COMBUSTION ADJUSTMENT AND OPERATION OPTIMIZATION OF A 240 t/h CIRCULATING FLUIDIZED BED BOILER

by

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The influence of main operating parameters on boiler performance was studied, such as bed pressure drop, primary air-flow and secondary air-flow. Combustion adjustment tests were carried out on a circulating fluidized bed boiler with rated capacity of 240 t/h. From the test results, it can be seen that the loss due to exit flue gas is the largest heat loss of the boiler, accounting for more than 70% of the total heat losses. For coal fired boilers, compared with the loss due to unburned solids, the loss due to unburned gases is quite small. The unburned carbon content in bottom ash is far lower than the value in fly ash. The trend of CO concentration in the exit flue gas is similar to that of the unburned carbon content in fly ash. To achieve higher boiler efficiency, the bed pressure drop is suggested to be maintained in about 8.5-9.0 kPa and the oxygen content in exit flue gas around 4%. The NO_x emission concentration usually presents a negative correlation with CO concentration in exit flue gas. Through combustion adjustment and operation optimization, the NO_x emission can be decreased by about 30% without affecting the boiler efficiency.

Key words: *circulating fluidized bed boiler, combustion adjustment, heat loss, optimal operating parameters, NO_x emission*

Introduction

In China, energy conservation and environmental protection have become more and more important in recent years. As coal plays a leading role in the energy consumption structure, coal-fired boilers have always been the focus of attention. One of the main problems associated with coal combustion is low combustion efficiency and high NO_x emission. In order to improve the coal-fired boiler performance, many techniques have been applied to new boilers as well as existing boilers [1-4].

Combustion adjustment is designed to change some adjustable parameters and then measure the boiler performance comprehensively. From the aspects of safety and economy, the optimal operation mode can be determined by analysing the results. High efficiency and

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low NO_x emission can be achieved in utility coal-fired boilers through comprehensive operation optimization, with NO_x emission decreased by 182 ppm [5].

Zhou *et al.* [6] solved the water wall overheating problems of a 600 MW supercritical W-flame boiler by using combustion adjustment, which was performed on the aspects of secondary air distribution, coal particle size, and primary air pressure. Wang *et al.* [7] and Xiao *et al.* [8] studied the effect of combustion adjustment on NO_x emission and boiler efficiency. Zhong *et al.* [9] carried out a combustion adjustment test on a 300 MW circulating fluidized bed (CFB) boiler, in aspects of total air, primary air, the particle size of coal and secondary air. Qi *et al.* [10] conducted a combustion adjustment test on a CFB boiler under a practical load.

In this work, a combustion adjustment test was carried out on a CFB boiler with a rated capacity of 240 t/h to achieve operation optimization. The orthogonal test method [11] was adopted to design test conditions. Main operating parameters, such as the bed pressure drop, primary air and secondary air-flow were adjusted. Then the boiler performance, including boiler efficiency and NO_x emission were measured. Based on the measurement results, the effect of operating parameters on boiler performance was analysed and the optimal operation modes were suggested.

The calculation method of boiler efficiency

The basis of boiler efficiency calculation is the First law of thermodynamics, namely the law of conservation of energy. It can be stated as [12].

Energy entering the system-energy leaving the system = accumulation energy in the system.

Since a boiler should be tested under steady-state conditions, such that accumulation is zero, the equation is energy entering the system = energy leaving the system, namely:

$$Q_{\mathrm{net.ar}}\left(\text{Input from fuel}\right)+Q_{\mathrm{ex}}\left(\text{Credits}\right)=Q_{\mathrm{out}}\left(\text{Output}\right)+Q_{\mathrm{loss}}\left(\text{Losses}\right) \tag{1}$$

According to GB/T 10184 [13], boiler efficiency usually refers to fuel efficiency, which can be calculated:

$$\eta = 100\frac{Q_{\mathrm{out}}}{Q_{\mathrm{net.ar}}}(\%) \tag{2}$$

Combining eq. (1) and eq. (2), eq. (3) can be obtained:

$$\eta = \left[100-100\frac{Q_{\mathrm{loss}}-Q_{\mathrm{ex}}}{Q_{\mathrm{net.ar}}}\right](\%) \tag{3}$$

which can be further expressed:

$$\begin{aligned}\eta &= \left[100-100\frac{Q_2+Q_3+Q_4+Q_5+Q_6+Q_7+Q_{\mathrm{oth}}-Q_{\mathrm{ex}}}{Q_{\mathrm{net.ar}}}\right](\%)\\ &=\left[100-\left(q_2+q_3+q_4+q_5+q_6+q_7+q_{\mathrm{oth}}-q_{\mathrm{ex}}\right)\right](\%)\end{aligned} \tag{4}$$

where Q_2 is the heat loss due to exit flue gas, which can be calculated:

$$\begin{aligned}Q_2 &= Q_{\mathrm{2.fg.d}} + Q_{\mathrm{2.wv.fg}}\\ &=V_{\mathrm{fg.d.AH.lv}}c_{\mathrm{p.fg.d}}\left(t_{\mathrm{fg.AH.lv}}-t_{\mathrm{re}}\right)+V_{\mathrm{wv.fg.AH.lv}}c_{\mathrm{p.wv}}\left(t_{\mathrm{fg.AH.lv}}-t_{\mathrm{re}}\right)\end{aligned} \tag{5}$$

where $Q_{2.\mathrm{fg.d}}$ is the heat loss due to dry flue gas, and $Q_{2.\mathrm{wv.fg}}$ – the heat loss due to water vapour in exit flue gas.

The $V_{\mathrm{fg.d.AH.lv}}$ is the volume of dry flue gas, and it depends on the fuel type and excess air ratio:

$$V_{\mathrm{fg.d.AH.lv}} = V_{\mathrm{fg.d.th.cr}} + (\alpha_{\mathrm{cr}} - 1)V_{\mathrm{a.d.th.cr}} \tag{6}$$

where $c_{p.\mathrm{fg.d}}$ is the specific heat of dry flue gas, $c_{p.\mathrm{wv}}$ – the specific heat of water vapour, $V_{\mathrm{wv.fg.AH.lv}}$ – the volume of water vapour in flue gas, $t_{\mathrm{fg.AH.lv}}$ – the exit flue gas temperature, t_{re} – the reference temperature, $V_{\mathrm{fg.d.th.cr}}$ – the volume of theoretical flue gas, α_{cr} – the excess air ratio, and $V_{\mathrm{a.d.th.cr}}$ – the volume of theoretical air.

The Q_3 is the heat loss due to unburned gases, which can be calculated:

$$Q_3 = V_{\mathrm{fg.d.AH.lv}}\left(126.36\varphi_{\mathrm{CO.fg.d}} + 358.18\varphi_{\mathrm{CH_4.fg.d}} + 107.98\varphi_{\mathrm{H_2.fg.d}} + 590.79\varphi_{\mathrm{C}_m\mathrm{H}_n\mathrm{.fg.d}}\right) \tag{7}$$

where $\varphi_{\mathrm{CO.fg.d}}$, $\varphi_{\mathrm{CH_4.fg.d}}$, $\varphi_{\mathrm{H_2.fg.d}}$, and $\varphi_{\mathrm{C_mH_n.fg.d}}$ are the volume fractions of CO, CH_4, H_2, and C_mH_n in flue gas, respectively. In general, only CO is considered.

The Q_4 is the heat loss due to unburned solids:

$$Q_4 = 3.3727\omega_{\mathrm{as.to.des}}\omega_{\mathrm{cr.rs.m}} \tag{8}$$

where $\omega_{\mathrm{as.to.des}}$ is the mass fraction of ash per kg of fuel after adding desulphurizer and $\omega_{\mathrm{cr.rs.m}}$ is the average combustible content in residue.

The Q_5 is the heat loss due to surface radiation and convection, Q_6 is the heat loss due to sensible heat of residue, Q_7 is the heat loss due to sulphur capture, and Q_{oth} is the other heat loss.

From the analysis, it can be seen that Q_2 and Q_6 are sensible heat losses, which are caused by the temperature of the gas and solid flow leaving the boiler system is higher than the ambient temperature. The Q_5 is the heat loss due to radiation and convection heat transfer of the furnace and tail flue wall, which is also caused by the fact that the temperature of the boiler outer wall is higher than that of the ambient temperature. Due to the difficulties and high cost of low temperature heat utilization, q_2 is usually the highest heat loss. The Q_3 and Q_4 are losses due to incomplete combustion. The Q_7, namely the loss due to sulphur capture, should be calculated for CFB boilers, which is also caused by reaction and is relatively small. In ASME PTC4, the loss due to the formation of NO_x is also considered. Therefore, the heat losses can be classified into two categories. The first category is about sensible heat losses, which are related to temperature difference. The second category concerns the losses caused by combustion or other reactions.

Field tests

Brief description of boiler

The combustion adjustment tests were carried out on a CFB boiler with a rated capacity of 240 t/h. The nominal steam pressure and temperature are 12 MPa and 540 °C, respectively. The guaranteed boiler efficiency is 90.75%, with design feed water temperature and exit flue gas temperature of 158 °C and 135 °C. The furnace structure is a membrane water wall, with the lower part covered by the refractory lining. Coal and limestone particles are injected into the furnace from four coal feeding holes, which are located on the front wall.

Test conditions

During the test, the boiler load was maintained around the rated capacity, namely 240 t/h (±5 t/h). To study the effect of main operating parameters on boiler performance, bed pressure drop, primary air-flow and secondary air-flow were adjusted. The bed pressure drop was adjusted in the range of 8-9 kPa, the primary air-flow was adjusted in the range of 13×10^4-14.5×10^4 Nm^3/h, and the secondary air-flow was adjusted in the range of 9.5×10^4-10.5×10^4 Nm^3/h. The mass fraction of the primary air was changed from 55% to 60% correspondingly. The orthogonal test method was adopted to design the test conditions. Details are shown in tab. 1. Bed temperature is also a key operation parameter, but it is determined by other parameters, such as boiler load, bed pressure drop and excess air ratio. Therefore, the bed temperature is usually not treated as a separate adjustment parameter, while the change of bed temperature before and after adjustment needs special attention. The proximate analysis of feed coal in different cases is shown in tab. 2.

Table 1. Test conditions

Cases	Bed pressure drop [kPa]	Primary air-flow [10^4 Nm^3/h]	Secondary air-flow [10^4 Nm^3/h]
1	9.1	14.0	9.5
2	8.8	13.4	9.5
3	8.4	12.9	10.4
4	8.5	12.8	10.7
5	8.6	13.6	10.7
6	8.8	14.1	10.0
7	8.0	13.0	10.2
8	8.4	13.9	9.4
9	8.7	14.4	9.4

Table 2. The proximate analysis of feed coal

Items	Units	Case 1, 2, 3	Case 4, 5, 6	Case 7, 8, 9
Moisture (total)	%	6.37	6.72	7.55
Moisture (air dried)	%	0.97	1.57	1.06
Ash (as received)	%	27.99	28.90	25.34
Volatile matter (dry ash free)	%	28.99	33.09	34.75
Net calorific value (as received)	MJ/kg	22.57	21.68	22.30

Testing methods

The main operating parameters during the test period were recorded every 15 minutes, including the temperature, pressure and flow of steam and feed water, exit flue gas temperature and composition, and ambient temperature, *etc*. Coal fed into the furnace was sampled at the coal feed belt with 2 kg each time. Sampling timing should be advanced appropriately to ensure that the sample is representative of coal particles burned in the furnace during the test. A roller ash cooler is adopted without utilizing the heat of cooling water. Bottom ash was sampled at the outlet of the ash cooler. In the calculation of loss due to sensible heat of residue, the bottom ash temperature was selected as the average bed temperature and the bottom ash fraction was 20%. The unburned combustible contents in fly and bottom ash were measured. Exit flue gas temperature was measured using a grid of Type K thermocouples at the outlet of the air heater. The number of grid points was 6×5. The flue gas samples were taken from the same measurement points used for temperature determination. Then the flue gas collected from the sampling grid was combined to form a composite sample, which was continuously analysed during the test. The average value of each constituent, namely volume fraction of O_2, CO, CO_2, and NO_x, was the measured value of the mixed analysis sample. The layout of measurement points is shown in fig. 1.

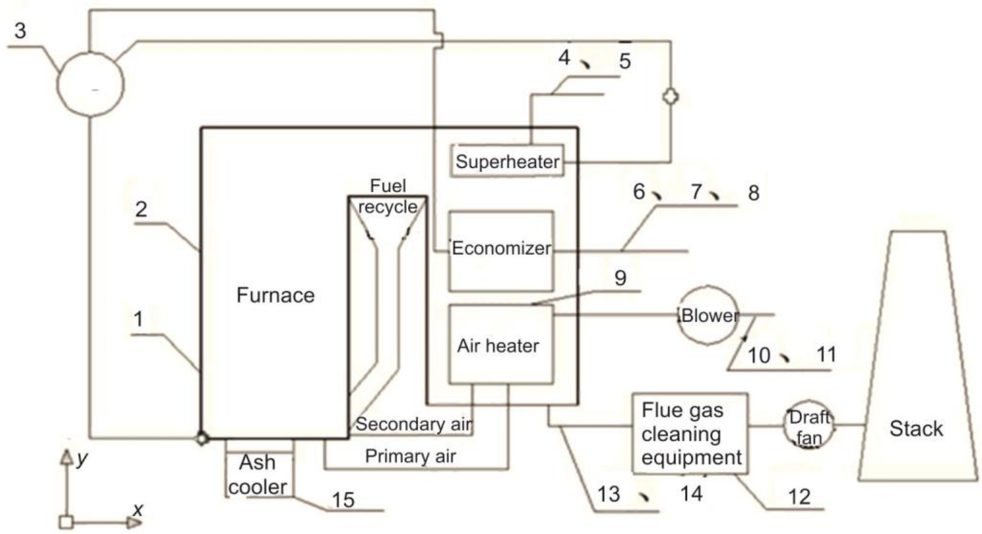

Figure 1. Layout of measurement points; *1 – fuel sampling at feed belt, 2 – boiler outer surface temperature at boiler outer surface, 3 – drum pressure at drum, 4 – steam pressure at main steam pipe, 5 – steam temperature at main steam pipe, 6 – feed water pressure at feed water pipe, 7 – feed water flow at feed water pipe, 8 – feed water temperature at feed water pipe, 9 – gas temperature at air heater inlet at air heater inlet, 10 – cold air temperature at blower inlet, 11 – air humidity at blower inlet, 12 – fly ash sampling at precipitator discharge port, 13 – exit flue gas composition analysis at air heater gas duct outlet, 14 – exit flue gas temperature at air heater gas duct outlet, and 15 – bottom ash sampling at ash cooler outlet*

Effect of operating parameters on boiler performance

Effect of operating parameters on combustion efficiency

The unburned carbon content in fly and bottom ash and CO concentration in exit flue gas in different cases are shown in fig. 2. Figure 2 shows that the unburned carbon content in bottom ash is far lower than the value in fly ash. This is because of the large amount of bed material with high temperature and adequate residence time of coarse particles. As the mass fraction of bottom ash was selected as 20%, the change in average unburned carbon content is similar to the change in unburned carbon content in fly ash. The trend of CO concentration in the exit flue gas is also similar to the unburned carbon content in fly ash.

Figure 3 shows the air-flow in different cases and corresponding oxygen and CO content in the exit flue gas. As the primary air-flow was adjusted, the secondary air-flow showed an opposite trend to reduce the change in total air-flow. The fraction of primary air-flow was kept in the range of 55-60%. For a fixed coal type and load, the trend of oxygen content in exit flue gas is consistent with that of total air-flow entering the furnace, while the trend of CO concentration presented an opposite trend. CO is generated from coal devolatilization and incomplete combustion of char particles. At the same time, CO reacts with O_2 to produce CO_2. Therefore, as the oxygen content increases, the CO concentration decreases.

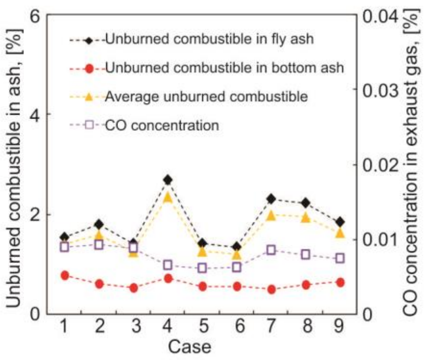

Figure 2. Unburned gas and solids

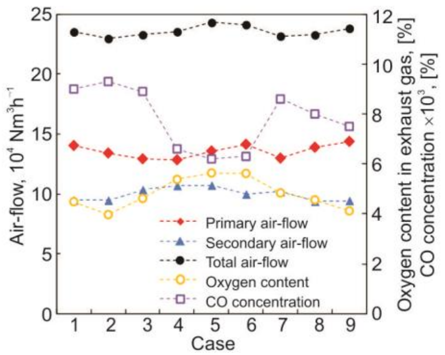

Figure 3. Air-flow and oxygen content in exit flue gas

The effect of main operating parameters on unburned carbon content in fly ash and the relationship among these operating parameters are shown in fig. 4. High bed temperature is favourable for combustion. At a certain load and with fixed coal particle size, a decrease in bed pressure drop yields a decrease in heat transfer coefficient, and an increase in bed temperature [14]. As air has a cooling effect on bed materials, there is a negative correlation between the bed temperature and the primary air-flow. The effect of bed pressure drop on char combustion is mainly reflected in two aspects. For a fixed separation efficiency of the cyclone, when the bed pressure drop decreases, the residence time of particles shortens, which is not beneficial to burning out of char particles [15, 16]. On the other hand, a decrease in bed pressure drop yields a decrease in solid concentration in the transition zone, which is favourable for secondary air penetration and oxygen mixing [17]. Besides, the primary air-flow determines the fluidization characteristics in the dense bed. As the primary air-flow decreases, the atmosphere in the dense bed tends to be lean oxygen, which is not beneficial to burning out of char particles, as shown in fig. 4.

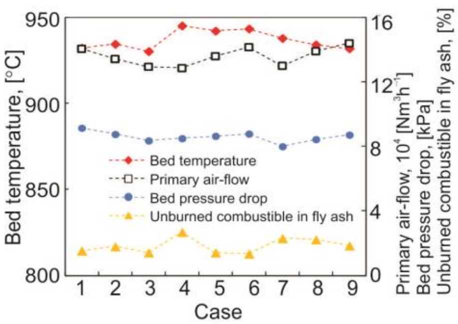

Figure 4. Effect of operating parameters on unburned combustible in fly ash

According to the unburned carbon content in fly and bottom ash and CO concentration in the exit flue gas, the losses due to unburned gases and solids can be calculated, as shown in tab. 3. It can be seen that for coal fired boilers, compared with the loss due to unburned solids, the loss due to unburned gases is quite small. Although the effect of the loss due to unburned gases on boiler efficiency can be neglected, CO concentration in the exit flue gas is an essential indicator of combustion state in the furnace. From the perspective of combustion efficiency, Cases 3, 5, and 6 are better. The recommended bed pressure drop is around 8.5 kPa and the oxygen content higher than 5.5%.

Table 3. Calculation results of heat losses and boiler efficiency

Items	Units	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Loss due to exit flue gas	%	5.86	5.61	5.88	5.95	6.03	5.94	6.33	6.24	6.15
Loss due to unburned gases	%	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.03	0.03
Loss due to unburned solids	%	0.64	0.72	0.57	1.14	0.61	0.58	0.83	0.81	0.68
Loss due to surface radiation and convection	%	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Loss due to sensible heat of residue	%	0.4	0.4	0.4	0.43	0.43	0.42	0.37	0.37	0.37
Loss due to sulphur capture	%	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.02
Total heat losses	%	7.74	7.57	7.69	8.34	7.89	7.77	8.38	8.25	8.03
Boiler efficiency	%	92.26	92.43	92.31	91.66	92.11	92.23	91.62	91.75	91.97

Effect of operating parameters on boiler efficiency

Based on the measurement results, heat losses can be calculated, as shown in tab. 3. It can be concluded that the loss due to exit flue gas is the largest heat loss of the boiler, accounting for more than 70% of the total heat losses. Compared with the loss due to exit flue gas, other losses are relatively small. As mentioned before, the loss due to unburned gases and loss due to sulphur capture are quite small. Main heat losses in different cases are shown in fig. 5. The loss due to sensible heat of residue depends on temperature of fly ash and bottom ash, with little change in different cases.

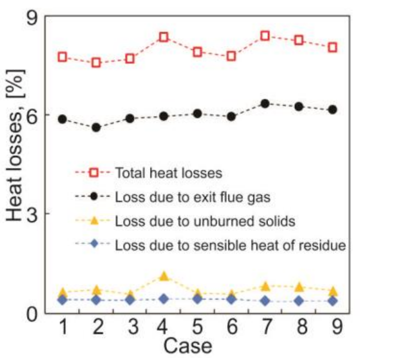

Figure 5. Heat losses in different cases

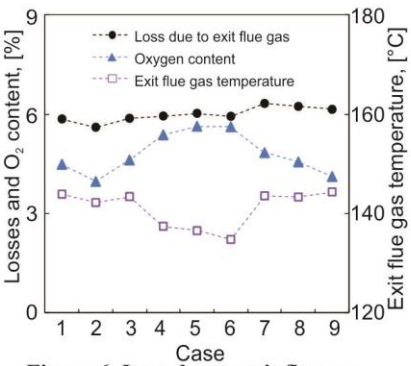

Figure 6. Loss due to exit flue gas

Due to the difficulties and high cost of low temperature heat utilization, a significant amount of energy resides in the exit flue gas. The loss due to exit flue gas is determined by the exit flue gas-flow and the temperature difference between exit flue gas temperature and ambient temperature, which can be seen from eq. (5). During the test period, the ambient temperature was basically unchanged. Therefore, as the exit flue gas temperature increases, the loss due to exit flue gas usually increases. For a fixed coal type and load, exit flue gas-flow is directly related to the excess air ratio, eq. (6), which can be reflected in the oxygen content in exit flue gas. An increase in oxygen content means an increase in exit flue gas-flow, leading to an increase in the loss due to exit flue gas, as shown in fig. 6.

Compared comprehensively, in Cases 1-3, the boiler efficiency is relatively high. Through analysis of the main operating parameters, the bed pressure drop is suggested to be maintained in about 8.5-9.0 kPa, the oxygen content in exit flue gas around 4%, and the bed temperature around 930 °C.

Effect of operating parameters on NO_x emission

For CFB boilers, desulphurization can be achieved by adding limestone into the furnace with relatively low cost. This work mainly focuses on NO_x emission. Generally, the NO_x emission of CFB boilers is much lower than that of pulverized coal boilers because of a lower furnace temperature and unique oxidation/reduction atmosphere in the dense zone. Operating parameters, such as excess air ratio, ratio of primary and secondary air-flow, and bed temperature, all affect the process of NO_x formation and reduction [18]. The reduction atmosphere can effectively inhibit NO_x formation, especially in the dense zone. As the excess air ratio increases or the ratio of primary and secondary air-flow increases, NO_x emission concentration usually increases, as shown in fig. 7. In addition, NO_x emission concentration increases significantly with increasing temperature. This is because when the bed temperature increases, the volatile matter release rate and production increase, and the proportion of volatile-nitrogen correspondingly increases. The conversion rate of nitrogen in coal particles to NO increases. Moreover, as the bed temperature increases, the NO generation reaction and the reduction reaction accelerate at the same time, and the effect of temperature on the generation reaction is more significant, which also increases the NO concentration. At the same time, when the temperature in the furnace increases, it is conducive to the char combustion reaction, which is also not beneficial to the reduction of NO. In general, the effect of operating parameters on NO emission is opposite to the effect on combustion, which can be seen from the negative correlation between CO and NO_x concentration, as shown in fig. 7. However, through combustion adjustment and optimization of operating parameters, NO_x emission can be decreased without affecting combustion in the furnace, for example, increasing the proportion of secondary air properly. As mentioned before, the effect of CO concentration in exit flue gas on boiler efficiency is quite small. Therefore, the NO_x emission can be decreased by about 30% without affecting the boiler efficiency, for instance, Case 2.

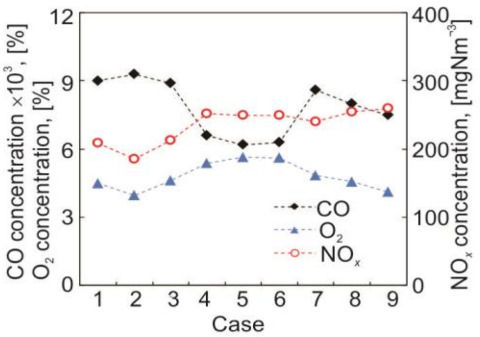

Figure 7. The NO_x emission in different cases

Conclusions

To investigate the influence of main operating parameters on boiler performance, combustion adjustment tests were carried out on a CFB boiler with rated capacity of 240 t/h. Bed pressure drop, primary air-flow and secondary air-flow were adjusted. The test results indicate that the unburned carbon content in bottom ash is far lower than the value in fly ash. The trend of CO concentration in the exit flue gas is similar to the unburned carbon content in fly ash. For coal fired boilers, compared with the loss due to unburned solids, the loss due to unburned gases is quite small. The loss due to exit flue gas is the largest heat loss of the boiler, accounting for more than 70% of the total heat losses. Through combustion adjustment, the boiler efficiency can be increased to 92.43%, which is 1.7% higher than the guaranteed boiler efficiency. To achieve higher boiler efficiency, the bed pressure drop is suggested to be maintained in about 8.5-9.0 kPa, and the oxygen content in exit flue gas around 4%. The NO_x emission usually presents a negative correlation with CO concentration in the exit flue gas. Through combustion adjustment and operation optimization, the NO_x emission can be decreased by about 30% without affecting the boiler efficiency.

Acknowledgment

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Nomenclature

$c_{p.\mathrm{fg.d}}$ – specific heat of dry flue gas, [$\mathrm{kJm^{-3}K^{-1}}$)]
$c_{\mathrm{p.wv}}$ – specific heat of water vapour, [$\mathrm{kJm^{-3}K^{-1}}$)]
Q_{ex} – energy entering the boiler envelope other than the chemical energy in the as-fired fuel, [$\mathrm{kJkg^{-1}}$]
q_{ex} – credits, [–]
Q_{loss} – energy that exits the boiler envelope other than the energy in the output stream, [$\mathrm{kJkg^{-1}}$]
$Q_{\mathrm{net.ar}}$ – lower heating value of fuel, [$\mathrm{kJkg^{-1}}$]
Q_{oth} – other heat loss, [$\mathrm{kJkg^{-1}}$]
q_{oth} – other heat loss, [–]
Q_{out} – energy absorbed by the working fluid that is not recovered within the boiler envelope, [$\mathrm{kJkg^{-1}}$]
Q_2 – heat loss due to exit flue gas, [$\mathrm{kJkg^{-1}}$]
$Q_{2.\mathrm{fg.d}}$ – heat loss due to dry flue gas, [$\mathrm{kJkg^{-1}}$]
$Q_{2.\mathrm{wv.fg}}$ – heat loss due to water vapour in exit flue gas, [$\mathrm{kJkg^{-1}}$]
Q_3 – heat loss due to unburned gases, [$\mathrm{kJkg^{-1}}$]
Q_4 – heat loss due to unburned solids, [$\mathrm{kJkg^{-1}}$]
Q_5 – heat loss due to surface radiation and convection, [$\mathrm{kJkg^{-1}}$]
Q_6 – heat loss due to sensible heat of residue, [$\mathrm{kJkg^{-1}}$]
Q_7 – heat loss due to sulphur capture, [$\mathrm{kJkg^{-1}}$]
q_2 – loss due to exit flue gas, [–]
q_3 – loss due to unburned gases, [–]
q_4 – loss due to unburned solids, [–]
q_5 – loss due to surface radiation and convection, [–]
q_6 – loss due to sensible heat of residue, [–]
q_7 – loss due to sulphur capture, [–]
$t_{\mathrm{fg.AH.lv}}$ – exit flue gas temperature, [°C]
t_{re} – reference temperature, [°C]
$V_{\mathrm{a.d.th.cr}}$ – volume of theoretical air, [$\mathrm{m^3kg^{-1}}$]
$V_{\mathrm{fg.d.AH.lv}}$ – volume of dry flue gas, [$\mathrm{m^3kg^{-1}}$]
$V_{\mathrm{fg.d.th.cr}}$ – volume of theoretical flue gas, [$\mathrm{m^3kg^{-1}}$]
$V_{\mathrm{wv.fg.AH.lv}}$ – volume of water vapour in flue gas, [$\mathrm{m^3kg^{-1}}$]

Greek symbols

α_{cr} – excess air ratio, [–]
η – fuel efficiency, [–]
$\varphi_{\mathrm{CO.fg.d}}$ – volume fraction of CO in flue gas, [–]
$\varphi_{\mathrm{CH_4.fg.d}}$ – volume fraction of CH_4 in flue gas, [–]
$\varphi_{\mathrm{H_2.fg.d}}$ – volume fraction of H_2 in flue gas, [–]
$\varphi_{\mathrm{CmHn.fg.d}}$ – volume fraction of C_mH_n in flue gas, [–]
$\omega_{\mathrm{as.to.des}}$ – mass fraction of ash per kg of fuel after adding desulphurizer, [–]
$\omega_{\mathrm{cr.rs.m}}$ – average combustible content in residue, [–]

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