Study on Combustion and Operation Optimization of Coal-fired Boilers in Power Stations

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Abstract: According to the coal quality characteristics of a 300MW boiler and corresponding operation monitoring parameters, this paper has established coal-fired boiler optimum excess air coefficient calculation models under different conditions by using the method of the boiler counter balance, the relationship curve between the boiler load and optimum excess air coefficient has been calculated, then the optimum thermal efficiency of boiler under different conditions can be calculated. In addition, this paper analyzes the parameters that affect the operation economy of power station boiler, then the influence degree of different parameters on boiler operation can be got based on hierarchy process theory, which provides theoretical guidance for the optimal operation of boiler.

1. Introduction

Along with the development of Chinese economy, the power industry has entered a period of rapid development, which causes the amount of coal increased. During the operation of power boiler, the excess air coefficient is an important control index, which directly affects the economy of boiler operation. If the excess air coefficient is too large, it will increase smoke exhaust heat loss, and increase fan power consumption rate. If the excess air coefficient is too small, the fuel cannot burn completely, which will increase the chemical incomplete combustion loss [1].

In this paper, the influence of excess air coefficient on boiler operation economy of coal-fired boiler in power station is taken as the starting point. By analyzing the variation of parameters in boiler operation and establishing mathematical models, the economic indexes of units under different conditions can be obtained. In addition, during the operation of coal-fired boilers in power stations, there are a wide variety of parameters that affect the boiler operation, and the technology is complex. This paper has a further study to find the weight relationship among the main indexes that affect the operation economy based on analytic hierarchy process (AHP) theory, this study will provide guiding suggestions for the optimization of power plants operation.

2. Determination of Optimum Excess Air Coefficient

Due to the proportion of the sum of q_2, q_3 and q_4 in all heat losses of the boiler is more than 95%, the optimal excess air coefficient should minimize the sum of q_2, q_3 and q_4 [2].

2.1.Calculation Models

2.1.1. Mechanical Heat Loss from Incomplete Combustion q_4

$$q_4 = \frac{32866A_{ar}}{Q_r}\left(\frac{\alpha_{fh}C_{fh}}{100-C_{fh}} + \frac{\alpha_{lz}C_{lz}}{100-C_{lz}}\right)\% \qquad (1)$$

where, A_{ar} is Coal receives base ash,%; α_{fh} is fly ash ratio,%; α_{lz} is slag ratio,%; C_{fh} is fly ash carbon content,%; C_{lz} is slag carbon content,%; Q_r is heat input from the boiler, kJ/kg.

2.1.2. Chemical Heat Loss from Incomplete Combustion q_3

During the calculation of the coal-fired boiler in the power station, the pulverized coal can be completely burned in the furnace, so the carbon monoxide produced is zero, the hydrogen and methane are ignored, which means $q_3=0$.

2.1.3. Heat Loss due to Exhaust Gas q_2

$$q_2 = \frac{Q_2}{Q_r} \times 100 = \frac{h_{py}-\alpha_{py}h_{lk}^0}{Q_r}(100-q_4)\% \qquad (2)$$

where h_{py} is exhaust enthalpy, kJ/kg; α_{py} is excess air coefficient at air preheater outlet; h_{lk}^0 is the cold air enthalpy, kJ/kg.

2.1.4. Excess Air Coefficient during Operation α_{py}

$$\alpha_{py} = \frac{21}{21-O_2} \qquad (3)$$

where O_2 is the percentage of oxygen in the composition of smoke, %; CO is the percentage of carbon monoxide in the composition of smoke, %.

2.2.Numerical Results

2.2.1. Original Data

The relationship between coal composition, operating data and carbon content of fly ash detected by the 300MW unit and excess air coefficient is shown in the following Tables:

Table 1: Coal quality ingredients.

Symbol	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}	M_{ar}	A_{ar}	V_{daf}	$Q_{ar,net,p}$
Unit	%	%	%	%	%	%	%	%	kJ/kg
Date	38.43	3.63	9.73	0.7	0.41	33.1	14	49.1	14100

Table 2: Boiler operating parameters.

Name	Symbol	Unit	Date			
			1	2	3	4
Unit load	P	MW	195	225	235	245
Boiler duty	D	t/h	579	701	705	723
Exhaust gas temperature	t	ºC	135	139	138.5	137.5
Flue gas oxygen content	O_2	%	6	5.33	4.2	4
Boiler rated evaporating capacity	D_0	t/h	1100			
Slag carbon content	C_{lz}	%	0.8			
Fly ash ratio	α_{fh}	%	0.9			
Slag ratio	α_{lz}	%	0.1			
Environmental temperature	t	ºC	20			

Table 3: Relationship between carbon content of fly ash and excess air coefficient.

α	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45	1.5
C_{fh}	5.90	5.10	4.75	4.6	4.55	4.50	4.45	4.43	4.50

2.2.2. Results

Table 4: Calculation results of q2 and q4 under different conditions.

195MW	Oxygen content（%）	5.4	6	6.4	7
	Excess air coefficient	1.350	1.400	1.440	1.500
	q_2（%）	7.085	7.297	7.435	7.718
	q_4（%）	1.410	1.394	1.389	1.410
225MW	Oxygen content（%）	4.8	5.3	54	6
	Excess air coefficient	1.310	1.340	1.350	1.400
	q_2（%）	7.171	7.276	7.422	7.555
	q_4（%）	1.423	1.413	1.404	1.394
235MW	Oxygen content（%）	4	4.2	4.6	4.8
	Excess air coefficient	1.200	1.250	1.280	1.300
	q_2（%）	6.720	6.864	6.969	7.088
	q_4（%）	1.472	1.442	1.433	1.426
245MW	Oxygen content（%）	4	4.2	4.6	4.8
	Excess air coefficient	1.200	1.250	1.280	1.300
	q_2（%）	6.703	6.801	6.897	7.025
	q_4（%）	1.462	1.442	1.468	1.426

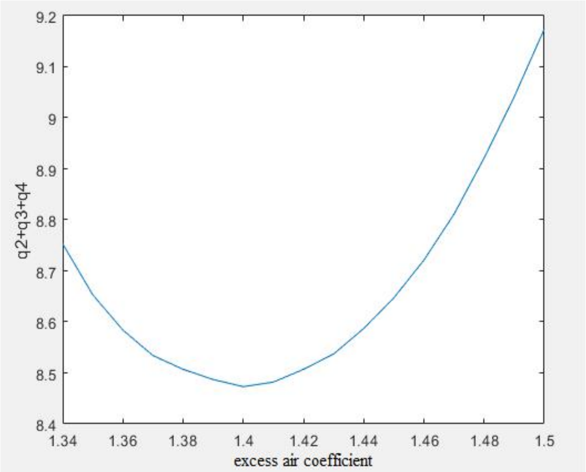

Figure 1: Relationship between boiler efficiency and excess air coefficient of 195MW.

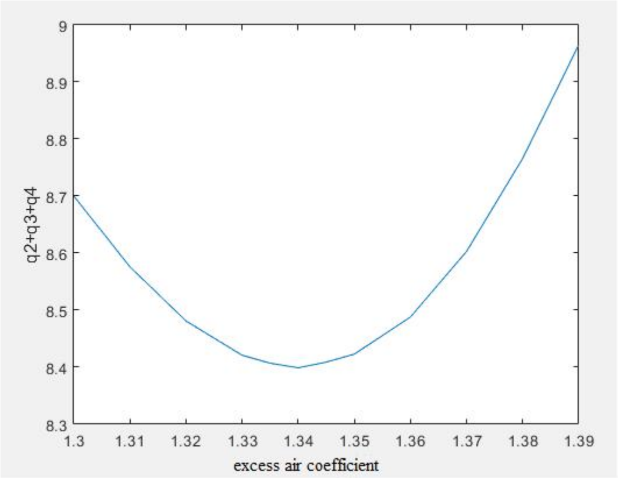

Figure 2: Relationship between boiler efficiency and excess air coefficient of 225MW.

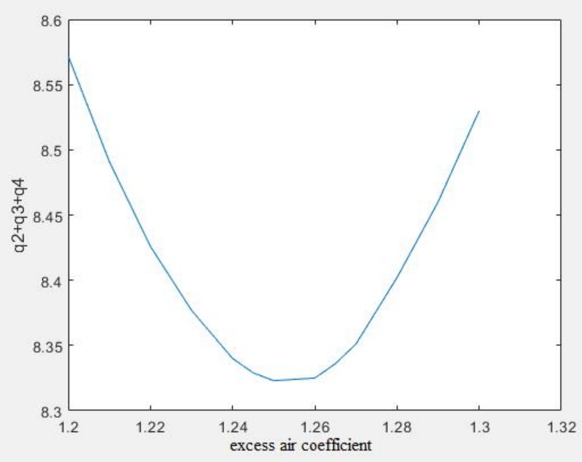

Figure 3: Relationship between boiler efficiency and excess air coefficient of 235MW.

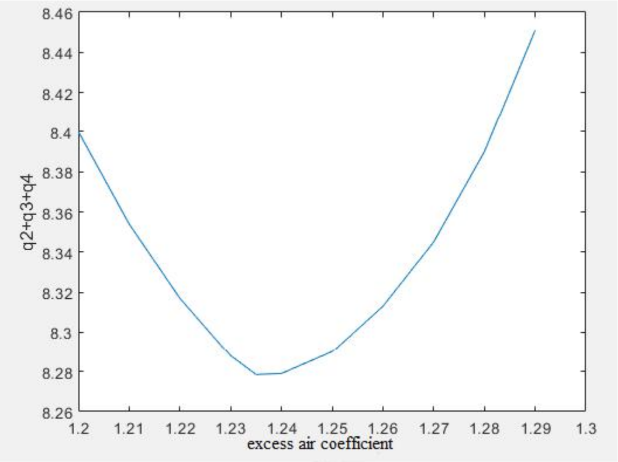

Figure 4: Relationship between boiler efficiency and excess air coefficient of 245MW.

Table 5: Boiler load and optimum excess air coefficient.

Load（MW）	195	225	235	245
Optimum excess air coefficient	1.400	1.340	1.250	1.235

3. Determination of Boiler Thermal Efficiency

Energy saving and consumption reduction of power station boilers has always been the key to the optimal control of power station units. As an important parameter reflecting unit economy and environmental protection, many researchers have pay more attention to the optimization problem of boiler efficiency [3].

3.1.Calculation Models

3.1.1. Boiler Thermal efficiency

$$\eta = 100 - (q_2 + q_3 + q_4 + q_5 + q_6) \qquad (4)$$

3.1.2. Heat Loss q_5

$$q_5 = q_5^e \frac{D_e}{D} \% \qquad (5)$$

where q_5^e is heat loss of boiler at rated evaporation rate; D_e is boiler rated evaporating capacity, t/h; D is actual boiler evaporation, t/h;

3.1.3. Physical Heat Loss from Ash q_6

$$q_6 = \frac{A_{ar}\alpha_{hz}C_h\theta_h}{Q_r} \% \qquad (6)$$

$c_h\vartheta_h = 559.8$kJ/kg, $q_6 = 0.0344\%$, where c_h is specific heat of slag, kJ/(kg·°C) ; ϑ_h is ash temperature.

3.2.Results

3.2.1. Original Data

Table 6: Boiler parameter list under different conditions.

Load（MW）	195	235	245
Boiler Evaporating capacity（t/h）	579	705	723
Exhaust gas temperature (°C)	135	138.5	137.5
Oxygen content in flue gas (%)	6	4.2	4

3.2.2. Results

Table 7: Heat losses of boilers under different conditions (q_3=0).

Load	MW	195	225	235	245
q_2	%	7.297	7.276	6.864	6.725
q_4	%	1.394	1.413	1.442	1.457
q_5	%	0.380	0.314	0.312	0.304
q_6	%	0.0556	0.0556	0.0556	0.0556
q_2+ q_4+ q_5+ q_6	%	9.127	9.059	8.674	8.542
η		90.873	90.941	91.326	91.458

4. Optimized Operation of Boiler Unit

The main parameters affecting coal consumption in boiler unit are: boiler load, oxygen content of smoke exhaust, smoke exhaust temperature, main steam pressure, main steam temperature, reheat steam temperature, carbon content of fly ash, coal fineness, water supply temperature. Considered the safety, economy and stability, this paper calculated the weights of the above nine parameters successively and sorted them based on the analytic hierarchy process theory, which is helpful to find the optimal method to control boiler operation and improve boiler efficiency [4].

4.1.AHP Method

AHP is a simple and convenient method for quantitative analysis to non-quantitative events in systems engineering, it is also an effective method for objective description to people's subjective judgment. when AHP method is used to analyze system, firstly, the problem should be hierarchical. According to the nature of the problem and the goal to be achieved, the problem is decomposed into different component factors, according to the mutual influence in the factors and the membership relationship, a multi-level analytical structure model can be established. Finally, the system analysis is reduced to the problem of determining the relative importance weight of the bottom layer (solutions, measures, etc.) and ranking relative to the top layer (overall target layer) [5].

4.2.Establish Hierarchical Models

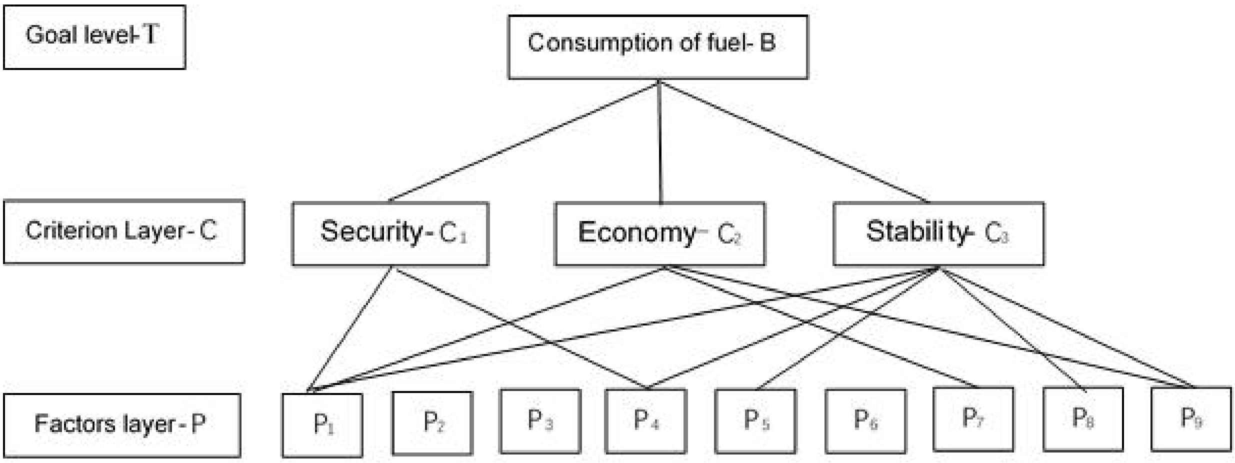

Figure 5: Classification system of factors affecting coal consumption.

where P_1 is flue gas oxygen content; p_2 is Exhaust temperature change; p_3 is Change in main steam pressure; p_4 is fineness of pulverized coal; p_5 is Main steam temperature; p_6 is boiler load; p_7 is unburned carbon in flue dust; p_8 is feed-water temperature; p_9 is Reheat steam temperature.

4.3.Establish Judgment Matrix

Table 8: Data table of weight of each element in the criterion layer.

C	C_1	C_2	C_3	W_i
C_1	1	6	8	0.7535
C_2	1/6	1	4	0.1811
C_3	1/8	1/4	1	0.0653

It can be known by calculation that, $\lambda max=3.05, CI=0.027, CR=0.046<0.1$, the test is passed and has satisfactory consistency.

The weight analysis of the above nine elements was carried out according to the safety criteria, the data obtained are shown in Table 9.

Table 9: Scheme layer security weight table.

C_1	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	W_1
P_1	1	3	4	8	5	4	5	9	5	0.3229
P_2	1/3	1	3	8	5	2	5	8	4	0.2184
P_3	1/4	1/3	1	6	4	2	5	8	3	0.1516
P_4	1/8	1/8	1/7	1	1/3	1/4	1/2	3	1/3	0.0272
P_5	1/5	1/5	1/4	3	1	1/3	3	4	1/2	0.0559
P_6	1/4	1/2	1/2	4	3	1	3	5	4	0.1166
P_7	1/5	1/5	1/5	2	1/3	1/3	1	5	1/2	0.0418
P_8	1/9	1/8	1/8	1/3	1/4	1/5	1/6	1	1/4	0.0172
P_9	1/5	1/4	1/3	3	1/3	1/8	2	4	1	0.0485

It can be known by calculation that: $\lambda max=9.4032$,$CI=0.0504$,$CR=0.0348<0.1$, The test is passed and has satisfactory consistency.

Then, weight analysis is carried out on each element of the scheme layer based on the "economy" criterion, the data obtained are shown in Table 10.

Table 10: Data table of "economy" weight of each element in the scheme layer.

C_2	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	W_2
P_1	1	1/3	1/5	4	3	1/4	3	4	3	0.0647
P_2	3	1	2	6	4	3	6	6	4	0.2748
.P_3	5	1/2	1	5	5	2	5	8	4	0.2483
P_4	1/4	1/6	1/5	1	1/5	1/4	1/3	3	1/4	0.0291
P_5	1/3	1/4	1/5	5	1	1/3	3	5	1/3	0.0647
P_6	4	1/2	1/2	4	3	1	4	5	5	0.1772
P_7	1/3	1/6	1/5	3	1/3	1/4	1	4	1/3	0.0433
P_8	1/4	1/6	1/8	1/3	1/5	1/5	1/4	1	1/5	0.0199
P_9	1/3	1/4	1/4	4	3	1/5	3	6	1	0.0781

It can be known by calculation that:$\lambda max=10.0957$,$CI=0.136963$,$CR=0.0945<0.1$, the test is passed and has satisfactory consistency.

Finally, according to, the weight analysis of each element of the scheme layer is carried out based on the "stability" criterion. The obtained data are shown in Table 11.

Table 11: Data table of "stability" weight of each element in the scheme layer.

C_3	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	W_3
P_1	1	1/4	1/4	5	4	1/3	4	5	4	0.1156
P_2	4	1	1/2	6	4	3	5	8	3	0.2315
P_3	4	2	1	8	3	3	6	9	3	0.2784
P_4	1/5	1/6	1/8	1	1/5	1/4	1/3	2	1/3	0.0258
P_5	1/4	1/4	1/3	5	1	1/3	3	4	1/2	0.0658
P_6	3	1/3	1/3	4	3	1	5	5	4	0.1524
P_7	1/4	1/6	1/6	3	1/3	1/5	1	3	1/2	0.0394
P_8	1/5	1/8	1/9	1/2	1/4	1/5	1/3	1	1/5	0.0200
P_9	1/4	1/3	1/3	3	2	1/4	2	5	1	0.0710

It can be known by calculation that:λmax=9.8827,CI=0.1103,CR=0.0761<0.1, the test is passed and has satisfactory consistency.

4.4.Results Analysis

Table 12: Total sort weights data table.

P	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
C_1	0.3229	0.2184	0.1516	0.0272	0.0559	0.1166	0.0418	0.0172	0.0485
C_2	0.0647	0.2748	0.2483	0.0291	0.0647	0.1772	0.0433	0.0199	0.0781
C_3	0.1156	0.2315	0.2784	0.0258	0.0658	0.1524	0.0394	0.0200	0.0710
The final sorting	0.2626	0.2294	0.1774	0.0274	0.0581	0.1299	0.0419	0.0179	0.0553

By integrating the weight ranking of each factor in three cases, the total weight ranking can be calculated by general weighted average method. From the above calculation results, we can get the weight of each factor. During the process of boiler operation, in order to maximize the efficiency, the influencing factors with large weight should be adjusted in priority, then the influencing factors with relatively low weight should be adjusted, and the influencing factors should be infinitely close to their optimal values, so as to achieve the purpose of boiler optimal operation.

5. Conclusions

According to the on-site data monitoring, the boiler operation parameters has been analyzed, based on the basic theory of boiler thermal balance and method, the pot grate smoke heat loss, incomplete combustion heat loss of gas, and the size of the solid incomplete combustion heat loss has been got. Through polynomial fitting to the calculation results, the optimum excess air coefficient curve has been calculated. Then the relationship between the excess air coefficient and boiler efficiency has been got by counter balance method, which provides theory basis for the optimal operation of boilers.

In addition, by integrating the weight ordering of each factor in the case of safety, economy and stability, the general weighted average method is used to calculate the total weight ordering of P layer. According to this order, the operator can be guided to give priority to adjust the influential factors with large weight during the process of operation adjustment, the target value can be infinitely close to the optimal value, which is beneficial to improve the boiler thermal efficiency and make the operation more energy-saving.

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