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Experiment Research on Pulverized Coal Combustion in the Tuyere of Oxygen Blast Furnace

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Abstract: The actual combustion rate of pulverized coal in the blast furnace tuyere is hard to be measured. In this research, the combustion rate of pulverized coal injected into oxygen blast furnace was obtained by a new equipment. This equipment can simulate the actual blast furnace well, and the relationship between pulverized coal injection (PCI) ratio and $A_{O/C}$ was established by mathematical deduction. The experimental results show that the best combustibility of the four pulverized coals is C, and when the coal injection ratio is 350 kg/tHM, the combustion rate can be reached 79%, while the combustion rate of B in the same case is only 45.6%. With the increase of $A_{O/C}$, the relative amount of oxygen to coal increases, the combustion conditions become better, and combustion rate of the pulverized coal increases. In addition, under the condition of high temperature and rapid combustion, with the increase of coal's volatile, the combustion rate increases and the corresponding PCI ratio is also increased. By using the new equipment, the unburned coal under the oxygen blast furnace conditions can be collected for further study.

Keywords: pulverized coal injection, combustion rate, oxygen blast furnace, unburned pulverized coal, new experimental equipment

JEL Classification: 82.33.Vx

Introduction

Oxygen blast furnace ironmaking process is the new iron-making process that uses the oxygen blast operation to

replace the traditional preheated air blast operation. The ore (pellet, sinter or lump ore) and a small amount of coke are put into the oxygen blast furnace. Industrial oxygen of the room temperature and a large number of coal are injected into the oxygen blast furnace through the tuyere. It not only can produce a large number of high-quality pig iron, but also can obtain a lot of the higher calorific value of gas [1]. The use of oxygen blast operation speeds up the burning of fuel. In order to maintain the appropriate theoretical combustion temperature, it also needs to increase the amount of fuel injection. So the amount of pulverized coal ratio can be increased to 300 kg/tHM or more, and the coke consumption can be reduced to 250 kg/tHM or less. In the oxygen blast furnace ironmaking process, pulverized coal consumption exceeds the amount of coke, and the coal has become the main energy of ironmaking; thus, the new ironmaking process can change energy structure of iron and steel plant.

As the actual combustion rate of pulverized coal in the blast furnace tuyere cannot be measured, the current determination of combustion rate of the pulverized coal is basically used for the model calculation [2–4]. Usually, the combustion rate of the pulverized coal is determined by numerical simulation or calculation with carbon content (rock facies analysis) in blast furnace dust [5]. Due to the lack of experimental verification, the results of these calculations cannot reflect the actual combustion rate of the pulverized coal in the tuyere.

In order to study the combustion effect of pulverized coal injected into the blast furnace and influence factors of the combustion, Prof. Tianjun Yang from University of Science and Technology Beijing and Dr Korthas of Aachen University of Technology in Germany developed a device for simulating the combustion of pulverized coal into the blast furnace [6]. The equipment has been continuously improved and has been successfully used to simulate blast furnace injection of pulverized coal combustion research. Aachen University of Technology used the device to obtain the results, and the results were in agreement with Thyssen's actual blast furnace pulverized coal test results, and it can be used to guide pulverized coal injection in the blast furnace. In recent years, University of Science and Technology Beijing made a greater improvement on the technology in the automatic control and data processing, and successfully developed

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the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace [7]. In this paper, the combustion rate of pulverized coal injected into oxygen blast furnace was researched by the equipment.

Experimental device

Figure 1 is the schematic diagram of the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace. As shown in the figure, the main device consists of high-pressure part and low-pressure part. Generally, the pressure of the high-pressure part was set as 5 atmospheres and the low-pressure part was 2 atmospheres. The low-pressure part includes two heating furnaces. In the experimental process, the furnace temperature was set as 1,200°C and 1,500°C, respectively. The function of the furnace with 1,200°C is pre-heated gas, and it mainly simulates the hot air supply system. The high-pressure part of the equipment is equivalent to coal injection duct, which plays the role of pulverized coal carrier during the experiment. The oxygen pressure value can be set according to the pressure of the actual gas of the blast furnace. The effect of the furnace with 1,500°C is to simulate the combustion zone of tuyere raceway. Due to the limited heating temperature of the silicon molybdenum rod, the temperature

of the part cannot reach the actual temperature of tuyere raceway and can only play an approximate simulation effect. In the experiment, the high-pressure gas will send the pulverized coal quickly to the junction of the high-pressure part and low-pressure part to simulate the coal injection process of the blast furnace. The pulverized coal starts to burn here, and then the unburned pulverized coal is rapidly passed through the furnace with 1,500°C to burn further.

Pulverized coal mixed with hot air and then burned rapidly in the furnace with 1,500°C will produce flue gas, coal ash and unburned coal. After filtering the flue filter layer, the gas produced after the combustion of the pulverized coal enters a pre-evacuated gas cylinder. The gas component can be measured by the gas analyzer, and the combustion rate of the pulverized coal can be calculated. At the same time, the collector below the equipment will collect the unburned coal and ash. The appearance of the equipment is shown in Figure 2.

In the process of the equipment, the maximum speed of the pulverized coal was accelerated to more than 35 m/s. The average speed of the pulverized coal was 17 m/s. The hot-blast air(oxygen) also had a high speed, and it flowed into the blowpipe in the form of turbulent. The maximum speed of the hot-blast air was 235 m/s. So the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace is very similar to the actual conditions of blast furnace.

Figure 1: Schematic diagram of the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace.

Figure 2: Appearance of the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace.

Calculation model

Derivation of calculation formula of combustion rate of carbon in pulverized coal

The new experiment calculates the combustion rate of carbon element by using the content of CO and CO₂ in the gas, that is, to calculate the proportion of CO and CO₂. The formula is deduced as follows:

Assuming that the pulverized coal sample contains N mol of carbon, which has X mol of carbon to produce X mol CO₂, Y mol of carbon to produce Y mol CO, obviously $N \geq X + Y$. So the combustion rate is:

$$\eta = \frac{X + Y}{N} \quad (1)$$

In the experiment, M mol gas (including the gas that did not contact with pulverized coal before entering into the gas cylinder and the gas contacted with pulverized coal) was introduced into the gas cylinder. X mol CO₂ was generated by X mol carbon, and X mol O₂ was consumed at the same time, so there is no effect on the number of moles of gas in the gas cylinder. Similarly, SO₂ generated by combustion of sulfur element has no effect on the number of moles of gas in the gas cylinder. Y mol CO was generated by Y mol C, while $1/2Y$ mol O₂ was consumed at the same time. In addition, a part of hydrogen, oxygen and nitrogen of coal decomposed q mol gas, So the total production of gas was $(Y - 1/2Y + q)$ mol. That is $(1/2Y + q)$ mol. Therefore, when N mol carbon was partially burned to produce X mol CO₂ and Y mol CO, the moles of gas in the cylinder are $M + 1/2Y + q$ mol.

Supposing that φ_{CO_2} and φ_{CO} are the mole fractions of CO₂ and CO of the combustion exhaust gas in the cylinder, so:

$$\varphi_{CO_2} = \frac{X}{M + 1/2Y + q} \quad (2)$$

$$\varphi_{CO} = \frac{Y}{M + 1/2Y + q} \quad (3)$$

$$\varphi_{CO} + \varphi_{CO_2} = \frac{X + Y}{M + 1/2Y + q} \quad (4)$$

When the N mol carbon is completely combusted to produce N mol CO₂, the molar fraction of CO₂ in the gas cylinder is:

$$\varphi_{CO_2 \text{ theory}} = \frac{N}{M + Q} \quad (5)$$

Q is the total number of moles of gas dissolved in oxygen, oxygen and nitrogen of the coal, and can be calculated from the ultimate analysis data of coal.

$$\begin{aligned} \frac{\varphi_{CO_2} + \varphi_{CO}}{\varphi_{CO_2 \text{ theory}}} &= \frac{(X + Y)(M + Q)}{N(M + 1/2Y + q)} = \frac{X + Y}{N} \cdot \frac{M + Q}{M + 1/2Y + q} \\ &= \frac{X + Y}{N} \left(1 - \frac{1/2Y}{M + 1/2Y + q} + \frac{Q - q}{M + 1/2Y + q} \right) \end{aligned} \quad (6)$$

where the value of $\frac{Q - q}{M + 1/2Y + q}$ is small, can be ignored, then:

$$\frac{\varphi_{CO_2} + \varphi_{CO}}{\varphi_{CO_2 \text{ theory}}} = \frac{X + Y}{N} \left(1 - \frac{1/2Y}{M + 1/2Y + q} \right) = \frac{X + Y}{N} \left(1 - \frac{1}{2} \varphi_{CO} \right)$$

So the combustion rate is:

$$\eta = \frac{X + Y}{N} = \frac{\varphi_{CO_2} + \varphi_{CO}}{(1 - \frac{1}{2} \varphi_{CO}) \cdot \varphi_{CO_2 \text{ theory}}} \quad (7)$$

The formula (7) is the formula for the calculation of the combustion rate of carbon in the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace.

Derivation of $A_{O/C}$

Here the $A_{O/C}$ refers to the ratio of the number of moles of oxygen atoms that contact with the carbon atoms during the combustion in the tuyere and raceway (J) to the number of moles of carbon atoms in the coal (N).

$$A_{O/C} = \frac{J}{N} \quad (8)$$

At the end of injection, although M mol gas went into the gas cylinder, the M mol gases included the gas did not contact with the pulverized coal. The gas was at the following position of the exit of the coal injection duct, and the amount of the gas was set as A mol. The amount of the gas contacted with the pulverized coal during the injection process was set as B mol. So $B = M - A$. Supposing that φ is the mole fraction of oxygen in the gas before the experiment. So the number of moles of oxygen contacted with pulverized coal is $B \times \varphi$, and the number of moles of oxygen atoms is $2 \times B \times \varphi$. So $J = 2 \times B \times \varphi$ and the $A_{O/C}$ is:

$$A_{O/C} = \frac{J}{N} = \frac{2B\varphi}{N} \quad (9)$$

Calculation of pulverized coal injection (PCI) ratio

The calculation formula of the oxygen content of the blast air in blast furnace is [8]:

$$O_{2b} = 0.21 + 0.29 \times \varphi + (\alpha - 0.21) \times W \quad (10)$$

The number of moles of oxygen atoms per hour in blast gas is:

$$n_o = \frac{2 \times V[0.21 + 0.29 \times \varphi + (\alpha - 0.21) \times W]}{0.0224} \quad (11)$$

The amount of the coal injection into blast furnace per hour is $PCI \times Fe$. So the number of moles of carbon atoms injected into the blast furnace per hour is:

$$n_C = PCI \times Fe \times C/12 \quad (12)$$

$A_{O/C}$ of pulverized coal injection of blast furnace is:

$$A_{O/C} = \frac{2V[0.21 + 0.29\varphi + (\alpha - 0.21)W]}{0.0224(PCI \times Fe \times C/12)} \quad (13)$$

When $A_{O/C}$ is certain, the calculation formula of PCI ratio of blast furnace is:

$$PCI = \frac{2V[0.21 + 0.29\varphi + (\alpha - 0.21)W]}{0.0224(A_{O/C} \times Fe \times C/12)} \quad (14)$$

In the formula:

V is the amount of the blast air per hour, m^3/h ;

W is gas volume of oxygen enriched in $1 m^3$ blast air, m^3 ;

φ is the blast humidity, %;

α is the purity of oxygen gas, %;

0.0224 is the molar volume of the gas in standard state, m^3/mol ;

PCI is the pulverized coal injection ratio, kg/tHM ;

Fe is the productivity of hot metal per hour, tHM/h ;

C is the quality of carbon in 1 kg coal, kg/kg .

From the formula (14), it can be seen that when the amount of blast air, blast humidity, oxygen content and the productivity of pig iron per hour are certain, the PCI ratio is inversely proportional to $A_{O/C}$.

Combustion experiment

The combustion experiment of four types of pulverized coal was carried out by using the new experimental equipment. The combustion rate of pulverized coal in the rapid combustion process with different $A_{O/C}$ was studied. The proximate analysis and ultimate analysis of the four pulverized coals are shown in Table 1.

In order to study the combustion performance of pulverized coal with different $A_{O/C}$, four kinds of pulverized coal were selected. Specific experimental methods are as follows: First of all, experimental coal samples were prepared as less than $74 \mu m$ particle size, then put them into the oven to fully dried at $105^\circ C$ temperature, and put the moisture of coal removed. Then, the coal samples were weighed by the balance and the corresponding values were 150, 200, 250 and 300 mg. Second, the furnace temperature was set as $1,200^\circ C$ and $1,500^\circ C$, respectively. Before loading the sample, the oxygen was used to clean the various parts of the equipment to ensure that the equipment was full with oxygen. Then, the gas collection cylinder was set to vacuum, and is connected to the outlet of combustion waste gas. The pressure value of high-pressure part and low-pressure part was set as 0.5 MPa and 0.35 MPa. When the experiment started, the pulverized coal was injected into the blowpipe by the air-flow of high-pressure part, and burned violently when meeting with the hot air from the furnace with $1,200^\circ C$. The gas products went into the gas cylinders, and unburned pulverized coal went into the collector. According to formula (7), the combustion rate of pulverized coal with different $A_{O/C}$ can be calculated. Also, the unburned pulverized coal can be analyzed by electron microscopy.

Table 1: Proximate analysis and ultimate analysis of coals (%).

Coals	Proximate analysis				Ultimate analysis (daf)				
	M_{ad}	V_{daf}	A_{daf}	FC_{daf}	C	H	O	N	S
A	5.95	14.53	8.3	77.83	79.65	2.03	2.72	0.69	0.66
B	4.46	12.16	8.4	79.44	80.52	1.88	3.26	0.74	0.75
C	11.92	31.81	9.87	58.33	63.83	3.89	8.96	0.65	0.89
D	9.68	22.23	9.59	68.19	69.87	3.13	6.41	0.73	0.59

Results and discussion

Combustion rate

Table 2 lists the process parameters of oxygen blast furnace based on the actual conditions by simulation. The degree of direct reduction is 0.4, and the oxygen content in the hot air is 40%. The amount of the blast air per hour (V) is 33,676.2 m³/h. The productivity of hot metal per hour (Fe) is 31.8 tHM/h. The blast humidity (φ) is 14.9%. The gas volume of oxygen enriched in 1 m³ blast air (W) is 0.4 m³/h. The purity of oxygen gas (α) is 99%.

Table 2: Process parameters of oxygen blast furnace.

Parameters	Values
Effective volume, m ³	380
Capacity factor, t/(m ³ ·d)	2.0
The number of tuyere	14
Oxygen-enriched air's volume of one ton hot metal, m ³ /tHM	1,059
Water vapor's volume of one ton hot metal, m ³ /tHM	158
Productivity of hot metal, tHM/min	0.53

According to the above data, PCI ratio can be obtained by formula (14). The combustion rate and $A_{O/C}$ can be measured by the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace. The experimental results and the corresponding calculation results are shown in Figure 3.

It can be seen from Figure 3 that with the increase of $A_{O/C}$, the relative amount of oxygen to coal increased, the combustion conditions became better and the combustion rate increases. However, under the same conditions of blast air and oxygen-enriched conditions, the increase of $A_{O/C}$ means that the amount of coal is reduced. That is, the increase of coal ratio will reduce the combustion rate of

the pulverized coal in tuyere raceway. It can be seen from the figure that the best flammability among the four types of pulverized coal is C, in the case of coal injection ratio with 350 kg/tHM, the combustion rate of it can be up to 79%, and the combustion rate of B in the same case was only 45.6%.

In order to study the combustion rate of different volatile coals, the results of the combustion rate of the pulverized coal at $A_{O/C}=2.5$ plot are shown in Figure 4.

It can be seen from Figure 4 that the combustion rate increases with the increase of the volatile content under the high-temperature and high-speed blowing combustion condition. In these coals, combustion rate of C coal is the highest, close to 80%, and the volatile of C was more than 30%. At the same time, it can also be found that in the case of the same $A_{O/C}$, with the increase of the volatile content, the corresponding PCI ratio was also increased. So keeping the smelting conditions unchanged and improving the volatile of pulverized coal can promote the pulverized coal's combustion rate and give a positive effect on improving PCI ratio.

Unburned pulverized coal

With the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace, unburned pulverized coal can be collected. The microscopic morphology of C coal before experiment and the unburned coal of it prepared by rapid combustion with high temperature was observed by scanning electron microscope at different magnification. Under 500× and 2,000× magnification, the microstructure is shown in Figures 5 and 6.

It can be seen clearly from Figure 5 that most of the raw coal particles were small and powdery. After the high-temperature rapid combustion treatment, the volatiles were rapidly evolved during the combustion process, and the fixed carbon was rapidly burned. The pulverized coal particles were agglomerated together to form massive particles, the particles became larger and the particle size distribution was also uniform.

Figure 3: Pulverized coal combustion rate and corresponding PCI ratio with various $A_{O/C}$.

Figure 4: Experimental results of coal's combustion rate with different volatile content.

Under the magnification of $2,000\times$, it can be seen more clearly that the surface of the raw coal particles was more dense, and it did not have obvious pores. But after the high-temperature rapid combustion treatment, the surface of unburned coal particles had the obvious pores and cracks, and the surface was rough. It can be found that there were some regular spherical particles between the pulverized coal particles and the pores, which were distributed in the

pores and prevented the diffusion of the gas during the gasification reaction of the unburned pulverized coal. The energy spectrum analysis of spherical particles in the pores of unburned pulverized coal particles is shown in Figure 7.

It can be seen from Figure 7 that the main elements of the spherical particles are C, Ca, Si, Al and O, where the mass percentage of C was 54.86%, the mass percentage of Ca was 1.99%, the mass percentage of O was 3.72%, the mass percentage of Al was 24.5% and the mass percentage of Si was 14.93%. It can be concluded that the spherical particle was the complex of ash slag and residual carbon obtained by the treatment of high temperature and rapid combustion. It showed that the pulverized coal has obvious slag phase precipitation in the process of rapid combustion with high temperature, and ash was melted into the ball.

Conclusions

(1) In this paper, the combustion rate of four kinds of pulverized coal at high temperature with high speed and the corresponding oxygen/carbon atomic ratio were

Figure 5: Microstructure under 500 × magnification.

Figure 6: Microstructure under 2,000 × magnification.

Figure 7: Energy spectrum analysis of spherical particle in unburned pulverized coal.

measured by the New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace. The relationship between PCI ratio and $A_{O/C}$ was established.

(2) The best combustibility of the four pulverized coals is C, and when the coal injection ratio is 350 kg/tHM, the combustion rate can be reached 79%, while the combustion rate of B in the same case is only 45.6%.

(3) With the increase of $A_{O/C}$, the relative amount of oxygen to coal increases, the combustion conditions become better and combustion rate of the pulverized

coal increases. But in the same condition, the increase of $A_{O/C}$ means the PCI ratio is reduced. Improving the oxygen enrichment rate is conducive to improving the combustion rate of the pulverized coal in the tuyere raceway.

(4) Under the condition of high temperature and rapid combustion, with the increase of coal's volatile, the combustion rate increases and the corresponding PCI ratio is also increased. Therefore, in the case of the same conditions of smelting, improving the volatile of

pulverized coal is beneficial to the combustion rate, and also it helps to improve the PCI ratio.

(5) The New Experimental Equipment for Combustion of Pulverized Coal in Blast Furnace can simulate the actual oxygen blast furnace conditions, and measure the combustion rate of coal in the tuyere raceway. Also it can obtain the unburned coal under the oxygen blast furnace conditions, and provide conditions for the follow-up study of unburned pulverized coal's behavior in the oxygen blast furnace.

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