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Thermal Efficiency Calculating Model of Pulverized Coal and Blast Furnace Gas Co-fired Boilers Based on Separate Combustion Calculation

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Abstract: Boiler thermal efficiency is a key index of unit performance assessment. The thermal efficiency of a pulverized coal and blast furnace gas co-firing boiler can be calculated based on either the mixed fuel combustion calculation or the separate combustion calculation. Based on the Chinese Standard Specification GB/T10184-2015 "Performance test code for utility boiler", this paper proposes a calculating model for the thermal efficiency of the co-firing boilers based on the calculation of the itemized fuel combustion, and takes a 220t/h boiler burning pulverized coal and blast furnace gas in a steel plant as the research object. The comparison between the proposed model and the traditional model based on mixed fuel combustion calculation shows that the boiler thermal efficiency calculated results obtained by the two methods are consistent. The new model proposed in this paper is reasonable and feasible. It can be used to calculate the thermal efficiency of the pulverized coal and blast furnace gas co-fired boilers.

1. Introduction

In recent years, pulverized coal and blast furnace gas co-fired boilers have been used successfully in many steel mills worldwide, especially in China. Through pulverized coal boilers co-firing blast furnace gas or blast furnace gas boilers co-firing pulverized coal, the problems happened to the separate combustion of blast furnace gas were effectively solved. From the standpoint of steel mills, this method can make the better use of blast furnace gas, and SO₂, NO_x and dust particulate emissions have a significant reduction compared with the traditional pulverized coal boilers. Therefore, the pulverized coal and blast furnace gas co-fired boilers have good application prospect and promotion value in the steel industry.

At present, many researchers have carried out relevant research on the boiler burning pulverized coal and blast furnace gas. However, the research scope mainly focuses on the combustion characteristics and heat transfer characteristics of the boiler [1-6]. Research that relevant to the calculation of the boiler thermal efficiency is less. The thermal efficiency of boiler is a key indicator for performance assessment of the unit. For newly built units, thermal efficiency assessment tests of the boiler are required to evaluate whether the performance of the boiler is up to standard. For in-service units, the self-provided power plant of the iron and steel mills regularly organizes a thermal efficiency test for the co-fired boiler, to analyze the thermal economy of the boiler. In China, the main basis for the test of the thermal efficiency of pulverized coal and blast furnace gas co-fired boilers is GB/T 10184 "Performance test code for utility boiler" developed in 1988 and updated in 2015 [7],



which provides the calculation method for the pulverized coal and blast furnace gas co-fired boilers. The idea of method solution is to firstly convert the volume components of blast furnace gas into solid fuels to represent the quality components, and then to synthesize the data with the coal combustion components to obtain the characteristics data of the fuel mixture. Finally, the boiler fuel combustion calculations and thermal efficiency are performed using the mixed fuel components to get the solution. It is currently the mainstream method commonly used in engineering.

From the principle of energy and mass balance, the combustion results of coal-blast furnace gas co-firing boilers can be regarded as the combustion results of mixed fuels or the synthesis of the combustion results of the individual fuels (coal and blast furnace gas). Therefore, the calculation for the thermal efficiency of co-fired boiler can be based on the mixed fuel characteristics. The characteristics of the two fuels are first converted into the mixed fuel characteristics according to the mass ratio of the two fuels transported into the furnace. Then, the mixed fuel characteristics are used for combustion calculation and solving thermal efficiency. It can also calculate the combustion data of each fuel separately from the respective characteristics of the sub-item fuels, which can be used for the calculation of the boiler thermal efficiency.

On the basis of Chinese national standard specification GB/T10184-2015, this paper proposes a boiler thermal efficiency solution model based on the separate combustion calculation. This model can provide reference for the efficiency test and calculation of the mixed-fired boiler, and have certain engineering practical significance.

2. Separate combustion calculation model

The calculation of fuel combustion is the primary task in the calculation of the thermal efficiency of a boiler. Its content mainly includes the calculation of the excess air ratio, the volume of air required for combustion, the volume of dry flue gas and water vapor generated by combustion.

For the boiler thermal efficiency model based on the separate combustion calculation, the combustion-related parameters of the pulverized coal and blast furnace gas are solved separately.

2.1 Coal Combustion Calculation Model

The main idea of coal combustion calculation is as follows: First, calculate the theoretical dry air volume $(V_{a,d,th})_{coal}$, theoretical dry flue gas volume $(V_{fg,d,th})_{coal}$ and excess air factor α_{coal} of per kilogram of coal combustion. Then, find the actual volume of dry flue gas $(V_{fg,d})_{coal}$ and the volume of water vapor in the flue gas $(V_{mv,fg})_{coal}$ produced from per kilogram of coal combustion. The relevant calculation models are as follows:

1) Theoretical dry air volume $(V_{a,d,th})_{coal}$:

$$(V_{a,d,th})_{coal} = 0.0888w(C_{ar}^r) + 0.0333w(S_{ar}) + 0.2647w(H_{ar}) - 0.0334w(O_{ar}) \quad (1)$$

Where $(V_{a,d,th})_{coal}$ represents dry theoretical air volume required for combustion of per kilogram of coal (unit: m^3/kg); $w(S_{ar})$, $w(H_{ar})$ and $w(O_{ar})$ represent the mass fraction of elemental sulfur, hydrogen, and oxygen in the received coal, respectively; $w(C_{ar}^r)$ represents the mass fraction of elemental carbon actually burned in the pulverized coal receiving base, which can be calculated by the following formula:

$$w(C_{ar}^r) = w(C_{ar}) - \frac{w(A_{ar})}{100} \left(\frac{w_s w_{c,s}}{100 - w_{c,s}} + \frac{w_{as} w_{c,as}}{100 - w_{c,as}} \right) \quad (2)$$

Where $w(C_{ar})$ and $w(A_{ar})$ represent the mass fraction of the carbon and ash components of the received coal, respectively; w_s and w_{as} represent the mass fraction of slag and fly ash in the total fuel ash, respectively; $w_{c,s}$ and $w_{c,as}$ represent the mass fraction of combustibles in slag and fly ash, respectively.

2) Theoretical dry flue gas volume $(V_{fg,d,th})_{coal}$:

$$(V_{fg,d,th})_{coal} = 1.8658 \frac{w(C_{ar}^r)}{100} + 0.6989 \frac{w(S_{ar})}{100} + 0.79V_{a,d,th} + 0.8 \frac{w(N_{ar})}{100} \quad (3)$$

Where $(V_{fg,d,th})_{coal}$ represents the theoretical dry flue gas generated by combustion of per kilogram

of coal (unit: m^3/kg); $w(\text{N}_{\text{ar}})$ represents the mass fraction of elemental nitrogen in the received coal.

3) Excess air coefficient α_{coal} :

$$\alpha_{\text{coal}} = \frac{21}{21 - 79 \frac{\phi'(\text{O}_2) - \phi'(\text{CO})}{\phi'(\text{N}_2) - \frac{0.8w(\text{N}_{\text{ar}})}{V_{\text{fg,d,th}}}}} \quad (4)$$

Where α_{coal} is the excess air coefficient corresponding to coal combustion; $\phi'(\text{O}_2)$, $\phi'(\text{CO})$, $\phi'(\text{N}_2)$ are the volume fraction of O_2 , CO and N_2 in dry flue gas, respectively.

4) Actual dry flue gas volume $(V_{\text{fg,d}})_{\text{coal}}$:

$$(V_{\text{fg,d}})_{\text{coal}} = (V_{\text{fg,d,th}})_{\text{coal}} + (\alpha_{\text{coal}} - 1)(V_{\text{a,d,th}})_{\text{coal}} \quad (5)$$

Where $(V_{\text{fg,d}})_{\text{coal}}$ is the volume of dry flue gas generated by per kilogram of coal combustion (unit: m^3/kg).

5) Water vapor volume in flue gas $(V_{\text{wv,fg}})_{\text{coal}}$:

$$(V_{\text{wv,fg}})_{\text{coal}} = 1.24 \left(\frac{9w(\text{H}_{\text{ar}}) + w(\text{M}_{\text{ar}})}{100} \right) + 1.293\alpha_{\text{coal}}(V_{\text{a,d,th}})_{\text{coal}} h_{\text{a,ab}} \quad (6)$$

Where $(V_{\text{wv,fg}})_{\text{coal}}$ is the volume of water vapor in the flue gas generated by per kilogram of coal (unit: m^3/kg); $w(\text{M}_{\text{ar}})$ represents the mass fraction of moisture received by the coal; $h_{\text{a,ab}}$ is the absolute humidity of the air (unit: kg/kg).

2.2 Blast Furnace Gas Combustion Calculation Model

In the engineering, the gas combustion calculation is generally based on 1Nm^3 (per standard cubic meter) of dry gas, with moisture. The benefit of this is that the dry gas component used in the calculation will not change with the change of gas humidity. Therefore, the gas component data under dry basis is recommended in the fuel combustion calculation.

The main idea of the calculation of blast furnace gas combustion is as follows: First, calculate the theoretical dry air volume $(V_{\text{a,d,th}})_{\text{gas}}$, the theoretical dry gas volume $(V_{\text{fg,d,th}})_{\text{gas}}$, and the excess air coefficient α_{gas} for per cubic meter of dry gas combustion. Then, the actual dry flue gas volume $(V_{\text{fg,d}})_{\text{gas}}$ and the water vapor volume $(V_{\text{mv,fg}})_{\text{gas}}$ in the flue gas generated by per cubic meter of gas combustion are obtained. The main calculation models are as follows:

1) Theoretical dry air volume $(V_{\text{a,d,th}})_{\text{gas}}$:

$$(V_{\text{a,d,th}})_{\text{gas}} = \frac{1}{21} \left(0.5\phi(\text{CO}) + 0.5\phi(\text{H}_2) + \sum \left(m + \frac{n}{4} \right) \phi(\text{C}_m\text{H}_n) + 1.5\phi(\text{H}_2\text{S}) - \phi(\text{O}_2) \right) \quad (7)$$

Where $(V_{\text{a,d,th}})_{\text{gas}}$ represents the theoretical dry air required for the combustion of per cubic meter of dry gas (unit: m^3/m^3); $\phi(\text{CO})$, $\phi(\text{H}_2)$, $\phi(\text{C}_m\text{H}_n)$, $\phi(\text{H}_2\text{S})$ and $\phi(\text{O}_2)$ are the volume fraction of CO , H_2 , hydrocarbons C_mH_n , H_2S , O_2 in dry gas, respectively.

2) Theoretical dry flue gas volume $(V_{\text{fg,d,th}})_{\text{gas}}$:

$$(V_{\text{fg,d,th}})_{\text{gas}} = \frac{1}{100} \left(\phi(\text{CO}_2) + \phi(\text{CO}) + \sum m\phi(\text{C}_m\text{H}_n) + \phi(\text{H}_2\text{S}) \right) + 0.79(V_{\text{a,d,th}})_{\text{gas}} + \frac{1}{100} \phi(\text{N}_2) \quad (8)$$

Where $(V_{\text{fg,d,th}})_{\text{gas}}$ represents the theoretical dry flue gas volume generated by per cubic meter of dry gas combustion (unit: m^3/m^3); $\phi(\text{CO}_2)$ and $\phi(\text{N}_2)$ are the volume fraction of CO_2 and N_2 in dry gas, respectively.

3) Excess air coefficient α_{gas} :

$$\alpha_{\text{gas}} = \frac{21}{21 - 79 \frac{\phi'(\text{O}_2) - \phi'(\text{CO})}{\phi'(\text{N}_2) - \frac{\phi(\text{N}_2)}{V_{\text{fg,d,th}}}}} \quad (9)$$

Where α_{gas} is the excess air coefficient corresponding to the blast furnace gas combustion; $\phi'(\text{O}_2)$, $\phi'(\text{CO})$ and $\phi'(\text{N}_2)$ are the volume fraction of O_2 , CO and N_2 in dry flue gas, respectively.

4) Actual dry flue gas volume $(V_{fg,d})_{gas}$:

$$(V_{fg,d})_{gas} = (V_{fg,d,th})_{gas} + (\alpha_{gas} - 1)(V_{a,d,th})_{gas} \quad (10)$$

Where $(V_{fg,d})_{gas}$ is the volume of dry flue gas generated by per cubic meter of dry gas combustion (unit: m^3/m^3).

5) Water vapor volume in flue gas $(V_{wv,fg})_{gas}$:

$$(V_{wv,fg})_{gas} = \frac{1}{100} \left(\phi(H_2) + \phi(H_2S) + \frac{m}{2} \phi(C_mH_n) \right) + \frac{h_{gas}}{0.804} + \frac{1.293\alpha_{gas}(V_{a,d,th})_{gas} h_{a,ab}}{0.804} \quad (11)$$

Where $(V_{wv,fg})_{gas}$ is the volume of water vapor in the flue gas generated by per cubic meter of dry gas combustion (unit: m^3/m^3); h_{gas} is the gas moisture content (unit: kg/m^3).

3. The boiler thermal efficiency calculating model based on separate combustion calculation

3.1 Boiler thermal efficiency calculating model

In this paper, the boiler thermal efficiency is obtained by the heat loss method, combined with the calculation results of the fuel combustion. The formula is as follow:

$$\eta = 100 - (q_2 + q_3 + q_4 + q_5 + q_6) \quad (12)$$

Where η is the boiler thermal efficiency; q_2 , q_3 , q_4 , q_5 and q_6 are the heat loss due to exhaust flue gas, the heat loss of incomplete combustion of the combustible gas, the heat loss due to the incomplete combustion of the solid, the heat loss due to radiation, the physical heat loss of ash and slag, respectively.

The advantage of using the heat loss method to solve the boiler thermal efficiency is that it can obtain each heat loss of the boiler, so it is convenient to determine and analyze the various impacts of the boiler thermal efficiency, and to explore the potential and means for improving the boiler thermal economy.

3.2 Key calculation models

The key calculation models of the boiler thermal efficiency based on the separate fuel combustion calculation mainly includes the following parts:

1) Boiler input heat Q_{in} :

$$Q_{in} = B_{coal}(Q_{net,ar})_{coal} + B_{gas}k(Q_{net,d})_{gas} + B_{coal}Q_{coal} + B_{gas}Q_{gas} + V_aQ_a \quad (13)$$

Where Q_{in} is the boiler input heat (unit: kJ/h); $(Q_{net,ar})_{coal}$ It is the net calorific power of the received coal (unit: kJ/kg); $(Q_{net,d})_{gas}$ is net calorific power of dry gas (unit: kJ/m³); B_{coal} is the mass flow of coal entering furnace (unit: kg/h); B_{gas} is the volume flow of blast furnace gas entering the furnace (unit: m³/h); V_a is the volume of air entering furnace (unit: m³/h); Q_{coal} is the physical sensible heat of coal (unit: kJ/kg); Q_{gas} is the physical sensible heat of blast furnace gas (unit: kJ/m³); Q_a is the physical sensible heat of the air (unit: kJ/m³); k is the flow conversion factor of dry to wet basis, calculated as follow:

$$k = \frac{0.804}{0.804 + h_{gas}} \quad (14)$$

In the formula (13), the last three items (physical sensible heat) are much smaller than the first two items (fuel net calorific power), so the boiler input heat can be simplified by the following formula:

$$Q_{in} = B_{coal}(Q_{net,ar})_{coal} + B_{gas}k(Q_{net,d})_{gas} \quad (15)$$

2) Heat loss due to exhaust flue gas q_2 :

$$q_2 = \frac{Q_{2,fg,d} + Q_{2,wv,fg}}{Q_{in}} \times 100 \quad (16)$$

Where $Q_{2,fg,d}$ and $Q_{2,wv,fg}$ are the heat taken away by dry flue gas and water vapor, respectively (unit: kJ/h). The solution models are as follows:

$$Q_{2,fg,d} = [B_{\text{coal}}(V_{fg,d})_{\text{coal}} + kB_{\text{gas}}(V_{fg,d})_{\text{gas}}]c_{p,fg,d}(t_{fg,lv} - t_0) \quad (17)$$

$$Q_{2,wv,fg} = [B_{\text{coal}}(V_{wv,fg})_{\text{coal}} + kB_{\text{gas}}(V_{wv,fg})_{\text{gas}}]c_{p,wv}(t_{fg,lv} - t_0) \quad (18)$$

In the two formulas, $t_{fg,lv}$ is the boiler exhaust temperature (unit: °C); t_0 is the reference temperature; $c_{p,wv}$ is the average specific heat at constant pressure of steam between t_0 and $t_{fg,lv}$ (unit: kJ/(m³·K)); $c_{p,fg,d}$ is the average specific heat at constant pressure of dry flue gas at the exhaust between t_0 and $t_{fg,lv}$ (unit: kJ/(m³·K)).

3) Gas incomplete combustion heat loss q_3 :

$$q_3 = 12636 \frac{B_{\text{coal}}(V_{fg,d})_{\text{coal}} + kB_{\text{gas}}(V_{fg,d})_{\text{gas}}}{Q_{\text{in}}} \phi'(\text{CO}) \quad (19)$$

4) Solid incomplete combustion heat loss q_4 :

$$q_4 = \frac{337.27 B_{\text{coal}} w(A_{\text{ar}})}{Q_{\text{in}}} \left[\frac{w_s w_{c,s}}{100 - w_{c,s}} + \frac{w_{as} w_{c,as}}{100 - w_{c,as}} \right] \quad (20)$$

5) Heat loss due to radiation q_5 :

$$q_5 = \frac{\beta Q_r}{Q_{\text{BMCR}}} q_{5,\text{BMCR}} \quad (21)$$

Where Q_r , Q_{BMCR} are the actual output heat of the boiler and the maximum output heat of the boiler, respectively (unit: MW); β is the emissivity coefficient of the boiler surface.

6) Physical heat loss of ash and slag q_6 :

$$q_6 = \frac{B_{\text{coal}} w(A_{\text{ar}})}{Q_{\text{in}}} \left[\frac{w_s (t_s - t_0) c_s}{100 - w_{c,s}} + \frac{w_{as} (t_{as} - t_0) c_{as}}{100 - w_{c,as}} \right] \quad (22)$$

Where c_s and c_{as} are specific heat capacity of slag and fly ash, respectively (unit: kJ/(kg·K)); t_s , t_{as} are slag temperature and fly ash temperature, respectively (unit: °C).

4. Comparison with traditional model

Combined with the analysis of the previous two sections, we can know:

1) The thermal efficiency calculation model based on the separate combustion calculation is quite different from the traditional model based on mixed fuel combustion calculation. The differences are mainly reflected in two aspects: First, the combustion calculation process of the proposed new model is a bit tedious, which requires not only combustion calculation of coal, but also combustion calculation of blast furnace gas. Therefore, the new model includes a fuel combustion calculation process more than the traditional model. Besides, the heat loss calculation in the new model takes into account the mass flow of each fuel, while the traditional heat loss calculation model is based on mixed fuel.

2) In general, the thermal efficiency solution model based on the mixed fuel combustion calculation is slightly more concise than the model based on the separate combustion calculation, and is more in line with the solution idea for conventional pulverized coal boiler, while the new model provides a new idea for the calculation of the thermal efficiency of gas-solid fuel co-fired boiler.

5. Calculation example

This article takes a 220 t/h pulverized coal and blast furnace gas co-fired boiler as the research object, which is in a certain self-produced power plant of a steel mill. Two test data of different working conditions was selected to calculate the boiler thermal efficiency adopting the new model and the traditional model respectively, in order to verify the consistency of the two models. The boiler is designed for high temperature and high-pressure parameters, with the superheated steam temperature 540°C and steam pressure 9.81 MPa. The fuel characteristics and main operating data of the boiler are

shown in Table 1. The calculation results of the boiler efficiency are shown in Table 2.

Table 1. The original data

	Item	Symbol	Unit	Operating conditions 1	Operating conditions 2
Burning coal characteristics	Carbon mass fraction	$w(C_{ar})$	%	48.19	48.47
	Hydrogen mass fraction	$w(H_{ar})$	%	2.98	2.64
	Oxygen mass fraction	$w(O_{ar})$	%	5.09	5.26
	Nitrogen mass fraction	$w(N_{ar})$	%	0.93	0.83
	Sulfur mass fraction	$w(S_{ar})$	%	1.94	1.75
	Moisture mass fraction	$w(M_{ar})$	%	7.30	7.86
	Ash mass fraction	$w(A_{ar})$	%	33.57	33.19
	Net calorific power	$(Q_{net,ar})_{coal}$	kJ/kg	18314	18014
Dry gas properties	CO content	$\varphi(CO)$	%	23.56	24.37
	H ₂ content	$\varphi(H_2)$	%	2.31	2.48
	CH ₄ content	$\varphi(CH_4)$	%	0.49	0.65
	CO ₂ content	$\varphi(CO_2)$	%	17.16	16.97
	N ₂ content	$\varphi(N_2)$	%	56.48	55.52
	Net calorific power	$(Q_{net,d})_{gas}$	kJ/Nm ³	3401	3582
Dry flue gas composition	Oxygen content	$\varphi'(O_2)$	%	3.76	3.64
	RO ₂ content	$\varphi'(RO_2)$	%	17.01	18.41
	CO content	$\varphi'(CO)$	%	0.00	0.03
	N ₂ content	$\varphi'(N_2)$	%	79.23	77.92
Environmental parameters	Atmospheric temperature	t_0	°C	16.50	17.90
	Absolute air humidity	$h_{a,ab}$	kg/kg	0.009	0.011
Slag and ash properties	Carbon in fly ash	$w_{c,as}$	%	4.67	5.28
	Carbon in slag	$w_{c,s}$	%	5.59	6.46
Main operation parameter	The volume flow of gas entering the furnace	B_{gas}	m ³ /h	27495	50324
	The mass flow of coal entering the furnace	B_{coal}	kg/h	30455	26720
	Gas temperature	t_{gas}	°C	33.5	37.2
	Exhaust fuel gas temperature	$t_{fg,lv}$	°C	143.9	151.6
	Boiler evaporation	D	t/h	218.3	219.4

Table 2. The boiler thermal efficiency calculation results

Item	Symbol	Unit	Operating conditions 1		Operating conditions 2	
			New Model	Traditional model	New Model	Traditional model
Heat loss due to exhaust flue gas	q_2	%	6.556	6.556	7.306	7.306
Gas incomplete combustion loss	q_3	%	0.000	0.000	0.139	0.139
Solid incomplete combustion loss	q_4	%	2.655	2.655	2.600	2.600
Heat loss due to radiation	q_5	%	0.504	0.504	0.501	0.501
Physical heat loss of ash and slag	q_6	%	0.289	0.289	0.257	0.257
Boiler thermal efficiency	η	%	89.996	89.996	89.197	89.197

It can be seen from the above results that the boiler thermal efficiency calculation results obtained by using the new model and the traditional model are completely consistent. In other words, the boiler

thermal efficiency solution model based on the separate combustion calculation proposed in this paper is reasonable and feasible.

6. Conclusions

1) The calculation of the thermal efficiency of a co-fired boiler can be based on the mixed fuel characteristics with mixed fuel characteristics data, and can also be based on the respective characteristics of the sub-item fuel.

2) This paper presents a calculation model for the thermal efficiency of a pulverized coal and blast furnace gas co-fired boiler based on the separate combustion calculation. In this model, the two kinds of fuel combustion were calculated respectively, and then the separate results are aggregated and applied to the boiler thermal efficiency calculation.

3) Compared with the two methods, the calculation model based on separate combustion calculation proposed in this paper need to carry out one more process of fuel combustion calculation, while the traditional model based on mixed fuel characteristics must perform one more process of solving mixed fuel property. Besides, the two models are obviously different in solving boiler thermal efficiency.

4) A practical example analysis shows that the results of this model and the traditional model based on mixed fuel combustion calculation are consistent. The new model can provide a new idea for the calculation of thermal efficiency of pulverized coal and blast furnace gas co-fired boilers, and can also be used to further analyze the effects of the two fuels on the boiler combustion and thermal efficiency, such as their respective contributions, etc.

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