Numerical Simulation of Oxygen-Enriched Combustion of Low-Quality Coal in Cement Rotary Kiln

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Abstract. On the basis of the original four-channel burner, the oxygen-enriched channel is added to control the oxygen-enriched rate by adjusting the opening of the valve at the entrance of the oxygen-enriched channel. In actual production, the oxygen concentration in rotary kiln can be adjusted more flexibly to meet the combustion needs of different coal types in kiln and realize oxygen-enriched combustion under different oxygen concentration. A physical model of rotary kiln--burner is established in this paper, using FLUENT to increase the oxygen-channel rotary kiln burner structure for numerical simulation of combustion of pulverized coal. The distribution of velocity field, combustion temperature and component concentration field in kiln were analyzed, and the combustion characteristics of pulverized coal in kiln were compared between two kinds of burners. The calculation results show that the addition of oxygen-enriched channels will not cause significant changes in the velocity field in the rotary kiln, and can promote the combustion of pulverized coal in the rotary kiln, thus verifying the feasibility of adding oxygen-enriched channels.

1. Introduction (Heading 1)
China is a big cement producer. For a long time in the past, due to the excessive production of cement and the limited output of high-quality cement, the economy of cement industry has been in a continuous depression [1]. With the introduction of advanced production technology from abroad in recent years, the cement industry has a great trend. In the final analysis, it is necessary to save energy and reduce consumption to improve the profit efficiency of cement industry. In the oxygen-rich environment, using low-grade and inferior coal as fuel for cement production has played a positive role in reducing production costs [2-3]. For ordinary four-channel burner [4], sufficient oxygen supply is needed to achieve stable combustion effect of inferior coal. Although it can improve the combustion effect of pulverized coal very well, the adjustment of oxygen concentration is not flexible enough for oxygen-enriched combustion, which increases the cost to a certain extent [5]. Additional oxygen-enriched channel can retain many advantages of four-channel burner, increase oxygen concentration without changing the velocity field in the kiln, and design the inlet of oxygen channel as a valve to regulate the oxygen concentration. As long as the oxygen-enriched air is steadily introduced, the oxygen concentration can be adjusted flexibly according to the type of coal and combustion characteristics [6], and the cost can be reduced. It is of great significance to the development of cement industry.
2. Rotary Kiln-Burner Structure
Taking cement rotary kiln with a length of 60 m, a radius of 1.7 m and an output of 2000 t/D as the research object, oxygen-enriched channel was added on the basis of the original NC four-channel burner. The air channels of burner are divided into central wind, swirl flow wind, pulverized, axial flow wind and oxygen-enriched wind. Oxygen-enriched wind, external wind and central wind are both axial wind. Swirling blade angle of swirl flow wind channel is designed to be 30 degrees. The schematic diagram of the system structure is shown in Fig.1.

![Figure 1. Structural sketch of cement rotary kiln—burner](image)

By means of the velocity differential jet formed before the high-speed axial flow wind, swirl flow wind and low-speed central wind, the burner can form a reflux zone in the kiln, accelerating gas exchange and promoting pulverized coal combustion. Meanwhile, the high concentration oxygen in the oxygen-enriched channel and the central flame stabilizer can enhance the circulation of high-temperature flue gas and form a stable combustion flame [7].

3. Geometry grid and boundary conditions
In this paper, the burner and furnace are simplified to establish two-dimensional model, which can greatly simplify the complexity of numerical calculation of three-dimensional structure and save calculation time. Due to the actual structure of the burner consists of a series of discontinuous nozzles at the exit, these nozzles need to be simplified into continuous circular passages when building two-dimensional model. In order to ensure that the primary air volume does not affect the aerodynamic field in the rotary kiln, the outlet of the air channel is designed as a slit structure to ensure that the area of the exit section is basically unchanged [8].

3.1. Geometry Grid
The structure of furnace and burner is symmetrical with respect to the central shaft of furnace, when building a model, only half of the structure should be drawn. Structured grids have been adopted through the software of Gambit [9]. As shown in Fig.2, the total number of grids is 736,000, and the quality of grids is good.

![Figure 2. Local grid of cement rotary kiln](image)
3.2. Boundary Conditions
Import boundary conditions: velocity inlet is used in each air channel of burner. At standard atmospheric pressure, the dynamic viscosity of air is 17.9×10^{-6} \text{ Pa}\cdot\text{s} and the density is 1.205\text{ kg/m}^3. The specific parameters of the boundary conditions of each channel are shown in Table 1.

| Wind type          | Central wind | Swirl flow wind | Pulverized coal wind | Axial flow wind | Oxygen enriched wind |
|-------------------|--------------|-----------------|----------------------|-----------------|---------------------|
| Speed (m/s)       | 50–100       | 100–150         | 15–25                | 180–240         | 0–15                |
| Hydraulic diameter| 0.02         | 0.1             | 0.21                 | 0.03            | 0.08                |

Export boundary conditions: kiln tail is pressure outlet; relative pressure value is -70Pa

4. Result and discussion
In this section, the results and discussions are based on oxygen-rich air and oxygen-free air in rotary kiln.

4.1. Aerodynamic field analysis
In cold simulation, the air flow in the rotary kiln is turbulent because of the large inlet velocity of the burner. RNG $k$-$\varepsilon$ two-equation turbulence model is selected for the turbulence model to ensure the accuracy of the calculation results and a certain calculation speed. The cold numerical simulation of rotary kiln was carried out under three conditions of no oxygen-enriched wind, 5 m/s oxygen-enriched wind speed and 10 m/s oxygen-enriched wind speed.

With other parameters unchanged, the influence of oxygen-enriched wind on the internal reflux zone is mainly reflected in the oxygen inlet. Fig. 3 shows the variation of the internal reflux zone under different oxygen-enriched wind conditions. The influence of the oxygen-enriched channel on the size of the internal reflux zone is mainly reflected in the oxygen inlet. With the oxygen-enriched wind from scratch, the internal reflux zone tends to decrease slightly in the Y-axis direction, but it is not obvious and the range of oxygen-enriched wind speed is very small, so the change of the internal reflux zone hardly interferes with the aerodynamic field in the rotary kiln.

![Figure 3. The effect of oxygen-enriched wind on the inner reflux zone](image1.jpg)

Fig.4 is a schematic diagram of the influence of oxygen-enriched wind on the external reflux zone. The external reflux zone keeps basically unchanged in the width direction, and there is a trend of...
reverse movement towards the kiln head in the length direction, and the length of reflux zone has increased, but it is not very obvious. When the oxygen-enriched wind rises from low speed to high speed, the external reflux zone tends to extend axially, but its shape remains basically unchanged.

4.2. Thermal simulation results
Thermal calculation needs to ensure that oxygen concentration in oxygen-enriched channel is different from that in other channels. Combustion model chooses Species Transport equation. Previous studies have shown that pulverized coal has the best combustion characteristics when oxygen concentration in combustion-supporting air is controlled between 26% and 30% [10-11]. In this paper, through theoretical calculation, the oxygen concentration in kiln is controlled by adjusting the oxygen-enriched wind speed to 26%. In order to get closer to the actual situation, the oxygen concentration in the oxygen-enriched channel is 40% of the oxygen concentration in membrane method, which is widely used at present. The air excess coefficient is 1.2 in the absence of oxygen-enriched channel and 1.1 in the presence of oxygen-enriched channel.

4.2.1. Temperature predictions. Fig. 5 shows that when oxygen-enriched air channel is added and oxygen-enriched combustion occurs in the kiln, the temperature field level in the kiln rises, the maximum temperature rises from 2190 to 2300, and the high temperature section is wider than that without oxygen-enriched air, the temperature distribution in the furnace is more uniform, the flame blackhead is shorter, and the ignition situation in the furnace is better.

4.2.2. Species concentration. The fuller the pulverized coal combustion in rotary kiln, the smaller the volume fraction of CO in the kiln. As shown in Fig. 6, when oxygen-enriched air flows into the kiln, the volume fraction of CO in both length and width directions decreases significantly, and the distribution range of CO is also reduced. This shows that the addition of oxygen-enriched channel can make pulverized coal combustion more complete.
With the introduction of oxygen-enriched air, the oxygen concentration distribution in the kiln is more uniform and the excess air coefficient is reduced, which reduces the N2 concentration in the furnace and the production of thermodynamic NOx. Fig. 7 shows that the addition of oxygen-enriched channel can reduce the production of NOx.

Analysis of temperature distribution and species distribution in rotary kiln after adding oxygen-enriched channel. Adding oxygen-enriched channel can improve the combustion characteristics of pulverized coal. It is feasible to control oxygen-enriched rate by adjusting the valve opening at the inlet of oxygen-enriched channel to realize oxygen-enriched combustion at different oxygen concentration.

5. conclusions
In this paper, numerical simulation of cement rotary kiln burner with oxygen-enriched channel and its rotary kiln system is carried out. The main conclusions can be drawn as follow:

1) The influence of oxygen-enriched wind on the internal and external reflux zone of rotary kiln is very small. Adding oxygen-enriched air channel will not cause a significant change in the air dynamic field of rotary kiln, and can maintain the effect of the original four-channel burner on the aerodynamic field.

2) Adding oxygen-enriched wind channel can realize the combustion characteristics of pulverized coal in rotary kiln in oxygen-enriched atmosphere. It is feasible to control oxygen-enriched rate by adjusting the valve opening at the inlet of oxygen-enriched air channel and realize oxygen-enriched combustion at different oxygen concentration.
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