Analysis model of coal consumption deviation for main operation parameters in boilers burning pulverized coal and BFG

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Abstract. For the boiler main operation parameters, the deviation of operating parameters from the target value can cause the decrease of boiler thermal efficiency, which can further lead to the increase of unit coal consumption for power generation. Aimed at this problem, the key points of the thermal efficiency calculation for boilers mixedly burning pulverized coal and blast furnace gas (BFG) were analyzed, and the coal consumption deviation analysis model was proposed based on the modified calculation formulas. This model can provide further guidance for boiler optimized operation. A 220t/h boiler was analysed as an example, which the extra coal consumption was obtained caused by the non-optimal operation parameters.

1. Introduction
The blast furnace gas (BFG) is generated from the still plant, which is characterized by lower thermal value, higher nitrogen residuals, and instability in combustion. Majority of the plants did not fully take advantage of the BFG, which caused energy wastes. It is still a technology concern on how to make use of the BFG to increase the energy efficiency of the still plants.

Lately, a few good applications were available for the BFG mixing together with the pulverized coal in the still plants [1-4]. Such applications have multiple advantages: 1) making the combustion easier for BFG comparing to the BFG alone; 2) reducing the drain rate of BFG into the environment directly; 3) helping the pressure balance of the gas pipe nets; 4) decreasing the emission of SO₂, NOx and BFG particles. Thus, it is advisable for this type of application in still plants, regarding the economic incentives and social benefits.

With the promotion of decreasing energy consumption and emissions, the economic operation of generators received attentions. The coal consumption deviation analysis is a promising technology to achieving the targets of lower energy consumption and emissions, which studies the deviations of operation parameters from the target values [5-6]. It is widely used in the common thermal power
plants with energy savings [7-11]. However, there is a lack of study for the mixing of BFG and pulverized coal in the thermal power plants. In this paper, we analyzed the calculation key points for thermal efficiency of mixed-fired boiler and improved the key formulas. On this basis, we proposed a coal consumption deviation analysis model that is suitable for the mixedly burned boiler. This model can be used to guide the boiler optimization adjustment, make the unit in or close to the optimal operating state, and finally save energy and reduce consumption.

2. Coal consumption deviation calculation model
The coal consumption model is given as below:

\[(\Delta b)_i = -(\delta E)_i b_b \]  

Where \((\Delta b)_i\) is the change of fuel consumption rate after the operating parameter deviating from the normal value, g/(kW·h); \((\delta E)_i\) is the change of thermal index of plants after the operating parameter deviating from the normal value; \(b_b\) is the standard coal consumption rate, g/(kW·h), which can be obtained from the equation below:

\[b_b = \frac{B_c (Q_{ar,net})_c + B_g (Q_{ar,net})_g}{29307 P_e}\]  

Where \(Q_{ar,net}_c\) is lower heating value of coal, kJ/kg; \(Q_{ar,net}_g\) is lower heating value of BFG, kJ/m³; \(B_c\) is the coal consumption rate, kg/h; \(B_g\) is the BFG consumption rate, m³/h; \(P_e\) is the plant power, MW.

The boiler operating parameters, such as the exhaust temperature, oxygen content in exhaust gas, unburn exhaust, CO content in exhaust gas, can be associated with the boiler efficiency. Thus equation (1) can be converted into:

\[(\Delta b)_i = -(\delta \eta_b)_i b_b \]  

Where \((\delta \eta_b)_i\) is the change of boiler efficiency after the operating parameters deviating from normal value.

Thus, the coal consumption change can be obtained from the change of boiler stove when the operating condition is deviating from target values.

3. Thermal efficiency calculation model of mixed-fired boiler

3.1. Mixed fuel characteristic calculation model
The final combustion characteristics of mixing fuels by BFG and pulverized coal can be obtained by the mass flow rate and characteristic data of each fuel. Then the correlation calculation of boiler thermal efficiency is carried out by mixed fuel characteristics.

The mixed fuel characteristics can be derived as:

\[y_i = b_{coal} x_{coal,i} + b_{gas} x_{gas,i} \]  

\[b_{coal} = \frac{B_c}{B_c + B_g \rho_{gas}} \]  

\[b_{gas} = \frac{B_g \rho_{gas}}{B_c + B_g \rho_{gas}} \]

Where \(y_i\) is the combustion characteristics of the combined fuels; \(x_{coal,i}\) is the combustion characteristics of pulverized coal; \(x_{gas,i}\) is the combustion characteristics of BFG; \(b_{coal}\) is the percentage of coal consumption rate to the total fuel rate; \(b_{gas}\) is the percentage of BFG consumption rate to the total fuel rate; \(\rho_{gas}\) is the density of BFG, kg/m³.
Due to the distinguishes between the BFG and coal, it is necessary to convert the BFG to be in accordance with the coal. Usually, the BFG are usually converted based on the elementary compositions like coal. It is the same for gases and waters.

3.2. Conventional solution model of boiler thermal efficiency

The boiler efficiency can be obtained by thermal loss, based on the combustion characteristics of the mixed fuel characteristics [12]:

$$\eta_b = 100 - (q_2 + q_3 + q_4 + q_5 + q_6)$$  \hspace{1cm} (7)

Where $q_2$ is thermal loss from exhaust gas, $\%$; $q_3$ is thermal loss from the imperfect combustion of gases, $\%$; $q_4$ is thermal loss from the imperfect combustion of solids, $\%$; $q_5$ is the thermal loss from boilers, $\%$; $q_6$ is thermal loss from ashes, $\%$; Among the thermal losses, the exhaust gas contribute most, which can be expressed by equation (8)-(13):

$$q_2 = \frac{(V_{g}\alpha V + V_{H_2}O\alpha V_{H_2}O)}{Q} (\theta_{py} - t_0) \times 100$$  \hspace{1cm} (8)

Where $V_{g}\alpha$ is actual volume of dry gases from each kilogram of mixing fuels, $\text{m}^3/\text{kg}$; $V_{H_2}O$ is the volume of water from each kilogram of mixing fuels, $\text{m}^3/\text{kg}$; $V_{g}\alpha$ is theoretical volume of dry gases from each kilogram of mixing fuels, $\text{m}^3/\text{kg}$; $\alpha$ is excess air coefficient; $\theta_{py}$ is exhaust temperature, $^\circ \text{C}$; $t_0$ is basic temperature, $^\circ \text{C}$; $Q$ is thermal value input, $\text{kJ/kg}$; $c_{py}$ is the average thermal capacity of dry gases between $t_0$ and $\theta_{py}$, $\text{kJ/(m}^3\cdot\text{K})$; $c_{H_2}O$ is average thermal capacity of water between $t_0$ and $\theta_{py}$, $\text{kJ/(m}^3\cdot\text{K})$; $d_4$ is absolute humidity of air, $\text{kg/kg}$; $C_{eq}$ is the carbon consumption from the converted calculation of combustion for mixing fuels $\%$; $C_{eq}, H_{eq}, O_{eq}, N_{eq}, S_{eq}$ is the elementary composition in the mixing fuels $\%$; $M_{eq}, A_{eq}$ is the elementary water and mass content in the mixing fuels, $\%$; $C_{eq}, C_{eq}$ is the carbon content in slag and flying gases, $\%$; $r_{eq}, r_{eq}$ is the ashes content from slag and flying ashes, $\%$.

The thermal loss from the imperfect combustion is given as:

$$q_3 = 12636 \frac{V_{g}\alpha V\phi'(CO)}{Q}$$  \hspace{1cm} (14)

Where $\phi'(CO)$ is the volume of CO in the dry gases, $\%$.

The thermal loss of solid $q_4$ can be obtained from equation (15):

$$q_4 = \frac{337.27A_{eq}}{Q} \left[ \frac{r_{eq}C_{eq}}{100 - C_{eq}} + \frac{r_{eq}C_{eq}}{100 - C_{eq}} \right]$$  \hspace{1cm} (15)
Where \( q_s \) is thermal loss from imperfect combustion of solids, \( \% \); Thermal loss of \( q_5 \) can be obtained by:

\[
q_s = q_{sc} \frac{D_e}{D}
\]

\( q_{sc} = 5.82 \times (D_e)^{-0.38} \) \( \quad (16) \)

Where \( q_{sc} \) is thermal loss under rated load, \( \% \); \( D_e \) is evaporation rate under rated load, t/h; \( D \) is actual evaporation rate, t/h; Thermal loss from the slag \( q_b \) can be obtained:

\[
q_b = \frac{A_w}{Q} \left[ \frac{r_u (t_u - t_0) c_{lu}}{100 - c_{lu}^c} + \frac{r_{fb} (\theta_{fb} - t_u) c_{fb}}{100 - c_{fb}^c} \right]
\]

\( \quad (18) \)

Where \( c_{lu} \) is thermal capacity of slags, kJ/(kg·K); \( c_{fb} \) is thermal capacity of flying ashes, kJ/(kg·K); \( t_u \) is the slag temperature: solid slag = 800 \( ^\circ \)C; liquid slag temperature=melting temperature of ashes plus 100 \( ^\circ \)C.

### 3.3. Improvement of several key calculation formulas

#### 3.3.1. The calculation of excess air ratio

The excess air ratio is calculated by the formula below:

\[
\alpha = \frac{21}{21 - \left( \varphi'(O_2) - 0.5\varphi'(CO) \right)}
\]

\( \quad (19) \)

Where \( \varphi'(O_2) \) is the volume of \( O_2 \) in dry gases, \( \% \).

However, the equation (19) is only appropriate for the case where the theoretical dry air is close to the theoretical dry gases(namely the nitrogen volume content is close to 79\%). It is not fit for the condition with higher nitrogen volume content. Because the nitrogen volume content in the mixing fuel of pulverized coal an BFG is mainly from the BFG.

\[
\alpha = \frac{21}{21 - 79 \left( \varphi'(O_2) - 0.5\varphi'(CO) \right) - 0.8N_u \varphi'(N_2) / V_{gy}}
\]

\( \quad (20) \)

Where \( \varphi'(N_2) \) is is the \( N_2 \) gas volume content in the dry gases, \( \% \).

Above equation is obtained from the combustion principle, which the results are given only.

#### 3.3.2. Solution of actual dry flue gas volume \( V_{gy} \) and excess air ratio \( \alpha \)

Conventionally, the \( V_{gy} \) and \( \alpha \) are obtained by iterations, which improves the computation burden. However, they can be obtained by the equation (21) from the chasing of Carbon and Sulfur in dry gases.

\[
V_{gy} = \frac{1.866C_u'}{\varphi'(RO_2) + \varphi'(CO)} + 0.7S_u'
\]

\( \quad (21) \)

Where \( \varphi'(RO_2) \) is the triatomic gases volume volume content in the dry gases, \( \% \).

It can be seen the \( V_{gy} \) can be obtained easily, as long as the flue gas/smoke compositions are known.

Subsequently the excess air ratio \( \alpha \) can be obtained from the equation (20) after the dry gases, which is easier than the iteration approach.
3.3.3. Further transformation of calculation formula for $V_{gy}$

The equation (21) can be further converted as below:

$$\varphi'(RO_2) = \frac{21 - \varphi'(O_2) - \varphi'(CO)(0.605 + \beta)}{1 + \beta}$$

(22)

Where $\beta$ is fuel characteristic factors, which can be calculated as below:

$$\beta = 2.35 \frac{H_u - 0.126O_u + 0.038N_u}{C'_u + 0.375S_u}$$

(23)

Substitute (22) into (21), the dry gas volume can be calculated by:

$$V_{gy} = \frac{(1 + \beta)(1.866C'_u + 0.7S_u)}{21 - \varphi'(O_2) + 0.395\varphi'(CO)}$$

(24)

Equation (24) can be further rewritten as:

$$V_{gy} = \frac{1.866C'_u + 0.7S_u + 4.385H_u - 0.553O_u + 0.167N_u}{21 - \varphi'(O_2) + 0.395\varphi'(CO)}$$

(25)

The numerator in above equation is only related with the characteristics of mixing fuels.

Assuming $k = 1.866C'_u + 0.7S_u + 4.385H_u - 0.553O_u + 0.167N_u$, then the above equation can be rewritten as:

$$V_{gy} = \frac{k}{21 - \varphi'(O_2) + 0.395\varphi'(CO)}$$

(26)

Equation (26) is more intuitive and easier to analyze the impacts of changes of Oxygen/CO volume content in exhaust gases to the dry gas volumes and subsequent boiler efficiency.

4. Coal consumption deviation analysis models for the main operating parameters of Boiler

4.1. Coal consumption deviation from the exhaust gas temperature

Once the exhaust gas temperature is deviating from the target value, the extra thermal loss and decreased boiler efficiency will occur.

$$\frac{\partial q_2}{\partial \theta_{py}} \Delta \theta_{py} = \frac{(V_{gy} C_{p,gy} + V_{H_2O} C_{p,H_2O})}{Q_x} \Delta \theta_{py} \times 100$$

(27)

The change of boiler efficiency is obtained by:

$$\left(\frac{\partial \eta_b}{\eta_b}\right)_{\theta_2} = \left(\frac{\Delta q_2}{\eta_b}\right)_{\theta_2} = \left(\frac{(V_{gy} C_{p,gy} + V_{H_2O} C_{p,H_2O})}{\eta_b Q_x}\right) \Delta \theta_{py} \times 100$$

(28)

The Coal consumption deviation can be calculated by:

$$\Delta b_{\theta_2} = -\eta_b \left(\frac{\partial \eta_b}{\eta_b}\right)_{\theta_2}$$

(29)

4.2. Coal consumption deviation from the $O_2$ volume content change in exhaust gas

The deviation of $O_2$ volume content in exhaust gas will also cause the thermal loss and boiler efficiency drop.

The thermal loss can be obtained from the equation (8) and (26), as shown in equation (30):
\[(\Delta q_{2})_{\varphi(O_2)} = \frac{\partial q_{2}}{\partial \varphi'(O_2)} \Delta \varphi'(O_2) = \frac{\partial q_{2}}{\partial V_{\varphi}} \frac{\partial V_{\varphi}}{\partial \varphi'(O_2)} \Delta \varphi'(O_2)\]

\[= \frac{c_{p,\varphi}}{Q} \left[ \theta - t_0 \right] k \Delta \varphi'(O_2) \times 100 \]  

The boiler efficiency drop can be obtained:

\[(\delta \eta_{b})_{\varphi(O_2)} = \frac{(\Delta \eta_{b})_{\varphi(O_2)}}{\eta_{b}} = -\frac{(\Delta q_{2})_{\varphi(O_2)}}{\eta_{b}}\]

\[= -\frac{c_{p,\varphi}}{\eta_{b}Q} \left( \theta - t_0 \right) k \Delta \varphi'(O_2) \times 100 \]  

The Coal consumption deviation can be calculated by:

\[(\Delta b)_{\varphi(O_2)} = -b \cdot (\delta \eta_{b})_{\varphi(O_2)} \]  

4.3. Coal consumption deviation from the CO volume content change in the exhaust gas

Similarly, the CO volume content change will also lead to the thermal loss and boiler efficiency drop.

The thermal loss of exhaust gas can be obtained from the equation (8) and (6):

\[(\Delta q_{2})_{\varphi(CO)} = \frac{\partial q_{2}}{\partial \varphi'(CO)} \Delta \varphi'(CO) = \frac{\partial q_{2}}{\partial V_{\varphi}} \frac{\partial V_{\varphi}}{\partial \varphi'(CO)} \Delta \varphi'(CO)\]

\[= \frac{c_{p,\varphi}}{Q} \left( \theta - t_0 \right) 0.395k \Delta \varphi'(CO) \times 100 \]  

The thermal loss from the imperfect combustion is given by:

\[(\Delta q_{3})_{\varphi(CO)} = \frac{\partial q_{3}}{\partial \varphi'(CO)} \Delta \varphi'(CO)\]

\[= \frac{\partial}{\partial \varphi'(CO)} \left[ \frac{12636k \varphi'(CO)}{Q[21-\varphi'(O_2)+0.395\varphi'(CO)]} \right] \Delta \varphi'(CO) \]  

\[= \frac{126.36k}{Q} \left[ 21-\varphi'(O_2)+0.395\varphi'(CO) \right]^{-1} \Delta \varphi'(CO) \times 100 \]

The boiler efficiency change:

\[(\delta \eta_{b})_{\varphi(CO)} = \frac{(\Delta \eta_{b})_{\varphi(CO)}}{\eta_{b}} = -\frac{(\Delta q_{2})_{\varphi(CO)}+(\Delta q_{3})_{\varphi(CO)}}{\eta_{b}}\]

\[= -\frac{0.395c_{p,\varphi}}{\eta_{b}Q} \left( \theta - t_0 \right) -126.36[21-\varphi'(O_2)]k \Delta \varphi'(CO) \times 100 \]  

The Coal consumption deviation from CO volume content change in the exhaust gas is:

\[(\Delta b)_{\varphi(CO)} = -b \cdot (\delta \eta_{b})_{\varphi(CO)} \]  

4.4. Coal consumption deviation from the Carbon content change in flying ashes

The thermal loss from imperfect combustion is mainly due to the unburned carbons in the flying ashes.

The carbon content in flying ashes will also influence the smoking gas, which will cause subsequent thermal losses in exhaust and imperfect combustions.

From equation (15), the thermal loss from imperfect combustion of the solid in the flying ashes can be obtained by:
The thermal loss from the carbon content change in flying ashes is:

\[
(\Delta q)_C = \frac{\partial q}{\partial C_n^c} \Delta C_n^c = \frac{337.27 A_{r_{n}}}{q_i (100 - C_n^c)} \Delta C_n^c \times 100
\]  

(37)

The thermal loss from the imperfect combustion due to the carbon content change in flying ashes:

\[
(\Delta q)_C = \frac{\partial q}{\partial C_n^c} \Delta C_n^c = \frac{\partial q}{\partial C_n^c} \frac{\partial V}{\partial C_n^c} \frac{\partial C_n^c}{\partial C_n^c} \Delta C_n^c
\]

\[=rac{1.866}{Q_i} \frac{\partial C_n^c}{21 - \phi'(O_2) + 0.395 \phi'(CO) (100 - C_n^c)^2} \Delta C_n^c \times 100
\]  

(38)

The thermal loss from the imperfect combustion due to the carbon content change in flying ashes:

\[
(\Delta q)_{C_k} = \frac{\partial q}{\partial C_n^c} \Delta C_n^c = \frac{\partial q}{\partial C_n^c} \frac{\partial V}{\partial C_n^c} \frac{\partial C_n^c}{\partial C_n^c} \Delta C_n^c
\]

\[= -\frac{126.36 \phi'(CO)}{Q_i} \frac{1.866}{21 - \phi'(O_2) + 0.395 \phi'(CO) (100 - C_n^c)^2} \Delta C_n^c \times 100
\]  

(39)

The boiler efficiency change is given as:

\[
(\Delta \eta)_C = \frac{\partial q}{\partial \eta} \frac{\partial \eta}{\partial C_n^c} = \left( \frac{\partial q}{\partial C_n^c} + \frac{\partial q}{\partial C_n^c} \frac{\partial C_n^c}{\partial C_n^c} \frac{\partial C_n^c}{\partial C_n^c} \Delta C_n^c \right)
\]

\[= \left[ \frac{1.866 c_{py} \phi (O_2 - \eta_0) + 235.79 \phi(CO)}{21 - \phi'(O_2) + 0.395 \phi'(CO) (100 - C_n^c)^2} \right] \frac{A_{r_{n}}}{\eta_0 Q_i (100 - C_n^c)^2} \Delta C_n^c \times 100
\]  

(40)

Thus, the coal consumption loss from the carbon content change of flying ashes is obtained:

\[
(\Delta b)_{C_k} = -b_k (\Delta \eta)_{C_k}
\]  

(41)

5. Calculation example

A 220t/h boiler is available from a house power plant with the mixing pulverized coal and BFG which was from the boiler burning pulverized coal. This boiler is operating under high temperature and high pressure, with gas temperature of 540°C, and gas pressure of 9.81MPa. The Coal consumption deviation model was analyzed based on two operating conditions under rated conditions, which the condition-1 has lower BFG rate and condition-2 has higher BFG rate. The results are shown in Table 1.

**Table 1.** Coal consumption deviation for main operation parameters of boiler

| Parameter | Operating condition number | Base value | Parameter change | Relative variation of boiler thermal efficiency /% | Power generation coal consumption variation /g·(kW·h)^{-1} |
|-----------|----------------------------|------------|------------------|---------------------------------|----------------------------------|
| exhaust gas temperature /°C | NO.1 | 145.5 | For every rise of 1°C | -0.0582 | 0.2245 |
| O2 volume content in exhaust gas /% | NO.1 | 3.8 | For increase of 0.1% | -0.0379 | 0.1464 |
| CO volume content in exhaust gas/ppm | NO.1 | 200 | For increase of 100ppm | -0.0452 | 0.1744 |
| flying ashes /% | NO.1 | 4.5 | For increase of 0.1% | -0.0547 | 0.2112 |

From Table 1, it can be seen that the exhaust temperature, oxygen content in exhaust gases, CO content in exhaust gases and flying ashes have bigger impacts to the coal consumption of boilers.
Taking the operating condition-1 as an example, the increase (decrease) of each 1 °C of exhaust temperature, will cause an increase (decrease) of 0.2245g/(kW·h) of coal consumption. The increase (decrease) of each 0.1% of oxygen content in exhaust gases, will cause an increase (decrease) of 0.1464g/(kW·h) of coal consumption. The increase (decrease) of each 0.01% of CO content in exhaust gases, will cause an increase (decrease) of 0.1744g/(kW·h) of coal consumption. The increase (decrease) of each 0.1% of carbon content in flying ashes, will cause an increase (decrease) of 0.2112g/(kW·h) of coal consumption.

It can be also seen that the coal consumption is higher in condition-2 than condition-1, even for the same change of exhaust temperature, oxygen content in exhaust gas, and CO content in gas. This reveals that the exhaust temperature, oxygen content in exhaust gas, and CO content in gas demonstrate much higher impacts to the coal consumption for boiler with higher BFG. This is also in good accordance with the larger gas amount in boilers. Conversely, the flying ashes have smaller impacts on the boilers with higher BFG, which is because the lower coal ratio in boilers.

6. Conclusion
The main operating parameters deviating from the normal value, will cause the boiler efficiency drop, and increase the coal consumption of power plant. This study proposed the equations to calculate the power plant efficiency with impacts of operating parameter changes for the pulverized coal and BFG, which can guide the optimization operation of boilers.

Based on the field data, the proposed model can be used to analyze the operating condition online, which can make the plant running in the optimal conditions.

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