCR process." Ciesc Journal.

Qiu Jihua, Liming, Sun Xuexin and Liu Yonggang. 1999. "The Corrosion of Water Wall in Wall Fired Boiler." Journal of Huazhong University Ofence & Technology 27(1): 63-65.

Ti, S., Z. Chen, M. Kuang, Z. Li, Q. Zhu, H. Zhang, Z. Wang and G. Xu. 2016. "Numerical simulation of the combustion characteristics and NO x emission of a swirl burner: Influence of the structure of the burner outlet." Applied Thermal Engineering 104: 565-576.

Wang, J., K. Zheng, R. Singh, H. Lou, J. Hao, B. Wang and F. Cheng. 2017. "Numerical simulation and cold experimental research of a low-NO x combustion technology for pulverized low-volatile coal." Applied Thermal Engineering 114: 498-510.

Wu, Z., Z. N. Zhuang, T. S. Liu, G. U. Jie and H. C. Xia. 2005. "Study on Slagging Problem in the Furnace of a Tangential Fired Boiler." Proceedings of the Csee 25(4): 131-135.

Xiu-Qing, X. U. and R. L. Zeng. 2001. "High Temperature Corrosion of Water Wall for Tangentially Fired Boiler Furnace." Power System Engineering.

Yang, W., R. You, Z. Wang, H. Zhang, Z. Zhou, J. Zhou, J. Guan and L. Qiu. 2017. "Effects of Near-Wall Air Application in a Pulverized-Coal 300 MWe Utility Boiler on Combustion and Corrosive Gases." Energy & Fuels 31(9): 10075-10081.

Zhang, J. B. 2011. "Research on High-temperature Corrosion of Ultra-supercritical Opposed Firing Boiler." Zhejiang Electric Power.

Zhang Zhixiang, Cheng Dingnan, Wang Yungang and Zhao qinxin. 2011. "Structure Design and Optimizing Simulation of a New Type Closing-to-wall Air Device." Journal of Chinese Society of Power Engineering 31(2): 79-84.

ZhengqiLi, LingyanZeng, GuangboZhao, JingLi, ShanpingShen and FuchengZhang. 2011. "Numerical Simulations of Combustion Characteristics and NOx Emissions for Two Configurations of Swirl Coal Burners in a 300 MWe Wall-Fired Boiler." Numerical Heat Transfer 60(5): 441-460.

Zhou, H., G. Mo, D. Si and K. Cen. 2011. "Numerical Simulation of the NOx Emissions in a 1000 MW Tangentially Fired Pulverized-Coal Boiler: Influence of the Multi-group Arrangement of the Separated over Fire Air." Energy & Fuels 25(5): 2004-2012.

Zhou, H., Y. Yang, H. Liu and Q. Hang. 2014. "Numerical simulation of the combustion characteristics of a low NO x swirl burner: Influence of the primary air pipe." Fuel 130(5): 168-176.

Zhou, Y. G., L. I. Pei, A. O. Xiang and Z. Hong. 2015. "High temperature corrosion inhibition for opposed firing boiler based on combustion distribution evenness." Journal of Zhejiang University.