STUDY ON THE STATIC BEHAVIORS OF CIRCULATING FLUIDIZED BED BOILER BASED ON OPTIMIZING COMBUSTION

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Abstract: It seems that the automatic generation control (AGC) system can be put into use for operation of circulating fluidized bed (CFB) unit, but in fact, the AGC is always in the process of turbulent regulation, and makes the control mechanisms act frequently. The reason is that the regulating rules of control variables with load are not clear for CFB combustion system. Taking account of the capacity, structure, cyclone performance and desulphurization efficiency, through adjusting the particle size distribution of feedstock, the bed pressure drop and the mass ratio of primary air to secondary air, the optimized combustion of CFB boiler can be achieved which is featured by the optimal particle size distribution of bed material, lower carbon content in fly ash and bottom ash. By setting up the equations of energy balance, material balance and carbon balance, the static behaviors of CFB boiler can be carried out in the conditions of different load, different coal type and different particle size distribution of feedstock, those optimal control variables such as feed coal flow, primary air flow, secondary air flow, limestone flow and bottom ash flow are given that is needed for optimizing operation of CFB boiler. Furthermore, with those optimal control variables as the set values, the decoupling control of combustion system of CFB boiler can be realized.

INTRODUCTION

Circulating fluidized bed (CFB) combustion technology is one of the clean coal combustion technologies. Compared with the conventional pulverized coal fired boiler, the CFB boiler usually faces the problems of low combustion efficiency, serious abrasion of the heating surface, high auxiliary power ratio and low automatic use rate of the combustion control system. At present, the AGC system of CFB power unit appears to be able to put into use, but as a matter of fact, the AGC is always in the process of turbulent regulation, and can not get the steady state. The reason is that CFB boiler is a large thermal inertia and strong coupling system, the change of one regulating variable can has influence on several control variables, the dynamic characteristics of CFB combustion system are extremely complicated [1-2]. And also, the CFB boiler can be operated in multi-mode, it is difficult to get the optimal regulating variables under different load which make CFB boiler operate effectively and automatically. Aiming at these problems, in this paper, the static behaviors of CFB boiler are studied, the regulating rules of CFB boiler under different load with different coal type and different coal particle size distribution(PSD) are obtained, and the optimal set values of the combustion control system are determined. Thereby, it is possible to achieve decoupling control and efficient operation for CFB boiler.

In the AGC system of CFB boiler, the relations of feed coal flow, the primary and secondary air flow versus load rate are set up, these functions are obtained from the results of combustion adjustment [3], but they are given for the test coal type and it's PSD. With the changes of PSD, the relations will change[4].

Taking this into consideration, the caloric value correction and main steam pressure correction are supplemented in the AGC system of some power units. But due to the lag of on-line calculation of the coal calorific value, the excess adjustment of main steam pressure usually appears[5], and it leads to a opposite regulation, so, the AGC system is always in turbulent. But also the correction of the calorific value only makes the feed coal flow change, it can not make the ratio of the primary air flow to the secondary air flow change optimally. And also the AGC system does not consider the influences of coal PSD, limestone composition, bed pressure drop, desulfurization efficiency and flue gas temperature on feed coal flow, primary air flow, and secondary air flow[6].

In this paper, the static regulation behaviors of CFB power unit are studied which determined the feed coal flow, primary air flow, secondary air flow, limestone flow and bottom ash flow under different loads and with different coal type. The static regulation behaviors will guarantee optimizing combustion which is characterized with the optimum oxygen content of flue gas, bed temperature, minimum temperature difference in the furnace and low carbon content of bottom ash and fly ash. Furthermore, those optimal static operating variables given by the static regulation rule can be taken as the set values of each control loop of the AGC system, this will actualize decoupling control of CFB boiler combustion system.

The main factors of the static behaviors of CFB boiler are: boiler capacity, boiler structure, designed parameters, cyclone performance, operating load, coal type, coal PSD, bed pressure drop and desulfurization efficiency. These factors should be taken into consideration when the static regulation behaviors are figured out. In this paper, the energy balance equation, material balance equation and carbon balance equation of CFB boiler are established to study the static regulation characteristics of CFB boiler.

2 The static balance equations of CFB boiler

（1）The energy balance equation

$$B \cdot Q_{ar,net} \cdot \eta_b = \frac{P}{\eta_{a,el}} \quad (1)$$

（2）The material balance equation

$$B(C_g + A_{ar}) + 2.5BS_{ar}\eta_{so_2} + 0.56B_{\text{limestone}} - G_{pz} - R_c - B(1-q_4)V_y\rho_{p,out}(1-\eta) = 0 \quad (2)$$

（3）The carbon balance equation

$$BC_g - \sum R_{ci} - G_{pz}C_{pz} - B(1-q_4)V_y\rho_{p,out}(1-\eta)C_{fh} = 0 \quad (3)$$

2.1 Determination of several important parameters in the static balance equations

2.1.1 Objective functions of the optimal combustion

Material balance is the core for the design and operation of CFB boiler [7-10]. At the given cyclone efficiency, by regulating the coal particle size distribution, the optimal material concentration profile along the height of furnace can be obtained which may both satisfy heat transfer and reduce abrasion[11] ; By regulating the bed pressure drop, the residence time of large coke particles in the furnace can be controlled to reduce the carbon content of bottom ash, energy consumption of fan and abrasion of furnace[12]; By regulating the ratio of secondary air to primary air and increasing the stiffness of secondary air, the oxygen conditions of the furnace center can be improved and the carbon content of fly ash can be reduced[13].

The combustion optimization objective functions are established as follows:

$$\begin{cases} \rho_{p,out,\min}(R) \le \rho_{p,out} \le \rho_{p,out,\max}(R) \\ t_{p\min} \le t_p \le t_{p\max} \\ 14 \le \dfrac{m_2 V_2}{m_1 V_1} \le 20 \end{cases} \tag{4}$$

The concentration range of furnace outlet material under the rated load is 2.2～3.2 kg/Nm^3. Based on the multi-cell models of material balance, by adjusting the coal PSD, the optimal material concentration distribution along the height of furnace is calculated.

2.1.2 The residence time of coarse particles

The average residence time t_p of coarse particles is calculated as follows:

$$t_p = \frac{M}{q_{m,fs} \cdot X_{coarse}} \tag{5}$$

The residence time of coarse particles can be changed by adjusting the bed inventory M or bed pressure drop p_l（ $p_l = M / A_b$, A_b is the cross-sectional area of air distributor）.The residence times of coarser particles from different coals were obtained through experiments of coal burnout [14]. Fig.1 shows the results of the experiments.

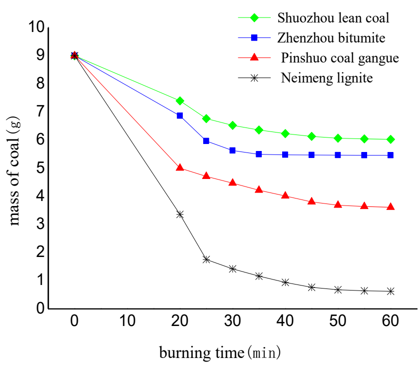

Fig.1 Burnout properties of the four coals

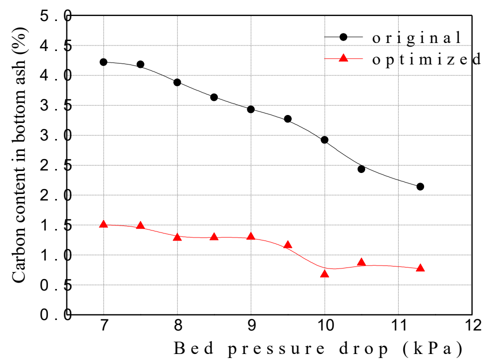

Fig.2 The carbon content in bottom ash before and after optimization

According to the bed pressure drop and the combustion of dense zone, and considering the layering properties of discharging slag in dense zone[15], the carbon content in bottom ash is determined. For different coal, by optimizing the bed pressure drop, the large coke particles can be burnout, and the carbon content in bottom ash will reduce, and also the energy consumption of primary fan will reduce as soon as possible. Fig.2 presents the carbon content in bottom ash under different bed pressure drop before and after optimization when burning Pingshuo gangue.

2.1.3 Effects of the momentum ratio of secondary air to primary air on the carbon content in fly ash

The carbon content in material of furnace outlet is related to the PSD of coke in the furnace outlet. The carbon content in fly ash is formed because of those fine coke particles which cannot be once burnout in furnace and also cannot be captured by the cyclone. Decreasing the central oxygen-deficient zone of furnace and improving the combustion condition, the carbon content in fly ash can be reduced. This can be achieved by regulating the momentum ratio of secondary air to primary air. The ratio range is as follows:

$$14 \le \frac{m_2 V_2}{m_1 V_1} \le 20 \tag{6}$$

2.1.4 The total separation efficiency η

Separator is the core device of system of material balance for CFB boiler. The two indicators for separator performance are fractional separation efficiencies: d_{50} and d_{99}, the total separation efficiency η is determined by fluidization air velocity u、d_{50} and d_{99} which is shown by formula (7).

$$\eta = \eta_0 - e^{-a_1 \cdot u^m} \tag{7}$$

Where, a_1 and m are obtained from d_{50} and d_{99}. η_0 is the maximum efficiency of the separator, it can be considered only related to d_{99}:

$$\eta_0 = -0.0005 d_{99} + 1.04 \tag{8}$$

2.1.5 The solid concentration of furnace outlet

The solid concentration of furnace outlet is obtained from the optimization of solid concentration distribution, the detail was present in reference [12].

2.2 Solution of the nonlinear equations

The Newton method is used to solve the nonlinear equations composed of energy balance equation, material balance equation and carbon balance equation to get feed coal flow B, bottom ash flow G_{pz} and burning rate R_c in the furnace.

2.3 Limestone flow

The ratio of calcium to sulfur $R_{Ca/S}$ is mainly affected by limestone activity index Rav1, sulfur content S_{ar} in coal, desulfurization efficiency η_{so_2} and bed temperature T_b. The mass flow ratio of limestone to coal is:

$$R_{B_{lime}/B} = \frac{100 R_{Ca/S}}{\mathrm{CaCO}_{3ar}} \times \frac{S_{ar}}{32} \tag{9}$$

The mass flow rate of limestone is:

$$B_{limestone} = R_{B_{lime}/B} \times B \tag{10}$$

2.4 The total air flow

CFB boiler basically are operated in constant air flow under 50% BMCR, above 50% BMCR, the total air flow increases linearly with the load rate R. The theoretical excess air coefficient of furnace outlet α_0 can be calculated by the following equations:

$$\alpha_0 = -0.001 \cdot V_{daf} + 1.3 \tag{11}$$

The total air flow is :

$$Q = \alpha \cdot B_j \cdot V^0 \qquad R \geqslant 50\% \tag{12}$$

$$Q = Q_{R=50\%} \qquad R < 50\% \tag{13}$$

2.5 Primary air flow

In the operation of CFB boiler, the ratios of primary air and secondary air flow to total air flow will change with coal type and load. As the running coal often deviates from the designed or the checked coal, the volatile content sometimes changes greatly, so, the ratio of primary air flow to secondary air flow should change. According to the requirements of economic operation and fluidization quality, the primary air flow can be controlled in formula (14). The control variable P_1 corresponds to the opening degree of linear valve.

$$\alpha_1 = P_1 \cdot (1 - k_{V_{daf}}) \cdot \alpha_1^0 \tag{14}$$

$$k_{V_{daf}} = \begin{cases} 0.0125V_{daf} + 0.688 & V_{daf} \ge 24 \\ 1.0 & V_{daf} < 24 \end{cases} \tag{15}$$

$$P_1 = \begin{cases} P_1^0 & R \le 50\% \\ 0.44 + 0.56R & R \ge 50\% \end{cases} \tag{16}$$

The value of P_1^0 can be obtained by operation test, the recommended value is 72%.

The control strategy for primary air flow can be directly shown in equation (17):

$$Q_1 = \begin{cases} (1 - k_{V_{daf}}) \cdot P_1^0 \cdot \alpha_1^0 \cdot Q & R \le 50\% \\ (1 - k_{V_{daf}})(0.44 + 0.56R) \cdot \alpha_1^0 \cdot Q & R > 50\% \end{cases} \tag{17}$$

2.6 Secondary air flow

The secondary air flow is controlled mainly according to the requirement of total air flow for coal combustion.

$$\alpha_2 = P_2 \cdot k_{V_{daf}} \cdot \alpha_2^0 \tag{18}$$

In formula(18), α_2^0=0.4～0.5, P_2 is the influence coefficient of boiler load on the secondary air flow ratio.

$$P_2 = \begin{cases} P_2^0 & R \le 50\% \\ -0.7 + 1.7R & R \ge 50\% \end{cases} \tag{19}$$

Where, the value of P_2^0 can be obtained by operation test, the recommended value is 15%.

The control strategy for secondary air flow can be directly shown in equation (20):

$$Q_2 = \begin{cases} P_2^0 \cdot k_{V_{daf}} \cdot \alpha_2^0 \cdot Q & R \le 50\% \\ (-0.7 + 1.7R) \cdot k_{V_{daf}} \cdot \alpha_2^0 \cdot Q & R > 50\% \end{cases} \tag{20}$$

2.7 The air flow for returning material and fluidizing in the external bed

The air flow for returning material and fluidizing in external bed Q_{fl} can be taken as the designed value under all operation conditions.

2.8 The air flow of secondary air fan

$$Q_2^{'} = Q_2 - Q_{fl} \tag{21}$$

3 Application of static characteristics in CFB boiler optimizing operation

According to the static characteristics, the optimal static operation variables can be carried out for CFB boiler in the conditions of burning different coal under different load, the optimizing combustion can be achieved. Fig.3 shows the calculation software of the static characteristics of CFB boiler, which is user-friendly. In which, the results of the static characteristics of 350MW CFB unit are presented before and after optimization.

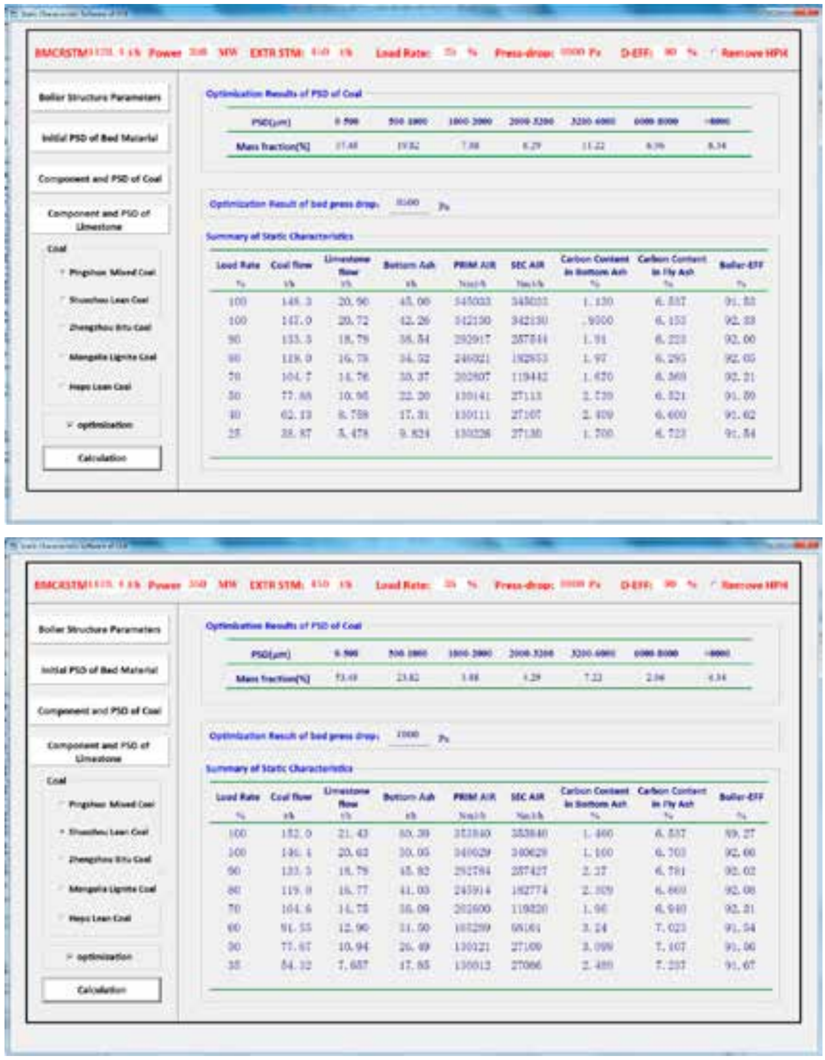

Fig.3 CFB static characteristic calculation software

4 Conclusions

In different operation conditions which are distinguished by coal type, load and structural features, through adjusting the PSD of coal, the bed pressure drop and the momentum ratio of secondary air to primary air, the optimal combustion of CFB boiler can be realized. Via establishing the equations of energy balance, material balance and carbon balance in the furnace, the optimal static operation variables are obtained, such as feed coal flow, primary air flow, secondary air flow, limestone flow and bottom ash flow. Taking these optimal control variables as the set values of the combustion control system of CFB boiler, the phenomena of "overshoot", " regulating frequently " in CFB boiler operation can be eliminated, and the decoupling control of CFB combustion system can be achieved.

NOTATION

A_{ar}	ash content in coal in received basis,%
B	feed coal flow, kg/s
B_j	the calculated fuel flow rate, kg/s
$B_{limestone}$	limestone flow, kg/s
C_{fh}	carbon content in fly ash,%
C_g	fixed carbon content, %
C_{pz}	carbon content in bottom ash,%
d_{50}	the cut size, μm
d_{99}	the critical size, μm
G_{pz}	bottom ash flow, kg/s
k_{Vdaf}	influence coefficient of volatile content in coal on secondary
m_1	primary air mass flow , kg/s
m_2	secondary air mass flow, kg/s
M	bed inventory, kg
P	power load, MW
P_1	influence coefficient of boiler load
PSD	particle size distribute
q_4	carbon loss of boiler, %
$Q_{ar,net}$	low calorific value of coal, kJ/kg
Q_2'	air output of secondary air fan, Nm^3/s
$q_{m,fs}$	material flow rate into the furnace, kg/s
R_c	combustion rate, kg/s
S_{ar}	sulfur content in coal, %
V_1	primary air velocity, m/s
V_2	secondary air velocity, m/s
V_{daf}	volatiles content in dry ash-free basis, %
V^0	required theoretical air flow when 1kg coal is burnt, Nm^3/kg
$X_{c,out}$	carbon content in material of furnace outlet, %
X_{coarse}	the mass fraction of coarse particles in feeding material, %
α_0	the theoretical excess air coefficient
α_1	the mass flow ratio of primary air to total air flow under some load, %
α_1^0	the ratio of primary air to total air flow under the rated condition,%
α_2	the mass flow ratio of secondary air to total air flow under some load, %
α_2^0	the ratio of secondary air to total air flow under the rated condition, %
$\rho_{p,out}$	solid particle concentration at furnace outlet, kg/Nm^3
$\rho_{p,out,min}$	minimum solid particle concentration at furnace outlet, kg/Nm^3
$\rho_{p,out,max}$	maximum solid particle concentration at furnace outlet, kg/Nm^3
η	cyclone efficiency,%
$\eta_{a,el}$	absolute electrical efficiency of turbine, %
η_b	boiler efficiency,%
η_0	maximum efficiency of separator, %
η_{so2}	desulfurization efficiency,%

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