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Optimization of The Exhaust Gas Oxygen Content for Coal-fired Power Plant Boiler

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Abstract

During the running of utility boiler, the flue gas oxygen content is one of the most important factors that affects boiler efficiency, and it affects each other with other thermal economic parameters such as flue gas temperature, unburned carbon in fly ash and slag and coal consumption of power supply. So it's a key parameter to optimize the combustion process of fuel in utility boiler through combustion control system. Colligating the effect of flue gas oxygen content, flue gas temperature and unburned carbon in fly ash and slag on coal consumption, and aim for reducing coal consumption, the equations for associating flue gas temperature with power and oxygen content, and unburned carbon in fly ash and slag with power and oxygen content are obtained by three dimensional data fitting. And model for calculating boiler efficiency based on boiler heat balance is established. With the formula of coal consumption, the partial differential equation for calculating the variation rate of coal consumption is obtained, and optimal oxygen content is obtained through theoretical analysis and experimental research. The analysis of a 1000MW coal-fired power unit in Guangdong Province shows that the coal consumption operated at optimal oxygen content is reduced.

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Keyword: the exhaust gas oxygen content ; optimization ; coal consumption

1.Foreword

The flue gas oxygen content affects each other with other thermal economic parameters such as flue gas temperature, unburned carbon in fly ash and slag and coal consumption of power supply, and it's ralated with heat loss in boiler and power consumed in forced draught and induced draft fans, so it can affect coal consumption seriously[1,2,3]. There are many Chinese scholars having commited to the study of optimal oxygen content, such as Cang Guochao, Gu Junjie, Shi Weijing etc[4,5,6]. It is hard to calculate exact model, and the association between variables is depends on changing-condition experiments.Intelligent algorithms can analyze the association of parameters in historical database and

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calculate optimal solutions by the principle of black box, but it can't analyze the physical meaning sufficiently.

Through three dimensional data fitting for relevant parameters, the equation for associating exit flue-gas temperature with load and oxygen content and the equation for associating unburned carbon in fly ash and slag with load and oxygen content are obtained. And the partial differential equation for calculating the variation rate of coal consumption is obtained, According to the model for calculating boiler efficiency based on the basic theory of boiler thermal balance and the model for calculating coal consumption. And the optimal oxygen content is obtained according to theoretical analysis and experimental research. Taking a 1000MW coal-fired power unit in Guangdong Province as research object, we obtain the method for calculating optimal oxygen content and analysis the effect of optimization.

2.Model for Calculating Optimal Oxygen Content

2.1.Model for calculating boiler efficiency

According to the law of conservation of energy, the equation for calculating coal consumption of power supply $b_g(g/kW\cdot h)$ is as follows:

$$b_g = \frac{H_{rt}}{0.2931\eta\eta_0(1-\xi)} \tag{1}$$

Here, $H_{rt}(kJ/kW\cdot h)$ is heat consumption of turbine, $\eta_0(\%)$ is insulation efficiency of pipe, $\xi(\%)$ is auxiliary power rate.

Making lower heating value of fuel $Q_{ar,net}(kJ/kg)$ as heat input, and ignoring heat loss due to unburned gas, the boiler efficiency $\eta(\%)$ can be calculated as follows[1,8,9]:

$$\frac{\eta}{100} = 1 - \frac{L_{uc}+L_m+L_{gy}}{Q_{ar,net}} - \frac{0.0582D_{ed}^{0.62}}{D} \tag{2}$$

Here, the last item of the equation is thermal dissipation loss of boiler, calculated by experiential formula[7], $D_{ed}(t/h)$ is rated evaporating capacity of boiler, $D(t/h)$ is practical evaporating capacity of boiler. Loss of unburned carbon $L_{uc}(kJ/kg)$, heat loss caused by water contained in fuels and air, and the water from hydrogen combustion $L_m(kJ/kg)$, heat loss of dry gas $L_{gy}(kJ/kg)$ can be calculated as follows[7]:

$$L_{uc} = 337.26\frac{A_{ar}C_{UCR}}{100-C_{UCR}} \tag{3}$$

$$L_m = 1.8911\left(\frac{M_{ar}}{100} + 0.08936H_{ar} + 1.293\alpha W_{am}V_{gk}^0\right)(t_{py}-t_0) \tag{4}$$

$$L_{gy} = C_{py}(t_{py}-t_0)\left(1.293\alpha V_{gk}^0 + 1 - \frac{A_{ar}}{100-C_{UCR}} - \frac{M_{ar}}{100} - 0.08936H_{ar}\right) \tag{5}$$

Here, $C_{UCR}(\%)$ is unburned carbon in fly ash and slag, $C_{py}(kJ/m^3\cdot{}^\circ C)$ is mean specific heat of flue gas, $t_{py}({}^\circ C)$ is exhaust temperature, $t_0({}^\circ C)$ is environmental temperature, $W_{am}(kg/kg)$ is absolute humidity of the air, $V_{gk}^{0}(m^3/kg)$ is theoretical volume of dry air, calculated according to literature[7], α is excess air coefficient of flue gas, A_{ar}, M_{ar}, H_{ar} are the content of ash,moisture and hydrogen(as received basis).

Pluging the formula (3)~(5) into the formula(2), the formula for calculating boiler efficiency is as follows:

$$\frac{\eta}{100}=1-b_0\frac{C_{UCR}}{100-C_{UCR}}-(b_1+b_2\alpha-\frac{b_3}{100-C_{UCR}})\cdot(t_{py}-t_0)-\frac{0.0582D_{ed}^{0.62}}{D} \quad (6)$$

$$b_0=\frac{337.26A_{ar}}{Q_{ar,net}} \quad (7)$$

$$b_1=\frac{(0.018911-0.01C_{gy})M_{ar}+(0.16899-0.08936C_{gy})H_{ar}+C_{gy}}{Q_{ar,net}} \quad (8)$$

$$b_2=\frac{1.293(1.891W_{am}+C_{gy})V_{gk}^{0}}{Q_{ar,net}} \quad (9)$$

$$b_3=\frac{A_{ar}C_{gy}}{Q_{ar,net}} \quad (10)$$

$$\alpha=\frac{21}{21-[O_2]^{'}} \quad (11)$$

$$[O_2]^{'}=\frac{21K+90[O_2]}{90+K} \quad (12)$$

Here, b_0, b_1, b_2, b_3 are constants related to elemental analysis and calorific value of fuel, specific heat of flue gas and humidity of air, $[O_2], [O_2]^{'}(\%)$ are oxygen content in import and export of preheater, $K(\%)$ is air leakage rate of air preheater, $C_{gy}(kJ/m^3\cdot{}^{\circ}C)$ is mean specific heat of dry flue gas.

2.2.Model for calculating optimal oxygen content

Oxygen content of flue gas can affect heat loss of flue gas, unburned carbon in fly ash and slag and temperature of flue gas. So the equation for calculating coal consumption of power supply related to $[O_2]$, C_{UCR} and t_{py} is as follows:

$$b_g=f([O_2],C_{UCR},t_{py}) \quad (13)$$

With the formula(1)(6)(13), the change rate of coal consumption related to oxygen content is as follows[1]:

$$\frac{db_g}{d[O_2]}=\frac{\partial f}{\partial\eta}\frac{\partial\eta}{\partial[O_2]}+\frac{\partial f}{\partial\eta}\frac{\partial\eta}{\partial C_{UCR}}\frac{\partial C_{UCR}}{\partial[O_2]}+\frac{\partial f}{\partial\eta}\frac{\partial\eta}{\partial t_{py}}\frac{\partial t_{py}}{\partial[O_2]} \quad (14)$$

Here, $\partial f/\partial\eta$ is change rate of coal consumption related to boiler efficiency, $\partial\eta/\partial[O_2]$, $\partial\eta/\partial C_{UCR}$, $\partial\eta/\partial t_{py}$ are change rate of boiler efficiency related to oxygen content in import and export of preheater, unburned carbon in fly ash and slag and flue gas temperature.

The increase of load will increase coal consumption, heat absorption of water wall, mean temperature of furnace, and flue gas temperature. The flue gas temperature also can be affected by oxygen content. And the unburned carbon in fly ash and slag is primarily affected by load and oxygen content. The equations for associating flue gas temperature with power and oxygen content, and unburned carbon in fly ash and slag with power and oxygen content are obtained by three dimensional data fitting. The data[10] is measured when the load is stabilized at 450MW, 600MW, 750MW and 1000MW.

$$C_{UCR} = 20.1813 + 0.3323[O_2]^2 - 5.6152O_2 - 0.0141P_e + 0.0032O_2P_e \quad (15)$$

$$t_{py} = 121 + 0.3435[O_2]^2 - 6.4517O_2 + 0.0119P_e + 0.0025O_2P_e \quad (16)$$

$$\xi = 5.9 - 0.00225P_e \quad (17)$$

P value by F-test of formula(22)(23) are 0.01 and 0, R^2 of formula(24) is 0.82,they all can be accepted. The three-dimensional surface of formula(22)(23) are showed in picture 1.

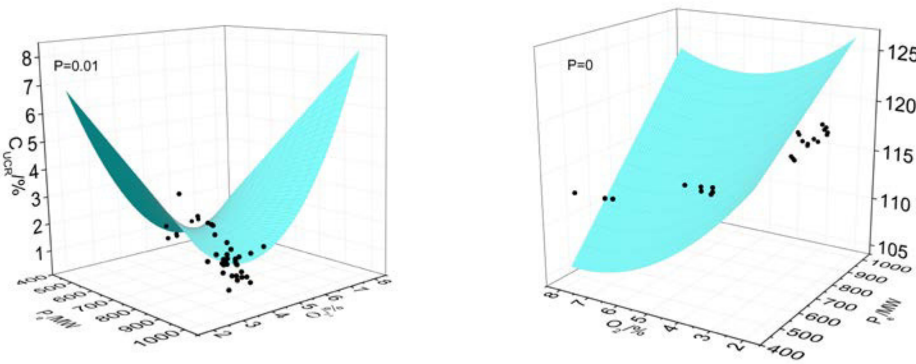

Fig.1. (a) fitting surface of unburned carbon in fly ash and slag; (b) fitting surface of flue gas temperature

With the formula(6)(15)(16)(17), the method for calculating every items in formula(14) is as follows:

$$\frac{\partial f}{\partial \eta} = \frac{H_{rt}}{0.2931\eta_0(0.00225P_e - 4.9)\eta^2} \quad (18)$$

$$\frac{\partial \eta}{\partial [O_2]} = -\frac{9000}{90+K} b_2(121 + 0.34[O_2]^2 - 6.45O_2 + 0.0119P_e + 0.0025O_2P_e - t_0)\frac{21}{(21 - \frac{21K + 90[O_2]}{90+K})^2} \quad (19)$$

$$\frac{\partial \eta}{\partial C_{UCR}} = 100\frac{b_3(121 + 0.34[O_2]^2 - 6.45O_2 + 0.0119P_e + 0.0025O_2P_e - t_0) - b_0(59.64 - 0.66[O_2]^2 + 11.23O_2 + 0.0282P_e - 0.0064O_2P_e)}{(79.81 - 0.33[O_2]^2 + 5.62O_2 + 0.0141P_e - 0.0032O_2P_e)^2} \quad (20)$$

$$\frac{\partial \eta}{\partial t_{py}} = -100(b_1 + b_2\frac{21}{21 - \frac{21K + 90[O_2]}{90+K}} - \frac{b_3}{79.81 - 0.33[O_2]^2 + 5.62O_2 + 0.0141P_e - 0.0032O_2P_e}) \quad (21)$$

$\partial C_{UCR}/\partial[O_2]$, $\partial t_{py}/\partial[O_2]$ are change rate of unburned carbon in fly ash and slag and flue gas temperature related to oxygen content in import and export of preheater, and can be calculating by experiments operated at different oxygen content or by design features.

2.3.Method for determinating optimal oxygen content

The decrease of oxygen content will reduce heat loss of flue gas to reduce coal consumption, but increase unburned carbon in fly ash and slag to increase coal consumption. They are interacted and the coal consumption will be minimum when the value of $db_g/d[O_2]$ is 0, and the oxygen content is optimal oxygen content.

3. Application Example

The research object is a ultra-supercritical coal-fired power plant, and the model of it's boiler is DG3000/26.15- . The data for calculation is got from literature[10]. With the formula(14) and the data, the running statu of unit can be analysed as Table 1. The change rate of coal consumption related to oxygen content and optimal oxygen content, coal consumption operated at optimal oxygen content are presented at Table 1 and Fig.2.

$[O_2]^{'}$, $b^{'}_{g\,\min}$, $C^{'}_{UCR}$, Δb_g are optimal oxygen content, coal consumption operated at optimal oxygen content, predicted unburned carbon in fly ash and slag operated at optimal oxygen content and increase of coal consumption operated at oxygen content deviated from optimal oxygen content.

Table 1. Effect of oxygen content on economic index and it's optimization at different loads

Symbol	Unit	Data			
P_e	MW	1000	900	750	500
$[O_2]$	%	3.4	3.4	4.7	5.3
C_{UCR}	%	2.1	2.6	2.7	1.3
η	%	94.2	94.1	94	93.8
H_{rt}	kJ/kWh	7416	7450	7514	7759
100ξ	%	3.85	3.68	4.12	4.86
b_g	g/kWh	277	280	283	287
$(\partial f/\partial\eta)(\partial\eta/\partial[O_2])$	g/kWh[1%]	1.07	1.09	1.22	1.32
$(\partial f/\partial\eta)(\partial\eta/\partial C_{UCR})(\partial C_{UCR}/\partial[O_2])$	g/kWh[1%]	-0.05	-0.05	-0.05	-0.05
$(\partial f/\partial\eta)(\partial\eta/\partial t_{py})(\partial t_{py}/\partial[O_2])$	g/kWh[1%]	-0.09	-0.11	-0.12	0.12
$db_g/d[O_2]$	g/kWh[1%]	0.93	0.93	0.96	1.1
$[O_2]^{'}$	%	2.8	2.9	4	5.1
$b^{'}_{g\min}$	g/kWh	276	279	782	286
$C^{'}_{UCR}$	%	2.06	2.03	1.7	1.37
Δb_g	g/kWh	0.56	0.47	0.67	0.2

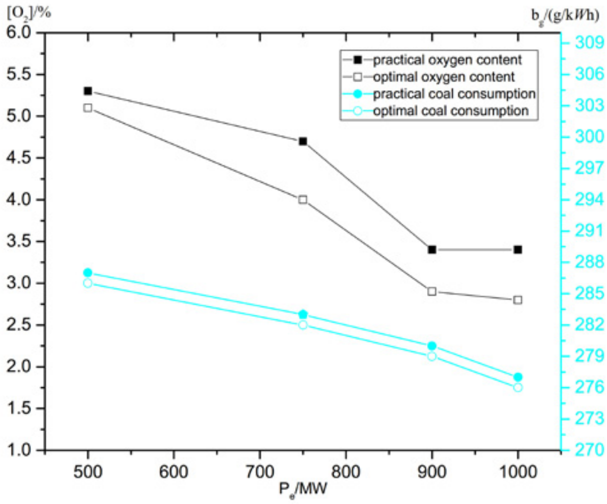

Fig.2. coal consumption of power supply operated at typical oxygen content and optimal oxygen content

4. Conclusion

Colligating the effect of flue gas oxygen content,flue gas temperature and unburned carbon in fly ash and slag on coal consumption, and aim for reducing coal consumption, the equations for associating flue gas temperature with power and oxygen content, and unburned carbon in fly ash and slag with power and oxygen content are obtained by three dimensional data fitting. And model for calculating boiler efficiency based on boiler heat balance is established. With the formula of coal consumption, the partial differential equation for calculating the variation rate of coal consumption is obtained, and optimal oxygen content is obtained through theoretical analysis and experimental research. The analysis of a 1000MW coal-fired power unit in Guangdong Province shows that the coal consumption operated at optimal oxygen content is reduced.

We can also predict the unburned carbon in fly ash and slag operated at optimal oxygen content according to the model obtained by three-dimensional data fitting. Predicted unburned carbon in fly ash and slag and optimal oxygen content can be used as reference values for power plant.

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