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Impact of co-firing lean coal on NO_x emission of a large-scale pulverized coal-fired utility boiler during partial load operation

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Abstract−The present work aimed at combustion optimization of a 1,000 MW tower-type ultra-supercritical boiler co-firing a lean coal with bituminous coals for reducing NO_X emission particularly at low load operations. Historic operation data were systematically analyzed to investigate the characteristics of NO_X emission. Through comparing between lean coal co-firing and sole bituminous coal firing, it was confirmed that, besides the big difference in quality and combustion characteristics of the lean coal from the bituminous coals, the excess air ratio in main combustion zone had a significant effect on NO_X emission. Keeping the ratio at properly lower level achieved lower NO_X emissions at low load operations. Based on the analyses, in-situ tests successfully brought NO_X emissions of co-firing down close to 300 mg/m^3 at the load of 700 MW, demonstrating the effectiveness of combustion optimization for controlling NO_X emissions at partial load operation of co-firing.

Keywords: Pulverized Coal-fired Boiler, Low NO_X Combustion, Low Load Operation, Lean Coal Co-firing, Combustion Optimization

INTRODUCTION

With the increasingly stringent environmental regulations in China, coal-fired power plants are under great pressure to reduce the emissions of air pollutants, among which NO_X is a major pollutant strictly regulated. The mandatory limit for NO_X emissions from coal-fired units was recently lowered from 100 mg/m^3 at 6% O_2 set by the national standard [1] to 50 mg/m^3 required for the ultra low emission targets [2]. To meet the limit, large-scale pulverized coal-fired (PCF) power plants are mostly equipped or retrofitted with low NO_X combustion and selective catalytic reduction (SCR) system to control the emission of nitrogen oxides [3-5]. The combustion system of the boiler consists of low NO_X burners and air-staging with a large quantity of overfire air [4-8]. The excess air ratio (equivalent to air/fual stoichiometric ratio) in the main combustion zone of the furnace is generally designed at low levels (0.7-0.95) [9,10] so as to achieve the NO_X emission from the furnace as low as possible and thereby to reduce the denitrification costs of the SCR system downstream [11-13].

Usually, the PCF boilers operated at full load can readily achieve the NO_X emissions below the designed level. However, because of the rapid increase in the total installed capacity of power plants, especially of coal-fired power plants, and the competition from renewable electricity generation in China, it is now of common practice for large-sacle PCF power plants to be frequently operated at partial loads for a long time. As a consequence, NO_X concentrations in the flue gas exhausted from the furnace often increase obviously with the decrease of the boiler operating load. In this case, although the volume of the flue gas required to be processed is reduced, the significant increase in NO_X concentration in the flue gas may cause the increase in the operation cost of the SCR system [11,13,14], which affects the unit economic performance under partial load operation.

Combustion optimization is one of the effective primary measures that is widely used for reducing NO_X emission from the PCF furnace [15-17]. It is expected to be equally applicable for tuning the combustion to control the NO_X emission at low load operation. NO_X emissions from PCF furnaces are affected by many factors, including coal quality and boiler design and operation factors. The combustion optimization [15-17] and the establishment of optimal control models [18,19] depend on understanding the operating characteristics of the combustion in the boiler. Therefore, one objective of the present work was mainly to investigate the combustion operation characteristics and combustion optimization of a typical 1,000 MW ultra-supercritical PCF boiler operated at partial loads. The boiler was designed to burn bituminous coals. However, to adapt to the volatile coal market in China and to reduce the fuel cost, a low-price and high-quality (presenting as high calorific value and low sulfur content) lean coal was co-fired with bituminous coals during daily operation, which resulted in significantly higher NO_X emissions especially at low load operation. To tackle this problem, our other objective was to explore the main reasons leading to the high NO_X emissions and the impacts of co-firing lean coal on NO_X emissions, aiming at providing a referential basis for optimizing the operation of the furnace combustion system to control NO_X emissions. The investigations were based on analyzing the historic oper-

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ation data extracted from the distributed control system (DCS) of the unit. The combustion-related NO_X emission characteristics, particularly at the low load operation, were systematically assessed. According to the analyses, in-situ tests of co-firing the lean coal at a low load were conducted for optimizing the combustion to reduce the NO_X emissions.

OVERVIEW OF THE BOILER COMBUSTION SYSTEM

The PCF unit is equipped with a 1,000 MW tower-type ultra-supercritical boiler manufactured by Shanghai Boiler Factory Co. Ltd, designed to burn bituminous coals with low NO_X tangentially fired system. The boiler and combustion system is shown schematically in Fig. 1. The main components of the combustion system include:

(1) The boiler is tangentially fired with 12 levels of enhanced ignition pulverized coal burners (total of 48 pulverized coal burners) mounted at the four corners of the furnace. Pulverized coal is supplied to the burners by six mills with each connected to two burner levels. The mills are named as mill A to mill F by their connections with the burners of A1 and A2 at the bottom to F1 and F2 at the upper levels (Fig. 1(a)). At full load operation, five mills are in service out of the total of six mills available.

(2) Six levels of offset air nozzles are set to provide a part of the secondary air. The jets from the nozzles are diverted away from the pulverized-coal primary-air streams toward the furnace walls to form a concentric firing system, as shown in Fig. 1(c). Such a firing system delays the secondary air mixing into the flame ball, actually resulting in horizontal air-staging combustion. Additionally, the offset air also maintains an oxidizing atmosphere for near water-wall zones to protect the water-walls against slagging and corrosion.

(3) Above the pulverized coal burners at each corner, one level of overfire air nozzles is closely assembled to the burners, called close coupled overfire air (CCOFA) ports.

(4) Further above the main burners, six levels of separated overfire air (SOFA) ports are set to provide the secondary air to achieve vertical air-staging combustion.

The tilting of the burners at vertical direction within a range of

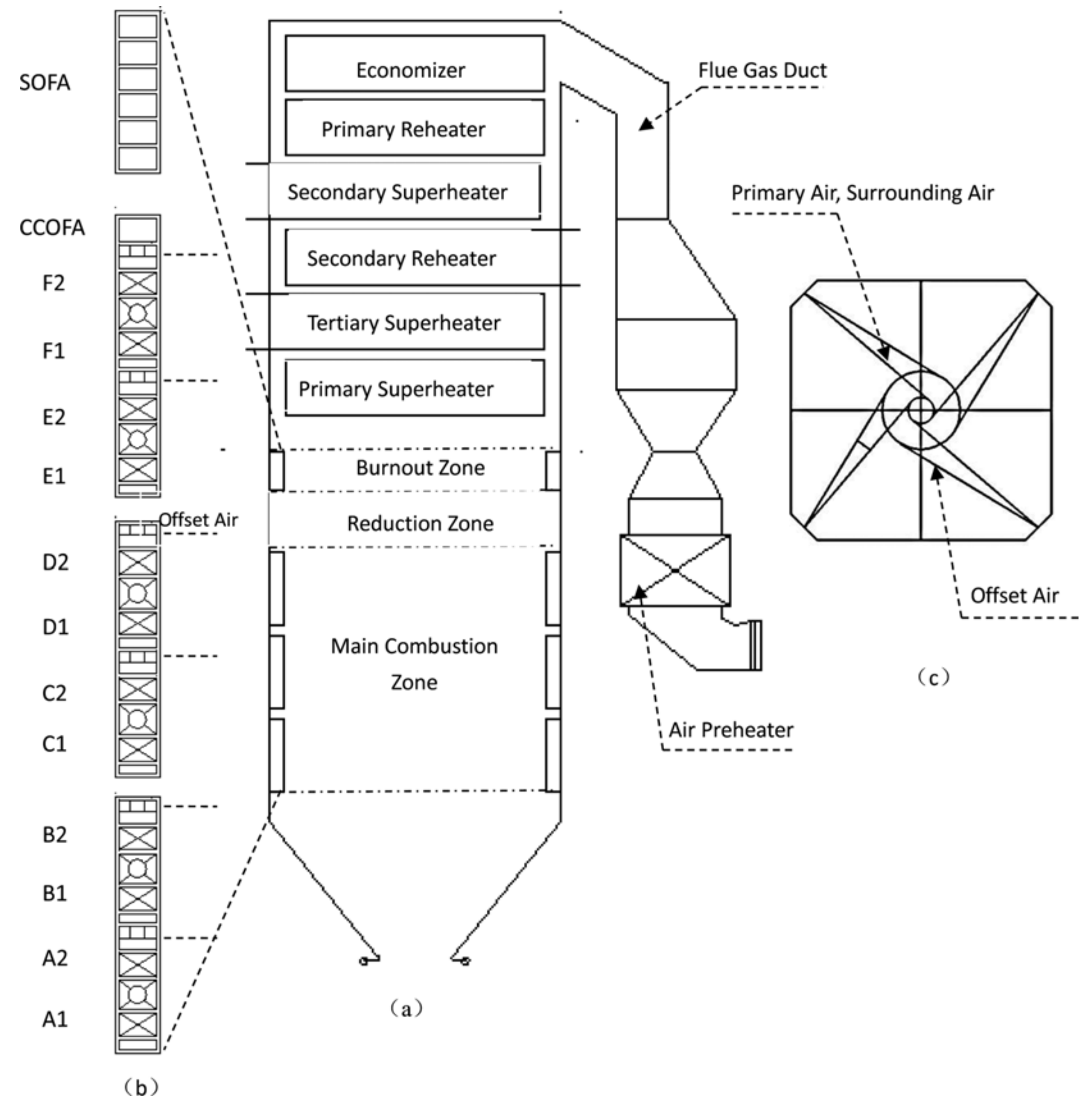

Fig. 1. The schematic diagram of the boiler and combustion system: (a) The boiler, (b) the burners and air nozzles, and (c) the circular firing system.

Table 1. Main design parameters of the combustion system

Parameter	Value
Individual burner thermal input, kJ/h	215.2×10^6
Primary air in total burning air, %	20.14
Secondary air in total air, %, including	79.86
SOFA, %	23.0
CCOFA, %	3.0
Burner air, %	16.1
Primary air temperature, °C	77
Secondary air temperature, °C	351
Primary air velocity, m/s	27.8
Secondary air velocity, m/s	57.3
Furnace excess air ratio	1.20

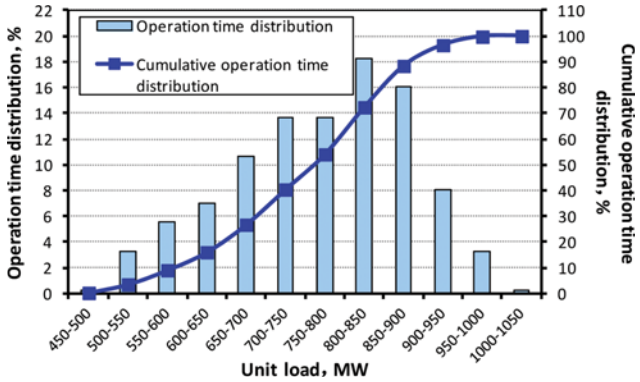

Fig. 2. Time-load distribution of the unit operated continuously for a duration of three months.

±30° is used as the main regulating mode for the reheat steam temperature. The swing of the SOFA ports at horizontal direction within a range of ±25° is used to control the thermal imbalance at the furnace exit.

The main design parameters of the combustion system are listed in Table 1. From the excess air ratio of the furnace and the percentages of the burning airs, the excess air ratio in the main combustion zone can be found to be designed at 0.92.

NO_X EMISSION CHARACTERISTICS

The characteristics of NO_X emission from the furnace were investigated based on analyzing the historic operation data from the unit DCS database. The data related to the combustion and NO_X emission were extracted, including unit load, coal feeding rate of each mill, flow rates of primary and secondary air and SOFA, concentrations of NO_X and O_2 in the flue gas at the SCR inlet, etc. Some parameters such as the excess air ratios of the furnace and main combustion zone were also calculated from the extracted data and used for the analysis. Note that the concentration of NO_X at the SCR inlet was taken as the NO_X emission from the furnace, assuming negligible formation of NO_X in the convection parts of the boiler and the gas ducts before the SCR. The concentration was recorded in mg NO_2 per cubic meter of dry flue gas. For reporting, it was normalized with the recorded O_2 concentration at the SCR inlet into the concentration in mg/m^3 dry flue gas at 6% excess O_2 according to the Chinese standard [1]. Certainly, it can be easily converted into the volumetric concentration in part per million (ppm) by dividing it by 2.05. For example, the designed NO_X emission of the boiler, 360 mg/m^3, is equivalent to 175.6 ppm.

1. Daily Operation Load Distribution

Fig. 2 presents the distribution of the unit operation load during a period of three months. For more than half the time in the statistics, the unit was operated at a load below 80% of the full load. It reflects that the unit operating at low loads was quite ordinary and also implies the necessity and importance of optimizing the combustion of partial load operation for achieving good performance.

2. Impact of Co-firing Lean Coal on NO_X Emission

Although both the design and check coal of the boiler are bituminous coals, a lean coal and a variety of bituminous coals and sometimes even lignite were co-fired, supplied through different mills, during daily operation. When the unit was operated at 50-100% of full load, the lean coal was usually fed with one mill (Mill C or D) or two mills (Mills C and D). The properties of the design and check coal, the lean coal and three examples of the as-fired bituminous coals are presented in Table 2. The properties of the as-fired coals for daily operation and the design and check coal for the boiler design are also compared in Fig. 3, showing the relationship

Table 2. Properties of the as-fired coals compared to those for boiler design

	Design coal	Check coal	Bituminous A	Bituminous B	Bituminous C	Lean coal
Moisture, %ar[a]	11.40	8.31	17.40	11.20	8.20	7.38
Ash, %ar	19.31	28.42	12.72	18.82	21.46	21.40
Volatile matter V_{daf}, %daf[b]	33.01	27.30	37.38	39.59	39.39	17.38
Sulfur, %ad[c]	0.52	0.92	0.46	0.65	1.07	0.32
Lower heating value $Q_{net,ar}$, MJ/kg	21.58	20.47	21.33	21.23	21.57	24.40
Stoichiometric air required, m^3/kg[d]	5.65	5.41	5.94	5.53	5.47	6.09
Adiabatic flame temperature, °C[d]	2298	2193	2274	2153	2083	2560

[a]On an as-received basis
[b]On a dry ash free basis
[c]On an air-dried basis
[d]Calculated under stoichiometric condition

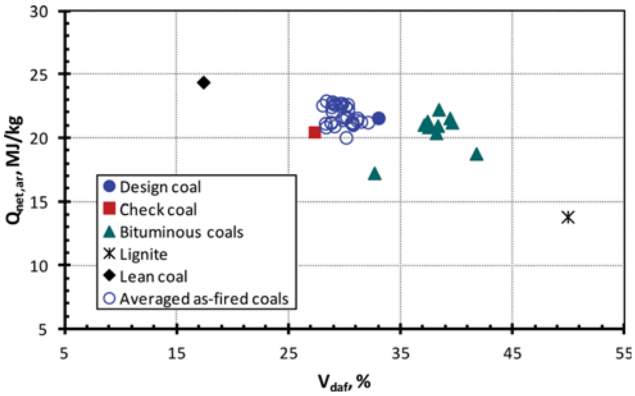

Fig. 3. Comparison of the properties between the as-fired coals and the design and check coal of the boiler.

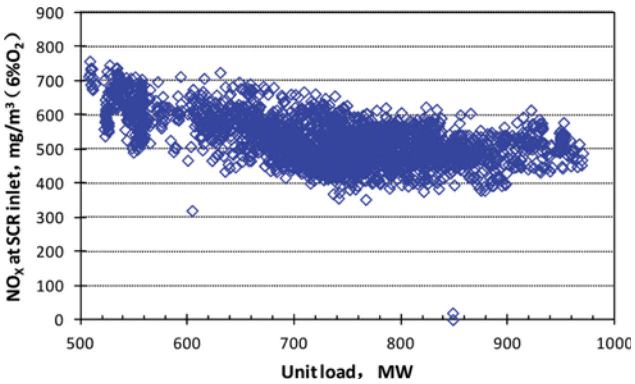

Fig. 4. NO_X concentration at the SCR inlet varying with the unit load during one-month operation with the lean coal fed by Mill C and Mill D.

between the lower heating value on an as-received basis, $Q_{net,ar}$, and volatile matter content on a dry ash-free basis, V_{daf}, of the coals. As can be seen, while all co-fired coals are significantly different from the design and check coal in quality, the weighted averages of the as-fired coals during usual operation are quite close to and between the design and check coal.

Fig. 4 shows the DCS recorded NO_X concentrations at the SCR inlet varying with the unit load during one-month operation of co-firing the lean coal fed by two mills. Despite the scattering of the data because of various factors affecting the boiler operation characteristics [15,17], the general trend indicates that the NO_X emission from the furnace increasing with the decrease of the operation load. As can be observed, the average NO_X emission level is above 450 mg/m^3 (6% O_2) at nearly full load, much higher than the designed value of 350 mg/m^3 for the unit burning the design coal; it increases gradually to as high as about 700 mg/m^3 with the operation load decreasing to 500 MW.

To clearly show the trends of the NO_X emission varying with the operation load and the effects of co-firing the lean coal on the NO_X emission characteristics, the data were statistically analyzed over the load ranges. The obtained averages were used to represent the variation trends, and the standard deviations show the extent of the data scattering over a certain load range. The results

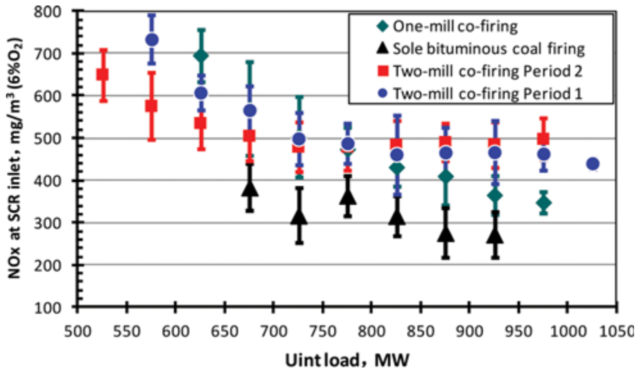

Fig. 5. Comparison of NO_X emissions varying with the unit operation load between co-firing the lean coal and burning sole bituminous coal.

of four operation periods are presented in Fig. 5 with the symbols presenting the averages and the error bars denoting the standard deviations.

Fig. 5 illustrates the impact of co-firing lean coal on NO_X formation through comparing the statistically analyzed data of four operation periods, including two different periods of two-mill co-firing (denoted as period 1 and 2, each for one-month continuous operation), one period of one-mill co-firing (15 days continuous operation), and one duration of one day testing operation of burning sole bituminous coals. The general trends are, during each operation period, NO_X emission just increases slightly with the load decreasing when the operation loads are higher than 80% of the full load but increases significantly when the loads are lower than 80% of the full load.

Fig. 5 indicates that, at all load levels, solely burning bituminous coals achieved very lower NO_X emissions, which is evidently lower than the designed value as the load is higher than 80% full load. It is expected because the as-fired bituminous coals have higher volatile matter content than the design coal (Fig. 3), leading to lower NO_X formation [15]. When the lean coal was co-fired with the bituminous coals, the concentrations of NO_X emissions from the furnace at the same load ranges were all remarkably higher than those of burning only bituminous coals; the NO_X emissions of two mills co-firing lean coal were generally higher than those of one mill co-firing as the operation load was above 80% of the full load. These reflect the significant impact of co-firing the lean coal on the NO_X emissions from the furnace. As indicated in Table 2 and Fig. 3, the lean coal is significantly different from the bituminous coals in quality. Even the weighted averages of co-fired coals have much lower volatile content than the bituminous coals (Fig. 3). The lower volatile content and less reactive combustion characteristics of the lean coal than those of bituminous coals result in later ignition and more concentrated combustion. These imply higher combustion temperature, as reflected by its much higher adiabatic flame temperature in Table 2, which favors the in-flame NO_X formation [15]. In addition, the slower burnout of the lean coal also influences the effectiveness of air staging to control NO_X formation to some extent [10], leading to higher NO_X emission. These may also imply co-firing more lean coal, resulting in more NO_X emission. Such an effect is reflected by the more NO_X emissions from two-mill co-firing than

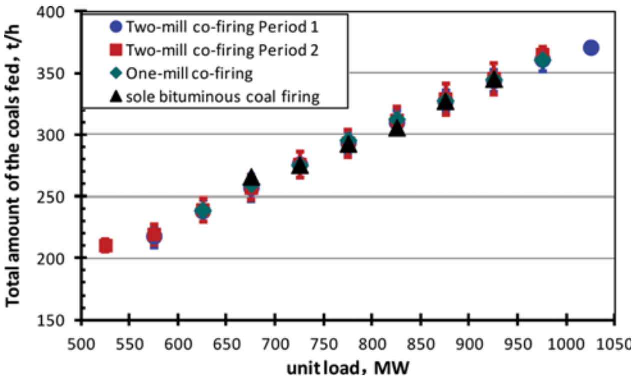

Fig. 6. Total amounts of the coals fed into the furnace changing with the unit operation load.

those from one-mill co-firing at the loads above 80% full load (Fig. 5). However, Fig. 5 also shows that below 75% of the full-load, the trends of NO_X emission varying with operation load are different for the three periods of co-firing, which will be further discussed in the following.

3. Reasons for Higher NO_X Emission under Lower Load Operation

Fig. 6 plots the total amounts of the as-fired fuels fed in the furnace varying with the operation load during the four operation periods. It is clear that the amounts of the fuels fed are consistent over the entire load range, having standard deviations within ±12 t/h, whether co-firing the lean coal or burning only the bituminous coals. The main reason is that the weighted average heating values of the as-fired fuels for co-firing are similar, and also close to those of the bituminous coals (see Fig. 3). Therefore, the higher NO_X emissions from the furnace co-firing the lean coal particularly at low loads are mainly attributed to the differences of the lean coal and bituminous coals in coal properties and combustion characteristics, as discussed above. Besides, it is well known that air staging and its extent are also likely to have impact on NO_X emissions [8,10,20]. To check their effects, the excess air ratio of the furnace combustion and the distribution of the combustion air between the main combustion zone and OFA zone were examined for the four operation periods. The results are summarized and illustrated in Fig. 7.

Fig. 7 presents the combustion excess air ratio of the furnace, the excess air ratio in the main combustion zone (including CCOFA), and the ratio of SOFA varying with the unit operation load. The furnace excess air ratio was derived from DCS recorded O_2 concentration in the flue gas; the latter two ratios were calculated from the recorded flow rates of primary and secondary air and SOFA. It can be seen from Fig. 7(a) that, except for period 1 of two-mill co-firing having the excess air ratio close to the design value at nearly the full load, the actual furnace excess air ratios were set in the operation significantly lower than the design value (denoted by the dashed curve) over the entire load range. The setting is mainly based on the consideration of reducing NO_X emission by using a lower furnace excess air ratio [15]. One of the consequences of such a measure adopted in the operation is that, in spite of the burners having already fully tilted up, the reheat steam temperatures were

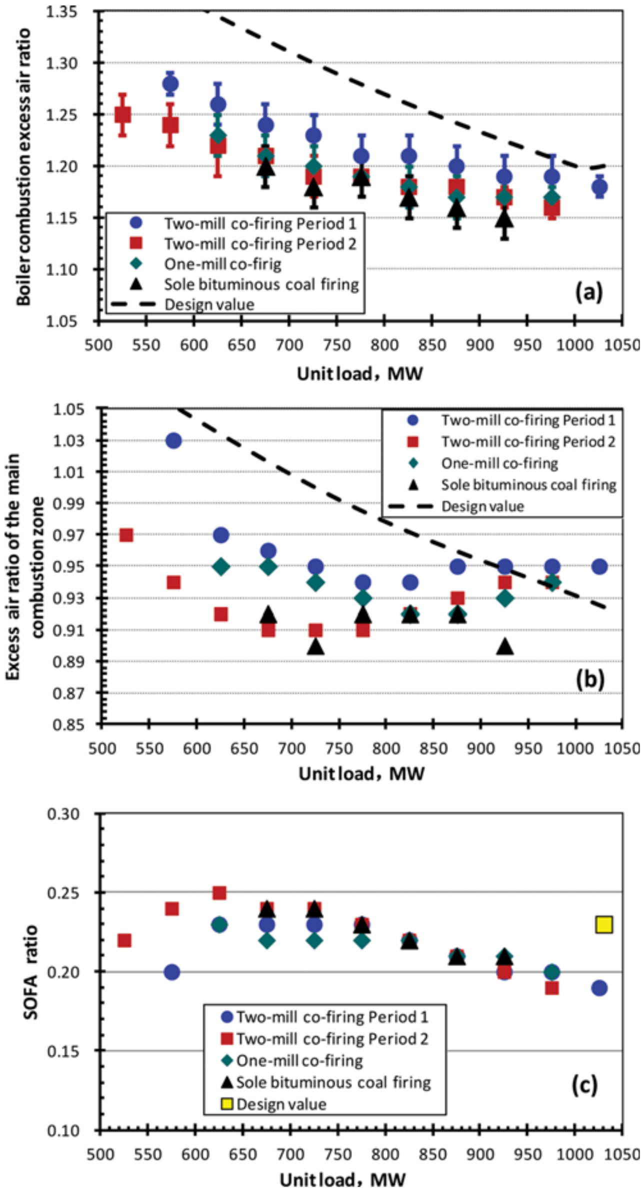

Fig. 7. The variations of (a) the excess air ratio for the combustion in the furnace, (b) the excess air ratio in the main combustion zone, and (c) the SOFA ratio with the unit load.

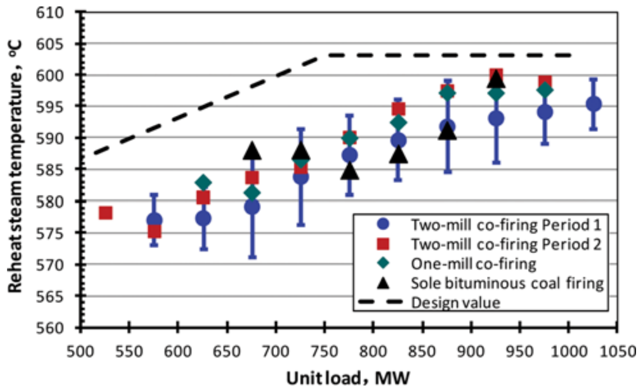

Fig. 8. Reheat steam temperature varying with unit operation load.

significantly lower than the designed values (Fig. 8). The reason is that a lower excess air ratio means a smaller volume of the flue gas produced, leading to less heat transferred to the reheaters through convection. Nevertheless, the NO_X emissions from the furnace were still much higher for co-firing particularly at lower load operations (Fig. 5).

In an air-staged combustion furnace, a low excess air ratio (<0.95) is usually designed for the main combustion zone, aiming at forming a reducing atmosphere to suppress NO_X formation [10]. For the boilers studied here, the design value of the excess air ratio in the main combustion zone was 0.92 at full load operation and increased with the load decreasing, as indicated with the dashed curve in Fig. 7(b). In practical operation, the ratio also varies with the unit load but with the trends significantly deviating from the designed one. It can be seen in Fig. 7(b) that for the operation of co-firing the lean coal at close to the nominal load, the excess air ratio in the main combustion zone was considerably higher than the design value. Such a measure was used mainly to meet the requirements for the flame stability and combustion of the lean coal, but was one of the main reasons for high NO_X emissions in high load operations (Fig. 5). During the low load operations, the excess air ratio levels of the main combustion zone for the four operating periods were all significantly lower than the design. When the three periods of co-firing are compared (Fig. 7(b)), the excess air ratios in the main combustion zone of the two-mill co-firing period 2 were evidently lower and close to those for only bituminous coal firing, while those of the other two periods were generally consistent but relatively higher. A lower excess air ratio favors depressing the NO_X formation in the main combustion zone [10]. It, accordingly, explains that the NO_X emissions of the two-mill co-firing period 2 are lower, while those of the other two periods are close to each other but relatively higher (Fig. 5). It also implies that controlling the excess air ratio of the main combustion zone at properly lower levels is critical for NO_X emission control during the low load operation of co-firing the lean coal. Note that the furnace overall excess air ratios of the two-mill co-firing period 1 were considerably higher over the whole load range (Fig. 7(a)). Nevertheless, the NO_X emissions are comparable to those of other two co-firing periods (Fig. 5). It implies that the influence of the furnace overall excess air ratio on NO_X emission is relatively smaller than that of the excess air ratio in the main combustion zone.

In air staging combustion, controlling the excess air ratio in the main combustion zone was achieved mainly through adjusting the supplies of the secondary air and the SOFA into the furnace. Fig. 7(c) shows the SOFA ratio varying with the unit operation load during four periods of operating time. SOFA ratios near the full load are obviously lower than the designed value: 0.23. It means that the extent of the actual air staging in the combustion system operation did not meet the design requirement and, as a consequence, resulted in the increase of the NO_X formation. However, the SOFA dampers had already been fully opened during the operations. It may imply that the air pressure in the SOFA wind box was relatively low or the secondary air was excessively supplied to the main combustion zone during the operations. When the boiler was operated at above 80% of the full-load, the SOFA ratios of the four operation periods were almost consistent, all increasing with the decrease of the load. It is mainly because the SOFA dampers were fully open in this range of the load.

For the operations below 80% of the full load, the typical operation was to gradually turn the SOFA dampers down to comply with the decrease of the unit load, which led to the SOFA ratio gradually increasing to a maximum and then decreased. As shown in Fig. 7(c), the SOFA ratios of two-mill co-firing period 2 were higher than those of the other two co-firing periods, namely the air staging was more intensified at low loads and, accordingly, the excess air ratios in the main combustion zone were lower (Fig. 7(b)). As a result, it led to remarkably lower NO_X formation (Fig. 5). An additional benefit was that the reheat steam temperature increased somehow under all load levels (Fig. 8). It is mainly attributed to the lower excess air ratio, accordingly lower fuel conversion in the main combustion zone. As a consequence, a considerable part of unburned fuel was carried by the up-flowing flue gas into the SOFA zone. Therefore, the higher temperature zone in the furnace shifted up, which is beneficial to enhancing the convective heat transfer of the reheaters. This also implies that for co-firing the lean coal, using a higher SOFA ratio and controlling the excess air ratio in the main combustion zone at a appropriately lower level through controlling the openings of secondary air and SOFA dampers may be the effective measures to reduce the NO_X emissions at low load operations without affecting the boiler economic performance.

4. Further Discussion

The analyses above on the operating characteristics of the combustion system indicate that co-firing lean coal is one of the main reasons for the overall high level of NO_X emissions during the boiler operation. While the air distribution between the main combustion zone and burnout zone affects the extent of the air staging, the low SOFA ratio is the main reason for the high NO_X emissions at low load operations. The low reheat steam temperatures are mainly attributed to the furnace operated at low excess air ratios.

In fact, when a boiler is designed, the combustion excess air ratio of the furnace is required to increase with the load decreasing, as shown with the dash curve in Fig. 7(a), mainly for achieving the nominal reheat and superheat steam temperatures. For the boiler studied, the designed value of the excess air ratio is 1.2 for nominal load operation. It is increased to 1.3 for 70-75% of the full-load. The consideration is that the decreases in both the volume and temperature of the flue gas in low load operations may cause the decrease in the convective heat transfer from the flue gas to the reheaters as well as the superheaters, and consequently result in the decrease in the reheat steam temperature and affect the economic performance of the unit. To minimize this effect, increasing the combustion excess air ratio is generally employed for design to increase the flue gas volume to some extent for low load operations. On the other hand, for the boiler applying air staging combustion, the excess air ratio in the main combustion zone is designed to be low, which has little impact on the combustion performance during full load operation because of the high heat release rate in the main combustion zone. In contrast, if the same excess air ratio of the furnace and SOFA ratio are still adopted for the low load operations, it would be not beneficial for pulverized coal combustion due to the low heat release rate and the low temperature in the main combustion zone. Therefore, during low load operations, appropriately elevating the excess air ratio of the boiler can correspondingly increase the excess air ratio level in the main combustion zone, which enhances the pulverized coal combustion process for keeping the fuel burnout unaffected. It is very necessary for burning the lean coal, reflected by the more stoichiometric air required than for bituminous coals (see Table 2). However, the degree of the reducing atmosphere in the main combustion zone also decreases. For example, according to the design requirements for the studied boiler, the excess air ratio in the main combustion zone is already higher than 1.0 at 70-75% of the full load as shown in Fig. 7(b), implicitly an evident loss in the capability of the air staging. The consequence of this operation measure is the concentration of NO_X emission from the furnace increasing with the decrease of the unit load.

The combustion excess air ratios of the furnace during daily operation were much lower than the design values, as indicated by Fig. 7(a), mainly for NO_X formation control. As a result, despite the burners being fully tilted up, the reheat steam temperatures were lower than the design (Fig. 8). Therefore, elevating the furnace excess air ratio may be a necessary measure to improve the economic performance of the unit operation. Under such a condition, it is particularly important to give full play to the capability and potential of air staging so as to simultaneously reduce NO_X emission. Although the operation values of the excess air ratio in the main combustion zone were already lower than the design, the practical operating experience of two-mill co-firing period 2 presented in Figs. 5 and 7(b) show that the potential exists allowing for deepening air staging under low load operations. Therefore, through controlling and optimizing the delivery of the combustion air, lower NO_X emissions are achievable for low load operations of co-firing the lean coal in the boiler.

COMBUSTION OPTIMIZATION TESTS

As discussed above, while NO_X emissions are generally higher for the boiler co-firing the lean coal particularly at low loads, the potential exists for optimizing the combustion to reduce the emission. Therefore, in-situ tests for low load (700 MW) operation of one-mill co-firing were conducted to achieve lower NO_X emissions through the combustion optimization. In all, seven test cases of varying main factors influencing NO_X formation were performed, summarized as follows:

- Case 1: Mills A-E in service, co-firing the lean coal through mill C, and the conditions of typical operation at 700 MW load.
- Case 2: Adjusting the openings of secondary air dampers to increase the SOFA and decreasing the excess O_2 level for the furnace combustion on the basis of case 1.
- Case 3: Tuning the distribution of coal feeding rates over the five mills based on case 2.
- Case 4: Decreasing the feeding rate of the lean coal (mill C) from case 3.
- Case 5: Increasing the excess O_2 level on the basis of case 3.
- Case 6: Changing mill group from A-E mills in service to B-E mills in service based on case 5.
- Case 7: Adjusting the openings of secondary air dampers to increase the SOFA and decreasing the furnace excess O_2 levels by 0.5% from case 6.

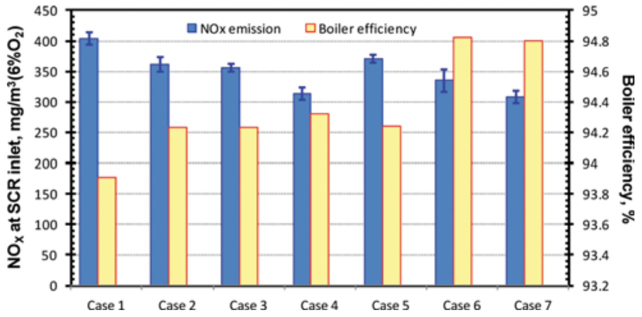

Fig. 9. NO_X emission and boiler efficiency of the tests for co-firing lean coal through mill C at 700 MW load.

During each test, NO_X concentrations at the inlet of SCR system as well as the related parameters such as O_2 concentrations and temperatures were recorded. For reporting purpose, the onsite recorded data were also converted to the concentrations of the gas species in mg/m^3 dry flue gas under 6% excess O_2 condition [1]. The boiler efficiency was determined by the measurements during the experiments followed the standard procedure (GB10184-88) for PCF utility boiler testing [21]. The obtained NO_X emission and boiler efficiency of the tests are presented in Fig. 9.

Fig. 9 shows that under typical conditions of operating the lower five mills NO_X emission was 404 ± 10 mg/m^3 (Case 1). It was lower than the average of daily operation (see Fig. 5) but still quite high. The main reason was confirmed to be the higher excess O_2 level of the combustion. Adjusting the openings of air dumpers to increase the SOFA together with lowering the excess O_2 level (Case 2) significantly reduced NO_X emission to 362 ± 12 mg/m^3, demonstrating the effectiveness of the combustion optimization for low load operation of co-firing. Further tuning the combustion by adjusting coal feeding rates of the mills (increasing the deliveries of the mid three mills, Case 3) just slightly decreased the NO_X emission. However, reducing the feeding of the lean coal (fed through mill C) (Case 4) by 5-10 t/h further decreased the NO_X emission to 313 ± 10 mg/m^3, verifying the significant contribution of co-firing the lean coal to the high NO_X emission from the furnace. Based on case 3, increasing the excess O_2 level by 0.5% (Case 5) resulted in a remarkable increase of NO_X emission. It implies the importance of controlling the combustion excess O_2 level, implicitly the distribution between the air for main combustion zone and SOFA, to NO_X emission control for partial load operation, and also proves that the higher combustion excess O_2 level is among the major causes of higher NO_X emission at usual low load operations.

Fig. 9 also shows that under typical conditions of operating the lower five mills (Case 1), the boiler efficiency is 93.95% and is relatively low. Tuning the combustion operation (Cases 2-5) not only reduces the NO_X emission to much lower than the usual operation level but also considerably increases the boiler efficiency.

Nevertheless, further optimization tests were conducted, Fig. 9 shows that the operation with the mid four mills (mills B-E in service) mode achieved a lower NO_X emission (335 ± 18 mg/m^3, Case 6), and even reached 305 ± 10 mg/m^3 when decreasing the furnace excess O_2 level and optimizing the combustion parameters (Case 7).

Moreover, the superheat and reheat steam temperatures matched those of usual operation (with upper five mills in service), and meanwhile the boiler efficiency was much higher (Fig. 9). The reason is that, as compared with the lower five mills operation, the mid four mills operation has little effect on the size of reduction zone but the concentrated combustion and consequent lower O_2 concentration in the main combustion zone favored depressing the NO_X formation. Therefore, for low load operation of co-firing lean coal, employing the mid four mills and optimizing the combustion under this mode is strongly recommended for the unit operation to achieve both low NO_X emission and high boiler performance.

The optimization successfully brought NO_X emissions of co-firing a lean coal with bituminous coal close to 300 mg/m^3 at 700 WM load, significantly lower than the averages of usual operation and even the design value for bituminous coal firing. The results demonstrated the effectiveness of combustion optimization in controlling NO_X emissions for low load operation of co-firing. Additionally, it was found that, for low load operation of co-firing, applying the mode of mid four mills in service to replace the often used mode of five mills in service enabled the achievements of not only low NO_X emission but also good boiler performance (high boiler efficiency and reheat steam temperatures).

CONCLUSION

The historic operation data were extracted from the DCS of a 1,000 MW ultra-supercritical utility boiler. With the data, the NO_X emission characteristics of the boiler were systematically analyzed to investigate the main factors affecting the NO_X emissions and the impact of co-firing the lean coal with bituminous coals on NO_X emissions. On the basis of the analysis, in-situ tests of co-firing the lean coal at a low load (700 MW) were conducted for optimizing the combustion to achieve low NO_X emissions. The main conclusions drawn from the study are as follows.

Co-firing the lean coal is one of the main reasons for the high overall level of the NO_X emission, especially for low load operation. This is mainly because of the big difference between the lean coal and the as-fired bituminous coals in quality and combustion characteristics. Compared to the bituminous coals, the lower volatile content and combustion characteristics, the later ignition and more concentrated combustion of the lean coal led to the higher combustion temperature, which certainly resulted in a significant increase in NO_X emission.

The excess air ratio in the main combustion zone is another main factor influencing the NO_X formation when the boiler is co-firing the lean coal for low load operation. It was found that the higher SOFA ratio and lower excess air ratio in the main combustion zone led to lower NO_X emission concentrations. Therefore, it can effectively reduce the NO_X emission in low load operation if the capability and potential of the air staging can be fully applied through controlling the excess air ratio in the main combustion zone at properly low levels. It also implies that the ratio can be used as a parameter, same as the excess air ratio of the furnace, for low NO_X combustion control.

The optimization of in-situ tests successfully brought NO_X emissions of co-firing the lean coal with bituminous coals down close to 300 mg/m^3 at the load of 700 MW, demonstrating that lower NO_X emissions can be achieved for low load operations of co-firing. In addition, without compromising the boiler performance, the mid four mills (mills B-E) operation mode was recommended for the low load operation.

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