Experimental and numerical investigation of combustion system improvement on 600MW bituminous coal boiler for burning lignite coal

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Abstract. A 600MW supercritical direct-current (DC) utility boiler co-firing bituminous coal with lignite, has the problems from over-large desuperheating water yield in the reheater and over-high NOx emission concentration. In this paper, the causes of the problems are analyzed through, the initial tests of pulverization system and combustion system, the adjustment of combustion, etc. The results show that the combustion in furnace lagged behind to some extent after co-firing the bituminous coal with the lignite and the center of the flame was elevated, which shortened the relative distance between the flame of the main burners and over fire air (OFA), enlarged the absorbed heat amount of the reheater and reduced the residence time of flame in the reduction zone prominently. The much less residence time would increase NOx emission. Based on the calculations of the actual operation conditions of the burners, a series of improvement measures were proposed. After performing numerical simulation and cold test verification for the improvement measures, the corresponding transformations of the power plant were carried out. The desuperheating water yield in the reheater decrease, obviously, and over-high NOx emission is controlled effectively.

1. Introduction

China is one of the world's largest energy consumers. The coal, based on abundant reserves and low prices in China, has become a major part of Chinese energy consumption for a long time now even in the future [1-4]. Low-ranked coal accounts for above 55% of total coal deposits in China, meanwhile, it is consumed extensively as a type of significant primary energy [5]. Utility coal-fired boilers are designed according to the specific coal rank. In China, non-designed coal is always combusted in the utility coal-fired boiler, and this common situation can bring a potential risk to operation security of the utility coal-fired boiler. A large number of experimental studies and theoretical calculations show that the blended coal combustion technology a feasible path to solve this problem, which can ensure the performance of the unit and improve the adaptability of coal type greatly [6,7]. There tend to exist complex chemical reactions between different coals in combustion process, and this reactions can cause combustion efficiency and pollutant emissions deviating from the expected values.

At present, a large number of experimental studies have been carried out on the combustion characteristics of blended coal, most of which are based on laboratory equipment, including the...
ignition point characteristics of coal blending [8-11], lithofacies characteristics [12], and gas pollutant emission characteristics [13], coal and biomass co-firing characteristics [14], less research on engineering applications. Zheng and Kong [15] studied the combustion characteristics of 660MW of inferior blended coal through experiments. Zhao [16] conducted a pilot study using a 600 MW supercritical cyclone hedge unit. Under the premise of no equipment modification, the boiler's adaptability to Indonesian lignite and Vietnamese bituminous coal was found for the stable combustion of boilers, pulverized coal burnout, and furnace coking control. Wang [17] and others obtained data on the combustion situation in the case of burning bituminous Coal blended with lignite, and summarized the proportion of lignite blending and boiler slagging when the lignite was blended. The results showed that the load capacity of the coal mill and the AGC (Auto Generation Control) following ability of the unit are obviously reduced, and the slagging problem occurs on the back wall after burning lignite. In recent years, the thermal power market has been shrinking. On the one hand, most power plants have to guarantee profitability by mixing low-quality lignite with relatively abundant and cheap reserves. These low-grade inferior coals with high moisture, large ash, low calorific value, and gray melting point, which lead the low-grade coal mixed combustion to a series of problems on the boiler energy efficiency. On the other hand, some boiler units need to be reformed for meeting the requirements of NO\textsubscript{x}, SO\textsubscript{x} and other pollutants after burning lignite. Therefore, it is necessary to reform the boiler experimental research on the combustion characteristics of blended coal. However, there are relatively few reports on engineering research in this area.

In this paper, the opposed firing supercritical bituminite-fired boiler of a 600MW unit in a power plant is taken as as search object. The causes of large desuperheating water volume and high NO\textsubscript{x} emission concentration after mixing lignite are analyzed. The above problems are solved by the modification of the combustion system and provided a reference for the same unit.

2. Equipment
The boiler code-named HG-1913/25.4-YM3 was designed and manufactured by Harbin Boiler Company Limited using the technical support steaming form Mitsubishi Babcock Energy (MBE). The boiler equipped with the direct-current burner is reheated intermittently, supercritical with a starting system of recirculation pump inside. The detailed design parameters of this boiler are shown in Figure 1. The original design of 30 low NOx axial swirl burners (LNASB) are arranged on the front and rear wall, opposed fire, of which 10 burners in the lower two layers are plasma burners. Above the uppermost pulverized coal burner, a layer of OFA burners are arranged on the front and rear walls, and each of the front and rear walls is six, a total of 12 OFA burners are used. Six HP963 medium speed coal mills are equipped with a positive pressure direct blown milling system, which is used for grinding coal to desired particle size. After the low-nitrogen transformation, a total of 20 pulverized coal burners in the middle and upper layers were replaced as a HG-ultra clean combustion swirl burner (HG-UCCS burner), the original 12 OFA burners were removed and replaced with 10 HG OFA burners. After low-nitrogen transformation, the boiler has excellent operating parameters and the NO\textsubscript{x} emission concentration is controlled within 260mg/Nm\textsuperscript{3} (6%, O\textsubscript{2}).

3. Boiler burning coal situation and analysis
The boiler design coal type is ShenHua coal (bituminous coal). The actual coal which the power plant often transports is ShenHun coal and high-moisture Indonesian lignite. The specific coal quality analysis is shown in Table 1. Each of the six coal mills supplies powder to one layer of pulverized coal burners, of which A and D mill correspond to the top two pulverized coal burners. The method of mixing high-moisture lignite in boiler is mixed with different coal mills, that is, the lignite is used for A and D mill, and the other coal mills are used to ShenHun coal.
Figure 1. Schematic diagram of the boiler system.

Table 1. Proximate and ultimate analyses of the boiler.

| Item                        | Design coal | ShenHun coal | Indonesia coal |
|-----------------------------|-------------|--------------|----------------|
| Proximate analysis (wt %)   |             |              |                |
| moisturea                   | 12.5        | 16.86        | 45.2           |
| ash                         | 16.17       | 10.45        | 5.60           |
| volatile matterb            | 39.56       | 36.26        | 51.83          |
| fixed carbona               | 43.11       | 46.33        | 23.7           |
| Ultimate analysis (wt %)a   |             |              |                |
| carbon                      | 56.12       | 60.1         | 34.85          |
| hydrogen                    | 3.77        | 3.81         | 2.43           |
| oxygen                      | 9.57        | 7.53         | 11.12          |
| nitrogen                    | 0.95        | 0.99         | 0.52           |
| sulfur                      | 0.92        | 0.27         | 0.29           |
| low heating value (KJ/Kg)   | 22080       | 23188        | 12370          |

* As received.  * Dry and ash-free basis

4. Problems and analysis of blending lignite

To ensure profitability, the operation mode of burning cheap lignite with some of the mill is adopted in some power plants. As the bottom layers plasma ignition burners are less adaptable to lignite, which is due to the significantly lower heating value of only 12.3MJ/kg, the power plant's up two-layer
pulverized coal burner on the boiler was improved by adopting high-moisture Indonesian lignite, in which the original pure-burned bituminous coal was changed to the bituminous coal and lignite mixed-burning operation. However, some problems began to arise in boilers, such as the over-temperature of the low-load screen, the increase in the amount of de-heating of the reheater, and the increase in the concentration of NOx emission. Moreover, the reducing atmosphere on both sides of the water wall increased obviously, which would cause high temperature corrosion of the water wall. The safety of the boiler operation is reduced greatly.

In view of the above problems, a comprehensive analysis of boilers is investigated, including boiler milling, combustion system test and burner design parameter check.

4.1. Pulverizing and burning system test
A large number of combustion adjustment tests were carried out on the boiler by adjusting the commissioning situation of the coal mill, the distribution of the air and the adjustment capacity of the burner itself. The results showed that: 1) some typical problems (including high NOx emission concentration and large amount of the desuperheating water of reheater) would occur in boilers; 2) It can be observed from the fire hole of the side wall that the high-moisture lignite burner exit flame is far away from the spout and it is almost impossible to see a bright flame. In addition, there are obvious unstable pulverized coal black strip and turbulent flow. The exit velocity of the burner based on the calibration result of the hot powder tube air speed exceeds the design value by a large margin and reaches 30 m/s or more.

| Mill NO. | Separator speed r/min | Coal supply t/h | R90 - | Tube No. 1 | Tube No. 2 | Tube No. 3 | Tube No. 4 | Tube No. 5 |
|---------|-----------------------|----------------|--------|------------|------------|------------|------------|------------|
| A mill  | 68                    | 49.7           | 29.4   | 46.58      | 42.24      | 38.25      | 47.65      | 48.18      |
| B mill  | 78.2                  | 50.2           | 20.9   | 4.49       | -5.25%     | -14.2      | 6.89       | 8.08       |
| C mill  | 70.5                  | 50.1           | 29.7   | 35.66      | 66.31      | 69.63      | 28.44      | 35.25      |
| D mill  | 73                    | 49.8           | 26.5   | -24.22     | 40.91      | 47.97      | -39.56     | -25.09     |
| E mill  | 66.9                  | 50.3           | 30     | 36.11      | 28.16      | 43.66      | 29.81      | 28.8       |
| F mill  | 75                    | 50             | 24.7   | 8.41       | -15.46     | 31.08      | -10.5      | -13.53     |
|         |                       |                |        | 44.00      | 36.42      | 42.15      | 50.65      | 47.05      |
|         |                       |                |        | -0.12      | -17.33     | -4.32      | 14.97      | 6.8        |
|         |                       |                |        | 24.16      | 29.65      | 26.39      | 30.23      | 27.7       |
|         |                       |                |        | -12.65     | 7.2        | -4.58      | 9.88       | 0.15       |
|         |                       |                |        | 39.2       | 40.4       | 46.3       | 43.6       | 35.1       |

The test of the milling system was completed by Xi’an Thermal Power Research Institute. Relevant data (the separation baffle position of each coal mill and the main operating parameters) is recorded under the daily running grinding force condition, namely, the stable operation of the milling system. The fineness of the pulverized coal is tested by using the flat-headed coal powder sampler to sample the pulverized coal at the outlet of each coal mill for the same speed. The grid method combined with the standard backrest tube is adopted to solve the hot state. Through taking the actual measurement with the primary air speed of the powder and weighting the pulverized coal of each primary air duct sampled at the same speed, we can get that the air and powder distribution of each outlet pipe of the coal mill during hot operation. The powder volume, air speed, fineness of coal powder (R90) and uniformity index of each mill were measured (see table 2, 3). The results show that the powder amount deviation: B, C grinding powder deviation is large; the two measurements of B2, B3, B4 deviations reached 40%, 40%, -40%, respectively; the two measurements of C3 deviation reached 30%; the rest of the grinding powder amount deviation is slightly smaller, within ±25%. Air speed deviation: B, F grinding deviation is large, the remaining grinding powder tube basically meets the requirement of ±10% deviation. Fineness of pulverized coal: Under the same separator rotation speed, the pulverized
coal fineness of each mill is significantly higher than designed. So the particle size of pulverized coal in actual operation is larger than the expected value.

Table 3. Air speed deviation test (hot state).

| Mill number | A   | B      | C   | D   | E   | F   |
|-------------|-----|--------|-----|-----|-----|-----|
| Powder tube primary air powder mixture speed deviation of No. 1 | -5.58% | 23.07% | -2.40% | -4.41% | -0.44% | -16.98% |
| Powder tube primary air powder mixture speed deviation of No. 2 | 4.42% | -5.01% | 3.23% | -4.65% | -1.22% | -4.82% |
| Powder tube primary air powder mixture speed deviation of No. 3 | -5.47% | 3.92% | -3.26% | 2.17% | 2.35% | 5.38% |
| Powder tube primary air powder mixture speed deviation of No. 4 | 7.48% | -20.19% | 2.05% | 6.14% | 1.67% | 11.50% |
| Powder tube primary air powder mixture speed deviation of No. 5 | -0.84% | -1.79% | 0.38% | 0.75% | -2.36% | 4.93% |

4.2. Burner design air speed check

The actual performance parameters of the bituminous coal and lignite pulverized coal burners are calculated according to the actual operation of the power plant and the test results of the milling system. The primary air volume of the single burner = (grinding inlet air volume disk value / calibration correction coefficient + 5% Sealed air volume) / 5, secondary air volume of single burner = (total air volume of the boiler - 7% air leakage at the bottom of the furnace - total primary air volume - burnout air volume) / 30. The total air volume of the boiler is taken from the original design value and the over fire air rate of the total secondary air is consistent with the design value. The comparison with the design parameters shows that the actual operating parameters of the burner are different from the design parameters regardless of the burning of bituminous coal or lignite. The overall performance is that the primary air volume is high and the secondary air volume is low. When the bituminous coal is burned, the primary air speed is 11.2% higher than the design value. The second, third and fourth air outlet speeds are 24.2% lower than the design value. When the lignite is burned, the primary air speed is 13.9% higher than the design value. The second, third and fourth air outlet speeds are 24.2% lower than the design value (see table 4). The bituminous coal has low moisture content and high hydrocarbon content, and needs large theoretical air volume per unit of fuel. While lignite has high moisture content and low hydrocarbon content, and needs small theoretical air volume per unit of fuel. Therefore, in the actual operation of the boiler, the actual air speed is higher for the combustion of Indonesian coal.

In addition, the numerical simulation results of a single burner also show that the actual primary air speed is higher than designed. Under the circumstance of existing burner used with ShenHun coal, the high-speed zone is elongated. These would be not conducive to the combustion of pulverized coal, and at the same time increases the risk of the flame center moving up. The simulated velocity field is shown in Figure 2 from which it can be seen that there is no recirculation zone under the actual operating conditions of Indonesian coal. The burner nozzle has no characteristics of swirling flow field and the ignition capacity is deteriorated.

There are two main reasons for the lag of pulverized coal combustion. First, the pulverized coal is coarser and cannot meet the requirements of fineness of coal quality. According to the rules of the milling system and the quality of coal, the bituminous coal R90 should be controlled at about 20%. The high moisture Indonesian coal R90 should be controlled below 35%. It is due to that the coarser the particle size, the longer it takes for coal particles to complete combustion. Many researchers have received the similar results by using the laboratory-scale reactors and full-scale facilities [18-20]. At present, only A and B mills can approach the requirements at high separator speed. Second, the primary air speed of the pulverized coal burner is higher than the design value. The second, third and fourth airs speed is lower than the design value, the air-filling capacity is insufficient, and the initial
fire delay of the burner nozzle is aggravated, causing the flame to rise as a whole. The upward movement of the flame center as a whole adversely would affect the amount of desuperheated water in the reheater. The lag of combustion in the main combustion zone also leads to a decrease in the relative distance between the pulverized coal burner flame and the OFA burner. The residence time of the flame in the reduction zone is too short, which increases NO\textsubscript{x} emissions to some extent.

Table 4. Pulverized coal burner design air speed check.

| Coal type                        | Design coal | Actual burning of bituminous coal | Actual burning of lignite |
|----------------------------------|-------------|-----------------------------------|--------------------------|
| Single burner primary air volume (m\textsuperscript{3}/s) | 5.674       | 6.308                             | 6.590                    |
| Single burner secondary air volume (m\textsuperscript{3}/s) | 19.535      | 14.802                            | 14.802                   |
| Burner primary air outlet speed(m/s)    | 27.48       | 30.55                             | 31.92                    |
| Burner secondary air outlet speed(m/s)  | 34.81       | 26.38                             | 26.38                    |
| Burner third air outlet speed(m/s)     | 30.26       | 22.93                             | 22.93                    |
| Burner fourth air outlet speed(m/s)    | 42.56       | 32.25                             | 32.25                    |
| Burner chemical equivalent         | 0.795       | 0.631                             | 1.345                    |

5. Transformation measures

In view of the above analysis conclusions, the following reform schemes are proposed: For the burner burning lignite, the flow area of the primary air outlet should be increased, and the secondary air volume of bituminous coal layer should be increased and the opening of the bellows should be cooperated. In the meantime, secondary air volume of the lignite layer should be reduced and the specific flowing area, such as the secondary air, third air and fourth air nozzle will be expected to been blocked. At the same time, OFA wind speed for pressing the furnace from the secondary air chamber of the pulverized coal burner and the OFA resistance level will increase due to the fact that OFA burner nozzle is partially blocked. More secondary air enter the furnace from the secondary air chamber of the pulverized coal burner, thus the burner exit air speed will be restored to the design value. In view of the high-moisture lignite used for the grinding of the upper layers A and D in the power plant, the pulverized coal burner reform is only for the upper 10. With the regard the fact that the grinding of the upper layers A and D in the power plant is usually used for the electricity company, only upper 10 of the pulverized coal burner will be reformed.

5.1. Numerical simulation

Based on the above transformation plan to establish a mathematical model, combined with the actual operation of the site, we calculate the numerical simulation of the boiler whole furnace before and after the transformation. ShenHun coal and Indonesian coal, which is selected as the simulation calculation coal are the most representative coal types in the actual operation of the power plant. Both coals are most common coal quality in power plants, and the main numerical simulation parameters are also intercepted from the actual operation picture of the power plant. Thus, more realistically restore the actual operating state of the pulverized coal burner. The Distributed Control System(DCS) operation screen took from basic test on 6 sets of grinding operation conditions, of which two coal mills operated Indonesian coal, and four mills operated ShenHun coal. Coal quality analysis is shown in Table 1.

Ansys14.0 is used for the numerical simulation software, and the standard \( \kappa-\varepsilon \) turbulent two-equation model is used to calculate the flow in the furnace. The pressure coupling equation adopts the full-implicit Simple algorithm. The particle phase uses the Lagrangian method, Discrete Random Walk Model is used to simulate the reverse coupling of the particles with respect to the flow field. The NO\textsubscript{x} studied in this paper only considers the thermal NO and the fuel NO. The thermal NO is generated by the Zeldovich mechanism [21], and the fuel NO is generated by the de Soete mechanism.
A high-quality hexahedral mesh is obtained by partitioned meshing, and the number of full furnace grids is approximately 3,000,000. In addition, to reduce false diffusion near the burner nozzle, the grid near the nozzle is encrypted.

**Figure 2.** Comparison of simulation results of single burner before and after transformation.

**Figure 3.** Furnace outlet horizontal section temperature field.

Working condition setting: working condition 1, existing burner structure and actual operating condition, that is, the primary air volume is the actual measured value of the basic test, and the secondary air volume is set as the secondary air equal distribution according to the equal opening.
degree of the secondary damper on site; Condition 2, on the basis of working condition 1, optimize the structure of burning lignite burner, adjust the secondary air proportion of different layers’s burners and OFA.

The numerical simulation results of a single burner show that the velocity field shows that the actual air speed is higher when burning Indonesian coal. The high speed zone is elongated, and there is no recirculation zone at the nozzle. After the nozzle is modified, the primary air velocity is reduced, the secondary air volume is decreased, then the recirculation zone is formed again and the power field is restored. The temperature field shows that the actual air speed is higher, the ignition is delayed, the average temperature of the outlet is reduced. After the nozzle is modified and the secondary air volume is reduced, the ignition situation is greatly improved and the average temperature of the outlet is increased. The oxygen distribution shows that, the oxygen output of the Indonesian coal is greatly reduced after the nozzle reform and the secondary air volume is decreased.

The numerical simulation results of the whole furnace show that the smoke temperature at the exit of the furnace is obviously reduced after the transformation (see Figure 3), which proves that the flame center moves down, and the problem of large amount of desuperheating water can be effectively alleviated.

5.2. Cold test verification

Table 5. Cold aerodynamic field working condition setting.

| Project                  | Unit  | Working condition 1     | Working condition 2     | Working condition 3     |
|--------------------------|-------|-------------------------|-------------------------|-------------------------|
| Burner structure         |       | Original burner structure | Retrofitted burner structure |                          |
| Center duct from the spout | mm    | 0                       | 0                       | 100                      |
| Core air                 | m³/h  | 211                     | 211                     | 211                      |
| Primary air              | m³/h  | 8106                    | 8106                    | 8106                     |
| Windbox total air volume | m³/h  | 9770                    | 9770                    | 9770                     |
| Secondary air baffle opening | %    | 100                     | 100                     | 100                      |
| Third air baffle opening | %     | 100                     | 100                     | 100                      |
| Fourth air baffle opening | %    | 100                     | 100                     | 100                      |
| Third air blade angle    | %     | 65                      | 65                      | 65                       |
| Fourth air blade angle   | %     | 65                      | 65                      | 65                       |

Figure 4. Physical map of burner test bench and wire mesh frame.

In order to further verify the effect of the transformation, according to the actual operating air volume of the burner, a single burner cold aerodynamic field test was carried out in the State Key Laboratory of Efficient and Clean Coal-Fired Utility Boilers - HBC Burning Test Center. The test related reference [23]. A wire mesh frame is installed in front of the burner nozzle, and a ribbon is attached to the wire mesh frame, as shown in Figure 4. Under the specified working condition, the shape of the
recirculation zone and the diffusion angle under different working conditions are drawn by the
direction of the yarn swinging on the wire mesh frame and the hand-held air direction detecting device.
The working condition setting is shown in Table 5. Figure 5 is a schematic diagram of the burner
nozzle after the modification.

Comparing the working condition 1 and 2 burner cold state dynamic field graph, it can be seen that
according to the actual running air volume of the site, the original burner nozzle does not generate a
recirculation zone. The expansion angle becomes large, and the airflow quickly disperses after flowing
out of the nozzle. After the transformation, the reappeared recirculation zone, the contracted expansion
angle and the re-formed swirling flow field, all are consistent with the numerical simulation
conclusion. In addition, compared with working condition 2 and 3, it is found that under the actual
operating air volume at the site, after the distance between the core air duct and the nozzle is reduced,
the expansion angle does not change significantly (see Figure 6), the area of the nozzle recirculation
area increases slightly, and the high-temperature smoke entrainment capacity is enhanced. The ignition
ability of pulverized coal is improved.

![Figure 6. Cold air aerodynamic field of the pulverized coal burner nozzle before and after the
transformation.](image)

5.3. Transformation effect

Both the numerical simulation and the cold test results are verified that the transformation plan is
feasible. According to above transformation plan, after the transformation of the power plant boiler,
the upper two sets of grinding coal are used for Indonesian coal. The middle and lower four sets of
grinding coal are used for bituminous coal. Under this operating condition, the flame center decreased
significantly, the black strip of unburned coal and the turbulence phenomenon disappeared, and the
flame was stably concentrated. Compared with the pre-reformation, the desuperheating water of
reheater has improved obviously. When the full load 600MW operating without steam extraction, the
reheater's desuperheating water is zero. Under normal steam extraction, the desuperheating water is
about 10-20t/h. Under the condition of full load of 600MW, the NOx conversion to the standard value
is about 260-300mg/Nm³, and the NOx load under 550MW is below 250mg/Nm³, the transformation
effect is obvious.

6. Conclusions

In this paper, a 600 MW supercritical direct-current boiler co-firing bituminous coal with lignite is
studied. Before transformation, its problems involved over-large desuperheating water yield in
reheater and over-high NOx emission concentration. To solve these problems, the combustion system
of this boiler was transformed. The influences of the transformation on actual operation of this boiler
and the relational research results are as follows:

(1) The initial tests of the pulverization system and combustion system show that there are different
degrees of pulverized coal deviation in each coal mill, and the fineness of outlet pulverized coal of
each coal mill is much higher than their corresponding design values at the same separator rotation speed. When the lignite is consumed by the burners suitable for bituminous coal, the burn-off rate is relatively low and the flow field of flue gas in furnace is relatively unstable.

2) Theoretical calculation and numerical simulation for the combustion process of the lignite consumed by the burners suitable for bituminous coal show that the actual running air speed of the boiler is higher than its design value. High-speed zone in furnace is elongated. There exist no recirculation zone near the outlet of burner nozzle. Second, third and fourth airs speeds are lower than their design values, hence their volume of air supplement is insufficient, which can lead to the low burn-off rate. Initial ignition delay of the burner nozzle is aggravated, which can make coal combustion delay and the center of the flame elevated.

3) The lag of combustion in main combustion zone can lead to a decrease in relative distance between the flame of main burners and OFA, hence the residence time of pulverized coal in reduction zone is reduced prominently, which can increase NO\textsubscript{x} emissions.

4) After improving the nozzle of the burner and adjusting the secondary air distribution, the desuperheating water yield in reheater is reduced, obviously, and NO\textsubscript{x} emission is controlled effectively. Reducibility of flue gas near both sides of the water walls decreases obviously. This transformation scheme is suitable for bituminous-coal-fired boiler co-firing bituminous coal with lignite, which can provide a simple and effective reference for transformation of the bituminous-coal-fired boiler.

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