One-dimensional mathematical model of coal combustion in furnace and its simulation

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Abstract. In order to accurately calculate the combustion rate of coal powder in the furnace, starting from the study of the combustion mechanism of coal particles, the combustion process of coal powder in the most complex burner area in the furnace is studied, and the combustion process of volatile points and Coke in coal powder is reasonably simplified. A one-dimensional macroscopic model of pulverized coal combustion along the Gaodufangxiang is established. The model takes into account the change of oxygen content in the combustion process of pulverized coal and is based on an equal density model of combustion of individual pulverized coal particles. The combustion process of pulverized coal reflects the whole process of pulverized coal combustion, and the formula for calculating the combustion rate of pulverized coal in furnace is deduced, which satisfies the requirement of real-time simulation calculation. The simulation results agree with the measured data and the existing literature, and the results are analyzed.

1. Introduction

Usually chemical, metallurgical and other reaction processes have strong nonlinear characteristics. Lanzhou Industry and Equipment Co. Ltd, Lanzhou University of technology researchers [1-19] proposed an only approximate to the small range process operation. When using modern control theory and intelligent control to control, it is necessary to know the mathematical model of the system accurately.

The linear characteristic is only approximate to the small range process operation, and the description ability of the nonlinear process is very limited.

The coal powder undergoes a violent chemical reaction in the boiler furnace to produce a burning flame, converts chemical energy into heat energy, raises the temperature of the flue gas, and at the same time transmits a large part of the heat to the water-cooled wall through radiation heat transfer. In order to calculate the radiative heat transfer in the furnace, we must first understand the chemical reaction of coal powder in the furnace to release heat. This requires the establishment of a mathematical model of the coal powder combustion process, and accurately estimates the burnout rate of coal powder. At the same time, the burnout rate of coal powder is also an economic indicator that reflects the operation status
of the boiler. During operation, the combustion status of coal powder can be changed by changing the ratio of air fuel.

The momentum differential equation [20] for the movement of a single coal particle, the energy differential equation for heat transfer, and the cracking equation for coal and the combustion equation for Coke are given. This method starts from the microscopic mechanism of coal combustion and considers too many factors. It is often difficult to guarantee the real-time requirement in power station simulation calculation. It is also from the microscopic state of a single coal particle that [21] a model of the double volatilization reaction is given for the cracking of coal. During the combustion of coal particles, it is considered that the same density changes in diameter or the same diameter changes in density. The equation of motion of the particles is also given, the same as the literature [20] it is also difficult to meet the needs of real-time computing. Documentation The micro model of coal combustion process of industrial boiler [23] is studied. The coal combustion model is used to predict the unburned maximum of coal in boiler. Lanzhou University of technology, Lanzhou Industry and Equipment Co. Ltd ZhangWanjun .et, at researchers [24-37] have several methods of reliability of the hydraulic system. The combustion conditions of coal particles of different original sizes were used to reflect the combustion process of coal particles in the furnace. Based on the above literature, the combustion process of pulverized coal is simplified appropriately, and the change of oxygen content in the combustion process is considered.

A one-dimensional set parameter model for coal combustion in a certain area of the chamber is derived. This model can be combined with a heat transfer model to automatically calculate the coal burnout rate and combustion discharge heat according to the operating parameters of the boiler without artificial intervention. To meet the needs of real-time simulation, at the same time, it has a certain degree of calculation accuracy.

2. Combustion structure of coal powder in furnace
The particle size of the pulverized coal produced by the grinder is of different sizes. The combustion rate of different particle size components is different in this heterogeneous group of suspended particles. However, it is not possible to completely separate one particle component in the particle group, because the concentration of oxygen that can be provided to this group of coal powder depends on the degree of burnout of the entire particle group. For this reason, the combustion of the particle size components in the group of suspended particles must be considered simultaneously. A combustion model is established based on the example of pulverized coal particles of a particle size and diameter. The actual pulverized coal combustion process is very complex and some simplified assumptions must be made:

1) The rapid thermal decomposition of coal powder from the burner into the furnace, all volatilization points escape and instantaneous combustion, while the coke particles begin to burn, and the diameter of the particles does not change when volatilization escapes; 2) The heterogeneous reaction of coke adopts the overall effect of generating CO2, and its reaction speed is controlled by both dynamic combustion and diffusion combustion; 3) The density of coke particles remains unchanged during the movement and combustion process, Coke particles are taken as spheres, and the loss of coke mass is reflected in the reduction of the size of spherical particles, the so-called is density model. The device diagram of coal powder in boiler furnace, as is shown in Figure.1.
The output error is applied to the actual industry to test its practicability and to model the components of propylene distillation column in the fractionation unit of Yangzi Petrochemical Company. A simple diagram of the acrylate process is shown in Figure 2.

A nonlinear dynamic soft measuring observer based on parameter forward error preprocessing data is established.

Data of steady state operation under normal working conditions of acrylate are shown in Table 1.
Feed board 124; Tower pressure $M_P$: 1.90;
Reflux ratio 16; Feed quantity, $\times 10^3\, \text{kg/h}$, 5.50;
Total number of towers 190; Tower Top Production $\times 10^3\, \text{kg/h}$ 3.70;
Tower bottom production $\times 10^3\, \text{kg/h}$ 1.80; Acrylic content on tower top, $\% > 99.55$;
Acrylic content at bottom of Tower, $\% < 5.00$

3. Mathematical model
It can be seen from the hypothesis (1) that the coal combustion process mainly depends on the combustion of coke particles. From hypothesis (2), the burning speed of coke particles can be described by the following formula:
In the formula, $K$ is the reaction speed of the outer surface of the coke particle; $\beta$ is the ratio of coke consumption to oxygen consumption in the reaction. In the reaction that fully generates CO2, $\beta = 0.375$; $C$ is the oxygen concentration; $k_s$ is the power combustion speed; $k_d$ is diffusion combustion speed; $k_0$ is the frequency factor; $E$ is the activation energy of coke oxidation; $R$ is the gas constant; $T$ is the reaction temperature; $D$ is the diffusion coefficient of oxygen; $Nu$ is the Nusselt number, and it is considered that the relative speed of motion between Coke particles and air is small enough to be 2; $\delta$ is the diameter of a component of coke particles.

For a certain granular component of coke particles, assuming (3) that the density does not change during the combustion process, the diameter decreases continuously, there are:

$$\delta_j = \delta_{j,0} \cdot \sqrt[3]{1 - \eta_j}$$

In the formula, $\delta_j$ is the particle size of the coke particle in Group $j$; $\delta_{j,0}$ is the initial particle size of coke particles in Group $j$; $\eta_j$ is the burnout rate of coke particles in Group $j$.

Assuming that the initial combustion mass of the coke particles in Group $j$ is 1kg, the total reaction surface area $A_j$ at a certain moment has:

$$A_j = \frac{6}{\delta_j} \cdot \frac{1 - \eta_j}{\rho_{ch}}$$

Where $\rho_{ch}$ is the density of coke particles. The oxygen concentration $C$ has a relationship:

$$C = C_0 \cdot \frac{T_0}{T} \cdot \frac{\alpha_{ch} - \eta}{\alpha_{ch}}$$

In the formula, $C_0$ is the initial oxygen concentration; $T_0$ is the initial air flow temperature of the combustion; $T$ is the airflow temperature at that time; $\alpha_{ch}$ is the excess air coefficient of coke combustion at the beginning of combustion; $\eta$ is the total depletion rate of each scale Coke particle from the initial moment to that moment.

The rate of change of combustion rate of particle size pulverized coal in Group $j$ is:
\[ \frac{d \eta_j}{dt} = K \cdot A_j \] (7)

The total burnout rate of coal powder is:

\[ \eta = \sum \eta_j \cdot m_j \] (8)

Among them, \( m_j \) is the mass percentage of particle size coal powder in Group j. Substituting formula (1)-(6) into type(7) is:

\[ \frac{d \eta_j}{dt} = \frac{2.25 C_0 \cdot \frac{T_0}{T} \cdot \left( \alpha_{ch} - \eta \right) \cdot \left(1 - \eta_j\right)}{\left(\frac{\delta_{j,0}}{\sqrt{2D}} + \frac{1}{k_s} \cdot \delta_{j,0} \cdot \sqrt{1 - \eta_j} \cdot \rho_{ch}\right)} \] (9)

If you think that the change in \( \eta_j \) has a small impact on \( \eta \), you can integrate the above formula:

\[ \eta_j = 1 - \left[ \frac{2D}{\delta_{j,0}^2} \cdot \left(\frac{\delta_{j,0}^2}{k_s} + \frac{\delta_{j,0}^2}{2D}\right)^2 \cdot 0.7 \cdot \frac{\delta_{j,0}^2}{k_s} \cdot \frac{C_0}{T} \cdot \frac{T_0}{T} \cdot \frac{\alpha_{ch} - \eta}{\alpha_{ch}} \cdot \rho_{ch} \cdot D \cdot t - \frac{2D}{k_s \cdot \delta_{j,0}} \right]^3 \] (10)

The burning time of coke particles is:

\[ t_{j,\text{max}} = \frac{\rho_{ch} \cdot \left(\frac{\delta_{j,0}}{k_s} + \frac{\delta_{j,0}^2}{8D}\right)}{0.375 C_0 \cdot \frac{T_0}{T} \cdot \frac{\alpha_{ch} - \eta}{\alpha_{ch}}} \] (11)

According to the literature [5], equation (2) can be replaced by the following formula:

\[ k_s = k_0 \cdot \exp\left[\frac{-E}{RT_{ch}} \cdot \left(1 - \frac{T_{ch}}{T_0}\right)\right] \] (12)

Among them, \( T_{ch} \) is the surface temperature of coke particles; \( k_0 \) can be 100m/s; \( T_0 \) is 2600K. According to the literature[2] The diffusion coefficient of oxygen is approximately:

\[ D = 2 \times 10^{-5} \cdot \left(\frac{T_g + T_{ch}}{2 \times 273.16}\right)^{1.75} \] (13)

In the formula, \( T_g \) is the airflow temperature. The particle size of the coal powder entering the boiler by the burner is considered to conform to the Rosin-Rammler relationship:
In the formula, $R(\delta)$ is the particle mass percentage of coal powder with a particle size greater than $\delta$; $\delta_c$ is the characteristic particle size of coal powder; $n$ is the uniformity index of coal powder, depending on the structure of the coal mill and separator, by the literature [6], $n=0.8$~1.3. Structure diagram of coal mill and separator, as is shown in Figure.3.

![Figure 3. Structure diagram of coal mill and separator.](image)

It should be emphasized that, as can be seen from formula (9), the burnout rate of coal powder is closely related to the temperature in the furnace, and the temperature must affect the burnout rate of coal powder. The heat released from combustion determined by the rate of pulverized coal also affects the temperature distribution in the furnace. Therefore, when the model is solved, the combustion model of coal powder needs to be established in conjunction with the heat transfer model in the furnace. After determining the temperature distribution in the furnace, the distribution of coal powder depletion rate can be accurately estimated. The heat transfer model can be found in another article of the author, "The mathematical model of radiation heat transfer in the furnace and its simulation."

4. Experiment simulation and analysis
A DG1025/18.3-II4 boiler was simulated and calculated by using this model. The boiler is a sub-critical natural circulation furnace, a single furnace, an intermediate reheat, balanced ventilation, suspended open-air arrangement, solid slag disposal, an intermediate stored-type powder production system, and hot air powder; The burner is arranged in DC four corners and double-cut circular reverse combustion. The diameter of the circle is case 500 and case 700. The burner is divided into two groups. The following group has a total of 7 layers of nozzles and the upper group has a total of 8 layers of nozzles. The main structural dimensions of the boiler are shown in Figure 4. We tested the experimental platform, as shown in Figure 5.
When calculating, the burner area is divided into 5 regions, and the area above the burner is divided into 6 divisions. Powder particles are divided into 16 groups according to the Rosin-Rammler relationship, with a minimum particle size of 10 μm, a maximum particle size of 160 μm, a coal powder uniformity index of 1.1, and a characteristic particle size of 50.284 μm. The activation energy of coke oxidation is taken as 90 kJ/mol, and the density of Coke is taken as 1500 kg/m³. Table 1 shows the amount of coal and air supply to the boiler at maximum load (BMCR), rated load (ECR) and 70% rated load (70% ECR). At 70% ECR, the burner in the combustion area. The burner in the fifth sub-area is turned off. Therefore, the coal flow and air flow in the sub-region are zero.

**Table 1. Operating parameters of DG1025/18. 3-II boilers under different loads**

| Area Number | New fuel volume /(kg/s) | New air volume /(kg/s) |
|-------------|-------------------------|------------------------|
|             | BMCR | ECR | 70%ECR | BMCR | ECR | 70%ECR |
| Combustor area | 1    | 8.20834 | 7.41222 | 6.48570 | 69.66661 | 62.90973 | 55.04601 |
|             | 2    | 8.20834 | 7.41222 | 6.48570 | 69.66661 | 62.90973 | 55.04601 |
|             | 3    | 8.20834 | 7.41222 | 6.48570 | 69.66661 | 62.90973 | 55.04601 |
|             | 4    | 8.20834 | 7.41222 | 6.48570 | 69.66661 | 62.90973 | 55.04601 |
|             | 5    | 8.20834 | 7.41222 | 0       | 69.66661 | 62.90973 | 0       |
The simulation results of combustion of coal powder along the furnace Gaodufangxiang are given. Average temperature of medium in furnace (REF.: Documentation), as is shown in Figure 6.

![Figure 6. Average temperature of medium in furnace (REF).](image)

It should be noted that the medium temperature in Figure 6 is the average temperature of the furnace cross section. This temperature is not the temperature of the center line of the furnace, but the aggregate temperature of the entire cross section. In Figure 6, the curve in the curve is the result of the calculation of the model and the heat transfer model. The curve REF is the literature[7] The measured temperature curve of the HG-670 / 140-6 boiler given can be seen that the measured curve is similar to the temperature curve at 70 % ECR, and the temperature of the medium in the furnace decreases with the reduction of the load.

Effect of load change on total burnout rate. He simulation results of combustion of coal powder along the furnace Gaodufangxiang are given, Effect of load change on total burnout rate, as is shown in Figure 7.

![Figure 7. Effect of load change on total burnout rate.](image)

Figure 7 gives the total burnout rate of the boiler under three types of loads. At the time of calculation, the excess air coefficient in the furnace is taken as 1.27, and the R90 (percentage of pulverized coal particles greater than 90 μm) is taken as 15 %. It can be seen that the total depletion rate under the BMCR and ECR does not change much. When the boiler is running at 70 ECR, due to the shutdown of the burner on the fifth floor, the center of the flame is moved downwards and the temperature of the entire medium in the furnace decreases. However, the length of stay of the medium in the furnace becomes longer and the combustion is more complete.

Effect of Excessive Air Coefficient in Furnace on Total Combustion Rate As is shown in Figure 8.
Figure 8. Effect of Excessive Air Coefficient in Furnace on Total Combustion Rate.

Figure 8 shows the effect of excess air coefficient on the total depletion rate under ECR load, and R90 is taken to 15%. It can be seen that the excess air coefficient increased from 1.1 to 1.4, and the total burnout rate at the top increased from 0.9865 to 0.99852. The increase in the total burnout rate was not significant because the increase in excess air coefficient although the oxygen concentration increased, However, the flow rate of smoke in the furnace has also increased, so the temperature of the medium in the furnace has dropped, and due to the increase in the flow rate of smoke, the stay time of coke particles in the furnace has also been shortened. Effect of particle size (R90) on total burnout rate, as is shown in Figure.9.

Figure 9. Effect of particle size (R90) on total burnout rate.

Fig. 9 shows the effect of particle size of coal powder on the total burnout rate under ECR load. The R90 is a parameter that reflects the percentage of large particles of coal powder. Since the burning time of large coal particles is relatively long, when the R90 increases, the total burnout rate is small before the relative height reaches 0.85, but with the increase of the burning time, the large particles of coal powder are burned one after another. The total burnout rate at the top of the furnace is also not much different.

Table 2 gives the literature [10] the experimental values of the fuel depletion rate in this model are compared with those of Figure 2 (b), (c), (d) and the temperature field solved from Figure 6-9. The calculation results of this model have relatively good accuracy.

5. Summary
(1) This model starts from the macroscopic mechanism of pulverized coal particle combustion, avoids the tedious differential equations of particle motion, and gives the explicit equation of coal coal
combustion in the furnace through the proper simplification of the combustion process. It meets the requirement of real time calculation of power station simulation.

(2) The combustion speed of coal mainly depends on the medium temperature, oxygen concentration and initial particle size.

(3) The calculation program compiled by this model can be used for combustion calculation of coal boiler in various power stations. The combustion process of boiler under different operating loads can be simulated by changing the amount of fuel and air entering the furnace.

Acknowledgements
The authors thank the financial supports from National Natural Science Foundation of China (Grant no. 51165024) and Science and Technology Major Project of “High-grade NC Machine Tools and Basic Manufacturing Equipment” (2010ZX040001-181).

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