Research on the Mechanism of Slagging and Fire-off for different capacity boilers

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Abstract. For slag extinguishing process of different capacities boilers (1000MW, 670MW, 300MW, 150MW), the slag extinguishing mechanism is analysed in terms of equipment, slagging characteristics, coal quality, furnace heat load, and operation mode. Prevention measures for slag extinguishing are put forward in terms of fire coal controlling, operation optimization, and technical transformation. Analyses results show that there are mainly three types of furnace pressure change during the slag extinguishing process. The common feature is that the furnace pressure goes up first, which is because of combustible gas explosion in the lower part of the furnace (primary reason) and the entry of a large amount of water vapor into the furnace (secondary reason). The degree of slagging for these four boilers is aggravated by the factors such as high ash content and sulfur content, the low input frequency of soot blower, and the large fineness of the pulverized coal.

1. Introduction
As the problems of unstable supply of coal, mismatch between the actual and design coal type, and use of low-quality coal (high ash and high sulfur content, low calorific value) are more common nowadays, slagging on the heating surface is becoming increasingly prominent. Slagging is a complex physicochemical process and a complex gas-solid multiphase turbulent transportation problem. When the molten or semi-molten particles entrained in the smoke hit the heating surface, they congeal and accumulate on it. There are mainly four forms of particle transportation and accumulation, namely, inertial migration, thermal migration, condensation, and chemical reaction [1-3]. The formation process of slagging can be roughly divided into three steps: first, the molten or semi-molten viscous mineral salt accumulates on the surface to form the initial deposition layer; second, when the surface temperature of the deposition layer reaches the viscosity limit under the effect of gravity, the initial deposition layer stops to get thicker, and a secondary deposition layer is formed [4-5]. There are many factors influencing furnace slagging, including the characteristics of the fuel, furnace thermal parameters, and boiler operating parameters [6-7].

Slagging on the heating surface will increase the contamination degree on the heating surface, reduce its heat absorption capacity, and affect the economic operation of the boiler. The slag damages the bucket wall, causing drastic fluctuation of the negative pressure in the furnace and even boiler MFT, thus affecting the safe operation of the boiler [8]. Furnace pressure is an important parameter to reflect the combustion condition. The slag extinguishing process is accompanied by large fluctuations in the furnace pressure. However, since the fire extinguishing accident occurs suddenly and ends quickly, it is impossible to observe the actual combustion situation in the furnace in the few seconds before the fire is extinguished, thus causing great difficulties to the analysis of furnace pressure.
fluctuation and the cause of slag extinguishing [9-10]. This paper focuses on the slag extinguishing process of four boilers with different capacities (1000MW, 670MW, 300MW and 150MW), and analyzes the slag extinguishing mechanism, thereby providing an important reference for the analysis of the cause of slag extinguishing in the boilers of the same type.

2. Overview

2.1. Equipment situation
The boilers of different capacities (1000MW, 670MW, 300MW, 150MW) in a power generation company all reported the cases of slag extinguishing. A boiler is a DG3000/26.15-II1 type front-and rear-wall counter-fired supercritical boiler designed and manufactured by Hitachi Technology and introduced by Dongfang Boiler Co., Ltd. B boiler is a SG-2102/25.4-M954 type four-corner tangential burning supercritical boiler designed and manufactured by Alstom Technology and introduced by Shanghai Boiler Factory Co., Ltd. A and B boilers are both equipped with six double-inlet and double-out direct-blowing steel ball coal mills, using scraper-type slag machine for slag removal. C boiler is a SG-1025/17.50-M885 four-corner tangentially fired subcritical boiler designed and manufactured by American CE technology introduced by Shanghai Boiler Factory Co., Ltd. It is equipped with three double-inlet and double-out direct-blowing steel ball coal mills. D boiler is a SG-480/13.7-M767 four-corner tangentially fired ultra-high pressure boiler designed and manufactured by American CE technology introduced by Shanghai Boiler Factory Co., Ltd. It is equipped with steel ball mill intermediate storage type powder-making system. Both C and D boilers adopt hydraulic slag removal.

2.2. Slagging situation
The slagging position of A boiler is mainly in the lower part of the platen superheater. During the rapid load reduction process, slag falling occurs in a great amount for many times, which often leads to the drastic fluctuation of furnace pressure and even boiler MFT. The water wall area of B water boiler is the place where slagging happens frequently and in a great amount. It is often the case that the slag machine is crushed by the falling slag, causing shutdown and even abnormal fluctuation of furnace pressure, triggering the protection setting, thereby leading to boiler MFT. Slagging in C boiler is mainly within the area from the main burner to the burnout zone at the front and side walls. Slag falling leads to frequent fluctuation of the furnace pressure and even dust discharge due to the forcibly-open fire hole. Slagging in D boiler is mainly within the area from the main burner to the burnout zone at the back and side walls. Slag falling worsens the combustion condition of the furnace, resulting in the boiler MFT.

(a) A boiler  (b) B boiler
Figure 1 shows the slagging situation in the four boilers. It can be seen that the slag in A boiler is mainly pale-yellow porous blocks mixed with a very small amount of black slag particles. The texture is hard and the size is relatively large. The slag in B boiler is glass-like, blue-black, compact and hard. The slag in C boiler spreads widely in the furnace. It is small in size and soft in texture. In D boiler after fire extinguishing, a 20 cm-thick φ40cm circular slag remains near the fire hole in the back wall, which is easy to break and fall off.

2.3. Slag extinguishing process

Figure 2 shows the furnace pressure fluctuations before and after the slag extinguishing. It can be seen that the furnace pressure of A boiler in its normal operation remains stable at around -67 Pa. Then, it jumps to +1049 Pa in 10s, and then drops to -376 Pa. The fire detection intensity of the lower burner is temporarily lower than 40%, less than 25%(the triggering value of fire detection). After 6s, it suddenly rises to +3162 Pa (the high furnace pressure of MFT protection is +3000Pa), and the boiler MFT takes action. The MFT front-furnace pressure fluctuation curve is nearly in the shape of "N". The furnace pressure of the B boiler in normal operation remains stable at -100 Pa, but it suddenly rises to +723 Pa within 7s. The fire detection of the A and B layers is lost and the A and B coal mills are tripped. Then, the furnace pressure drops rapidly to -3065 Pa within 5s (the low furnace pressure of MFT protection is -2000 Pa), and the boiler MFT takes action. The MFT front-furnace pressure fluctuation curve is nearly in the shape of "Λ". The furnace pressure of C boiler in normal operation stays stable at -80 Pa. During the short soot blowing, the furnace pressure quickly rises to +928 Pa within 6s, losing the individual fire detection signals in the lower layer. Then the furnace pressure rapidly falls to -1869 Pa in 4s (the low pressure of MFT protection is -1800 Pa), so the boiler MFT actions. The MFT front-furnace pressure fluctuation curve is nearly in the shape of "Λ". The furnace pressure of D boiler in normal operation remains stable at -70 Pa. But the furnace pressure jumps to +414 Pa within 4s, and the fire detection intensity of each layer is instantly reduced, losing all fire detection signals at all layers. The boiler MFT takes action, and MFT front-furnace pressure fluctuation curve is nearly in the shape of "/".
3. Cause analysis

3.1. Causes of slag extinguishing

The effects of slag falling on the combustion condition and furnace pressure fluctuations are: 1) The slag fallen from the upper part of the furnace will carry the high-oxygen smoke to the high-concentration zone of the combustible gas, which is 1 m below the lowermost burner, leading to micro-explosion and rapid furnace pressure rise. Then, the pressure wave generated by the sudden increase of the gas volume shifts instantaneously or blows out the pulverized coal gas flow, leading to the successive loss of fire detection signals from the lower layer to the upper layer, causing a sharp decline in furnace pressure; 2) When the slag in the upper part of the furnace falls into the slag pool, the water in the slag pool will rapidly vaporize and produce a large amount of steam, leading to gas volume increase in the furnace, causing higher furnace pressure and lower combustion temperature. The steam may also block some fire detection probes, and the coal mill continues to work. The pulverized coal gas stream may accumulate and explode, causing the furnace pressure to rise sharply again.

Combined with Fig. 2, it can be seen that in A boiler, the slag deflagrates the combustible gas in the lower part of the furnace. Then, with the entry of a large amount of water vapor in the slag pool, the furnace pressure rises for the first time, but failing to reach the protection value of "high furnace pressure". The pressure wave generated by the sudden increase of the gas volume affects the fire detection intensity of the lower burner, but failing to reach the operating condition of fire detection. The vaporized water vapor lowers the combustion temperature, further worsening the combustion condition, resulting in furnace pressure drop. The coal mill continues to work, and the pulverized coal...
gas flow accumulates and then partially explodes, causing the furnace pressure to rise sharply again, thereby reaching the protection value of "high furnace pressure" and causing boiler MFT. The mechanism of slag extinguishing in B boiler and in C boiler is the same: the slag deflagrates the combustible gas in the lower part of the furnace. Then, with the entry of a large amount of water vapor in the slag pool, the furnace pressure rises, but failing to reach the protection value of "high furnace pressure". The pressure wave generated by the sudden increase of the gas volume causes the loss of lower layer fire detection one after another. In addition, the water vapor may also has the possibility to block some fire detection probes, and the corresponding coal mill is tripped, thus worsening the combustion situation and lowers the furnace pressure, thereby reaching the protection value of "low furnace pressure" and causing boiler MFT. In D boiler, the fallen slag causes the combustible gas in the lower part of the furnace to explode. With the entry of a large amount of steam into the furnace, the furnace pressure increases sharply, but failing to reach the protection value of "high furnace pressure". The pressure wave caused by the sharp increase of explosive gas causes the sudden decrease of the fire detection intensity of each layer. The large amount of water vapor may also block some fire detection probes, leading to the lost of fire detection signals from the lower to the upper layers, thereby reaching the MFT operating condition of “fire extinguishing in the whole furnace”.

Furnaces of different capacities are different in the change of furnace pressure, but they share similar mechanism of slag extinguishing. A boiler has the largest capacity and the strongest stable-combustion ability. The gas deflagration and water vapor blocking reduce the fire detection intensity, but do not lead to the fire detection loss. The furnace pressure increases first and then slightly decreases. However, partial explosion leads to a sharp increase in the furnace pressure, reaching the MFT condition of "high furnace pressure". B boiler and C boiler have a relatively large capacity and relatively strong stable-combustion ability. But the gas deflagration and water vapor blocking cause the loss of lower layer fire detection. The furnace pressure rises and then drops sharply, reaching the MFT condition of "low furnace pressure". D boiler has a small capacity and relatively poor stable-combustion ability, and it loses all the fire detection signals from the lower to the upper layers due to gas deflagration and water vapor blocking, reaching the MFT condition of "fire extinguishing in the whole furnace".

3.2. Causes of Slagging

3.2.1. Slagging characteristics of design coal

The slagging characteristics of different coal types are quite different, which is mainly related to the chemical composition of the ash and rock structure. The current parameters used to judge the slagging degree mainly include coal ash softening temperature, silicon-aluminum ratio, acid-base ratio and silicon ratio. However, since the parameters are not very effective and consistent in slagging judgment, it is necessary to adopt the comprehensive discriminant index $R_Z$ obtained based on over 250 kinds of power coal in China with the orderly optimal distribution method, and its judgment resolution can reach 90%, making the prediction of the slagging characteristics more reliably.

The comprehensive discriminant index $R_Z=0.31C_{t2}+0.24(C_{BA}+C_G)+0.22C_{SO2/Al2O3}$. When $R_Z < 1.5$, the slagging degree is slight; when $1.5 \leq R_Z \leq 2.0$, the slagging degree is medium; when $R_Z > 2.0$, the slagging degree is serious. $C_{t2}=12.197-0.0076t_2$; $C_{BA}=0.4381+5.1546(B/A)$; $C_G=7.705-0.078G$; $C_{SO2/Al2O3}=1.282(SiO_2/Al_2O_3)-0.8974$; $B/A=(Fe_2O_3+CaO+MgO+K_2O+Na_2O)/(SiO_2+Al_2O_3+TiO_2)$; $G=SiO_2·100/(SiO_2+Fe_2O_3+CaO+MgO)$.

Table 1 shows the comprehensive slagging discrimination index of A~D boilers. It can be seen that the slagging degree of A, B and D boilers is medium, while that of C boiler is slight.
Table 1. Comprehensive slagging discrimination index

| Name                        | Slagging index | A boiler | B boiler | C boiler | D boiler |
|-----------------------------|----------------|----------|----------|----------|----------|
| Coal ash softening temperature | $t_2$         | 1350     | 1390     | 1400     | 1390     |
| Silicon-aluminum ratio      | $\text{SiO}_2/\text{Al}_2\text{O}_3$ | 2.53     | 1.32     | 1.61     | 1.80     |
| Acid-base ratio             | $B/A$         | 0.16     | 0.29     | 0.11     | 0.23     |
| Silicon ratio               | $G$           | 84.33    | 70.45    | 85.98    | 72.35    |
| Comprehensive discriminant index | $R_Z$     | 1.69     | 1.67     | 1.22     | 1.70     |

3.2.2. Analysis of actual coal quality

Table 2 compares the quality characteristics of the design coal and those of the actual coal. It can be seen that in A and D boilers, the actual coal has lower calorific value but higher ash content than the design coal. In the C and B boilers, the sulfur content of the actual coal used is higher than that of the design coal. Sulfur content directly affects the slagging characteristics of coal (higher the sulfur content, the easier it is to slag).

Higher ash content and severe fouling of heating surface further aggravate the slagging. Lower calorific value, higher fuel quantity, and higher ash content lead to more serious slagging. Therefore, the actual coals used in A~D boilers are easier to slag compared with the design coals.

Table 2. Comparison between the designed coal and the actual coal

| Name                        | Unit      | A boiler | B boiler | C boiler | D boiler |
|-----------------------------|-----------|----------|----------|----------|----------|
| Designed coal               |           |          |          |          |          |
| Net calorific value         | MJ/kg     | 21.27    | 22.03    | 20.07    | 22.99    |
| Ash content                 | %         | 24.40    | 27.96    | 26.36    | 17.21    |
| Sulfur content              | %         | 0.60     | 1.20     | 0.85     | 0.94     |
| Actual coal                 |           |          |          |          |          |
| Net calorific value         | MJ/kg     | 19.70    | 22.73    | 20.55    | 18.53    |
| Ash content                 | %         | 29.74    | 26.22    | 26.49    | 27.21    |
| Sulfur content              | %         | 0.63     | 1.62     | 1.63     | 1.09     |

3.2.3. Furnace heat load analysis

The parameters such as cross-sectional area of furnace, outlet smoke temperature, $q_V$ (volumetric heat load) and $q_F$ (section heat load) have a great influence on the slagging state and provide an important reference for furnace structure design. Higher $q_V$ leads to shorter residence time of the fuel in the furnace. In this way, the smoke cannot be effectively cooled when it reaches the exit. Higher smoke temperature at the exit leads to higher possibility of slagging on the upper surface of the furnace. Higher $q_F$ leads to smaller furnace circumference, thus higher temperature and severer slagging in the burner area. In general, as the boiler capacity increases, $q_V$ decreases and $q_F$ increases accordingly.

Table 3 shows the design parameters of the furnace. It can be seen that $q_V$ and $q_F$ of A boiler are not much different from those of the boiler of the same type. But its outlet temperature is 1373 °C, which is higher than 1350 °C, the softening temperature of the design coal. In this way, it is easy to cause slagging in the superheater. Generally speaking, $q_F$ of a 600MW lean-coal boiler furnace is about 4525. If the design coal is easy to slag, then the furnace cross-sectional area should be greater than 390m². B boiler furnace has a smaller cross section and relatively large $q_V$, making it easy to slag. C boiler and D boiler have $q_V$ and $q_F$ similar to the boiler of the same type. But the softening temperatures of the blended coal before slag extinguishing in C and D boilers are 1190 °C and 1265 °C, respectively. The burning of low-ash-fusion coal causes slagging in the boiler.
Table 3. Design parameters of the furnace

| Name                        | Unit  | A boiler | B boiler | C boiler | D boiler |
|-----------------------------|-------|----------|----------|----------|----------|
| Furnace cross-sectional area| m²    | 529      | 333      | 177      | 92       |
| Furnace volumetric heat load $q_v$ | kW/m³ | 79       | 79.6     | 103.1    | 132.9    |
| Furnace section heat load $q_f$ | kW/m² | 4300     | 4964     | 4456     | 3982     |
| Furnace outlet temperature  | °C    | 1373     | 1361     | 1332     | 991      |

3.2.4. Analysis of operation mode
The soot blower of A boiler is arranged on both sides of the superheater, but it cannot remove the slag the lower part of the platen superheater in time due to its low input frequency. The slag block rapidly cools down, breaks and falls off when the load is reduced. The fineness of pulverized coal used (R90=27.1%) is higher than that of design pulverized coal (R90=21%). The flame is away from the nozzle, and its center moves up. The smoke temperature at furnace exit is too high, causing slagging at the superheater.

Burner of B boiler adopts 6 layers of concentrated coal powder nozzle and 6 layers of light ones arranged separately. The smoke temperature at the concentrated pulverized coal burner is high and its water wall is severely slagging. The reducing atmosphere further aggravates the degree of slagging of the water wall of the burner. The slagging rate changes exponentially with the smoke temperature. Generally, smoke temperature reduction by 50 °C leads to 50% reduction of the slagging rate. Complex coal types, inaccurate blending ratio, a lack of effective detection means if the mixed coal, and large ratio of low-ash-fusion coal are the reasons for serious slagging.

The incircle size of C boiler is large, and the flame center is slightly close to the front wall, which leads to serious slagging within the area from the front-wall main burner to the burnout zone. The fineness of actual coal powder used (R90=25.2%) is higher than that of the design coal powder (R90=19%). Coarser pulverized coal particles are more likely to cause slagging due to the action of inertia force.

The incircle size of D boiler is large, and the flame center is slightly close to the back wall, which leads to serious slagging within the area from the back-wall main burner to the burnout zone. Complex coal types, inaccurate blending ratio, a lack of effective detection means of the mixed coal, and large ratio of low-ash-fusion coal are the reasons for serious slagging.

4. Prevention measures

4.1. Fire coal controlling measures
It is necessary to establish a database of coal quality and quantity and store the coal in different areas according to their quality characteristics so as to improve the uniformity of coal blending. It is feasible to formulate reasonable blending ratio, and conduct industrial analysis and ash melting point of the characteristics of the mixed coal, thereby avoiding serious slagging due to low ash melting point and large proportion of high-sulfur coal. In addition, it is necessary to maintain the fineness of pulverized coal within a proper range, because excessively coarse pulverized coal will cause high smoke temperature at the exit, leading to slagging at the heated surface while excessively coarse pulverized coal will catch fire too early, leading to slagging in the burner area.

4.2. Operation optimization measures
Reasonable air distribution method can be used to strengthen the disturbance and mixing at the lower part of the furnace, reduce the pulverized coal deposition, and eliminate the high-concentration gas area, thus avoiding violent fluctuations of the furnace negative pressure caused by gas explosion. An appropriate reduction of combustion temperature in the furnace can reduce heat load concentration, thus avoiding the rapid release of alkali metal during combustion and reducing the slagging rate. The incircle of the furnace should be in the middle and its size should not be too large, preventing the
flame center from defecting. In addition, continuous de-slagging should be replaced by intermittent de-slagging and the slag level should remain higher than the water seal, thereby avoiding direct contact between hot slag and water and reducing the formation of water vapor. Last but not least, it is necessary to increase the frequency of soot blowing in the furnace and on the heating surface. When slag falling is frequent, it is feasible to perform soot blowing once per shift.

4.3. Technical transformation measures

Equipment or optimization of the online monitoring system for slagging on the heating surface of boilers can help to guide the operators to properly control the soot blowing procedure, achieving on-demand and effective soot blowing. The lower burner shall be changed to double fire detection so as to reduce the distraction of the fire detection signal caused by slag falling. When necessary, it is feasible to use a suitable de-slagging agent to reduce the slagging strength and avoid the slag extinguishing.

5. Conclusion

The larger the boiler capacity, the stronger the balance capacity of furnace pressure fluctuations, and the lower the risk of slag extinguishing. There are mainly three types of furnace pressure change during the slag extinguishing process. The pressure fluctuation curve of A boiler is in the shape of “N”, that of B and C boilers are in the shape of “A”, and that of D boiler is in the shape of “\U2615”. Their common feature is that the furnace pressure goes up first, which is because of combustible gas explosion in the lower part of the furnace (primary reason) and the entry of a large amount of water vapor into the furnace (secondary reason).

There are many factors influencing boiler Slagging. For A boiler, its design coal of is easy to slag, the burning coal is low in calorific value of and high in ash content, the smoke temperature of the furnace exit is high, the input frequency of soot blower is low, and the fineness of the pulverized coal is too large. For B boiler, the design coal is easy to slag, the burning coal is high in sulfur content, the furnace cross section has a high heat load, and the blending ratio is unreasonable. For C boiler, the burning coal is high in sulfur content, the proportion of low-ash melting point coal is high, the incircle size is large and the flame center is slightly biased toward the front wall, and the fineness of the pulverized coal is large. For D boiler, the design coal is easy to slag, the burning coal is low in calorific value and high in ash content, the proportion of low-ash melting point coal is high, the incircle size is large and the flame center is slightly biased toward the back wall.

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