Study on the application of coal blending technology based on quantum particle swarm optimization in large circulating fluidized bed boiler

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Abstract. Based on the theory of quantum particle swarm optimization, the calculation method of coal characteristics is integrated. The calculation analysis model and theoretical method are put forward to determine the distribution characteristics of lignite blended coal parameters. The CFB furnace heat transfer model with partitioned section calculation and the overall algorithm of boiler thermal calculation with sequential module iteration are applied to carry out thermal calculation of mixed coal with different proportions of lignite coal and variable conditions. The influence rule of the parameters is analyzed, and the range of reasonable mixing ratio is 50 ~ 70%. Based on the theory of combustion air dynamics and clean combustion theory, the performance of a large CFB boiler with high proportion of lignite burning is optimized, and the thermal efficiency of the boiler is increased to 90.845%. The power consumption of the integrated plant is reduced to 10.59 - 11.23%

1. Introduction

The technology of large circulating fluidized bed (CFB) has great environmental advantages, and has a wide range of adaptability for coal combustion. Therefore, in recent years, the development of the central and western regions of Inner Mongolia has developed rapidly. But the tense situation of coal burning will not be alleviated in the short term. In order to reduce the cost of power generation, the power generation enterprises have to use low quality coal, burn lignite and slime. Because the fuel quality and composition is not stable, and burning lignite moisture, low calorific value, there is a big deviation from the designed coal, resulting in the consume of coal and flue gas volume increases, the flame moves up, flue gas temperature and thermal characteristics of circulating fluidized bed boiler has a large deviation from the design. Some of the safe operation of the unit economy, problems, such as high temperature, coke, wear, smoke temperature, low thermal efficiency of boiler burning, plant electricity rate increased, decrease the operation reliability, reduce the unit load capability, and even become a major hazard on reliable operation of the unit.

2. Equipment

A Thermo Electron Corporation 2 ×150 MW generating unit is equipped with a 480 t/h super high pressure and one intermediate reheat circulating fluidized bed boiler, the model is UG-480/13.7-M3, designed and manufactured by Hua Guang Boiler Company of Wuxi. The boiler can operate steadily in the range of 30 to 100%, and the superheated steam and reheat steam can maintain the rated parameters within the range of 70 to 100%. The circulation material is separated by a volute high
temperature insulation cyclone separator, and the self-balancing U type return valve is arranged under the separator feed leg, and the fluidized seal air is supplied separately by the high-pressure fan. The boiler adopts water cooling cloth wind plate, with bell shaped hood; the combustion temperature, graded air supply; the bottom of the furnace is provided with 4 sets of HBSL drum type cold slag extractor; tube type air preheater is arranged in the tail flue. A bag filter is used in the design. Technical specification for boiler is shown in Table 1.

| Algorithm                        | Design | Check |
|----------------------------------|--------|-------|
| Superheated steam flow (t⋅h⁻¹)   | 480.0  | 480.0 |
| Superheated steam pressure (Mpa) | 13.73  | 13.73 |
| Superheated steam temperature (°C)| 540    | 540   |
| Reheat steam flow (t⋅h⁻¹)        | 390    | 390   |
| Reheated steam outlet pressure (MPa)| 2.456  | 2.456 |
| Reheated steam outlet temperature (°C)| 540    | 540   |
| Working pressure of steam drum (MPa)| 15.10  | 15.10 |
| Exhaust gas temperature (°C)     | 136    | 136   |
| Boiler thermal efficiency (%)    | 90.62  | 90.79 |
| Calculation of fuel consumption (kg⋅h⁻¹)| 104017 | 77244 |

3. Study on the characteristics of blending coal

3.1. Establishment of mixed coal blending model

Through the analysis of the coal quality data and its characteristic index in the 2010–2011 year, the proportion of the mixing ratio of the coal is analyzed. The characteristics and control equations of mixed coal in different proportions of lignite are obtained [1]. The characteristics of bituminous coal and lignite are studied in depth, and the integrated coal blending model is optimized. The QPSO algorithm is used to check and calculate, which improves the accuracy and speed of convergence [2]. According to the characteristics of engineering application, the characteristics, parameters and distribution curves of mixed coal are obtained by mixing different kinds of coal in different proportions. The main parameter control equation of coal quality after mixing is equations (1) to (4).

\[ Q_{\text{net,ar mix}} = xQ_{\text{net,ar lignite}} + k_1(1-x)Q_{\text{net,ar bituminous}} \]  
\[ A_{\text{ar mix}} = xA_{\text{ar lignite}} + k_2(1-x)A_{\text{ar bituminous}} \]  
\[ W_{\text{ar mix}} = xW_{\text{ar lignite}} + k_3(1-x)W_{\text{ar bituminous}} \]  
\[ \sum_{i=1}^{n} Q_{\text{net,i}} \cdot x_i \geq Q_{\text{net,min}} \quad \sum_{i=1}^{n} A_{\text{ar}} \cdot x_i \leq A_{\text{ar,max}} \]  
\[ \sum_{i=1}^{n} M_{\text{ar}} \cdot x_i \leq M_{\text{ar,max}} \quad V_{\text{ar,min}} \leq \sum_{i=1}^{n} V_{\text{ar}} \cdot x_i \leq V_{\text{ar,max}} \]  

Where \( Q_{\text{net,ar mix}} \)—Mixed coal net calorific power as received basis, kJ⋅kg⁻¹; \( Q_{\text{net,ar lignite}} \)—Lignite coal net calorific power as received basis, kJ⋅kg⁻¹; \( Q_{\text{net,ar bituminous}} \)—Bituminous coal net calorific power as...
received basis, $kJ \cdot kg^{-1}$; $A_{ar \text{ mix}}$, $W_{ar \text{ mix}}$—Mixed coal ash, water content as received basis, %; $A_{ar \text{ lignite}}$, $W_{ar \text{ lignite}}$—Lignite coal ash, water content as received basis, %; $A_{ar \text{ Bituminous}}$, $W_{ar \text{ Bituminous}}$—Bituminous coal ash, water content as received basis, %; $X$—Mixing ratio; $k_1$, $k_2$, $k_3$—coefficient.

### 3.2. Thermodynamic calculation of circulating fluidized bed

Based on the CFB furnace heat transfer model with partitioned section and the total algorithm of boiler thermal calculation with sequential module iteration, the thermal calculation of CFB boiler with different proportions of lignite and coal blending is carried out under variable coal and variable conditions \[3, 4\]. The summary of the calculation results is shown in table 2.

| Name                        | Actual bituminous coal | 30% lignite | 50% lignite | 80% lignite |
|-----------------------------|------------------------|-------------|-------------|-------------|
| Furnace exit gas temperature ($^\circ C$) | 907.7                  | 898.7       | 895.5       | 891.0       |
| Exhaust gas temperature ($^\circ C$) | 139.1                  | 142.3       | 144.9       | 148.4       |
| Theoretical air volume (Nm$^3$kg$^{-1}$) | 4.535                  | 4.423       | 4.351       | 4.098       |
| Theoretical flue gas quantity (Nm$^3$s$^{-1}$) | 135.70                 | 153.59      | 164.42      | 172.03      |
| Main Desuperheater (t:h$^{-1}$) | 29.0                   | 27.9        | 25.9        | 21.1        |
| Heat Efficiency (%)         | 90.092                 | 89.871      | 89.603      | 89.074      |
| Fuel consumption (kg·h$^{-1}$) | 85187                  | 97763       | 103276      | 112202      |

The analysis shows that the effect of mixing proportion on the operating parameters of boiler can be divided into 3 intervals, initial coal mixing area, transition zone and gentle zone. The proportion of mixed combustion in the initial coal mixing area is 0 ~ 30%, and the change rate of brown coal to boiler parameters is larger. The proportion of combustion in the transition zone is 50 ~ 60%, and the lignite and bituminous coal have a great influence on the boiler parameters, but the influence of the bituminous coal is rapidly weakened. The proportion of mixed burning in the gentle zone is more than 60%, and the change rate of the ratio of lignite's blending ratio has a little change on the influence of the boiler parameters. Therefore, the operation economy of high proportion burning lignite is the main research direction, which has practical significance and comprehensive comparative advantage.

### 4. Field test research

According to the above calculation, the mixed coal is used in the field test, the proportion of lignite blending is 60 ~ 70%, and the following tests are carried out at the 90% load condition.

#### 4.1. Adjustment of air supply and oxygen content

Through the analysis of the coal quality data and its characteristic index in the 2010~2011 year, the When the bed pressure is constant and the primary air volume is set to 220 Nkm$^3$/h, the secondary air volume is adjusted between 165~175 Nkm$^3$/h and the measured oxygen volume is changed from 2.2% to 3.8%. With the change of oxygen, the content of flammable substance in fly ash and slag is analyzed to make $q_2 + q_3 + q_4$ minimum. The test shows that with the increase of oxygen content, the content of combustibles in fly ash is generally reduced, and the total decrease is 0.55%. The efficiency of the boiler is 89.479 ~ 89.761%. The optimum oxygen content is 2.8 ~ 3.1%. The data is shown in table 3.

| Name                  | Condition 1    | Condition 2   | Condition 3   |
|-----------------------|----------------|---------------|---------------|
| Oxygen (%)            | 2.45/2.16      | 3.17/2.65     | 3.72/3.17     |
| Fly ash combustible content (%) | 7.63       | 7.24          | 7.08          |
| Slag combustibles content (%) | 0.72       | 0.10          | 1.38          |
| Exhaust gas temperature ($^\circ C$) | 141.8/143.4 | 143.3/145.2 | 144.7/147.6   |
| Boiler Efficiency (%)  | 89.553         | 89.761        | 89.479        |
4.2. The adjustment of the primary and secondary air ratio
The secondary air volume keeps 160 to 165 Nkm$^3$/h, and the primary air volume decreases from 200 to 250 Nkm$^3$/h. The trend of the content of combustibles in fly ash and the change of exhaust temperature with the first air volume was analyzed. As good fluidization conditions are ensured, secondary air penetration is increased to optimize the combustion dynamic conditions in the furnace and reduce the wear of the heated surface. The test shows that with the decrease of primary air volume, the content of flammable fuel in fly ash is generally reduced, and the maximum decrease is 3.64%. When the primary air volume is less than 210 Nkm$^3$/h, the drop slows down. The efficiency of the boiler is 89.362 ~ 89.698%. The best operation air volume is at 210~220 Nkm$^3$/h. Data is shown in table 4.

| Name                          | Condition 1 | Condition 2 | Condition 3 |
|-------------------------------|-------------|-------------|-------------|
| Primary air volume (Nkm$^3$.h$^{-1}$) | 250         | 220         | 200         |
| Fly ash combustible content (%) | 4.96        | 1.32        | 3.02        |
| Content of slag combustibles (%) | 0.18        | 0.08        | 0.26        |
| Exhaust gas temperature (°C) | 146.5/151.6 | 142.5/148.6 | 146.2/150.5 |
| Boiler Efficiency (%)         | 89.362      | 89.698      | 89.521      |

4.3. Operating bed pressure adjustment
Keep the bed temperature and air quantity stable, change the bed pressure and air chamber pressure by controlling the amount of slag discharge, and study the change of the carbon content of the ash in different conditions. The increase of bed pressure can increase the concentration of material in the furnace and increase the frequency of particle collision, which can significantly reduce the content of flammable combustibles in fly ash. But the excessive increase of the bed pressure will increase the power consumption of the primary fan, which has adverse effects on the combustion of dense phase area and the mixing effect of the secondary air. The test shows that as the bed pressure and wind chamber air pressure become larger, the content of the flammable substance in the ash and slag tends to decrease. The content of flammable substance in fly ash is reduced by 0.86%, and the content of slag combustibles is reduced by 0.23%. The boiler efficiency is 89.566 ~ 89.972%. The operating air chamber pressure should be kept at 9900 ~ 10000 Pa. Data is show in figure 1.

![Figure 1. Proportion diagram of air chamber pressure and boiler efficiency.](image)

4.4. Particle size distribution of coal in furnace
According to the size distribution of coal and lignite particle, the thermal fragmentation of coal into the furnace, the particle size distribution is adjusted to reduce the proportion of fine particles, improve the ash material circulation, reduce the loss of fly ash. Test data are shown in table 5.
Table 5. Data of particle size test.

| Sieve diameter | Condition 1 | Condition 2 | Condition 3 |
|----------------|-------------|-------------|-------------|
| >Φ10 (%)       | 8.00        | 10.41       | 16.07       |
| Φ10--Φ6 (%)    | 12.00       | 15.32       | 17.83       |
| Φ6--Φ1.5 (%)   | 33.00       | 36.65       | 33.77       |
| <Φ1.5 (%)      | 47.00       | 37.62       | 32.33       |
| Fly ash combustible content (%) | 9.86 | 6.40 | 2.56 |
| Slag combustibles content (%) | 3.11 | 0.11 | 0.09 |
| Boiler efficiency (%) | 87.532 | 88.698 | 89.936 |

4.5. Combustion temperature adjustment

In view of the current situation of coal quality, keep parameters unchanged, change the anti-ash amount and circulating ratio by adjusting the anti-feeding air pressure and quantity, and adjust secondary air dampers to increase the bed temperature. At different lower bed temperature (900~940℃), the content of combustibles in fly ash and the change of bed temperature are analyzed, and the content of combustibles is tested. The test shows that with the increase of bed temperature, the content of combustibles in fly ash is generally declining, and the overall change of the content of combustibles in large slag is slow. The efficiency of the boiler is 88.698 ~ 89.972%. The operating bed temperature should be kept at 930~945℃. Data are show in figure 2.

![Figure 2. Proportion diagram of bed temperature and boiler efficiency.](image)

4.6. Test of mixing coal blending and optimizing operation efficiency

The blending ratio of lignite is controlled from 50 to 70%. The thermal efficiency test of the boiler after performance optimization is carried out. Test data is shown in table 6.

Table 6. Summary table of main test data for boiler combustion optimization/

| Name                     | Before Optimization | After Optimization |
|--------------------------|---------------------|--------------------|
| Electric power (MW)      | 135                 |                    |
| Superheated steam flow (t/h) | 453            | 434.3              |
| Feed water flow (t/h)    | 448.1               | 427.8              |
| Feed water temperature (℃) | 241.8           | 239.9              |
| Air temperature (℃)      | 28.5/26.3           | 33.9/34.8          |
| Oxygen of Air Preheater outlet (%) | 3.29/3.36 | 3.75/2.28 |
| Exhaust gas temperature (℃) | 145.3/147.8 | 141.03/140.17     |
5. Benefit analysis

Economic benefit:

Statistics and test data show that the boiler efficiency is increased about 2.045 to 3.174%, and the comprehensive plant power consumption rate is decreased by 0.458 to 1.127%, which reduces the coal consumption of each unit by 14 to 16 g/kW.h. When the load factor is set to 0.85 and the available hourage of unit is set to 6500 hours, amount of coal is saved about 15 g/kW.h × 150000 kw × 0.85 × 6500h/106 = 12430t in each year for one unit. The total amount of standard coal can be saved about 12430 × 2 = 24860t and about 700 yuan/t × 24860 = 1740 Million yuan RMB can be saved in one year.

Using 60% lignite instead of bituminous coal, the annual amount of converted coal is 290795t, and the difference price of coal is 100 yuan/t, which can save RMB 290795 × 0.6 × 100 = 1744.8 million yuan. Two items totaling 3484.8 Million yuan.

Social benefit:

Create favorable conditions for the power plant to further actively carry out energy saving and consumption reduction work.

It can quantitatively analyze operation status, variable operating conditions and coal type assessment, evaluate and demonstrate the technical transformation plan quickly and accurately, and guide optimization adjustment, maintenance and underload peaking operation. The safety, economy and reliability of the circulating fluidized bed boiler unit are improved, and the fuel utilization rate is improved. It is helpful to equipment overhaul, formulate maintenance standards, optimize maintenance procedures, and gradually carry out state maintenance.

6. Conclusion

The coal resources in Inner Mongolia are very rich, and the reserves of lignite are large, and there are a large number of fluidized bed boilers with a capacity of 420 to 1080 t/h, and the technology covers the three major schools of international popularity. The combination of both technical and environmental advantages is remarkable. However, the high proportion of blended lignite can increase the flue gas volume by 30 to 50% under the same load condition, increase the flue gas temperature by 10~20℃, increase the comprehensive plant power consumption by 0.5 to 1%, increase the carbon content of fly ash to 8%, and reduce the boiler efficiency to 87 to 88%. Using advanced scientific theories and reasonable technical methods, the efficiency of the boiler is increased to 90% and the power consumption of the plant is reduced by 1%. The technical and economic benefits are remarkable, the wear of the heated surface is alleviated. So the prospect of application is broad.

References

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