Study on the Law of the Influence on Slag Blocking in Combustors Produced by Coal Blending Combustion Strategy of Slag-tap Boiler

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Abstract; Slag blocking and slagging of combustors are influenced by the coal blending combustion strategy of slag-tap boiler, this paper studies these influence factors, analyzes the problems of slag blocking and slagging of combustors from the perspective of fuel, and examines the calorific value, ash content, ash melting point, ash melting characteristics of coal quality and slag captured rate of boiler. Based on the above researches, the writer summarizes the effects on slag blocking and slagging in the combustors produced by different coal combustion of slag-tap boiler, and forms coal blending combustion strategy suitable for the slag-tap boiler.

1.Introduction
The third-phase boiler of a plant is manufactured by BABCOCK, a company of Germany. Its boiler are divided into the following types: subcritical, primary reheat, direct fired pulverizing system, double U-shaped flame combustion, 100% fly ash reburning, liquid slag discharge and tower type once-through boiler. Its special combustion mode and liquid deslagging characteristics have higher requirements for the type of the coal. At present, the capacity of China’s self-designed and manufactured slag-tap boiler is relatively small, and it also lacks design and manufacturing experience in capacity slag-tap boiler1 [1-2]. However, with the recent changes in the coal market, slag blockage occurred several times in a year, and the frequency of slagging also increased significantly, which seriously affect the economic and safe operation of the boiler.

In order to solve the slag blocking in the combustor of the third-phase slag-tap boiler, this paper analyzes the problem from the perspective of fuel, studies the calorific value, ash content, ash melting point, ash melting characteristics of coal quality and the slag capturing rate of the boiler. After that, the writer summarizes the effects on slag blocking and slagging in the combustors produced by different coal combustion in slag-tap boiler, and forms coal combustion strategy of the slag-tap boiler.

2.Analysis of the Factors Affecting the Slag Blocking in Combustors
The third-phase of the plant’s slag-tap boiler is designed to maintain the operation of the liquid slag discharge combustion system at the load above 27.3% MCR. It means that the ash provided by coal must be heated above the melting temperature to ensure successful deslagging. At low load, the liquid slag combustor will absorb more heat in proportion, leading to the drop of outlet flue gas temperature. Therefore, the following factors must be taken into account in the mixed combustion of slag-tap boiler:
This paper, under the condition of relatively fixed boiler form and combustion system, mainly studies the first four factors of coal blending combustion, which are fuel calorific value, ash melting characteristics, the fineness of the pulverized coal and slag catching rate, and explores the influence of these four factors on slag blocking of the combustor.

3. Test Data and Analysis
Through the laboratory analysis of coal, ash, slag and other samples of the plant, and the long-term monitoring of the operation data about the third-phase slag-tap boiler, the writer obtains and analyzes operation data of slag-tap boiler when it uses mixed combustion of various coal types.

3.1. Calorific Value of the Fuel

3.1.1 The heat released when the unit weight of fuel is completely burned, which calls the calorific capacity or calorific value of the fuel. In general, the calorific value of the fuel concerned by coal-fired power plants is net calorific value. It means that the residual heat after deducting the latent heat of vaporization carried away by steam from the gross calorific value of fuel, which is called net calorific value. The calorific value of fuel is closely correlated with the temperature of furnace. According to the numerical simulation calculation, Figure 1 is obtained.

![Figure 1 Relationship between calorific value of coal combustion and theoretical flue gas temperature](image1)

According to Figure 1, it can be estimated that every 100kcal heat change of 1kg fuel will bring about 30℃ change of the furnace flue gas temperature. In order to ensure the slag flows smooth in the slag-tap boiler, the furnace temperature should be kept at least 100℃ higher than the ash melting point. Therefore, when the ash melting point stands at 1350℃, the minimum calorific value of coal can not be lower than 4650kcal.

3.1.2. The ash in the fuel can absorb heat and reduce the temperature of the furnace. Figure 2 is obtained based on the numerical simulation calculation of the solid slag boiler. According to figure 2 it can be estimated that every 1% ash content of 1kg fuel will affect the furnace temperature by about 20 ℃. Moreover, unlike the solid slag boiler, the ash in the fuel of the slag-tap boiler can not only decrease the combustible content, but also concerns the heat absorbed by the transformation of ash and slag and the heat carried by the slag liquid during the liquid deslagging. Based on 50% slag feeding rate, if the fuel has the same calorific value, every 1% increase in ash content will consume additional 2.6kcal heat[4], which will reduce efficiency of the boiler by more than 0.05%. Therefore, in order to
ensure the normal slag flow and the efficiency of the boiler, the coal’s ash content can not be higher than 17% when the ash melting point stands at 1350 ℃.

### 3.2 Melting Characteristic of the Ash

#### 3.2.1 Components

The components of Mixed coal and their content ratio are the most basic factors to determine the ash melting point. The ash is generally composed of alumina (AL₂O₃), silica (SiO₂), iron oxide (FeO,Fe₂O₃,Fe₃O₄), calcium magnesium oxide (CaO, MgO) and alkali metal oxide (Na₂O, K₂O), but it contains four main components: SiO₂, AL₂O₃, Fe and CaO, while other components only account for a very small proportion.

| Name     | Melting Point℃ | Name     | Melting Point℃ |
|----------|----------------|----------|----------------|
| SiO₂     | 2230           | FeS₂     | 1170           |
| Al₂O₃    | 2050           | K₂O N₂O | 800-1000       |
| MgO      | 2800           | 3Al₂O₃+2SiO₂ | 1850          |
| CaO      | 2570           | CaOAl₂O₃ | 1500           |
| FeO      | 1540           | 3Al₂O₃+2SiO₂ | 1000-1100     |
| Fe₂O₃    | 1550           | +2FeO₃SiO₂+SiO₂ |        |
| FeO      | 1420           | CaO+FeO+CaO/Al₂O₃ | 1200       |

Different components have different melting points, some are difficult to melt, while some are easy to melt. However, the combined components will change the melting point. Therefore, the components of ash is the basic factor to determine the melting point of ash.

Ash, the complex mixture, is composed of various components, so its melting point not equals to the arithmetic average value of all components. The more substances (SiO₂, Al₂O₃, MgO) with high melting point are contained in ash, the higher its melting point is[5]. If the content of pyrite (FeS₂), Na₂O and K₂O in coal is high, the ash melting point will be lower. The enrichment of Fe-compound has great impacts on the formation of liquid slag, which adheres easily on the surface of quartz particles and increases the viscosity[6]. However, some refractory substances (FeO,Fe₂O₃,CaO,MgO) in the mixture can reduce the ash melting point. For example, the melting point of CaO is 2570 ℃, but when it is mixed with FeO and Al₂O₃, the ash melting point will drop to 1200 ℃, which is the result of the fusing. Similarly, changes of the properties of the surrounding medium will affect the melting point of ash. For example, the existence of reducing gases such as CO and H₂ will lower the melting point’s temperature. At this time, the reducing gas can reduce the high valent iron oxide (Fe₂O₃) in the ash and produce ferrous oxide (FeO) with a low melting point.

#### 3.2.2 Relationship among viscosity, temperature and components of slag

For the same kind of ash, the higher the temperature is, the smaller the viscosity of slag is, and vice versa. Generally, higher ash melting point means greater viscosity, and greater viscosity of the slag means easier slag blockage. In addition, when the viscosity temperature characteristic curve of slag is too steep, that is, the viscosity of slag liquid changes too fast under different temperature, it is easy to see slag notch clogged. What’s more, too high slag viscosity will block the slag capturing screen, resulting in the increasing outlet pressure of forced draught fan under constant load. Therefore, monitoring the pressure of forced draught fan can also indirectly judge the flowing of the slag.

#### 3.3 The Fineness of the Fulverized Coal

The fineness of pulverized coal is directly related to the temperature and efficiency of boiler combustion[7]. The third-phase boiler is a kind of slag-tap boiler, and the temperature of its furnace is high, so it is inevitable to generate thermal NOx, which will pollute atmospheric environment.
Therefore, in order to reduce NOx emission, the combustion should be operated under the status of lacking oxyg
e. The small value about the fineness of pulverized coal in the pulverizing system is $R_{90} = 10\%$, by doing so, it can adapt to the combustion mode. In recent years, the pulverized coal fineness of the third-phase boiler in the plant has not reached the standard. The power plant has carried out several adjustments and measurements. However, the HGI (Hardgrove Grindability Index) of the coals used in recent three years tells that HGI surpasses 60 while design coal and the check coal are less than 55. Thus it is difficult to ensure the fineness of pulverized coal under the same output of coal mill. If the fineness of pulverized coal is excessively coarse, the combustion of the boiler will move backward and the furnace temperature will drop relatively, which will cause slag blocking. Furthermore, due to the hard coal and the limited output of the pulverizing system, it is difficult to ensure that the average fineness of pulverized coal is more than 1. If the pulverized coal are in different fineness, there must be insufficient combustion during the start-up of grinding, which will easily lead to scum in the boiler. As a result, it is suggested to blend coals with lower HGI, which at least can ensure that the HGI of base coal is similar to that of Mixed coal.

3.4. Slag Capturing Rate

In order to discharge more liquid slag turned by fly ash, a slag capturing screen is added at the furnace outlet of the slag-tap boiler to increase the collision probability of fly ash and the slag capturing rate. The designed slag catching rate of the third-phase boiler is not lower than 50%.

According to the on-site sampling analysis of slag blocking in No.1 slag chamber of No.5 boiler on September 11, 2018, its components are as follows:

| Text Items               | Symbol | Unit | 5#Boiler 30 Grinding Coal Ash | Slag in #1Slag Chamber | Comparison Results |
|-------------------------|--------|------|-------------------------------|------------------------|-------------------|
| Silica in ash           | SiO$_2$% | 41.7 | 58.72                        | Enrichment             |
| Aluminum oxide in ash   | Al$_2$O$_3$ % | 16.78 | 22.66                        | Enrichment             |
| Ferric oxide in ash     | Fe$_2$O$_3$ % | 9.37 | 8.99                         | Equal                  |
| Calcium oxide in ash    | CaO % | 16.51 | 4.17                         | Loss                   |
| Sulfur trioxide in ash  | SO$_3$ % | 9.65 | 0.17                         | Loss                   |
| Magnesium oxide in ash  | MgO % | 2.27 | 1.02                         | Loss                   |
| Sodium oxide in ash     | Na$_2$O % | 1.19 | 0.91                         | Loss                   |
| Potassium oxide in ash  | K$_2$O % | 1.05 | 1.97                         | Enrichment             |
| Titanium dioxide in ash | TiO$_2$ % | 0.65 | 0.99                         | Enrichment             |
| Phosphorus pentoxide in ash | P$_2$O$_5$ % | 0.20 | 0.11                         | Loss                   |
| Others                  |        | 0.63 | 0.29                         |                        |

It can be seen that unlike the laboratory, in the process of boiler combustion and the formation of liquid slag, some elements are enriched in the formation of liquid slag, and some elements are lost. In the operation of slag-tap boiler, some low melting point substances in fly ash, such as S, P and Na, will precipitate out and become gas, and then change into solid compounds as they flow with flue gas into low temperature zone. Some high melting point substances, such as the compounds of Si, Al and Ti, will remain in the liquid slag in large quantities, resulting in the increase of slag viscosity and unsmooth fluidity, which finally affects the normal slag discharge[8]. Therefore, a large gap among the components of coal ash, fly ash and slag in the slag-tap boiler are formed, and the physical and chemical characteristics of coal ash and slag are also quite different.

Therefore, the analysis results of the coals’ ash components can not be used as the basis of the slag characteristics of the slag-tap boiler, and the evaluation should be carried out after correcting the enrichment and loss of ash composition.

4. Test Results
After analyzing the above test data, the writer summarizes the impacts on furnace combustion made by
fuel calorific value, ash melting characteristics, pulverized coal fineness and slag capturing rate. And then the writer analyzes the influence law of the fuel calorific value, ash melting characteristics, pulverized coal fineness and slag catching rate on boiler slag blockage. Next, the influence law is applied to practice before the analysis of ash components of several main coals in the plant. The results of ash components are as follows:

Table 3 Analysis results of common coals’ ash components

| Test Items                  | Symbol | Unit | Shen Mixed Coal (high calorific value) | Shen Mixed Coal (low calorific value) | Yuzhou Mixed Coal | Inner Mongolia Mixed Coal (high calorific value) | Inner Mongolia Mixed Coal (low calorific value) |
|-----------------------------|--------|------|----------------------------------------|---------------------------------------|-------------------|-----------------------------------------------|-----------------------------------------------|
| Ash melting point           | SiO₂   | ℃    | 1289                                   | 1311                                  | 1330              | 1179                                          | 1283                                          |
| Silica in ash               |        | %    | 57.67                                  | 53.29                                 | 56.97             | 49.02                                         | 53.93                                         |
| Aluminum oxide in ash       | Al₂O₃  | %    | 21.87                                  | 23.2                                  | 23.39             | 18.54                                         | 20.36                                         |
| Ferric oxide in ash         | Fe₂O₃  | %    | 5.17                                   | 5.14                                  | 3.59              | 8.06                                          | 5.22                                          |
| Calcium oxide in ash        | CaO    | %    | 5.76                                   | 6.57                                  | 6.06              | 10.31                                         | 8.69                                          |
| Magnesium oxide in ash      | MgO    | %    | 1.46                                   | 1.91                                  | 2.53              | 1.81                                          | 2.1                                           |
| Sodium oxide in ash         | Na₂O   | %    | 2                                      | 1.2                                   | 1.15              | 1.89                                          | 0.74                                          |
| Potassium oxide in ash      | K₂O    | %    | 2.23                                   | 1.55                                  | 1.69              | 1.27                                          | 1.38                                          |
| Titanium dioxide in ash     | TiO₂   | %    | 0.87                                   | 0.87                                  | 0.86              | 0.75                                          | 0.72                                          |

Table 4 Calculation results of ash components discrimination standard for common coals

| No.  | Discrimination Standard | Shen Mixed Coal (high calorific value) | Shen Mixed Coal (low calorific value) | Yuzhou Mixed Coal | Inner Mongolia Mixed Coal (high calorific value) | Inner Mongolia Mixed Coal (low calorific value) |
|------|------------------------|----------------------------------------|---------------------------------------|-------------------|--------------------------------------------------|-----------------------------------------------|
| 1    | Iron content           | 5.17                                   | 5.14                                  | 3.59              | 8.06                                             | 5.22                                          |
| 2    | Silicon ratio G        | 62.73                                  | 59.14                                 | 61.56             | 55.87                                            | 59.72                                         |
| 3    | Si / Al ratio          | 2.64                                   | 2.30                                  | 2.44              | 2.64                                             | 2.65                                          |
| 4    | Fe / Ca ratio          | 0.90                                   | 0.78                                  | 0.59              | 0.78                                             | 0.60                                          |
| 5    | Alkali / acid ratio    | 0.21                                   | 0.21                                  | 0.18              | 0.34                                             | 0.24                                          |

According to the above-mentioned data:

1. As the design coal of the third-phase boiler, the ash components of Shen Mixed coal have been deviated greatly from the original design about the boiler. Under the same ash melting point, the risk of slag blocking and slagging is higher than that of the original one.

Table 5 Components analysis of designed coal

| No.  | Name            | Symbol | Unit | Designed Coals | Checked Coals | Variation Range |
|------|-----------------|--------|------|----------------|---------------|-----------------|
|      | silicon dioxide | SiO₂   | %    | 46.16          | 31.0-51.0     |                 |
|      | Aluminum oxide  | Al₂O₃  | %    | 17.89          | 11.0-21.0     |                 |
|      | titania         | TiO₂   | %    | 0.8            | 0.7-0.11      |                 |
Compared with Shen Mixed coal, the content of Ca and Fe in Inner Mongolia Mixed coal is higher, while the contents of Na, K and other alkali metals are less. Combined with the analysis of the enrichment and loss of elements in slag of slag-tap boiler, the risk of slag blocking and slagging about Inner Mongolia Mixed coal is greater due to the composition of coal ash elements under the same ash melting point.

Compared with Inner Mongolia Mixed coal, the ash components of Yuzhou Mixed coal is closer to Shenhua, but its ash content and ash melting point are higher. Therefore, Yuzhou Mixed coal is not suitable to be mixed with Inner Mongolia one, or the furnace temperature will drop more with the increase of ash content. Besides, excessively high content of CaO in Inner Mongolia Mixed coal will lose the fusibility, which is easy to cause slag blocking and slugging.

According to the proximate analysis, there is less ash and more moisture in the Mixed coal of Gaotou Kiln. Because the moisture absorption is calculated at the low calorific value, the influence produced by the Mixed Gaotou Kiln with less ash on the furnace temperature is relatively small. Theoretically, it can be Mixed with any coal as long as the calorific value is met.

According to the coal blending and burning situation of the third-phase unit, the risk order of slag blocking and slagging is as follows:
1. Base coal: designed coal < Shen Mixed Coal < Inner Mongolia Mixed Coal.
2. Coal blending: Gaotou Kiln < Yuzhou Mixed Coal.
3. Inner Mongolia Mixed Coals are not suitable for blending with Yuzhou ones.

Therefore, in principle, the coal blending mode of the slag-tap boiler in the plant should conform to the combination in table 6.

| No. | Base Coal | Mixed Coal |
|-----|-----------|------------|
| 1   | Shen Mixed Coal | Yuzhou Mixed Coal |
|     | Inner Mongolia Mixed Coal | Mixed Coal of Gaotou Kiln |

According to the above results, we can obtain the anti blocking slag standard of slag-tap boiler.

| No. | calorific value Kcal/Kg | average ash melting point of burning coal °C | Maximum ash melting point of burning coal °C | full water % |
|-----|-------------------------|--------------------------------------------|------------------------------------------|--------------|
| 1   | 4770                    | 1300<FT≤1350                               | FT>1380                                 | ≤21          |
|     | 4835                    |                                            |                                          |              |
|     | 4900                    |                                            |                                          |              |
|     | 4966                    |                                            |                                          |              |
|     | 5035                    |                                            |                                          |              |
5. Conclusion
The paper analyzes the slag blocking in combustors of the in-service slag-tap boiler, examines the effects on the slag blocking in the combustors created by the coal blending combustion strategy of slag-tap boiler, and studies the calorific value, ash content, ash melting point, ash melting characteristics of coal quality and slag capturing rate of boiler. Based on the above researches, the writer summarizes the effects on slag blocking and slugging in the combustors produced by different coal combustion in slag-tap boiler, and forms coal combustion strategy of the slag-tap boiler. After practical application, the strategy is proved to be effective at present, and the slag blocking in the combustors of the boiler has not occurred again.

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References:
[1] Zhang Qinghong. The Design and Operate for 35t/h Slag Tapping Pulverized Coal Fired Boiler[J]. Industrial Boiler, 2006(02): 18-21.
[2] Zhang Yongli, Xu Hui, Wu Dongyin. Design and Operation Characteristic of a 1025t/h Slag-tap-Boiler[J]. Boiler Manufacturing, 2004(04): 24-26.
[3] CEN Kefa, FAN Jianren, CHI Zuohe, et al. The principle and calculation of foul, slag, wear and corrosion of boilers and heat exchangers[M]. Beijing: Science Press, 1994: 24-32.
[4] Lin Bin. Research on Phase Chang of High Temperature Blast Furnace Slag during cooling process[D]. Chongqing: Chongqing University, 2016: 5.
[5] WANG Xuebin, WEI Bo, ZHANG Limeng, et al. Effect of temperature and silicon additives on occurrence and transformation characteristics of alkali metal in Zhundong coal[J]. Thermal
Power Generation, 2014, 43(8): 84-88.

[6] Lan Dehui, Zhang Zhongxiao, et al. Experimental study on combustion of high alkali coal in horizontal liquid slag cyclone furnace [J/OL]. Clean Coal Technology, 2019.

[7] XU Xuchang, LU Junfu, ZHANG Hai. *Combustion theory and equipments* [M]. Beijing: Science Press, 2012.

[8] LIU Jing, WANG Zhihua, XIANG Feipeng, et al. Modes of occurrence and transformation of alkali metals in Zhundong coal during combustion [J]. Journal of Fuel Chemistry and Technology, 2014, 42(3): 316-322.