CB07 - Research on Premixed Stable Combustion Process of Vertical Shaft Furnace for Coke Calcination

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Abstract

The traditional process and structure of vertical shaft furnace (VSF) are described, and the problems existing in the traditional process are deeply analyzed. Using CFD method and simulation, we developed an optimized premixed stable combustion process and furnace structure. We then carried out simulation calculations to obtain temperature distribution in the flue. At the same time, the turbulent saturated flame formed by the new process solves many problems of the traditional process. Through the simulation results of premixed stable combustion structure, it is concluded that the combustion flame changes from diffusion suspended flame, into turbulent saturated flame. This solves the problem of uneven heating due to the open-air valve, flame suspension. When adjusting the temperature of the flue, if the air valve opening increases from 10 % to 50 %, the total air combustion only increases by 20 %, even though the proportion of cold air increases nearly by 50 %, this indicates that the preheating air and cooling air temperature combined have a self-regulation effect on the control. Premixed stable combustion technology improves the adaptability of VSF to volatile content of raw materials and reduces the production cost.

Keywords: Vertical shaft furnace, Premixed stable combustion, Process simulation, Self-regulation.

1. Introduction

There are two kinds of technologies of dealing with green delayed petroleum coke used in prebaked anode: rotary kiln and vertical shaft furnace (VSF). But, the VSF is widely used because of quality of CPC, carbon loss and the stability of continuous production. Figure 1 shows the statistical data of CPC's production capacity from 2010, and we can know that the rotary kiln was replaced by VSF. The calcination companies overseas are planning to adapt Chinese VSF technology, and the matching anode plants of the large aluminum companies overseas are purchasing CPC produced by VSF [1-2].

2. Problems of the Traditional Processes

The preheating combustion air or the cooling combustion air is adopted in the traditional process of VSF, and the structure of the furnace is matching for the process. Figures 2 and 3 show respectively the furnace structure corresponding to the process.

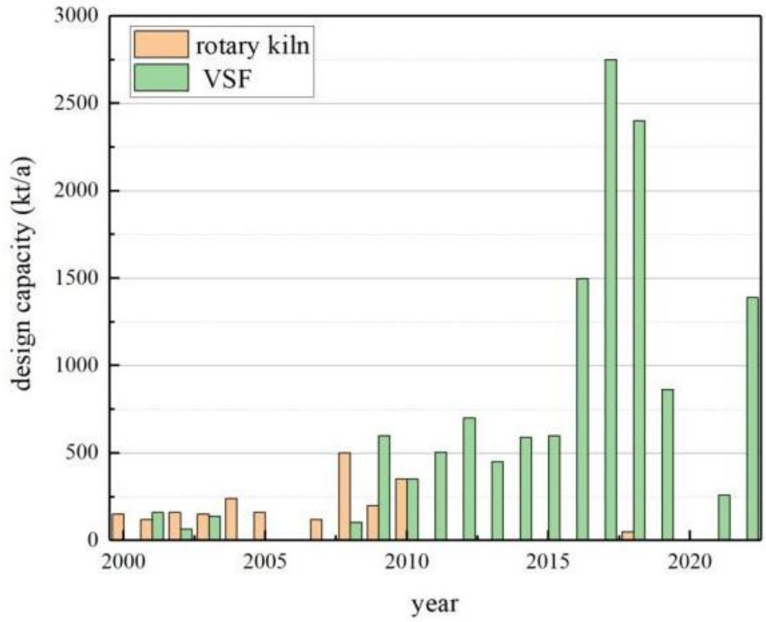

Figure 1. Production statistics comparison between VSF and rotary kiln designed by SAMI.

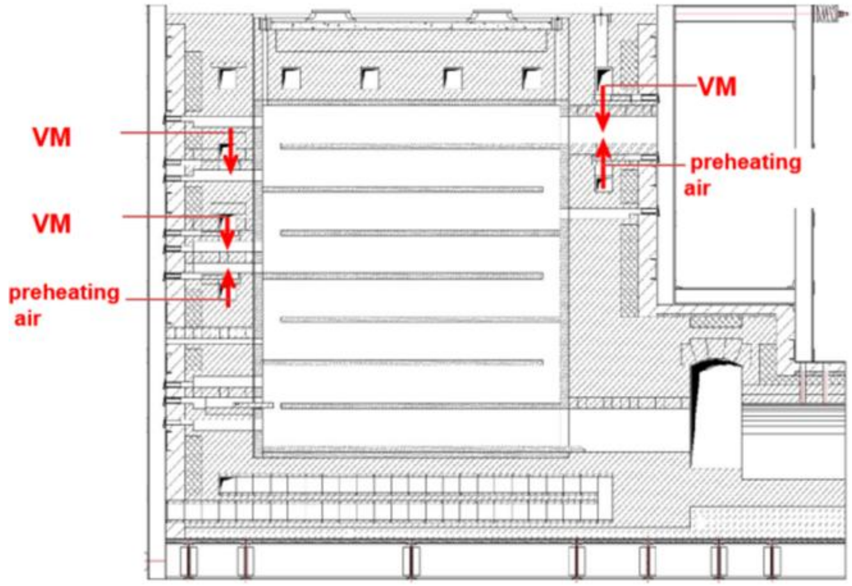

Figure 2. The furnace structure corresponding the preheating combustion air process.

The preheating combustion air process and furnace structure in the early stage as shown in Figure 2. The preheated air and volatile matters enter the flue from different positions, so there is burning flame in multiple layers in the flue. The position entering the flue of the fuel and air was reduced by optimizing. The biggest advantage of this traditional process is intense combustion and full flame, but it is no longer suitable for raw materials with increasing volatile content. There are two main defects:

1) When the volatile content of raw materials increases, the heat income of the VSF will increase. Under the environmental pressure, the volatile matters cannot be discharged, and will generate excessive heat, which finally leads to the phenomenon of "overcalcination" of CPC. The produced anode will produce more carbon dust and reduce the performance of the electrolytic cell.

2) The preheating air temperature is about 400 °C. After entering the flue, on the one hand, the temperature of the flue is improved. On the other hand, the high temperature of the combustion flame makes it easy to burn out the refractory material in the flame area, and the life of the VSF is reduced.

The cooling combustion air process is shown in figure 3. The cooling air enters the flue horizontally from the front wall of the first floor. This combustion process has the following advantages over the preheating air combustion process:

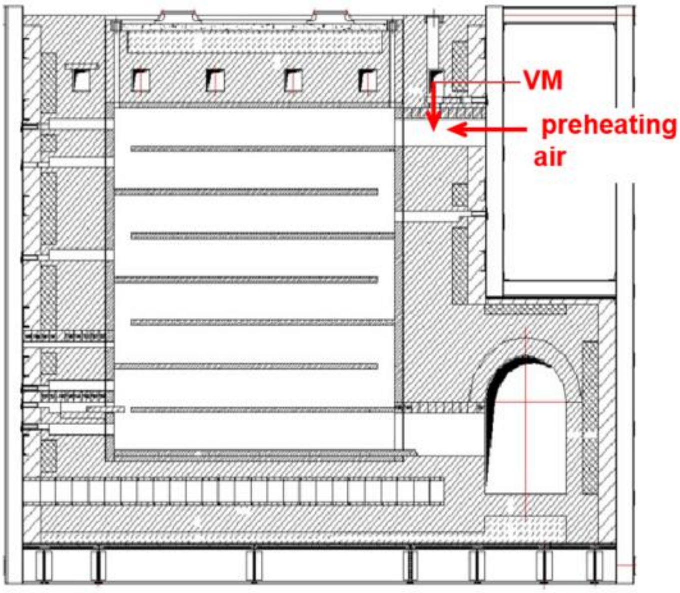

Figure 3. The furnace structure corresponding the cooling combustion air.

Cooling air is normal temperature air, relative to preheating air, and can greatly reduce the flue temperature, compared to the preheating combustion air process, the flue temperature is reduced by (100-150) °C, so that it can adapt to high volatile content of raw materials and will not cause the problem of "over-calcination".

All volatile matter enters the flue from the first floor of the front wall. Because it is cooling air, the combustion temperature will not be too high, and it will not easily burn out the refractory materials in the flame area. All the combustion air is located in one place, and the temperature of the fire channel is controlled by adjusting the cooling air damper. The operation is very simple. New staff can take up the post after a period of simple training, without rich experience.
However, after a period of application of cooling combustion air, its disadvantages are also exposed. That is, when the volatile content of raw materials is unstable, when the volatile content is high (> 11 %), in order to ensure stable monitoring point temperature, the cooling air valve is opened more (> 40 %), and the amount of cooling air directly entering the flue caused the following problems:

The combustion air and volatile matters are mixed and burned to form a diffused flame, and stratification occurs directly (as shown in figure 4). The upper space is dominated by high temperature flame, while the lower space is dominated by cold air.

Due to the suspended flame, the opening of the valve is always running at a high level, and more cold air enters. The silicon brick in the lower space of the first layer gradually darkens, and the temperature gradually decreases, reducing the life of the silicon brick.

Figure 4. Diffusion suspended flame.

After the above situation occurs in the fire passage of the first flue, the material temperature in the corresponding position of the tank area is low, and the volatile matters escape rate in coke is lower than the normal speed. In addition, the proportion of powder in raw materials is large, so the volatile matters cannot escape in time in the upper area of the tank and are wrapped by powder and brought to the lower area of the tank. Deflation phenomenon is easy to occur at the crusher, and in serious cases, the crusher equipment will collapse. It may require shutting down the fuel tank for repairs.

After the temperature of the silicon brick in the lower space of the first flue decreases, the process is slow to restore the original state, and the phenomenon of "down fire" is easy to occur in this process, resulting in high smoke exhaust temperature and over-temperature of the furnace bottom steel plate.

To sum up, the traditional process and furnace structure cause the flame suspension in the first flue, resulting in many adverse consequences, which seriously affect the production, and need to be solved from the aspects of combustion process and furnace structure.

3. Simulation of Combustion Process of Premixed Stable Combustion Structure in VSF

By means of CFD (Computational Fluid Dynamics) and simulation platform, the premixed combustion stabilization process, coupled furnace structure tank and refractory materials are simulated by calculation. The thermal parameters such as pressure, temperature, concentration and material temperature distribution in the flue are obtained.

3.1 Physics Model

The VSF is composed of flue, tank body and flue wall. The flue is divided into 8 layers in height. The tank body is arranged in pairs according to the word "field", together with 4 heating channels to form a group. According to the principle of symmetry, this study selected a group of partial areas as the model area, namely half of the tank, adjacent flue and half of the flue wall [3].

3.2 Mathematical Model

3.2.1 Continuity Equation

The equation of continuity is also known as the equation of conservation of mass. Any fluid problem must satisfy the law of conservation of mass, which can be described as: the increase of mass in the fluid cell in unit time is equal to the net mass flowing into the cell in the same time interval. According to this law, the equation of mass conservation can be obtained:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{1}$$

where:

ρ Fluid density;
t Time;
U Velocity.

3.2.2 Momentum conservation equation

The law of conservation of momentum is also a fundamental law that any flowing system must satisfy. The law can be expressed as: the rate of change of the momentum of the fluid in the cell with respect to time is equal to the sum of the external forces acting on the cell. This law is actually Newton's second law. Momentum conservation equation:

$$\frac{\partial(\rho U)}{\partial t} + \nabla \cdot \left(\rho \vec{U}\right) = -\nabla p' + \nabla \cdot \left(\mu_{eff} \nabla U\right) + \nabla \cdot \left(\mu_{eff} (\nabla U)^T\right) \tag{2}$$

where: the corrected pressure $p' = p + \left(\frac{2}{3}\mu - \xi\right) \nabla \cdot U$

p Static pressure;
ξ Volume viscosity coefficient. The value is 0.
$\mu_{eff} = \mu + \mu_T$, where μ—laminar viscosity coefficient, μ_T—turbulent viscosity coefficient, in $k - \varepsilon$ model, turbulent viscosity coefficient $\mu_T = c_\mu \rho\, k^2/\varepsilon$ (c_μ=0.09)

3.2.3 Energy Conservation Equation

The law of conservation of energy can be expressed as the rate of increase of energy in a cell is equal to the net heat flow into the cell plus the work done by physical and surface forces on the cell. Expression:

$$\frac{\partial \rho H}{\partial t} + \nabla \left(\rho U H - \left(\frac{\lambda}{c_p} + \frac{\mu_T}{P_{rH}}\right) \nabla H\right) = \frac{\partial p}{\partial t} + Q_R \tag{3}$$

where:

H Enthalpy;
λ Thermal conductivity;
P_{rH} Enthalpy Prandtl number, value 0.9;
c_p Specific heat at constant pressure;
Q_R Source entry.

3.2.4 Composition Equation

The combustion process in the pot furnace can be characterized by a single step irreversible reaction, which is controlled by the mixing rate and has reached chemical equilibrium. The combustion reaction can be described as:

1 kg fuel +i kg oxidizer→ (1+i) kg product

Define a mixed score f :

$$f = \frac{x-x_0}{x_F-x_0} \tag{4}$$

where, x_F=1, $x_0 = -1/i$; $x = w_F - w_0/i$
i Mass of the oxidizer;
w_F, w_0 Mass fraction of fuel and oxidizer.

The average mixed component $\overline{f}$ satisfies the following Equation (5):

$$\frac{\partial\rho\bar{f}}{\partial t} + \cdot\left(\rho U\bar{f}\right) - \nabla\cdot\left[\left(\frac{\mu_T}{P_{rT}} + \frac{\mu}{P_{rL}}\right)\nabla\bar{f} = 0 \tag{5}$$

where:
P_{rL}, P_{rT} Laminar and turbulent Prandtl numbers.

4. Simulation Results Analysis

The premixed combustion stabilization structure realizes the calcination process in which both preheated air and cooling air are used as accelerants. The premixed air and cooling air participate in combustion reaction, improving the stability of flame and temperature distribution. Figure 5 shows the combustion temperature distribution of flue under premixed combustion stabilization process.

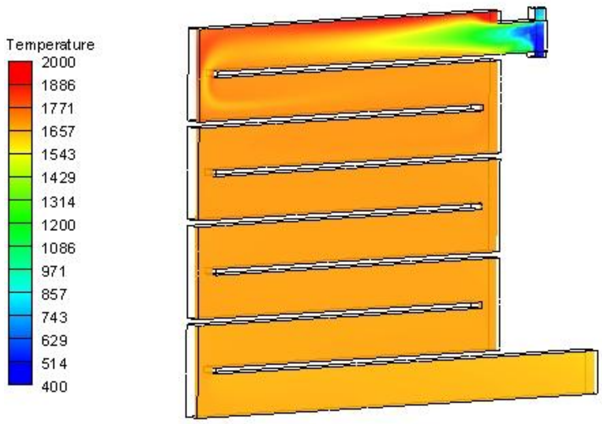

Figure 5. Temperature distribution of longitudinal section of flue (unit: K).

As can be seen from the figure, volatile matters and combustion air form a blending before entering the flue, with strong turbulence intensity and sufficient mixing. Therefore, the flame is no longer the diffusion flame before optimization, but fills the entire first flue. And the flame is not suspended, the length is greatly shortened, and basically only exists in the first layer area. The average temperature of the whole flue is higher than before optimization, especially in the first layer, the shape of the flame is stable, and will not fluctuate greatly with the change of the air valve, so as to ensure the relative stability of the temperature monitoring point, and completely avoid the risk of the first layer darkening after the air valve is opened.

5. Simulation Calculation of Premixed Stable Combustion Structure

5.1 The Model of Premixed Stable Combustion Structure

Premixed stable combustion structure not only changes the mixing mode of combustion air and volatile matters, improves the flame stability, but also changes the reaction rate and combustion mode of volatile matters and oxidants. The cooling air combustion mode into preheating air mixed cooling air combustion mode. Figure 6 shows the computational model of premixed stable combustion structure. The combustion air is divided into two parts, namely, cooling air and preheated air. After mixing them, they enter the first flue upward along the air vertical passage, and then fully mix with the down-flowing volatile matter to enter the flue for combustion.

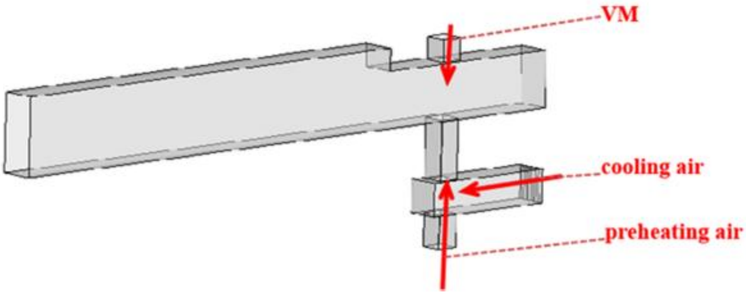

Figure 6. Computational model of premixed stable combustion structure.

5.2 Calculation of the Influence of Air Valve Opening on Combustion Air

In normal operation, the brick for flow rate controlling located in the preheating air channel is fixed, and the temperature of the flue is adjusted by adjusting the cold air valve. Therefore, the cold air is actively regulated, while the preheating air is passively regulated due to the regulation of the cold air. The airflow velocity vector diagram is shown in Figure 7, where the flow rate of cold air and preheating air are mutually affected. As the amount of cold air increases, the preheating air throttle decreases. For this reason, if the volatile matter in the raw material increases and the flue temperature increases, in order to maintain a stable flue temperature, an appropriate increase in the amount of cold air will gradually decrease the flue temperature. At the same time, the amount of preheated air will decrease, which will also lower the flue temperature. Under the dual effect, the flue temperature will be accelerated to return to the normal range. Therefore, the premixed stable combustion structure has better adaptability compared to the cold air combustion support structure shown in Figure 3 in the face of volatile fluctuations in raw materials.

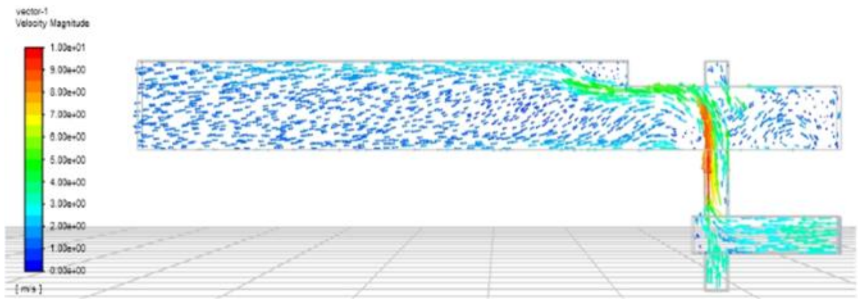

Figure 7. The airflow velocity vector diagram in the premixed stable combustion structure.

The ratio of cooling air to total combustion air varies with the opening of air valve, as shown in Figure 8. As can be seen from the figure, when the opening ratio of the air valve increases by 40 %, the proportion of cooling air volume increases by nearly 50 %. When the preheating air flow rate is fixed, the cold air valve changes from 10 % to 50 %, and the proportion of cold air increases by about 35 %. However, when the preheating air flow rate automatically changes with the opening of the cold air valve, the proportion of cold air increases by about 50 %, indicating the advantage of the premixed stable combustion structure in regulating temperature.

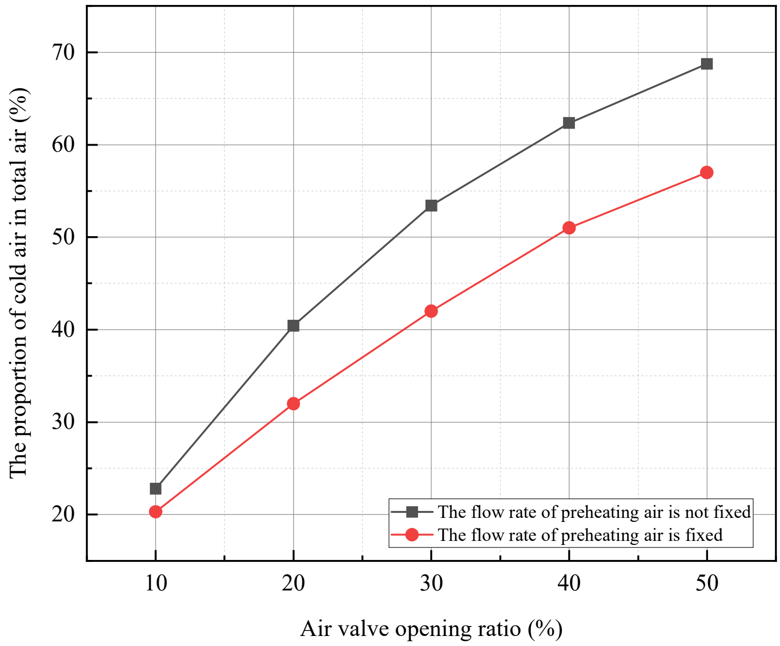

Figure 8. The curve relationship between the opening degree of air valve and the proportion of cooling air.

6. Conclusions

Using CFD as the calculation platform, and using the developed physical and mathematical model, the simulation calculation of combustion in flue of VSF is carried out. Through the combination of design and simulation optimization, the premixed stable combustion process is developed, which solves the following problems:

The premix stable combustion process changes the combustion mode, realizes the new process of preheating air and cooling air combustion, and at the same time changing the combustion flame from suspended diffusion flame, into turbulent saturated flame, solving the problem of uneven heating due to the open air valve, flame suspension.

On adjusting the temperature of the flue by increasing the air valve from 10 % to 50 %, the total combustion air only increased by 20 %, but the proportion of cooling air volume increased by nearly 50 %, indicating that the preheating air and cooling air temperature control effects superpose, showing system self-regulation.

The combustion in the flue and the temperature distribution state are more stable, which improves the adaptability of the VSF to the volatile content of raw materials, broadens the acceptable fluctuation range of volatile content of raw materials, and reduces the production cost.

7. References

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