Exploratory Research on Full Cycle Sintering of Flue Gas

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Abstract. The pollution caused by sintering process in China's iron and steel industry is especially serious. Strengthening the research on sintering process is of great significance to sustainable development. In this paper, a physical model of flue gas full-cycle sintering process is established, and the new process is simulated and calculated. The distribution of material layer temperature, flue gas temperature and flue gas composition content is obtained, and compared with the conventional sintering process from the five aspects of material layer maximum temperature, high temperature duration, material layer cooling speed, sintering time and emission reduction. The results show that the new process can increase the maximum temperature of the upper material layer, improve the uniformity of the temperature distribution in the material layer, and can enrich SO2, improve the removal efficiency of pollutants, and reduce emissions.

Keywords: Smoke circulation, Sintering, Porous media, Simulation.

1. Introduction

Foreign flue gas circulation sintering technology has been applied industrially, for example, EOS technology [1-2] has been adopted in Kruse Emerson Plant in Holland. Germany HKM Company adopts LEEP process [3]; EPOSiNT process of aogang iron and steel co. [4]; Japan's Nippon Steel adopts a regional flue gas circulation process [5]. China's Central South University [6] has developed an iron ore sintering method with ultra-high proportion of flue gas circulation and a method of subsection circulation of iron ore sintering flue gas [7]; Tsinghua University [8] developed a flue gas recirculation denitration system for sintering machines. Zhejiang University [9] has developed a process and system for removing various pollutants from sintering. Li Guanghui et al [10]. Proved by experimental simulation that the flue gas circulation sintering process reduces the flue gas emission. Fan Zhenyu [11] used artificial gas distribution method to carry out cyclic process experiments. The results show that various properties of sinter have been improved.

The existing flue gas circulation sintering process is only the circulation of part of flue gas and has not recycled all flue gas. Based on previous studies, this paper proposes a flue gas circulation sintering process. Through simulation calculation, the feasibility of the new process is verified by comparing with the conventional sintering process.
2. Simulation Model of Flue Gas Circulation Sintering

In this paper, a new method of full circulation of sintering process flue gas is proposed. A preheating and drying section is arranged between the distributor and the ignition device of the sintering machine. The hot flue gas from the ring cooler is led to the preheating and drying section of the sintering machine to condense the flue gas from the preheating and drying section. After removing the water vapor from the flue gas, the flue gas with high oxygen and high temperature at the tail of the sintering machine is discharged, and the flue gas with high oxygen and high temperature is circulated through an ignition section, a combustion section and a discharge section in sequence, and finally SO2 and NOx are enriched. Each section of the preheating and drying section, the ignition section, the combustion section and the discharge section can be divided into several small sections for circulation according to actual production requirements. Oxygen is supplemented by an oxygen supplementing fan in each circulation section to keep the O2 content of circulating flue gas at 21%. The full cycle process of sintering flue gas is shown in fig. 1.

1-Preheating the drying section;2-Ignition section;3-combustion section;4-Discharge section; 5- high temperature and high oxygen section; 6- distributor; 7- Ignition device; 8- condenser; 9- Fan; 10- Dust collector; 11- Denitrification; 12- desulfurization; 13- sealed hood;14- Oxygen supplement fan; 15- Chimney

Fig. 1 Schematic diagram of flue gas full cycle sintering process

2.1. Physical model

In this paper, only the material layer area of a sintering trolley is taken for simulation calculation, and the fluid area is modeled. As shown in fig. 2, a three-dimensional diagram of a physical model is shown. the lower cuboid is a material layer, the upper trapezoidal body is a circulating smoke hood, the two end surfaces in the z-axis direction are the central surfaces of two adjacent inlets, which are set as symmetrical surfaces, and the material layer height is set as 500mm.

Fig. 2 Three-dimensional map of physical model
2.2. Mathematical model

FLUENT software is used to solve the problem, and the control equation is as follows:

**Continuity equation:**

\[ \text{div}(\mathbf{U}) = 0 \]  

(1)

**N-S equation:**

**X direction:**

\[ \text{div}(u\mathbf{U}) = \text{div}(v\nabla u) - \frac{1}{\rho} \frac{\partial p}{\partial x} \]  

(2)

**Y direction:**

\[ \text{div}(b\mathbf{U}) = \text{div}(v\nabla b) - \frac{1}{\rho} \frac{\partial p}{\partial y} \]  

(3)

**Z direction:**

\[ \text{div}(w\mathbf{U}) = \text{div}(v\nabla w) - \frac{1}{\rho} \frac{\partial p}{\partial z} \]  

(4)

**K-\varepsilon equation:**

**K equation:**

\[ \text{div}(\rho \varepsilon \nabla k) = \text{div} \left( \eta \frac{\sigma_v}{\sigma_i} \nabla \varepsilon \right) + \varepsilon_c \varepsilon - \rho \varepsilon \]  

(5)

**\varepsilon equation:**

\[ \text{div}(\rho \varepsilon \nabla \varepsilon) = \text{div} \left( \eta \frac{\varepsilon}{k} \nabla \varepsilon \right) + c_i \varepsilon_i \varepsilon - c_s \frac{\varepsilon^2}{k} \]  

(6)

Represents a cut-out occurrence, and the expression is

\[ G_k = \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_j}{\partial x_i} \right) \]

Energy conservation equation:

\[ \nabla (\rho h) = \nabla \left[ \left( \eta + \frac{\eta_c}{\sigma_i} \right) \nabla h \right] - q \]  

(7)

**Component transport equation:**

\[ \text{div}(\rho m \mathbf{U}) = \text{div}(D_i \nabla m_i) + R_i \]  

(8)

FLUENT provides a vortex dissipation model. The formation rate \( R_{i,r} \) of substance I in chemical process R is given by the following formula:

\[ R_{i,r} = \min \left\{ \frac{V_{i,r} M_{v,i} A \rho}{k} \min \left( \frac{V_{v,i}}{V_{r,i} M_{v,r}} \right) \right\} \]  

(9)

\[ R_{i} = M_{v,i} \sum_{j=1}^{N} R_{i,j} \]  

(10)
3. Numerical Simulation of Conventional Sintering Process

3.1. Solution and verification

In this paper, FLUENT and UDF are used for simulation calculation. The upper surface of the material layer is set as the Interior boundary surface. The turbulence model uses the standard k-ε equation, the control equation is discretized by the second-order upwind scheme, the flow field is solved by SIMPLEC algorithm, and the chemical reaction adopts the finite rate/vortex dissipation model. Firstly, air with a temperature of 1400K for 90s is introduced into the inlet to replace the ignition process, and the outlet pressure is -10 kpa; Air with a temperature of 870K for 60 seconds is introduced to replace the heat preservation process, and the outlet pressure is -14 kpa; Finally, normal temperature air of 300K is introduced to enter the normal sintering stage, and the reaction triggering temperature is set [12]. The major chemical reactions are shown in Table 1.

The calculation results of temperature field are verified by the test data [13] of a sintering cup. The comparison between the calculated and measured values of the temperature curves at the material layer heights of 0.47m and 0.2m is shown in fig. 3. The temperature curve of the test is slightly delayed due to factors such as air leakage and outward heat, but the error between the calculated value and the test value is within a reasonable range.

| Chemical reaction                        | Chemical reaction equation |
|------------------------------------------|----------------------------|
| Coke combustion                          | 2C+O_2=2CO                 |
| CO combustion                            | 2CO+O_2=2CO_2              |
| Limestone decomposition                  | CaCO_3=CaO+O_2             |
| Mineral melting                          | Solid mixture=Melt mixture |
| Mineral solidification                   | Melt mixture= Solid mixture|
| Fe2O3 reduction                          | Fe_2O_3+3CO=2Fe+3CO_2      |
| Oxidation of s                           | S+O_2=SO_2                 |
| Evaporation of water                     | H_2O(l)=H_2O(g)            |
| Condensation of water                    | H_2O(g)= H_2O(l)           |

1- calculated value at material height of 0.47m; 2- Test value at material height of 0.47m; 3- calculated value at material height of 0.2m; 4- Test value at material height of 0.2m

Fig. 3 Comparison between calculated and measured values of temperature curve
3.1.1. Material layer temperature distribution. As shown in fig. 4, the combustion process of the material layer moves from top to bottom, and the temperature of the material layer at the same position and at different times is different, which is reflected in the temperature curve, i.e. the curve moves in a wave shape with the passage of time, and the temperature gradually increases with the enhancement of the heat storage effect of the material layer.

![Figure 4](image)

1- material height 0.47m; 2- material height 0.3m; 3- material height 0.2m; 4- material height 0.1m; 5- material height 0.01m

Fig. 4 Average temperature curve of sinter at different material layer heights

3.1.2. Smoke component content. As shown in fig. 5, when sintering starts, the O2 content decreases, which reaches an extreme value at about 100s s. this is due to the high temperature of the inlet air in the ignition stage, which consumes a large amount of O2 violently and generates CO2 and co. When normal temperature air is introduced, the temperature of the gas above the material layer becomes lower, the reaction process weakens, the O2 content gradually increases, and the CO2 and CO content gradually decreases. After a period of time, the sintering process tends to be stable, and the contents of O2, CO2 and CO in flue gas are stable at 11.4%, 10.9% and 1.1% respectively. SO2 content gradually increased, reaching the maximum emission at 900 s ~ 1500 s.

![Figure 5](image)

1- O2; 2-CO2; 3-CO; 4-SO2

Fig. 5 The component content of the outlet flue gas changes with time

4. Study on Full Cycle Sintering Process of Flue Gas

4.1. Numerical Simulation of Flue Gas Full Cycle Sintering Process

The biggest difference between the flue gas circulation sintering process and the conventional sintering process is the change of the composition content and temperature of the inlet air. The inlet and outlet of
each cycle of the flue gas full cycle process are shown in fig. 6. In this paper, three schemes are studied. The scheme has three cycles, each cycle is 15 meters long. The second cycle of the scheme is 4 times, each cycle length is 11.1m; Scheme 3 has 5 cycles with each cycle length of 9.24 meters.

Firstly, the average temperature of flue gas in the high-temperature section of the conventional sintering process is taken as the circulating gas temperature in the first section, and the average content of each flue gas component in the high-temperature section is taken as the flue gas component in the circulating inlet of the first section. The inlet temperature and composition content of the circulating gas in the subsequent sections are the average value of the outlet gas temperature and composition content in the previous section, and the inlet gas composition keeps the O2 content at 21%. The inlet and outlet parameters for each cycle of the three schemes are shown in Table 2, Table 3 and Table 4.

**Table 2.** Option 1 inlet and outlet parameters

| Frequency | Entrance Temperature/K | O2/% | CO2/% | CO/% | SO2/ppm | Export Temperature/K | O2/% | CO2/% | CO/% | SO2/ppm |
|-----------|------------------------|------|-------|------|---------|-----------------------|------|-------|------|---------|
| 1         | 845.19                 | 21   | 2.70  | 0.22 | 39.00   | 345.65               | 8.80 | 13.15 | 0.86 | 146.28  |
| 2         | 345.65                 | 21   | 10.11 | 0.66 | 112.52  | 352.36               | 8.56 | 21.09 | 1.56 | 387.82  |
| 3         | 352.36                 | 21   | 16.22 | 1.20 | 298.32  | 398.16               | 8.61 | 25.98 | 1.60 | 684.74  |

**Table 3.** Option 2 inlet and outlet parameters

| Frequency | Entrance Temperature/K | O2/% | CO2/% | CO/% | SO2/ppm | Export Temperature/K | O2/% | CO2/% | CO/% | SO2/ppm |
|-----------|------------------------|------|-------|------|---------|-----------------------|------|-------|------|---------|
| 1         | 831.35                 | 21   | 6.05  | 0.50 | 93.53   | 343.30               | 9.56 | 14.98 | 1.26 | 179.41  |
| 2         | 343.30                 | 21   | 13.03 | 1.10 | 156.01  | 346.27               | 9.15 | 23.74 | 2.10 | 371.43  |
| 3         | 346.27                 | 21   | 20.64 | 1.82 | 322.98  | 350.35               | 9.04 | 30.99 | 2.92 | 688.44  |
| 4         | 350.35                 | 21   | 26.95 | 2.53 | 598.64  | 404.06               | 8.85 | 36.30 | 3.56 | 995.44  |

**Table 4.** Option 3 inlet and outlet parameters

| Frequency | Entrance Temperature/K | O2/% | CO2/% | CO/% | SO2/ppm | Export Temperature/K | O2/% | CO2/% | CO/% | SO2/ppm |
|-----------|------------------------|------|-------|------|---------|-----------------------|------|-------|------|---------|
| 1         | 837.19                 | 21   | 5.22  | 0.39 | 68.50   | 333.14               | 9.52 | 13.91 | 0.74 | 141.37  |
| 2         | 333.14                 | 21   | 12.10 | 0.63 | 122.93  | 345.79               | 9.38 | 22.74 | 1.17 | 313.33  |
| 3         | 345.79                 | 21   | 19.77 | 1.02 | 272.46  | 347.39               | 9.56 | 29.98 | 1.23 | 569.06  |
| 4         | 347.39                 | 21   | 26.07 | 1.07 | 494.83  | 353.12               | 9.28 | 35.99 | 1.26 | 917.09  |
| 5         | 353.12                 | 21   | 31.29 | 1.10 | 797.47  | 632.64               | 9.40 | 40.88 | 1.30 | 1143.9  |
4.1.1. Material layer temperature distribution. As shown in fig. 7, the maximum combustion temperature of the three schemes is significantly increased. For the material layer with a height of 0.47m, the time when the temperature of the three schemes is above 1100K is respectively prolonged by 82s, 46s and 35s, and the heat preservation effect is obvious. For the increase of the material layer temperature, the first scheme has the most obvious effect. As can be seen from fig. 8, the maximum temperature of the material layer at 0.47m, 0.3m, 0.2m, 0.1m and 0.01m has been increased by 44.59k, 26.23k, 15.74 k, 6.17k and 2.62k respectively, which has a good effect on improving the phenomenon of the upper material layer not burning through.

![Temperature curves comparison](image1)

1- temperature curve at 0.47m high of conventional sinter; 2- temperature curve at 0.47m high of scheme I material
3- temperature curve at 0.47m high for scheme 2; 4- temperature curve at 0.47m high for scheme 3
5- temperature curve at 0.3m high of conventional sinter; 6- temperature curve at 0.3m high of scheme I material
7- Temperature Curve at 0.3m High of Scheme II Material; 8- temperature curve at material height 0.3m in scheme 3

**Fig. 7** Comparison of temperature curves between conventional sintering and three cyclic sintering schemes

![Temperature height contrast](image2)

1- conventional sinter material layer; 2- Scheme I Material Layer; 3- Scheme II Material Layer; 4- Scheme 3 Material Layer

**Fig. 8** Contrast graph of highest temperature at different heights of material layer
4.1.2. **Smoke component content.** As shown in fig. 9, the O2 consumption in scheme 1 is the largest, and the O2 content has been relatively stable, with scheme 2 taking second place. Although the O2 consumption in scheme 3 is smaller than that in schemes 1 and 2, it is still larger than that in conventional sintering process. The flue gas full cycle sintering process has been introducing high temperature flue gas into the material layer to promote the reaction, which can effectively solve the problem of unstable combustion in the initial stage of conventional sintering process.

![Variation curve of O2 content with time](image)

1- O2 content in conventional sintering; 2- Scheme I O2 content; 3- Scheme II O2 Content; 4- Scheme III O2 Content

**Fig. 9** Variation curve of O2 content with time

As shown in fig. 10, the rate of CO2 generation increases in the first 100s, indicating that the reaction rate increases. During each cycle, the CO2 content will jump, indicating that CO2 is enriched. The more cycles, the greater the enrichment degree. The CO2 content is the highest at about 1100 s ~ 1500 s. At this time, the flue gas will be discharged to prevent CO2 from further enrichment.

![Changes of CO2 content with time](image)

1- CO2 content in conventional sintering; 2- Scheme I CO2 content; 3- Scheme II CO2 Content; 4- Scheme III CO2 Content

**Fig. 10** Changes of CO2 content with time

As shown in fig. 11, the CO content in the full cycle process increases. Although the CO combustion increases the temperature, the amount of co participating in the reaction is limited, and then a certain enrichment occurs.
1- CO content in conventional sintering; 2- Scheme I CO content; 3- Scheme II CO content; 4- Scheme III CO Content

Fig. 11 Changes of CO content with time

From fig. 12, it can be seen that in the range of 1,000 s to 1,500 s, SO2 content is significantly increased, indicating that SO2 gas is enriched, and the more cycles, the greater the degree of enrichment, which is conducive to the centralized treatment of SO2.

1- SO2 content in conventional sintering; 2- Scheme I SO2 Content; 3- Scheme II SO2 Content; 4- Scheme III SO2 Content

Fig. 12 Changes of SO2 content with time

5. Evaluation of Flue Gas Full Cycle Sintering Process

As shown in fig. 13, the material layer high temperature duration (1373~1773K duration) of the three schemes is greater than that of the conventional process, and the closer to the upper surface of the material layer, the more obvious the material layer high temperature duration is prolonged. The first scheme has the most obvious effect, the temperature field of the material layer is more stable, and the heat preservation effect is achieved at the same time, and the high temperature duration of different material layer heights is respectively increased by 47.5s, 14.9s, 12.9s and 4.7s compared with the conventional sintering process.
As can be seen from fig. 14, under the condition of conventional sintering process, the cooling rates of different heights of the material layer are 78K/min, 73 K/min, 66 K/min and 60 K/min respectively. The flue gas full cycle sintering process has a positive effect on the reduction of the cooling rate of the material layer. The lower the cooling rate, the more stable the temperature field of the material layer, providing a good environment for the chemical reaction in the material layer, of which the first scheme has the best effect.

The sintering time of conventional sintering is 1850s, and the sintering time of the three schemes of flue gas full cycle sintering process are 1829s, 1835s and 1842s, respectively. The sintering time is shortened, which can improve the output of sintering machine.

Through the above analysis and comparison, it can be concluded that the flue gas full cycle sintering process is superior to the conventional sintering process in terms of high temperature duration, material layer cooling speed and sintering time, and the flue gas full cycle sintering process can promote the sintering process to proceed better. Therefore, the flue gas full cycle sintering process proposed in this paper has reference significance for the development of sintering industry.
6. Summary

Through the above analysis and comparison, it can be concluded that the flue gas full cycle sintering process is superior to the conventional sintering process in terms of high temperature duration, material layer cooling speed and sintering time, and the flue gas full cycle sintering process can promote the sintering process to proceed better. Therefore, the flue gas full cycle sintering process proposed in this paper has reference significance for the development of sintering industry.

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