Effects of Temperature and Circulating Flue Gas Components on Combustion and NOx Emissions Characteristics of Four Types Quasi-particles in Iron Ore Sintering Process

Hao ZHOU,* Pengnan MA, Ming CHENG, Mingxi ZHOU and Yawei LI

State Key Laboratory of Clean Energy Utilization, Institute for Thermal Power Engineering, Zhejiang University, Hangzhou, 310027 China.

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It’s significant to deeply understand the combustion and NOx yield characteristics of quasi-particles in flue gas recirculation sintering process. In present study, effects of temperature and different circulating flue gas components on the mass conversion rate and conversion of fuel-N to NOx of quasi-particles were investigated in a vertical quartz tube reactor. Four types quasi-particles were considered according to the existing state of coke in granules: C type, P type, S type and S’ type. The mass conversion rate of four types quasi-particles ranked in the order of $C > P > S > S'$ at different temperature. It was found that $D_1$ model was most appropriate to describe the combustion characteristics of $S$, $S'$ and $P$ type while $D_2$ model was better than other models to describe the combustion characteristics of C type quasi-particles through the comparison of correlation coefficients calculated by different mechanism models. Effect of circulating flue gas components on the conversion of fuel-N to NOx of quasi-particles was studied. $O_2$ has a positive impact on the conversion of fuel-N to NOx for $S$, $S'$ and $C$ type but an inhibitory effect for $P$ type quasi-particles. $CO_2$ and $CO$ could decrease the conversion rate of fuel-N to NOx for all types quasi-particles. $H_2O(g)$ has a positive impact on the conversion of fuel-N to NOx firstly increases then decreases for $S'$, $S$ and $C$ type quasi-particles while continuously increases for $P$ type quasi-particles with increasing $H_2O(g)$ content.

KEY WORDS: quasi-particles; iron ore sintering; flue gas recirculation; NOx emissions.

1. Introduction

In 2016 China’s crude steel production was 808 million tons, accounting for 49.6% of the world’s total crude steel production. Iron ore sintering, a critical process for steel production, provides agglomeration for blast furnace. Raw materials used in iron ore sintering process are mainly iron ore, coke, fluxes, etc. The grain size of iron ore, coke breeze, fluxes is no more than 10 mm, 5 mm and 3 mm, respectively. Raw materials were uniformly mixed and then granulated in drums with required water addition to increase the average particle size. The process of iron ore sintering is the major source of NOx emissions, occupying about 40% of the total NOx emissions in the iron and steel industry. NOx removal in iron ore sintering industry has already become a significant research topic with stricter environmental protection policy.

Different types quasi-particles were formed in the process of granulation. The distribution state of coke in quasi-particles was affected by the granulating process. $\sim0.25$ mm coke particles would be uniformly distributed in the adhering fine layer, $+1$ mm coke particles are mostly free particles, and medium fine coke particles (plus $0.25$ mm minus $1$ mm) are located in the outside of adhering fine layer and easy to fall off. Maeda$^6$ evaluated quantitatively the distribution of coke breeze in the quasi-particles and the effects of particle size of iron ore and coke breeze on granulation properties. It was found that conversion of fuel-N to NOx could be decreased by mixing iron power and coke breeze.$^7$ Hida$^8$ divided the quasi-particles into four types according to the existing state of coke in quasi-particles: $S$ type - single coarse coke particle coated with fine iron ore powder, $P$ type - pellet of well mixed fine coke and fine iron ore powder, $C$ type - large iron ore particle coated with fine coke and fine iron ore powder, $S'$ type - free coke particle. The four types quasi-particles were shown in Fig. 1. Ohno$^9$ investigated the combustion rate of $P$ type quasi-particles considering void rate and liquid formation. Hou$^{10}$ pointed out that the combustion rate of $C$ type quasi-particles was higher than that of $P$ type quasi-particles. Kasai$^{11}$ pointed out that the combustion rate and average conversion rate of NO of $S'$ type quasi-particles both decreased with increasing particle size. Gan$^{12,13}$ studied the effect of different granulating methods on the combustion characteristics of quasi-particles and proposed that fuel pre-granulation technology is conducive to inhibiting the conversion of fuel-N to NOx during iron ore sintering. Katayama$^{14}$ found that lime coating coke particles, and iron ore sintering; flue gas recirculation; NOx emissions.

* Corresponding author: E-mail: zhouhao@zju.edu.cn
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could decrease NOx because of the formation of CF melt on coke surface. Numerical model was widely used to study the combustion behavior of fuel in iron ore sintering. Ogi H15) studied the effect of coke breeze distribution on coke combustion rate using unreacted core model. Kasai16) conducted the combustion rate of P type and S type quasi-particles using unreacted core model.

There are many researches focused on the methods of NOx reduction in iron ore sintering. These methods to control NOx contain selective catalytic reduction,17) selective non-catalytic reduction,18) flue gas recirculation,19) process parameter control20,21) modification of fuel,22) as well as biomass utilization, etc.23,24) Flue gas recirculation sintering is a potential method to reduce NOx emissions. It has many advantages including decreasing fuel consumption and pollutant emissions, etc.25) Figure 2 shows the conventional iron ore sintering process and flue gas recirculation sintering process. Flue gas recirculation in iron ore sintering is a technique recycling part of the heating flue gas to the sinter bed. It’s especially different in combustion atmosphere between conventional sintering and flue gas recirculation sintering process. The main gas components in flue gas recirculation sintering process were O2, CO, CO2, H2O. The combustion of CO2, providing heat for sintering process, affects the heat exchange between gas phase and solid phase in sinter zone. Coke combustion efficiency is influenced by O2 and CO2 concentration. Moreover, the content of steam affects the formation of over-wet zone since it influences the moisture content.25) Chen22) found the modification of coke in flue gas recirculation sintering process was conducive to decreasing the NOx emissions. Fan and Chen26–28) determined appropriate circulating flue gas components concentration range by studying the effect of recirculating flue gas components on sintering parameters and coke combustion efficiency.

In conclusion, many researchers have investigated the combustion behavior of quasi-particles in conventional sintering conditions as well as the effect of flue gas recirculation on sinter quality, however there are little research about the effects of recirculating flue gas components on the combustion and NOx emissions characteristics of different types quasi-particles. The present work may provide more fundamental understanding in optimizing the combustion behavior and decreasing pollutants emissions in iron ore sintering process.

In this study, a flow tube reactor was used to investigate the influence of temperature and recirculating flue gas components (O2, CO2, CO, H2O) on the combustion and NOx emissions characteristics of different types quasi-particles. The most appropriate models, which were used to describe the combustion characteristics of four types quasi-particles, were determined by calculating correlation coefficients between different mechanism models and time t. Then the influence mechanism of different circulating flue gas components on NOx emissions characteristics of quasi-particles was revealed.

2. Experimental

2.1. Sample Preparation

The constitute and ratio of four types quasi-particles are listed in Table 1 according to the classification method by Hida.8) Coke and iron ore were screened to −0.25 mm and 2.0–2.8 mm, −0.25 mm for adhering fines and 2.0–2.8 mm for core particle. Limestone was sieved to −0.25 mm for adhering fines. The S type quasi-particles were made of 2–2.8 mm coarse coke particles adhering with −0.25 mm limestone and iron ore with the weight ratio of core to adhering layer being 3 to 1. The quasi-particles of P type were the mixture of −0.25 mm coke, limestone and iron ore with the weight ratio being 1:0.5:0.5. The C type quasi-particles had −0.25 mm coke and limestone adhering on nuclei particles of 2–2.8 mm iron ores. The quasi-particles of S’ type were 2–2.8 mm single coke particles. The quasi-particles were prepared by an small experimental drum mixer. For S type quasi-particles, −0.25 mm limestone particles and iron ore particles were well mixed in the small experimental drum mixer first, 2–2.8 mm coke particles whose surfaces wetted with moderate moisture were mixed with them later. And similar for C type quasi-particles, −0.25 mm limestone
particles and coke particles were well mixed in the small experimental drum mixer first, 2–2.8 mm iron ore particles whose surfaces wetted with moderate moisture were mixed with them later. For P type quasi-particles, −0.25 mm limestone particles, coke particles and iron ore particles with moderate water adding were well mixed in the small experimental drum mixer. As for S’ type quasi-particles, they are 2–2.8 mm coarse coke particles only.

The diameters of all types quasi-particles used in tests were about 3 mm and the mass of different types quasi-particles used in tests was about 1 g. The mass fractions of coke were different in each quasi-particles, 5% for C type, 50% for P type, 75% for S type and 100% for S’ type. The chemical compositions of raw materials and the ultimate and proximate analysis of coke were listed in Table 2 and 3, respectively. All of the samples were dried in an oven at 378 K for 4 hours prior to the tests.

2.2. Experimental Apparatus and Operation Procedure

A laboratory-scale experimental rig was set up to investigate the effects of temperature and circulating flue gas components on the combustion and NOx emissions characteristics of four types quasi-particles. Figure 3 shows the schematic diagram of experimental system for quasi-particles combustion. The experimental system mainly consists of a vertical quartz tube reactor, a steam generator, a gas supply system, an electric balance and a gas analyzer. The quartz tube reactor was heated electrically and the temperature was controlled by a temperature controller with the accuracy of ±0.5%. Furthermore, the flow rate of deionized water was controlled by a peristaltic pump calibrated in advance. The deionized water was carried by the supplied gas into the steam generator. In order to guarantee the complete evaporation of the deionized water, the temperature of the steam generator was set to 600°C. Meanwhile, O2, N2, CO, and CO2 were also preheated in the steam generator before they were introduced into the reactor. It was time to end the experiment when the sample weight remained the same.

In order to study the effect of circulating flue gas components on NOx emissions characteristics of different types quasi-particles, the inlet gas compositions (O2/N2/H2O) were introduced into the reactor in the experiments. The total flow rate of the inlet gas was set to 5 NL/min to maintain the same boundary condition. The flue gas composition was measured by Testo 350 gas analyzer with the sampling time of 5 s. To investigate the influence of temperature on combustion characteristics of quasi-particles, the experiments were conducted at different temperature (1 073 K, 1 173 K, 1 273 K) with the gas atmosphere of O2/N2=21%/79%. In present work, 64 tests were designed to study the influence of circulating flue gas components on NOx emissions characteristics of four types quasi-particles based on components and proportions of circulating flue gas of different flue gas recirculation ratio in sintering process.25) All of the circulating flue gas conditions were listed in Table 4, such as O2 content in circulating flue gas varied from 12% to 21%, CO2 from 3% to 12%, CO from 0.5% to 2%, and H2O(g) from 5% to 20%.

Moreover, It should be mentioned that at least 3 parallel tests had been done for effect of temperature on conversion

Table 1. Composition and mass ratio of four types quasi-particles.

<table>
<thead>
<tr>
<th>Type</th>
<th>Core species size (mm)</th>
<th>Adhering layer species size (mm)</th>
<th>Weight ratio (core: adhering layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Coke 2–2.8 Limestone</td>
<td>0.25</td>
<td>3:1</td>
</tr>
<tr>
<td>P</td>
<td>Coke 2–2.8 Limestone</td>
<td>0.25</td>
<td>9:1</td>
</tr>
<tr>
<td>C</td>
<td>Iron ore 2–2.8 Coke</td>
<td>0.25</td>
<td>1:0</td>
</tr>
<tr>
<td>S'</td>
<td>Coke 2–2.8 Limestone</td>
<td>0.25</td>
<td>1:0</td>
</tr>
</tbody>
</table>

Table 2. Chemical compositions of Raw materials (wt.%).

<table>
<thead>
<tr>
<th>Item</th>
<th>Fe</th>
<th>FeO</th>
<th>Al2O3</th>
<th>SiO2</th>
<th>MgO</th>
<th>CaO</th>
<th>LOI1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron ore</td>
<td>62.39</td>
<td>0.35</td>
<td>2.23</td>
<td>4.28</td>
<td>0.13</td>
<td>0.15</td>
<td>3.51</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.36</td>
<td>0.1</td>
<td>0.98</td>
<td>2.23</td>
<td>0.48</td>
<td>53.40</td>
<td>42.00</td>
</tr>
<tr>
<td>Coke</td>
<td>1.07</td>
<td>0</td>
<td>4.32</td>
<td>6.11</td>
<td>0.04</td>
<td>0.62</td>
<td>86.85</td>
</tr>
</tbody>
</table>

Table 3. Ultimate and proximate analysis of coke.

<table>
<thead>
<tr>
<th>Proximate analysis (%)</th>
<th>Ultimate analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mad 1.12</td>
<td>13.42</td>
</tr>
<tr>
<td>Vad 1.12</td>
<td>13.42</td>
</tr>
<tr>
<td>Vdaf 1.12</td>
<td>13.42</td>
</tr>
<tr>
<td>FCdaf 1.12</td>
<td>13.42</td>
</tr>
<tr>
<td>M 1000 1.12</td>
<td>13.42</td>
</tr>
</tbody>
</table>

Fig. 3. Schematic diagram of the experimental rig for quasi-particles combustion.
of fuel-N to NOx of four types quasi-particles and similar results were obtained.

2.3. Analysis Method

NOx formation mechanism includes thermal NOx, prompt NOx and fuel NOx. The formation temperature of thermal NOx is more than 1 800 K, however the highest temperature in sinter bed was only about 1 600 K. Therefore there was little thermal NOx in iron ore sintering process. Prompt NOx is mainly from the impact of N\textsubscript{2} molecules and CH radicals generated by the decomposition of fuel. The fuel generally used in iron ore sintering was coke, which contains low volatile matter content and high fixed carbon content. Hence the generation of prompt NOx could be neglected. The NOx in iron ore sintering is mainly from fuel NOx.

In order to quantify the NOx emissions in the process of quasi-particles combustion, the conversion rate of fuel-N to NOx during quasi-particles combustion was calculated by following equation:

\[
\eta = \frac{Q \times M_N}{60 \times 22.4 \times m_0 \times w_1 \times w_2} \times \int_{t_0}^{t_1} C(\text{NOx}) \times 10^{-6} \, dt \times 100\%
\]

where \( Q \) is total gas flow rate (L/min), \( t_0 \) and \( t_1 \) are the starting time and terminal time of NOx calculation (s), \( C(\text{NOx}) \) is the NOx concentration (ppm), \( t \) was time (s), \( M_N \) is the molar mass of nitrogen atoms (g/mol), \( m_0 \) is the initial mass of quasi-particles (g), \( w_1 \) is mass fraction of coke in quasi-particles (%), \( w_2 \) is the mass fraction of N\textsubscript{ad} (%). 22.4 is molar volume of gas (L/mol).

3. Kinetic Analysis

3.1. Data Analysis

In the experiments with different temperature, the mass reduction of sample was considered to be mainly caused by the following chemical reactions:

\[ C(s) + O_2(g) \rightarrow CO_2(g) \]  \hspace{1cm} (R1)

\[ CaCO_3(s) \rightarrow CaO(s) + CO_2(g) \]  \hspace{1cm} (R2)

\[ C + CaCO_3 \rightarrow CaO + 2CO \]  \hspace{1cm} (R3)

\[ C + Fe\textsubscript{2}O_3 \rightarrow 2FeO + CO \]  \hspace{1cm} (R4)

Sample mass conversion rate could be defined as follows:

\[
x(t) = \left( \frac{m_0 - m_t}{m_0 - m_e} \right) \times 100\%
\]

Table 4. Gas components conditions in the experiments.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Circulating flue gas components (%)</th>
</tr>
</thead>
</table>
| \( O_2 \) | 12, 15, 18, 21                    0        0        0       
| \( CO_2 \) | 21                                 3, 6, 9, 12 0        0       
| \( CO \)  | 21                                 0        0.5, 1.0, 1.5, 2.0 0       
| \( H_2O(g) \) | 21                                 0        0        5, 10, 15, 20 |

The rest part of circulating flue gas was filled by N\textsubscript{2}.

Table 5. Different reaction mechanism functions of \( f(x) \) and \( G(x) \).

<table>
<thead>
<tr>
<th>code</th>
<th>Reaction model</th>
<th>Differential ( f(x) )</th>
<th>Integrate ( G(x) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_m )</td>
<td>Shrinkage core model</td>
<td>( m(1-x) ) ( m )</td>
<td>( 1 - (1-x)^{m-1} )</td>
</tr>
<tr>
<td>( R_{1/2} )</td>
<td>( m=1/2 )</td>
<td>( \frac{1}{2}(1-x)^{3} )</td>
<td>( 1 - (1-x)^{3} )</td>
</tr>
<tr>
<td>( R_{1/3} )</td>
<td>( m=1/3 )</td>
<td>( \frac{1}{3}(1-x)^{2} )</td>
<td>( 1 - (1-x)^{2} )</td>
</tr>
<tr>
<td>( R_{1/4} )</td>
<td>( m=1/4 )</td>
<td>( \frac{1}{4}(1-x)^{3} )</td>
<td>( 1 - (1-x)^{3} )</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>( m=2 )</td>
<td>( 2(1-x)^{2} )</td>
<td>( 1 - (1-x)^{2} )</td>
</tr>
<tr>
<td>( R_3 )</td>
<td>( m=3 )</td>
<td>( 3(1-x)^{3} )</td>
<td>( 1 - (1-x)^{3} )</td>
</tr>
<tr>
<td>( D_m )</td>
<td>Diffusion model</td>
<td>( \frac{1}{2}t ) ( x )</td>
<td>( x )</td>
</tr>
<tr>
<td>( D_1 )</td>
<td>Dimensional diffusion</td>
<td>( \frac{1}{2}t ) ( x )</td>
<td>( x )</td>
</tr>
<tr>
<td>( D_2 )</td>
<td>Two-Dimensional diffusion</td>
<td>( -ln(1-x) ) ( x )</td>
<td>( (1-x)ln(1-x) )</td>
</tr>
<tr>
<td>( D_3 )</td>
<td>Three-Dimensional diffusion</td>
<td>( \frac{3}{2}(1-x)^{2} ) ( 1 - (1-x)^{2} )</td>
<td>( 1 - (1-x)^{2} )</td>
</tr>
</tbody>
</table>

where \( x(t) \) was the sample mass conversion rate (%), \( m_0 \) and \( m_e \) are the initial and final mass of the sample, respectively (g), and \( m_t \) is the mass of the sample at time \( t \) (g).

3.2. Mechanism Model

The product of two independent functions was used to present the reaction rate for gas-solid reaction. The reaction rate of quasi-particle could be expressed as follows:

\[
\frac{dx}{dt} = kf(x)
\]

where, \( k \) was the total reaction rate constant for quasi-particle combustion, \( f(x) \) was proper mechanism model used to describe the reaction.

Equation (3) could be rewritten as:

\[
\frac{dx}{f(x)} = kdt
\]

Integrate Eq. (4), the conversion time was a constant for certain quasi-particle:

\[
\int_{0}^{t_1} \frac{dx}{f(x)} = \int_{0}^{t_1} kdt = kt
\]

\[
G(x) = \int_{0}^{t} \frac{dx}{f(x)}
\]

\[
G(x) = kt
\]

where \( G(x) \) was the mechanism function, \( t \) was time (s).

The most suitable mechanism function could be obtained through the comparison of correlation coefficients between \( G(x) \) and \( t \) using different models. The ordinary models and mechanism functions were listed in Table 5.
4. Results

4.1. Combustion Characteristics of Quasi-particles at Different Temperature

In order to explore the effect of reaction temperature on the combustion characteristics of quasi-particles, three temperature (1 073 K, 1 173 K, 1 273 K) were considered. The mass conversion rate of C type quasi-particles at different temperature was shown in Fig. 4(a). From this figure, it was found that the mass conversion rate of C type quasi-particles was larger with higher temperature. Although not shown, the other three types quasi-particles also showed the same tendency. The results obtained were in good agreement with those of other investigators.9,16)

Figure 4(b) shows the mass conversion rates of four types quasi-particles at 1 273 K. It could be obtained that the mass conversion rates were high in the initial stage and then gradually slowed down. The mass conversion rate of four types quasi-particles ranked in the order of C > P > S > S'. Although not shown, this phenomenon could be observed at all temperature investigated.

The correlation coefficients of four types quasi-particles at different temperature were calculated to find the most appropriate mechanism function for quasi-particles combustion. The calculated results were shown in Table 6. As shown in Table 6, D1 model was the most appropriate model for S, S’, and P type quasi-particles. Nevertheless, D3 model was better than other models for C type quasi-particles.

To further investigate the relation between reaction rate of quasi-particles and temperature. The total reaction rate constants of four types quasi-particles at different temperature were derived using the most applicable mechanism function. Figure 5 shows the temperature dependence of apparent total reaction rate of four types quasi-particles at different temperature. The apparent total reaction rate constants of different types quasi-particles ranked in the order of C > P > S > S’. This result was agreed well with previous results in this work. The apparent total reaction rate constants of four types quasi-particles at different temperature were listed in Table 7.

The formation rate of NOx was proportional with combustion rate of quasi-particles. Apparent total reaction rate constant of C type quasi-particles was greater than other three types quasi-particles. Therefore, NOx could be decreased by reducing the ratio of C type quasi-particles in

Table 6. Correlation coefficients of four types quasi-particles at different temperature according to different mechanism models.

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature</th>
<th>R1/2</th>
<th>R1/3</th>
<th>R1/4</th>
<th>R2</th>
<th>R3</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1 073 K</td>
<td>0.922</td>
<td>0.850</td>
<td>0.798</td>
<td>0.982</td>
<td>0.991</td>
<td>0.973</td>
<td>0.897</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 173 K</td>
<td>0.927</td>
<td>0.849</td>
<td>0.777</td>
<td>0.982</td>
<td>0.996</td>
<td>0.991</td>
<td>0.885</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 273 K</td>
<td>0.915</td>
<td>0.825</td>
<td>0.739</td>
<td>0.987</td>
<td>0.996</td>
<td>0.997</td>
<td>0.898</td>
<td></td>
</tr>
<tr>
<td>S’</td>
<td>1 073 K</td>
<td>0.903</td>
<td>0.823</td>
<td>0.756</td>
<td>0.982</td>
<td>0.991</td>
<td>0.975</td>
<td>0.903</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 173 K</td>
<td>0.908</td>
<td>0.828</td>
<td>0.788</td>
<td>0.992</td>
<td>0.992</td>
<td>0.978</td>
<td>0.913</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 273 K</td>
<td>0.918</td>
<td>0.838</td>
<td>0.769</td>
<td>0.997</td>
<td>0.998</td>
<td>0.966</td>
<td>0.853</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1 073 K</td>
<td>0.624</td>
<td>0.502</td>
<td>0.440</td>
<td>0.965</td>
<td>0.983</td>
<td>0.945</td>
<td>0.998</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 173 K</td>
<td>0.482</td>
<td>0.370</td>
<td>0.318</td>
<td>0.899</td>
<td>0.941</td>
<td>0.835</td>
<td>0.917</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 273 K</td>
<td>0.542</td>
<td>0.421</td>
<td>0.350</td>
<td>0.893</td>
<td>0.926</td>
<td>0.842</td>
<td>0.910</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>1 073 K</td>
<td>0.862</td>
<td>0.769</td>
<td>0.695</td>
<td>0.999</td>
<td>0.993</td>
<td>0.996</td>
<td>0.995</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 173 K</td>
<td>0.823</td>
<td>0.695</td>
<td>0.590</td>
<td>0.995</td>
<td>0.988</td>
<td>0.997</td>
<td>0.995</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 273 K</td>
<td>0.844</td>
<td>0.710</td>
<td>0.598</td>
<td>0.996</td>
<td>0.988</td>
<td>0.993</td>
<td>0.993</td>
<td></td>
</tr>
</tbody>
</table>
iron ore sintering process.

During quasi-particles combustion, reaction rate of four types quasi-particles was not constant. Reactivity index was adopted to further investigate the influence of different temperature on quasi-particles combustion. The reactivity index could be expressed as follows:

\[ R_{0.5} = \frac{0.5}{\tau_{0.5}} \]  

where, \( \tau_{0.5} \) was the time needed for mass conversion rate achieving 50% (s).

Figure 6 shows the reactivity index of four types quasi-particles at different reaction temperature, it could be drawn that the reactivity index increases with increasing temperature. Temperature has a significant influence on reactivity index, especially for C type quasi-particles. For example, the reactivity index of C type quasi-particles at 1 273 K was 3.2 times greater than that at 1 073 K. The reactivity index of four types quasi-particles ranked in the order of C > P > S > S’ and the result was agreed well with previous results in this work.

4.2. Conversion of Fuel-N to NOx of Quasi-particles at Different Temperature

As shown in Fig. 7, the conversion rate of fuel-N to NOx decreases with higher temperature for C and P types quasi-particles but first decreases then increases for S and S’ types quasi-particles. In other words, the conversion rate of fuel-N to NOx changes slightly with the increasing temperature for S, S’ and P type quasi-particles. However, the conversion rate of fuel-N to NOx obviously decreases with increasing temperature for C type quasi-particles. For example, the conversion rate of fuel-N to NOx decreases from 44.94% at 1 073 K to 19.58% at 1 273 K for C type quasi-particles.

4.3. Conversion of Fuel-N to NOx of Quasi-particles Vary with Circulating Flue Gas Components

In the process of flue gas recirculation sintering, the main components of circulating flue gas were \( \text{O}_2 \), \( \text{CO} \), \( \text{CO}_2 \), \( \text{H}_2\text{O(g)} \). The combustion of \( \text{CO} \) provides heat for iron ore sintering process and affects the heat front. \( \text{O}_2 \) and \( \text{CO}_2 \) affect the atmosphere of coke combustion. Moreover, the content of steam affects the formation of over-wet zone. A series of reactions, including coke combustion, \( \text{Fe}_2\text{O}_3 \) reduction and \( \text{CaCO}_3 \) decomposition and so on, affect the NOx yield in the process of quasi-particles combustion. In present work, the effect of different circulating flue gas components on the NOx emissions during quasi-particles combustion was investigated.

4.3.1. Conversion of Fuel-N to NOx of Quasi-particles Vary with \( \text{O}_2 \) Concentration

As shown in Fig. 8, the conversion rate of fuel-N to NOx increases with increasing \( \text{O}_2 \) concentration for C, S and S’ type quasi-particles. However, the conversion rate of fuel-N to NOx decreases with increasing \( \text{O}_2 \) concentration for P type quasi-particles.

The increasing \( \text{O}_2 \) concentration is conducive to conversion of fuel-N to NOx for S, S’ and C types quasi-particles due to the reactions of R5–R9.31)

\[ \text{O}_2 + 2(\text{C}) \rightarrow 2(\text{CO}) \]  

(\( \text{R5} \))

\[ (\text{CO}) \rightarrow \text{CO} + \text{free carbon site} \]  

(\( \text{R6} \))

\[ 2(\text{CO}) \rightarrow \text{CO}_2 + (\text{C}) + \text{free site} \]  

(\( \text{R7} \))

\[ \text{O}_2 + (\text{C}) + (\text{CN}) \rightarrow (\text{CO}) + (\text{CNO}) \]  

(\( \text{R8} \))

\[ (\text{CNO}) \rightarrow \text{NO} + (\text{C}) \]  

(\( \text{R9} \))

4.3.2. Conversion of Fuel-N to NOx of Quasi-particles Vary with CO Concentration

The effect of CO concentration on conversion of fuel-N to NOx was shown in Fig. 9. With the concentration of CO increasing, the conversion rate of four types quasi-particles all decreased. CO has a great capacity to decrease NOx

<table>
<thead>
<tr>
<th>Temperature</th>
<th>S</th>
<th>S’</th>
<th>P</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 073 K</td>
<td>3.19E-04</td>
<td>3.06E-04</td>
<td>4.12E-04</td>
<td>0.00251</td>
</tr>
<tr>
<td>1 173 K</td>
<td>3.71E-04</td>
<td>3.28E-04</td>
<td>3.94E-04</td>
<td>0.00212</td>
</tr>
<tr>
<td>1 273 K</td>
<td>3.21E-04</td>
<td>3.18E-04</td>
<td>7.30E-04</td>
<td>0.00481</td>
</tr>
</tbody>
</table>

Table 7. Apparent total reaction rate constant of four types quasi-particles at 1 073 K, 1 173 K, 1 273 K.
emissions. For example, the conversion rate of fuel-N to NOx of C type quasi-particles decreased from 27.18% to 10.28% when CO increased from 0.5% to 2%.

Effect of CO on the conversion of fuel-N to NOx was attributed to two aspects. On one hand, CO reacts with NO directly through R10 to decrease the conversion of fuel-N to NOx. On the other hand, CO can reduce the NO yield through reactions with char (R11 and R12).

4.3.3. Conversion of Fuel-N to NOx of Quasi-particles Vary with CO2 Concentration

To investigate the effect of CO2 on NOx yield during quasi-particles combustion, a mixed gas components of CO2, O2, N2 were adopted. N2 was used to adjust the concentration of CO2. As shown in Fig. 10, the conversion rate of fuel-N to NOx of four types quasi-particles all decreased with increasing CO2 concentration.

The results shown in Fig. 10 were consistent with previous investigation.32,33) The increasing CO2 concentration promotes the production of CO through R13. CO could either react with NO directly or react with char indirectly to decrease the conversion of fuel-N to NOx and hence suppressing the NOx yield (R10–R12).

4.3.4. Conversion of Fuel-N to NOx of Quasi-particles Vary with H2O Concentration

As shown in Fig. 11, the conversion rate of fuel-N to NOx increases with the increasing H2O(g) content for P type quasi-particles. Nevertheless, the conversion rate of fuel-N to NOx firstly increases then decreases with increasing H2O(g) content for S’, S and C type quasi-particles.

The increasing H2O(g) content decreases combustion temperature,28) which is conducive to NOx yield. Effect of H2O(g) on the conversion of fuel-N to NOx mainly depends on decreasing the sintering bed temperature28) and enhancing the reducing atmosphere.33) With the excessive H2O(g) content, the enhanced reducing atmosphere through R14 plays a major role. The conversion rate of fuel-N to NOx decreases owing to the NOx reduced by CO and H2 (R10 and R15).34)

Fig. 8. Conversion of fuel-N to NOx for four types quasi-particles varying with O2 concentration.

Fig. 9. Conversion of fuel-N to NOx for four types quasi-particles varying with CO concentration.

Fig. 10. Conversion of fuel-N to NOx for four types quasi-particles varying with CO2 concentration.

Fig. 11. Conversion of fuel-N to NOx for four types quasi-particles varying with H2O concentration.
5. Discussion

5.1. Effect of Temperature on Combustion Characteristics of Quasi-particles

The results obtained from Fig. 4(b) were agreed with Ohno\(^9\) who found that quasi-particles with smaller coke proportion made the combustion reaction rate larger. The mass fraction of coke was only 5% for C type quasi-particles, much less than other three types quasi-particles. The combustion rate of C type quasi-particles could be greatly influenced by temperature compared with other three types quasi-particles.

Kasai\(^1\) found that the combustion rate of quasi-particles decreased with increasing particle size. Diameters of coke particles for C and P type quasi-particles were \(2-0.25\) mm, smaller than that in S and S’ type quasi-particles in present experiment hence higher mass conversion rate of C and P type than S and S’ type quasi-particles. Moreover, there were significant effects of adhering layer on coke combustion. The reactions between coke and limestone or hematite (R3 and R4) can decrease the mass of quasi-particles. Close contact of hematite and limestone with coke will accelerate those reactions to lower the ignition temperature.\(^{30-37}\) Therefore the mass conversion rate of S’ type quasi-particles which have no adhering layer was the lowest.

5.2. Effect of Temperature on Conversion of Fuel-N to NOx of Quasi-particles

It could be seen from Fig. 7 that conversion rate of fuel-N to NOx for C type quasi-particles decreases more obvious than other three types quasi-particles with increasing temperature.

The rising temperature enhances the adsorption capacity of char to NO and increases the heterogeneous reduction reaction rate constant between char and NO. Moreover, the rising temperature accelerates the combustion speed and decreases the \(O_2\) concentration at the surface of coke, causing the decrease of conversion rate of fuel-N to NOx for C type quasi-particles.\(^{38,39}\) Apart from that, coke particles with the diameter of \(2-0.25\) mm and mass fraction of 5% for C type quasi-particles result in combustion rate greatly influenced by temperature. For other three types quasi-particles, mass fraction of coke is higher (50% for P type, 75% for S type, 100% for S’) and relative influence is not so obvious. Additionally, the loose distribution of coke on the surface of C type quasi-particles leads to burning more intensively with higher temperature compared with S and P type quasi-particles. S’ type quasi-particles were coarse coke particles and conditions for contact with \(O_2\) were worse than C type quasi-particles, although decrease of \(O_2\) concentration also occurred on the surface of S’ type quasi-particles.

Taking the factors mentioned above into comprehensive consideration, C type quasi-particles were affected by temperature more obviously than other three types quasi-particles.

5.3. Effect of \(O_2\) Concentration on Conversion of Fuel-N to NOx of Quasi-particles

Effect of \(O_2\) concentration on the conversion rate of fuel-N to NOx is very complex. On one hand, the increase of \(O_2\) content is conducive to the production of NOx. On the other hand, the increase of \(O_2\) content will promote the heterogeneous reduction reaction between NOx and char.\(^{40}\)

For S’ and S types quasi-particles, the combustion occurs on the surface of \(2-2.8\) mm coke slowly. For C type quasi-particles, coke fraction is just 5%. Therefore, oxidizing atmosphere may occur in the combustion process for S, S’ and C types quasi-particles.

The increasing \(O_2\) concentration occupies more carbon active sites, reducing the carbon active sites where happens heterogeneous reduction reaction between char and NO. In addition, the formation of oxidizing atmosphere is unfavorable for reduction reaction.\(^{41}\)

However, Coke particles with diameter of \(2-0.25\) mm and fraction of 50% were uniformly distributed in P type quasi-particles resulting in faster \(O_2\) consumption and more generation of CO hence a stronger reductive atmosphere compared with the other three types quasi-particles. The effect of NOx reduced by char and CO, which was promoted by \(O_2\), plays a major role for P type quasi-particles.

Moreover, it was estimated that calcium ferrite has been formed inside P type quasi-particles, resulting in the decrease of conversion rate of fuel-N to NOx with increasing \(O_2\) concentration. For S type quasi-particles, existence of adhering layer hinders the radiation effect and temperature inside S type quasi-particles may be lower than 1 273 K. For S’ type quasi-particles, on one hand, coke size was 10 times larger than P type quasi-particles; on the other hand, conditions for contact with \(O_2\) are worse than P type quasi-particles. Therefore, temperature inside S’ type quasi-particles may be lower than the generation temperature of calcium ferrite. Coke fraction is only 5% for C type quasi-particles, limited heat was produced and temperature inside which may be lower than formation temperature of calcium ferrite, although diameter of coke was \(2-0.25\) mm and evenly distributed on the surface of quasi-particles. Coke particles with diameter of \(2-0.25\) mm and mass fraction of 50% are evenly distributed in P type quasi-particles. They burned more intensively with increasing \(O_2\) concentration, temperature inside P type quasi-particles may have been raised above 1 273 K and the calcium ferrite may have been formed.\(^{52}\) Conversion rate of fuel-N to NOx could be decreased by calcium ferrite effectively. More calcium ferrite may be generated with increasing \(O_2\) concentration, resulting in the decrease of conversion rate of fuel-N to NOx for P type quasi-particles.

5.4. Recommendations on Decreasing NOx Emissions in Iron Ore Sintering

Effect of circulating flue gas components on iron ore sintering process has been researched by many scholars.\(^{25,43}\) The suitable \(O_2\) concentration in circulating flue gas is greater than 15% considering the combustion speed and combustion efficiency. The post-combustion of CO improves the sinter indexes, therefore it’s conducive to sintering process. In order to avoid the decrease of combustion efficiency, the \(CO_2\) concentration should be lower than 6%. The appropriate \(H_2(O)\) concentration is no higher than 8% considering the width of over-wet zone.

The above experimental results exhibits that the conversion rate of fuel-N to NOx of C type quasi-particles was higher than that of other types quasi-particles in different flue gas atmosphere. Hence, NOx emissions could
be reduced by decreasing the proportion of C type quasi-particles and improving the proportion of other types quasi-particles. Controlling the fuel existing state in granules is a useful method for reducing NOx emissions during iron ore sintering process. Fuel pre-granulation technology has been considered as an effective measure to reduce NOx emission.\(^{12-14}\) The structure of granule was divided into inner layer consisting of coke, limestone and iron ore and outer layer composing of limestone and iron ore. Fuel combusts in a low O\(_2\) concentration due to the restriction of in-diffusion of O\(_2\), which is detrimental for NOx yield. Furthermore, NOx was reduced by reacting with CO during the out-diffusion process. Compared with conventional granulation process, fuel pre-granulation is a more promising method to reduce NOx emissions. Moreover, NOx could be further reduced by coupling fuel pre-granulation with flue gas recirculation technology.

6. Conclusions
Experimental investigation of the conversion of fuel-N to NOx for four types quasi-particles under different circulating flue gas components and the mass conversion rate of four types quasi-particles at different temperatures was conducted in a vertical quartz tube reactor. The following conclusions were drawn:

(1) The mass conversion rate of four types quasi-particles was larger with higher temperature and ranked in the order of C > P > S > S\(^{\prime}\) at all temperature investigated.

(2) Through calculating the correlation coefficient between different mechanism models G(x) and t, it was found that D\(_1\) model was the most appropriate model to describe the combustion behavior of S, S\(^{\prime}\) and P type quasi-particles and D\(_2\) model was better than other models to describe the combustion behavior of C type quasi-particles. The apparent total reaction rate constant of four types quasi-particles ranked in the order of C > P > S > S\(^{\prime}\).

(3) The conversion rate of fuel-N to NOx increases with increasing O\(_2\) concentration for S, S\(^{\prime}\) and C type quasi-particles due to the oxidation of char-N. However, the conversion rate of fuel-N to NOx decreases with the increasing O\(_2\) concentration for P type quasi-particles due to two competing reactions: NOx reduction in the surface of coke and the oxidation of char-N. The conversion rate of fuel-N to NOx of four types quasi-particles all decreased with the increasing CO\(_2\) and CO concentration. Effect of H\(_2\)O(g) content on the conversion rate of fuel-N to NOx for four types quasi-particles was different. For S\(^{\prime}\), S and C type quasi-particles, the conversion rate of fuel-N to NOx firstly increases and then decreases with the increasing H\(_2\)O (g) content. However, the conversion rate of fuel-N to NOx increases with the increasing H\(_2\)O(g) content for P type quasi-particles.

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