Study on Optimum Excess Air Coefficient for Power Plant Boilers

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Abstract—Boiler's combustion efficiency directly reflects the status of its operation and affects the economical efficiency of the power plant. As we know, what mainly influences the combustion efficiency is the heat loss, and the excess air coefficient is an important factor affecting the heat loss. This paper's objective is to explore a method for calculating the optimum excess air coefficient. Firstly, by analyzing combustion mechanism of boilers, the mechanism analysis model is employed to obtain the relationships between excess air coefficient and all the heat loss. Secondly, the unconstrained function optimization model is carried out to determine the optimum excess air coefficient, then the golden section method and the quadratic interpolation method are used to obtain the optimum excess air coefficient minimizing the sum of all the heat loss under different loads. While in order to simplify the problem, some reasonable assumptions are made. Moreover, using the data of a certain power plant, the method in this paper is verified, and the optimum excess air coefficient should be around 1.21.Thus this primary study provided some basis for the exploration about optimum operation of boilers.

Keywords-optimum excess air coefficient ; heat loss; mechanism analysis; unconstrained function optimization; golden section

I. INTRODUCTION

Boiler is one of the core equipment in thermal power plants, and its efficiency directly affects the economical efficiency of the power plant. In the boiler combustion equipment, fuel and air are difficult to be mixed uniformly. Therefore, if the air is supplied by theoretical quantity, part of the fuel always cannot get enough oxygen to burn completely. Thus the boiler efficiency was reduced. In the boiler practical operation, the actual quantity of air supplied is always greater than the theoretical ones, the excess is referred to as Excess Air quantity, and excess air coefficient refers to the ratio of the actual air quantity and air theoretical quantity. Excess air coefficient directly affect the exhaust gas heat loss, the chemistry(flammable gas)incomplete combustion heat loss and solid incomplete combustion heat loss(as shown in Fig .1)The heat loss is the main cause of boiler combustion efficiency, therefore, to develop a suitable excess air coefficient is very critical to improve the efficiency of the boiler.

II. ASSUMPTION

1.According to Testing method for power station performance (GB PTC),the anti-balance method is adopted to calculate the efficiency of boilers in power plants.

$$\eta_{gl} = q_1 = \frac{Q_1}{Q_r}\times 100 = 100-(q_2+q_3+q_4+q_5+q_6),\% \qquad (1)$$

Where $q_i = \frac{Q_i}{Q_r}\times 100(i=1,2,\cdots,6)$ denotes respectively the effective utilization heat q_1 ,exhaust gas heat loss q_2 ,chemistry(flammable gas)incomplete combustion heat loss q_3 ,solid incomplete combustion heat loss q_4 , heat dissipation physical heat loss of ash and slag q_5 ,and Q_r is the heat generated by 1kg fuel after complete combustion.

2.While calculating the exhaust gas heat loss, ignore the heat CO takes away.

3.Assume that flammable gas which burns incompletely only contains CO .

4.Assume that the boiler under analysis is solid pulverized coal boiler furnace.

III. MODEL BUILDING

A. Mechanism analysis on Exhaust Gas Heat Loss

Exhaust Gas Heat Loss is due to that great heat in exhaust smoke losses into air without utilizing, which is the most of all heat loss.

1) Symbol description

α:excess air coefficient

Q_2 : exhaust gas heat loss

Q_2^{dg} : the heat dry flue gas takes away

V_{dg} : the volume of dry flue gas produced by 1kg flue incomplete combustion

$c_{p,dg}$:dry flue gas's specific heat capacity at constant pressure from t_0 to θ_{py}

θ_{py} : exhaust smoke' s temperature

t_{amb} : ambient temperature

V_{dg}^0 : dry flue gas's theoretical volume

$V_{CO_2}, V_{N_2}, V_{O_2}, V_{H_2O}$: CO_2, N_2, O_2 *and* H_2O 's volumes in dry flue gas

$c_{p,CO_2}, c_{p,O_2}, c_{p,N_2}, c_{p,CO}$:Heat Capacity at Constant Pressure of CO_2 , O_2, N_2 and CO

$\lambda_{N_2}, \lambda_{O_2}, \lambda_{CO_2}, \lambda_{CO}$:percentage of N_2 , O_2, CO_2 and CO

in dry flue gas

d_k : absolute moisture of moist air, generally

$d_k = 0.01 kg/kg$

V^0 : the air's theoretical volume that 1kg flue consume after complete combustion

$V^0_{H_2O}$: water vapor's theoretical volume

C^y H^y O^y N^y W^y : carbon, hydrogen,oxygen, nitrogen and inorganic water contents of 1kg fuel

2) Solving Process

Assume that under working condition i

$$Q_{2i} = Q_{2i}^{dg} + Q_{2i}^{H_2O}, \quad kJ/kg \tag{2}$$

$$q_{2i} = \frac{Q_{2i}}{Q_r} \times 100,\% \tag{3}$$

In which the heat dry flue gas takes away is

$$Q_2^{dg} = V_{dg} c_{p,dg} (\theta_{py} - t_{amb}), \quad kJ/kg \tag{4}$$

The volume of dry flue gas produced by 1kg flue incomplete combustion is

$$V_{dg} = V_{dg}^0 + (\alpha - 1)V^0, \quad m^3/kg \tag{5}$$

$$V_{dg}^0 = V_{CO_2} + V_{N_2}, \quad m^3/kg \tag{6}$$

$$V_{CO_2} = 1.866 \frac{C^y}{100}, \quad m^3/kg \tag{7}$$

$$V_{N_2}^0 = 0.8 \frac{N^y}{100} + 0.79 V^0, \quad m^3/kg \tag{8}$$

When the flue gas composition is known, it can be calculated according to the type

$$c_{p,gy} = c_{p,RO_2}\lambda_{RO_2} + c_{p,O_2}\lambda_{O_2} + c_{p,N_2}\lambda_{N_2} + c_{p,CO}\lambda_{CO}, kJ/(m^3 \bullet {}^\circ C) \tag{9}$$

Because the combustion in modern boilers is relatively complete, CO is very few in flue gas($CO < 1\% - 2\%$). Ignoring the influence of CO ,it can be calculated approximately by

$$c_{p,gy} = c_{p,RO_2}\lambda_{RO_2} + c_{p,N_2}\lambda_{N_2} + c_{p,O_2}\lambda_{O_2}, \quad kJ/(m^3 \bullet {}^\circ C) \tag{10}$$

$$\lambda_{N_2} + \lambda_{O_2} + \lambda_{RO_2} = 100,\% \tag{11}$$

Gases' heat capacity at constant pressure is

$$c_{p,CO_2} = 1.7002 + \frac{\theta_{py} - 100}{200 - 100} \times (1.7873 - 1.7002) \tag{12}$$

$$c_{p,N_2} = 1.2958 + \frac{\theta_{py} - 100}{200 - 100} \times (1.2996 - 1.2958) \tag{13}$$

$$c_{p,O_2} = 1.3176 + \frac{\theta_{py} - 100}{200 - 100} \times (1.3352 - 1.3176) \tag{14}$$

the sensible heat of water vapor in flue gas is

$$Q_{2i}^{H_2O} = V_{H_2O} c_{p,H_2Oi} (\theta_{py} - t_0), \quad kJ/kg \tag{15}$$

$$V_{H_2O} = V_{H_2O}^0 + 1.61 d_k (\alpha - 1) V^0, \quad m^3/kg \tag{16}$$

$$V_{H_2O}^0 = 11.1 \frac{H^y}{100} + 1.24 \frac{W^y}{100} + 1.61 d_k V^0, \quad m^3/kg \tag{17}$$

$$V^0 = 0.0899 C^y + 0.265 (H^y - \frac{O^y}{8}), \quad m^3/kg \tag{18}$$

3) Conclusion

According to the appendix data, the exhaust gas heat losses under different loads can be worked out as below.

TABLE I Exhaust gas heat loss under different loads

Load (MW)	Exhaust gas heat loss
298	$(4.123\alpha + 0.273)\%$
245.3	$(3.992\alpha + 0.265)\%$
215.8	$(3.716\alpha + 0.246)\%$
192.3	$(3.601\alpha + 0.239)\%$

From what has been discussed above, the exhaust gas heat loss has a linear relation with excess air coefficient α,and increases with it.

B. Mechanism analysis on Flammable gas incomplete combustion heat loss

Flammable gas incomplete combustion heat loss is due to that the residual gases (CO, H_2, CH_4, C_mH_m etc.) in the boiler smoke burn incompletely, it equals to the sum of the products of the combustible gas's volume and its calorific value.

1) Symbol description

β: fuel characteristic coefficient

RO_2 :percentages of CO_2 and SO_2 in gas flue

R_{ar} :1kg flue contains $\frac{R}{100}kg$ R

2) Solving Process

$$q_3 = \frac{Q_3}{Q_r} \times 100,\% \tag{19}$$

$$Q_3 = \frac{V_{dg}}{100}(12636CO + 10798H_2 + 35818CH_4 + 59079C_mH_m), kJ/kg \tag{20}$$

As for the solid fuel, it can be considered that H_2, CH_4, C_mH_m are equal to zero.

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

$$V_{dg} = \frac{1.866 R_{ar}}{RO_2 + CO}, \quad m^3/kg \tag{22}$$

3) solution and conclusion——taking bituminous coal as example

For bituminous coal,β equals to 0.15 and C equals to 62.61%.Based on some main parameters of certain boilers, TABLE II can be obtained.

TABLE II Relationship of boiler Unit load with Flammable Gas Incomplete Combustion Heat Loss

Boiler load[MW]	flue gas oxygen content (%)	CO content (%)	V_{dg} [m³/kg]	Q_3 [kJ/kg]	q_3 (%)
298	5.21	1.04	8.29	1086.18	4.34
245.3	5.08	1.21	8.19	1251.34	5.00
215.8	5.88	0.15	8.85	166.66	0.67
192.3	6.84	0.02	8.94	22.59	0.09

According to the table, q_3 is less, that is to say, chemistry incomplete combustion heat loss is so little that it can be regarded as a constant or neglected.

C. Mechanism analysis on solid incomplete combustion heat loss

Solid incomplete combustion heat loss is due to that the carbon in ash didn't burn or burn incompletely and the Medium-speed mill exhaust pebble coal while milling coal. This paper only considered the former.

1) Symbol explanation

G_{fa}, G_{sl} :mass of fly ash and slag, kg/h ;

C_{fa}, C_{sl} :carbon content of fly and slag, % ;

B :coal-burning of a boiler, kg/h ;

α_{fa}, α_{sl} :fly ash ratio and slag rate;

C_{hz} :percentage of combustible in fly ash;

2) Solving process

a) Exploration of relation ship of carbon content in Fly ash at furnace exit and Excess Air Coefficient

TABLE III Experimental data of Fly ash carbon content and Excess Air Coefficient

α	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45	1.5
C_{fa}	5.9	5.1	4.75	4.6	4.55	4.5	4.45	4.43	4.5

Using fitting method for function to make $f(x)$ nearest to those data points. Then getting the scatter diagram by Excel.

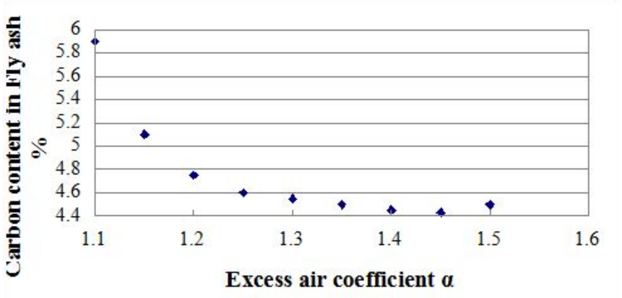

Figure 1. scatter plot of Carbon content in Fly ash and Excess Air Coefficient

The characteristics of the scatter plot show that the carbon content in fly ash(C_{fa})at exit and excess air coefficient α are in quadratic nonlinear correlation approximately. Therefore we select quadratic polynomial to fit, namely take n=2,and let be $f(x) = ax^2 + bx + c$,utilize least square criterion, namely let be $\sum_{i=1}^{n}[f(x_i) - y_i]^2$ minimum, and work out a , b , c .Then using Matlab assistant calculation to get fitting curve:

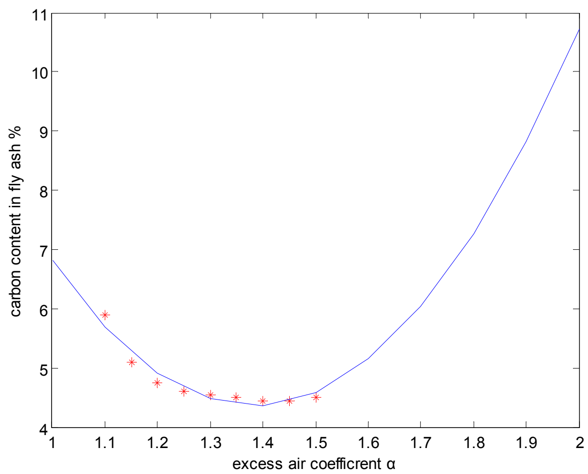

Figure 2. Fitting chart of Carbon content in Fly ash and Excess Air Coefficient

Solutions:

a = 16.7143 b = -46.2271   c = 36.3229

namely:

$$f(x) = 16.7143x^2 - 46.2271x + 36.3229 \qquad (23)$$

From (23) ,the TABLE IV can be got.

TABLE IV Relational table of Fitting curve and the actual value

α	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45	1.5
C_{fa}	5.9	5.1	4.75	4.6	4.55	4.5	4.45	4.43	4.5
$f(x)$	5.6971	5.2663	4.9189	4.655	4.4748	4.378	4.3649	4.4353	4.5893
error	-0.0343	0.0326	0.0355	0.0119	-0.0165	-0.0271	-0.0191	0.00119	0.0198

From TABLE IV, the maximum error is 3.55%, the minimum error in 0.119%,in the acceptable range, so the fitting curve can represent the relationship between the fly ash carbon content and the excess air coefficient:

$$C_{fh} = 16.7143\alpha^2 - 46.2271\alpha + 36.3229\ \% \qquad (24)$$

b) exploration of the heat loss caused by fly ash at furnace exit

According to ash balance, the total ash content of fuel in the furnace should be equal to the sum of fly ash and slag, namely

$$\frac{BA_{ar}}{100}=G_{fh}(\frac{100-C_{fh}}{100})+G_{lz}(\frac{100-C_{lz}}{100}) \quad (25)$$

Based on the certain data, it can be derived:

$$G_{fa}=\frac{6338.493\times100}{100-C_{fh}} =\frac{6338.493\times100}{100-16.7143\alpha^2+46.2271\alpha-36.3229},\ kg/h \quad (26)$$

So the fly ash rate is:

$$\alpha_{fa}=\frac{G_{fh}}{B}=\frac{4.9}{100-16.7143\alpha^2+46.2271\alpha-36.3229}\ . \quad (27)$$

Assume that carbon is the only combustible in fly ash at the exit of furnace, thus the carbon content is:

$$\alpha_{fa}\times C_{fa},kg/kg \quad (28)$$

The quantity of released heat by the carbon's complete combustion is the heat loss caused by the combustibles in fly ash at the exit of furnace. According to the chemical reaction equations:

$$C+O_2\rightarrow CO_2$$

Known that the heat released by 1g carbon completely burn is 32.791667kJ, the heat of this carbon released can be calculated as follow:

$$Q_{fa}=\frac{4.9}{100\text{-}16.7143\alpha^2+46.2271\alpha-36.3229}\times (16.7143\alpha^2-46.2271\alpha+36.3229) \times3279.1667,\ kJ/kg \quad (29)$$

This heat is the heat loss caused by fly ash at the furnace exit.

c) exploration of the heat loss caused by slag at the bottom of the furnace

Based on the certain data, the quality of combustibles in slag is:

$$\alpha_{sl}\times C_{sl},kg/kg \quad (30)$$

Assume that carbon is the only combustible in slag at the bottom of the furnace, thus the carbon content is:

$$0.1\times2\%,kg/kg \quad (31)$$

The quantity of released heat by the carbon's complete combustion is the heat loss caused by the combustibles in slag at the bottom of the furnace. According to the chemical reaction equations:

$$C+O_2\rightarrow CO_2$$

Known that the heat released by 1g carbon completely burn is 32.791667kJ, the heat of this carbon released is $Q_{hz}=65.5833\text{kJ/kg}$.

This energy is the heat loss caused by slag at the bottom of the furnace.

3) conclusion

From what has been discussed above, solid incomplete combustion heat loss is:

$$Q_4=Q_{fh}+Q_{hz}= \frac{4.9}{100\text{-}16.7143\alpha^2+46.2271\alpha-36.3229}\times (16.7143\alpha^2-46.2271\alpha+36.3229)\times3279.1667 +65.5833,\ \text{kJ/kg} \quad (32)$$

$$q_4=\frac{Q_4}{Q_r}\times100= \frac{4.9}{100\text{-}16.7143\alpha^2+46.2271\alpha-36.3229}\times(16.7143\alpha^2 -46.2271\alpha+36.3229)\times13.10+0.26212,\% \quad (33)$$

It is clear that there is a nonlinear relationship between solid incomplete combustion heat loss and excess air coefficient..When the excess air coefficient increases, the solid incomplete combustion heat loss first reduces and then increases, there being an excess air coefficient making solid incomplete combustion heat loss minimal.

D. Optimization model of optimum excess air coefficient

In actual operation of the boiler, in order to make the fuel burning completely, the actual amount of air supply is always greater than the theoretical air volume, the excess part is called excess air amount, and the ratio of the actual air quantity and theoretical air quantity is referred to as the excess air coefficient. When excess air coefficient increases, $q_2+q_3+q_4$ increases after decreases first, there is an minimum. And the air coefficient corresponding to it is called the optimum excess air coefficient.

With the example of the 298MW boiler, it can be derived from the models above.

$$\min q(\alpha)=q_2+q_3+q_4 =(4.123\alpha+0.273)+4.34+\frac{4.9}{100\text{-}16.7143\alpha^2+46.2271\alpha-36.3229} \times(16.7143\alpha^2-46.2271\alpha+36.3229)\times13.106+0.26212 \quad (34)$$

This is a Unary function of α,golden section method and quadratic interpolation are employed to obtain the minimum of the function. Based on the calculation by Matlab for a 298MW boiler, the corresponding optimum excess air coefficient is $\alpha=1.2092$,and the minimum heat loss is $q=q_2+q_3+q_4=13.14\%$.

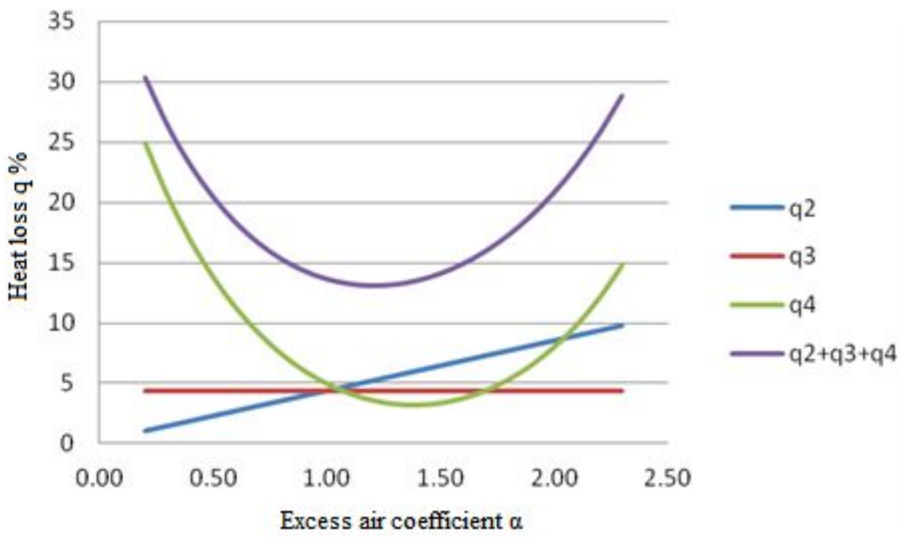

Figure 3. The relationship between Excess air coefficient and heat loss

From Fig .3,it can be found

- The exhaust gas heat loss q_2 has a linear relationship .
- α has little influence on q_3 so that q_3 could be basically regarded as a constant.
- The solid incomplete combustion heat loss q_4 has a nonlinear relationship with α ,and it reduces first and then increases with increasing α .
- As α increases, the sum of q_2 , q_3 and q_4 reduces first and then increases.

So the sum of $q_2 + q_3 + q_4$ could reaches the minimum, in this case, the heat loss is least, and the corresponding the excess air coefficient is optimal.

Namely while the unit load of a boiler is 298MW, the heat loss is 13.14% minimal, at this time the excess air coefficient is 1.2092 ,being the optimum excess air coefficient.

By using the same algorithm, the optimum excess air coefficients under different loads can be obtained.

As shown in Fig .4.

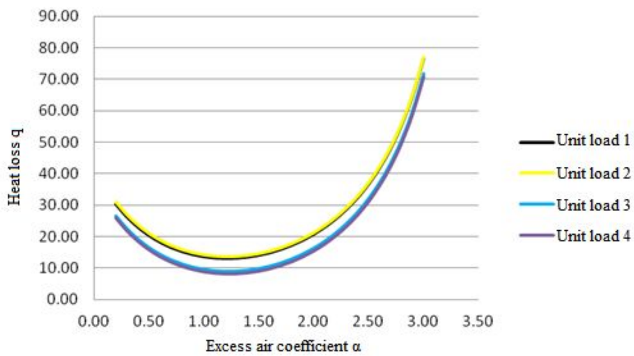

Figure 4. Relation-curve of Optimum excess air coefficient and Heat loss

According to Fig .4.with the excess air coefficient increasing, the heat loss shows the tendency of increasing after reducing, and the minimum point is around 1.1-1.3;For different loads, the curves' s positions are different, but the shapes are roughly same. The unit load influences the heat loss, but doesn't influence the excess air coefficient.

IV. CONCLUDING REMARKS

When α is too small, fuel and air were not well mixed, which resulted in incomplete combustion and great heat loss; when α is too large, air flow rate is so high that the carryover increases, the heat loss is relatively great, too. Therefore the optimum excess air coefficient could be obtained being medium of the two mentioned above.

Controlling the excess air coefficient to be optimal could greatly decrease the heat loss, increase the confident of the boiler and reduce the generating cost.

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