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A mathematical model for optimized operation and control in a CDQ-Boiler system

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Abstract: Based on analyzing the thermal process of a CDQ (coke dry quenching)-Boiler system, the mathematical model for optimized operation and control in the CDQ-Boiler system was developed. It includes a mathematical model for heat transferring process in the CDQ unit, a mathematical model for heat transferring process in the boiler and a combustion model for circulating gas in the CDQ-Boiler system. The model was verified by field data, then a series of simulations under several typical operating conditions of CDQ-Boiler were carried on, and in turn, the online relation formulas between the productivity and the optimal circulating gas, and the one between the productivity and the optimal second air, were achieved respectively. These relation equations have been successfully used in a CDQ-Boiler computer control system in the Baosteel, to realize online optimized guide and control, and meanwhile high efficiency in the CDQ-Boiler system has been achieved.

Key words: coke dry quenching-boiler system; optimized operation and control; mathematical model

1 Introduction

The Coke Dry Quenching (CDQ) is the most advanced technology in quenching red hot coke home and abroad at present. The red hot coke (950-1050°C) charged from the upper part of the CDQ cooling chamber is quenched and cooled down by circulating gas and removed from the lower side. The circulating gas is heated to about 800°C, and then is blown in from the lower side of the CDQ cooling chamber after being cooled to about 200°C through the boiler and the second dust collector. This technology is better in energy-conservation, environmental protection and improvement of coke quality compared with the coke wet quenching. However, besides the enormous investment, it also consumes nitrogen, low-pressure steam and pure water of certain quantity, *etc.* These factors make its running cost much higher and be a barrier to popularize and apply this technology to a certain extent. However, studying and developing the "Optimized Operation and Control Model of CDQ-Boiler Systems", which can make full use of its self-consumed energy, has already become one of the important subjects in the world.

2 Mathematical model

To understand the control and operate parameter of a CDQ-Boiler system precisely and quantitatively, a mathematical model for optimized operation and Control in the CDQ-Boiler System was developed. The mathematical model consists of three parts, including the mathematical model for heat transferring process in the CDQ unit developed in the reference [1], the mathematical model for heat transfer process in boiler of the CDQ-Boiler system developed in the reference [2] and the combustion model for circulating gas in the CDQ-Boiler system developed in this paper. The mathematical model for heat transferring process in the CDQ unit can predict the temperature of discharging coke and circulating gas outside the CDQ cooling chamber. The temperature of discharging coke can be controlled within the rational range. The mathematical model for heat transfer process in the boiler of the CDQ-Boiler system can predict the temperature of circulating gas outside of the boiler and the amount of steam recovery. The temperature of circulating gas outside of boiler can be controlled within the rational range. The combustion model for circulating gas in the CDQ-Boiler system can predict the change law of the temperature of circulating gas inside of the boiler because of blowing air accurately.

2.1 Combustion model of circulating gas

The combustion model of circulating gas is set up based on the heat balance theory. Its equations are [3-4]:

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$$Q_1 + Q_2 + Q_3 = Q_4 \quad (1)$$

$$Q_1 = c_1 T_1 V_{xh} \quad (2)$$

$$Q_2 = c_a T_a V_{ercifeng} \quad (3)$$

$$Q_3 = 19.47 \times 10^6 V_{ercifeng} / 3600 \quad (4)$$

$$Q_4 = c_4 T_4 (V_{xh} + V_{ercifeng}) \quad (5)$$

where Q_1 is the sensible heat of circulating gas outside CDQ, kJ/h; c_1 the constant volume heat capacity of circulating gas at the temperature of T_1, kJ/(m^3·K); T_1 the temperature of circulating gas at the outlet of CDQ, °C; Q_2 the sensible heat of blowing air, kJ/h; c_a the constant volume heat capacity of circulating gas at the temperature T_a, kJ/(m^3·K); T_a the temperature of blowing air, °C; Q_3 the combustion heat because of blowing air, its equation is obtained from reference [4], kJ/h; Q_4 the sensible heat of circulating gas inside the boiler, kJ/h; c_4 the constant volume heat capacity of circulating gas at the temperature of T_4, kJ/(m^3·K); T_4 the temperature of circulating gas at the inlet of the boiler, °C; V_{xh} the amount of circulating gas, m^3/h; $V_{ercifeng}$ the amount of blowing air, m^3/h.

Through the combustion model can predict the temperature changes of circulating gas inside the boiler when the amount of the blowing air is changed.

2.2 Calculation flow

It can be found out through the above-mentioned analysis: the mathematical model is formed of three separate models concerned with each other, which is showed in **figure 1.** The calculation flow chart of the mathematical model is showed in **figure** 2.

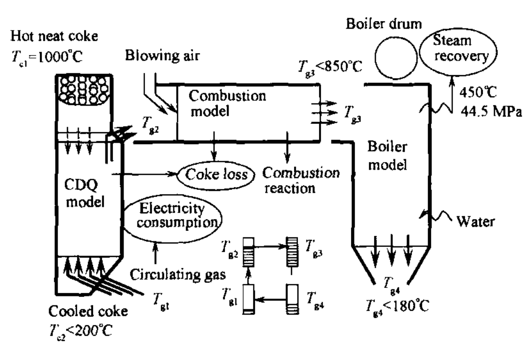

Figure 1 Mathematical model including three separate models concerned with each other. Subscript: 1—inside CDQ; 2—outside CDQ; 3—inside boiler; 4—outside boiler. T_g is the temperature of circulating gas at different positions; T_c is the temperature of coke at different positions.

2.3 Optimized flux of circulating gas

The steam recovery is the main goal in optimizing circulating gas of CDQ, while the combustion happened in the system is not considered. The steam recovery is influenced by CDQ heat exchange efficiency and boiler heat exchange efficiency, which depends on the heat flux and temperature difference between the circulating gas, coke or steam.

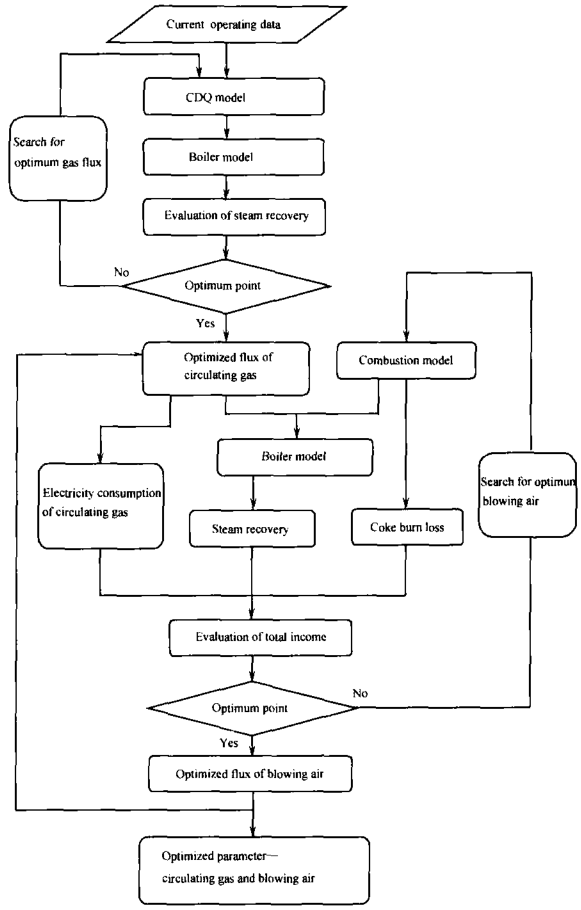

Figure 2 Calculation flow of the mathematical model.

The best point of the circulating gas exists for the following reasons. As the amount of circulating gas increases, the amount of heat exchange in the CDQ cooling chamber increases and the sensible heat of circulating gas which comes out the CDQ cooling chamber rises. However, the amount of large heat exchange in the CDQ cooling chamber comes up to its optimum point in the range of large amount of the circulating gas. Also, the boiler efficiency decreases due to the decrease in temperature of the circulating gas inside the boiler.

As this best point chiefly depends on the amount of coke, when calculating in actual simulation with the mathematical model for heat transferring process in CDQ unit and the mathematical model for heat transfer process in the boiler. 45, 50, 55, 60, 65, 70, and 75 t/h are used as the typical operating conditions to search for the optimized flux of circulating gas. **Figure** 3 shows the result of the simulating steam recovery as a function of the amount of circulating gas under each typical productivity.

It can be found in figure 3 that under each typical productivity, the amount of steam recovery has its optimum point with the change of circulating gas. If a line is used to connect these optimum points approximatively, a formula which shows the linear relation of the productivity and circulating gas can be obtained (shown as the following equation). Its coefficient correlation is 0.996.

$$y_1 = 10^4 \times (0.1202x + 3.4617) \quad (6)$$

where y_1 is the optimized flow of circulating gas, m^3/h; x is the productivity, t/h.

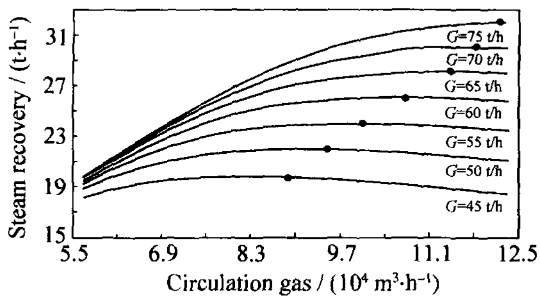

Figure 3 Change profile between circulating gas and steam recovery.

2.4 Optimized flux of blowing air

In the course of practical production, after mixed with the blowing air, the circulating gas which comes from the CDQ burns and results in rising the temperature, strengthening the heat exchange, improving the steam recovery, and finally increasing the steam incoming. But meanwhile, with the increase of blowing air, the coke burn loss increases, and the expenditure increases, at the same time the expenditure of electricity consumption caused by circulating gas also increases a little. So, there must be an optimized flux of blowing air under the optimized flow of circulating gas and a constant productivity. Under this optimum blowing air, the total systematic economic benefit can reach the peak. The total systematic economic benefit can be calculated by the following,

$$M_{total} = M_{zq} - M_{ssc} - M_{fj} \quad (7)$$

$$M_{zq} = G_{zq} p_{zq} \quad (8)$$

$$M_{ssc} = G_{ss} p_c \quad (9)$$

$$G_{ss} = G_c \varphi \quad (10)$$

$$\varphi = 0.001 \times (0.18b^2 - 3.62b + 330) \quad (11)$$

$$M_{fj} = (V_{xh} + V_{ercifeng}) p_{fj} \quad (12)$$

where M_{total} is the systematic total economic benefit, Yuan; M_{zq} the steam incoming, Yuan RMB; M_{ssc} the coke burn loss expenditure, Yuan RMB; M_{fj} the electricity consumption caused by circulating gas expenditure, Yuan RMB; G_{zq} the amount of steam recovery, t/h; p_{zq} the price of steam, Yuan RMB/t; G_{ss} the coke burning loss, t/h; p_c the price of coke, Yuan RMB/t; φ the ratio of coke burning, its equation is derived from the real testing data, %; b the ratio of blowing air and productivity, m^3/t; p_{fj} the price of electricity, Yuan RMB/km^3.

45, 50, 55, 60, 65, 70 and 75 t/h are used as the typical operating conditions to search for the optimized flux of blowing air under the corresponding optimized circulating gas. **Figure 4** shows the result of the total systematic economic benefit as a function of the amount of blowing air.

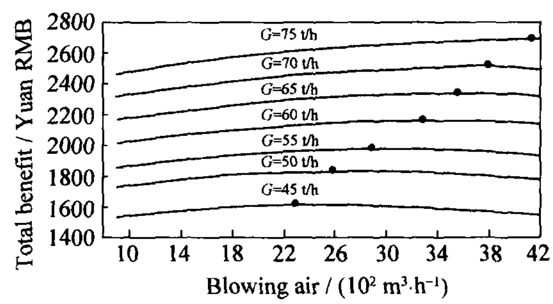

Figure 4 Change profile between blowing air and total benefit

It can be found in figure 4 that under each typical productivity, the value of systematic total economic benefit has its optimum point with the change of blowing air.

If a line was used to connect these optimum points approximatively, a formula which shows the linear relation of the productivity and blowing air can be obtained (shown as the following equation). Its relational coefficient is 0.975.

$$y_2 = 52.14x + 228 \quad (13)$$

where y_2 is the optimized flux of blowing air, m^3/h; x is the productivity, t/h.

3 Application results

The "Mathematical Model for Optimized Operation and Control in CDQ-Boiler Systems" developed in this paper for obtaining the maximum of total systematic economic benefit has been practically used in the third CDQ-Boiler system in Baosteel. In order to compare the application results, the production data of each month in 2003 were collected. It is notable that the online guidance was not operated during the former six months while it was operated during the latter six months. **Figures** 5-7 show the change chart of the air blower power consumption of per ton coke, the coke burning loss rate, the vaporizing water rate of per ton after and before the model's application. And the change of main parameters is shown in **table 1.**

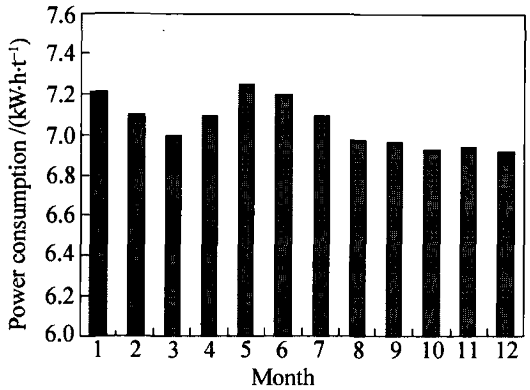

Figure 5 Change in air blower power consumption of per ton coke before and after application.

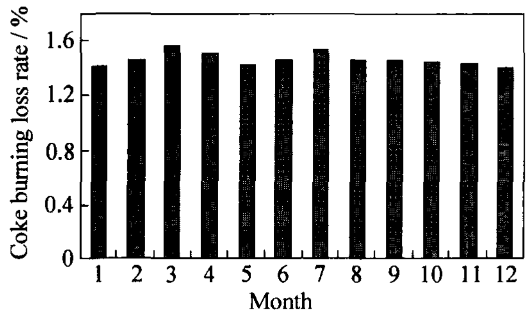

Figure 6 Change in coke burning loss rate before and after control model's application.

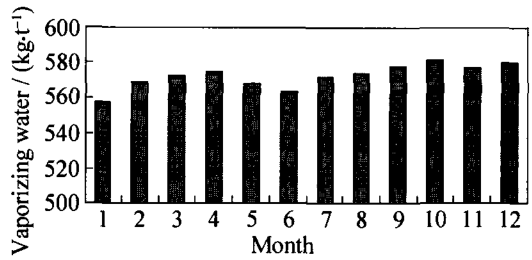

Figure 7 Change in vaporizing water of per ton coke before and after model's application.

4 Conclusions

(1) A mathematical model for optimized operation and control in a CDQ-Boiler system has been developed on the base of analyzing the thermal characteristics of the CDQ-Boiler system systematically in this paper. The model consists of three parts: the mathematical model for heat transferring process in the CDQ unit, mathematical model for heat transfer process in the CDQ-Boiler and the burning model for circulating gas in the CDQ-Boiler system.

(2) Based on the mathematical model for optimized operation and control in the CDQ-Boiler system, a series of numerical simulation under several typical operating conditions of the CDQ-Boiler were carried on.

Table 1 Change of the main thermal parameters in CDQ production

Item	Coke burning loss rate/%	Vaporizing water rate / (kg·t^{-1})	Air blower power consumption / (kW·h·t^{-1})
Before the model's application	1.480	568.4	7.146
After the model's application	1.436	578.0	6.955
Absolute difference value	0.044	9.6	0.191
Relative difference value / %	2.97 (decreased)	1.68 (increased)	2.67 (decreased)

The online related formula between systematic productivity of the CDQ-Boiler and optimal circulating gas, and the one between the productivity and the optimal blowing air were concluded. And with these related formulas, the mathematical model for optimized operation and control in the CDQ-Boiler system has been successfully used in a CDQ-Boiler computer control system, online optimized guide and control were realized.

(3) The control model make the CDQ-Boiler system reach the high efficiency of production. According to the production data which were gotten from Baosteel after the control model was operated, it can be found that the coke burning loss has decreased with the vapor rates of per ton coke improved greatly, and the air blower power consumption of per ton coke decreasing. The mathematical model developed in this paper also can be transplanted to other similar systems and the work has played an important role in promoting the computer optimized control of CDQ-Boiler.

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