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**Experimental study of commercial charcoal as alternative fuel for coke breeze in
iron ore sintering process**

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Abstract

Coke breeze and anthracite are the traditional heat suppliers to iron and steel industry while global warming issue has been a focus of concern. Using biomass for partial or complete replacement of coke breeze in the iron ore sintering process is an attractive technique for reducing emissions of greenhouse gas and gaseous pollutants. However, short supply of charred wood and low sinter quality for raw biomass are the biggest constraints for wide application in sinter production at present. In this paper, the commercial charcoal made from sawdust, nutshell and some other waste biomass (with extensive source and low cost) was employed as the alternative fuel in the sintering process. The primary fuel was coke breeze with 20%, 40%, 60%, 80% and 100% substitution of the fixed carbon input with

charcoal. The flame front characteristics and sintering performance were compared at different substitution rates. The results indicated that the flame front accelerated with the increase of charcoal substitution rate due to its higher intrinsic reactivity and larger specific reaction area. Both duration time of melting temperature and melt quantity index reached their peak values at 60% charcoal substitution rate. When the substitution rate exceeded 60%, duration time of melting temperature and melt quantity index dropped sharply, suggesting that the sinter strength was deteriorated badly. Reasons for the weakened sinters were analysed from the views of combustion efficiency (heat generation) and heat accumulation performance (heat utilization). NO_x emission concentration reduced significantly with the increase of charcoal proportion. Finally, suggestions for improving charcoal sintering performance were discussed based on the present study. To maintain high sinter strength, it is recommended to avoid the excessively high combustion rate at high charcoal proportion.

Keywords: iron ore sintering; commercial charcoal; substitution rate; flame front; combustion efficiency; heat utilization performance

Nomenclature

c	Specific heat capacity in constant pressure, $\text{J}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$
T	Temperature, $^{\circ}\text{C}$
q_m	Gas flowrate, $\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$
x	Coordinate direction, mm
y	Coordinate direction, mm
$DTMT$	Duration time of melting temperature, s
FFS	Flame front speed, $\text{mm}\cdot\text{min}^{-1}$
MQI	Melt quantity index, $^{\circ}\text{C}\cdot\text{s}$
$HTFS$	Heat transfer front speed, $\text{mm}\cdot\text{min}^{-1}$

Greek symbols

τ	Time, s
ε	Porosity
ρ	Density, $\text{kg}\cdot\text{m}^{-3}$

Subscripts

g	Gas
s	Solid

1. Introduction

In the last five years, the Chinese government has implemented a set of intensity reducing policies to reduce either energy consumption or carbon emissions per unit of gross domestic product. However, the intensity reducing policies have not sufficiently released the intensive pressures on China's climate-change mitigation, because the total carbon emission continues increasing at a rapid pace due to the fast economic growth [1]. Iron and steel industry, accounting for 18% [2] of total CO₂ emission, is one of the top three greenhouse gas emission (GHG) sectors in China. Traditionally, coke and anthracite supply heat for the iron ore sintering process which agglomerates iron ore fines to lump cakes with better permeability as the feed materials for efficient liquid iron production in blast furnace. Iron ore sintering process was schematically illustrated in the previous paper [3]. Zhao [4] described the operating procedures, as well as the physical and chemical phenomena in sintering process in detail. In the integrated iron and steel production, coking and iron ore sintering procedures contribute the highest share of CO₂ emission [5], as well as SO₂ and NO_x. Therefore, reducing CO₂ emission in iron ore sintering procedures has been strongly required for the current environmental pressure and high cost of carbon emission in the coming decades.

Some energy-saving technologies were proposed for reducing CO₂ emission. For example, the performance of adding fuel externally to the raw ore was examined and found to be beneficial to fuel combustion condition [6]. The effect of less expensive fuel substitution of coke such as anthracite coal on iron ore sintering performance was evaluated [7]. Optimum coke segregation and charging condition were investigated with the aim at controlling the bed temperature [8]. Enrichment of oxygen in the induced air was also tested [9]. Flue gas recirculation was very helpful to reduce the volume of flue gas

to be treated and reduce the coke consumption rate since CO will be burnt and release heat [10]. Zhou [11] proposed a novel technique, three-layered bed structure sintering, to study the effect of coke level, properties and combustion behavior on NO_x emission. While for a longer term, fossil fuels need to be replaced by renewable heat suppliers gradually in the sintering process. Biomass is an environmentally friendly energy source due to its carbon neutral, low N and S contents. Okasha [12] carried out experimental studies on co-combustion of rice straw and natural gas in a fluidized bed. Wang [13] investigated the injection of biomass into blast furnaces, in place of pulverized coal from fossil sources. However, some challenges have to be dealt with before applying biomass into industrial sintering production, such as biomass supply [14], cost evaluation, substitution rate and sinters quality control and optimization. At a strategic level, solving the problems should be divided into three steps, as shown in Fig. 1. At present, researchers only pay attentions on step 1 and step 2.

Recently, a plenty of investigations were conducted to test the sintering performance using different kinds of biomass to partially or completely replace coke breeze. Lovel [15] performed small scale sintering tests using hard wood char, woody weed prickly and red gum charcoal. The results suggested that there were no apparent technical barriers in iron ore sintering with red gum charcoal. However, short supply and high cost of charred wood are significant constraints for sinter plants. After that, Ooi examined the sintering performance adopting sunflower seed husk [16] and commercial charcoal [17] which have low cost and extensive source. However, the suitable substitution proportion, 10% for sunflower seed husk and 20% for commercial charcoal, was limited for CO₂ emission reduction. In their subsequent work, iron ore sintering characteristics adopting olive residues, sunflower husk pellets, almond shells and hazelnut shells were carefully compared [18]. The work

provided a very important reference for biomass sintering. Authors noted that less of energy would be available in the sintering process due to the loss of volatile matter ahead of flame front. They also found the size of biomass pellets was a key factor to sintering performance. The emissions of NO_x and SO_x were also reported. Lu [19] adopted red gum charcoal as an alternative fuel to partially substitute coke breeze in sintering process. It was found that the sinter quality was weakened at high charcoal proportions. Authors tried to explain the reasons from the view of waste gas composition variations. They presented a comprehensive understanding of the influencing mechanism of charcoal on the granulating, sintering indices and emissions characteristics including O_2 , CO , CO_2 , SO_2 , NO_x and H_2O . Abreu [20] adopted charcoal as supplementary fuel in the iron ore sintering process. The results indicated that the blend with 50% charcoal in the fuel mix was possible from both environmental and operational perspectives. Gan compared the performance of raw biomass and charred wood in iron ore sintering [21]. The substitution rate of raw biomass was very limited due to its high volatiles content. The flame acceleration mechanism in iron ore sintering when using biomass was also discussed [22]. By increasing the size of biomass [22] and improving the distribution of biomass particles [23], sinter indices were improved since the burning speed of biomass was optimized. Kawaguchi [24] claimed that it is not recommended for using raw biomass directly as the carbon material for sinter production. The main information of important literatures on biomass sintering, including biomass type, suitable substitution rate and substitution principle, was summarised in Table 1.

According to the above literature survey, researchers focused on the raw biomass and charred wood as alternative fuels in iron ore sintering. However, the raw biomass (low grade) failed in achieving suitable sinter quality. The short supply and high cost of charred wood (high grade) were the

biggest constraints for its wide application. There is little research on applying medium grade alternative fuels with extensive source and low cost into iron ore sintering, which can maintain sinter quality at a relatively high substitution rate. Moreover, most work in the past was performed to find the relationships between input (operating parameters) and output (evaluation indices of sintered ore, such as tumble index, shatter index and microstructure) of the sintering “black box”, rather than to get direct information and knowledge inside it. The influencing mechanism of sintering process when introducing biomass is still under discussion. Acknowledging the direct information in “black box”, such as local temperature, combustion efficiency and waste gas composition, is very helpful to understand the sintering behaviours. In the present study, the commercial charcoal is adopted to carry out sintering tests at different substitution rates. To clarify the influencing mechanism when introducing charcoal to sintering process, the key parameters of flame front (peak temperature and propagating speed), melting zone (holding time and index of melt phase quantity) were extracted and compared. Beyond that, the combustion efficiency and heat utilization performance were analyzed at different charcoal proportions. In brief, this paper aimed to the in-depth understanding of applying medium grade charcoal in iron ore sintering.

2. Experimental method and materials

2.1 Experimental method

The sintering process was simulated in a fixed reactor with a height of 400 mm and a diameter of 142 mm. Figure 2 shows the schematic diagram of experimental system including gas burner, sintering pot, draft fan and data acquisition system. The sintering pot was surrounded by a Kaowool high-temperature insulation material layer with a thickness of 65 mm to minimize heat loss. Seven

S-type thermocouples were positioned in the axis of reactor at an equal interval of 40 mm from $y=80$ mm (TC 1) to $y=320$ mm (TC 7) where the start of these dimensions was located at the top of sinter pot ($y=0$ mm), as shown in Fig. 2. Obvious air leakage near the reactor wall due to radial shrinkage would result in great heat lose. As recommended in [17], very fine particles were filled in the annular space separated the raw materials and reactor wall by using a paper sleeve. This method was effective for “edge effect” controlling. The major operating parameters are listed in Table 2. Moreover, drop test (sinters were freely dropped from two meters four times) was carried out to determine sinter yield. Gas analyser (Testo 350) was arranged at reactor outlet to record the concentration profiles of O_2 and NO_x . The accuracy of S-type thermocouple is ± 3 °C. The accuracies of concentration sensors in gas analyser are ± 0.2 vol.% for O_2 , ± 5 ppm (from 0 to 99 ppm) and $\pm 5\%$ of reading value (from 100 to 1999 ppm) for NO_x . The pictures of solid fuel microstructure were examined using a scanning electron microscope (SEM) (Hitachi S-4700). The detailed information of operating parameters was presented at the bottom of Fig. 3. The “intrinsic reactivity” of solid fuels was approximately regarded as the reactivity obtained by non-isothermal thermogravimetric analysis where the samples were grinded into very fine particles (0-30 μm). Approximately 10 mg of each sample was reacted with air in NETZSCH-STA409PC at a flow rate of $200\text{ ml}\cdot\text{min}^{-1}$ and a heating rate of $10\text{ }^\circ\text{C}\cdot\text{min}^{-1}$. The thermogravimetric analysis results, such as TG and DTG, are shown in Figs. 4(a) and 4(b).

2.2 Experimental materials

Raw sinter materials contain iron ores, return fine, hydrated lime and solid fuel, as listed in Table 3. Coke breeze was replaced by charcoal on the basis of equivalent fixed carbon content. To improve the air flow uniformity, the iron ores bigger than 5 mm were crushed. For each test, 350 g hearth ore

and approximate 10 kg raw materials after granulation were fed into the sintering reactor. The commercial charcoal adopted in the present study was obtained from The Primitive Company in China. It was made from sawdust, nutshell and some other waste biomass after drying, shaping and charring. Proximate analysis results of the fuels selected for sintering tests, including coke breeze and charcoal, are shown in Table 4. Compared with coke breeze, charcoal had lower fixed carbon content, higher volatiles content and heat value. The calorific values listed in Table 4 are the calorific value as dry basis. The size distribution of solid fuels can be found elsewhere in the previous paper [26]. Generally, the fuel apparent reactivity is attributed to the specific surface area and intrinsic reactivity. As shown in Fig. 3, there were more pores and wrinkles in charcoal than those in coke, contributing a larger specific area of charcoal. Furthermore, as indicated in Fig. 4(a), the starting combustion temperatures were 280 °C for charcoal and 485 °C for coke. And ending combustion temperatures were 590 °C for charcoal and 910 °C for coke. The starting and ending combustion temperatures of charcoal were much lower. Moreover, the maximum weight loss rate of charcoal was $-11.7 \text{ \%} \cdot \text{min}^{-1}$ which was almost the double of coke maximum weight loss rate ($-6.2 \text{ \%} \cdot \text{min}^{-1}$), as presented in Fig. 4(b). Lower combustion temperature range and higher weight loss rate made charcoal burn much earlier and faster than coke breeze. In other words, charcoal had a higher “intrinsic” reactivity than coke breeze. In order to improve the gas permeability in sintering bed, raw materials were granulated by adding water to adhere fines onto the surfaces of coarser particles. According to bed permeability versus mix moisture curves obtained in [27], the optimum moisture required for granulation of all coke case was approximately 10.02%. To ensure the single variable (charcoal substitution rate) in this study, the target moisture content of other cases was kept 10.02%.

3. Parameters quantification

In the sintering process, coalescence of melt phase is the driving force to convert iron ore fines to lump cakes. Melt phase formation occurs over a narrow layer where the temperature is above 1100 °C [19]. For certain raw mixtures, sintered ores strength is highly related to the thermal condition and combustion performance in sintering bed. In this paper, peak temperature, duration time of melting temperature (*DTMT*) and melt quantity index (*MQI*) were extracted from temperature-time profiles. In addition, the heat transfer front speed (*HTFS*), flame front speed (*FFS*) and combustion efficiency in sintering bed were estimated. The related parameters used in the following analysis are defined below.

- (1) Peak temperature is the maximum value of temperature-time profile recorded by S type thermocouple.
- (2) *FFS* is defined as the ratio of sintering bed height and consumed time for flame front propagating from top to bottom of the reactor. Usually, Sintering time is started from ignition to waste gas temperature reaching to its maximum value. *FFS* is directly related to sinter productivity and the amount of melt phase generated.
- (3) *DTMT* is the holding time of temperature above 1100 °C (the initiating temperature of melting process), as shown in Fig. 5. *DTMT* can be obtained by Eq. (1). Since the residence time of flame front at a particular location is not long, *DTMT* should be sustained long for producing sufficient melt phase.

$$DTMT = \tau_2 - \tau_1 \quad (1)$$

- (4) *MQI*, expressed as Eq. (2), is defined as the enclosed area above 1100 °C in temperature-time profile, as shown in Fig. 5.

$$MQI = \int_{\tau_1}^{\tau_2} (T - 1100) \cdot d\tau \quad (2)$$

(5) *HTFS* is the travelling speed of heat transfer front, which can be estimated by Eq. (3) [3].

$$HTFS = q_m c_g / [\varepsilon \rho_g c_g + (1 - \varepsilon) \rho_s c_s] \quad (3)$$

(6) The sinters after drop test are screened to determine yield which is expressed as the ratio of produced sinter mass (>5 mm) to the total mass of sinter produced in sintering process.

4. Results

According to the preliminary study by Cheng et al. [3], three tests were carried out to evaluate the experimental repeatability. As coke content in the raw mixture is quite low (approximately 10% on volume basis), it is not surprising to temperature fluctuations in different tests at the same operation due to the random distribution of fuel particles in sintering bed. For example, the thermocouple tip closer to the fuel particles would record higher temperature, while the tip farther to fuel particles corresponded to lower temperature. Usually, researchers care about the radial temperature distribution in small scale sinter pot test, because the radial heat loss through the wall would have obvious effect on test results. The radial temperature distribution at the height of 200 mm was shown in Fig. 6. Three thermocouples were arranged in the same height ($y=200$ mm) at different radial positions, as illustrated in Fig. 6. On the horizontal cross section, one can see that the temperature peaks fell from 1227 °C (Position 1) to 1126 °C (Position 3): the maximum temperature difference compared to the bed center is only 101 °C. In the preliminary tests, the peak temperature near the wall was only about 900 °C without heat insulation. Therefore, the control of radial heat loss through the wall in small scale sinter pot test was improved obviously and acceptable in this paper. In practice, operators have several choices when using charcoal to replace coke in sintering process, such as equivalent calorific heat substitution and

equivalent fixed carbon substitution. In previous investigations, many researchers adopted equivalent calorific heat method, as shown in Table 1. Calorific heat is highly depended on the volatiles and fixed carbon contents. However, volatiles of fuels were volatilized below 1100 °C (beginning temperature of melting process) and flowed to the downstream. They were rarely helpful to the melting process, except for preheating raw materials of downstream. If equivalent calorific heat method was employed when using the charcoal with high volatiles content, the heat supply in melting zone would decline. Thus, equivalent calorific heat substitution method may not be the optimum choice for charcoal. Compared with volatiles, the fixed carbon of high combustion temperature and low reacting rate was more helpful to the melting process which was important to sinter strength. Inspired by this, the equivalent fixed carbon substitution method was employed in the present study. With the sufficient heat supply in melting zone, sintering performance was promising to be maintained at higher charcoal substitution rate. Figure 7 shows the typical temperature-time profiles at the positions from $y = 80$ mm (TC 1) to $y = 320$ mm (TC 7). After a certain time delay for heating and evaporating, reactive raw materials started to burn. Local temperature of sintering bed exceeded 1100 °C rapidly, and further rose to the peak value where melting process were occurring. Then the bed temperature dropped due to convective cooling by fresh air. Both of available reactive materials ahead of flame front and fresh air supply drove flame front moving downward. It was noted that, the temperature profiles from TC 1 to TC 7 became higher and wider as sintering process progressed. These phenomena can be reasonably explained by the advantages of porous medium combustion: solid porous matrix serves a means of recirculating heat from the high temperature zone to the incoming fresh air in preheating zone. As flame front propagated downward, the increasing preheating time enhanced heat accumulation effect in sintering bed.

4.1 Influence of substitution rate on flame front characteristics

In the present study, sintering tests were carried out at different charcoal substitution rates, while the other operating parameters were kept unchanged. The primary fuel was coke breeze with 20%, 40%, 60%, 80% and 100% substitution of the fixed carbon input with charcoal. Figure 8 shows the thermal profiles at different substitution rates at the position of $y=200$ mm. It was found that, temperatures started to rise earlier at higher substitution rates, which indicated higher travelling speed of high temperature layer. Figure 9 shows the influence of substitution rate on flame front speed (*FFS*). The results indicated that the *FFS* increased slowly at low substitution rates from 20% to 60%. When charcoal substitution rate exceeded 60%, *FFS* increased rapidly. The acceleration mechanism of *FFS* with charcoal proportion is interesting and important, since *FFS* is directly related to sinter productivity. With the help of scanning electron microscope (SEM) and non-isothermal thermogravimetric analysis, the microstructures and thermogravimetric profiles of coke breeze and charcoal were obtained. The data (in Section 2.2) indicated that charcoal was more reactive than coke, which meant the burning rate of charcoal was higher. Consequently, once the solid fuels were ignited, the burning rate and heat release rate accelerated at higher charcoal proportion, which contributed to a higher *FFS* with the rise of charcoal proportion.

Peak temperature plays an important role on the generation of melt phase. The melting kinetics and melt phase fluidity are dependent on peak temperature in combustion layer of sintering bed. On the other hand, it is also required to hold the peak temperature of sintering bed lower than 1400 °C [25] for maintaining the sinter reducibility. As indicated in Fig. 8, peak temperatures slightly increased at low substitution rates from 20% to 60%. However, the peak temperatures decreased significantly at 80%

and 100% charcoal substitution. For detailed description of flame front characteristics, both of local and average peak temperatures were extracted and compared, as presented in Fig. 10. For a certain case, local peak temperature rose from upstream to downstream within a small fluctuation. The fluctuation of recorded temperature was not surprising here because solid fuels randomly distributed in the sintering bed, as mentioned in the previous paragraph. For the cases of different substitution rates, it was noted that local peak temperature decreased significantly when charcoal substitution rate exceeded 60%. The average peak temperature of sintering bed was also presented in Fig. 10. Average peak temperature increased slightly at the beginning, but decreased rapidly at high charcoal substitution rates. Low temperature of flame front inevitably reduced the degree of melting process, thereby decreasing the sinter strength. The slight rise of peak temperature was attributed to the increase of calorific heat input. In fact, the calorific heat of charcoal was higher (+21.49%) than that of coke. However, the fixed carbon content of charcoal was lower (-2.98%) than that of coke. Consequently, calorific heat input increased with the rise of charcoal substitution rates at the same fixed carbon input, as shown in Table 5. The sharp drop of peak temperature at 80% and 100% substitution rates was resulted from the poorly organized combustion and heat utilization the in sintering bed. (See the explanations in Section 4.2).

4.2 Influence of substitution rate on sintering performance and gaseous pollutant emission

As an elementary research, ensuring the single variable (charcoal substitution rate) in the investigation was very important and had high priority. As a result, the return fines balance can't be achieved at different charcoal substitution rates, because the return fines addition must be fixed at a constant. Therefore, some other ways need to be found to compare the sinter strength at different charcoal substitution rates based on the data recorded by thermocouples. Melt phase provides the main

bonding force for coherency to produce high strength sinters. The amount of melt generated is highly dependent on the residence time at temperature above 1100 °C. In other words, the real sinter strength can be practically transparent once the thermal performance is characterized. *DTMT* was adopted to characterize sinter strength [25]. Other than *DTMT*, the amount of melt phase generated is also relied on actual temperature of melting layer in sintering bed since this will affect the melting kinetics and fluidity of melt phase. Inspired by Loo [28], combining the *DTMT* and actual temperature above 1100 °C, the *MQI* was employed to characterize sinters strength in the present study. To valid this method, a simple test was performed to reveal the relation between *MQI* and sinters yield, as shown in Fig. 11. In Fig. 11, the test was carried out at the operating conditions where the fixed carbon content was 3.48% supplied by all coke, while the other parameters were the same with the parameters listed in Table 2. Actually, the yields of sinter cakes divided into four parts: 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm were tested respectively. The yield tests results in Fig. 11 were plotted on the middle positions of 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm. As indicated in Fig. 11, the yield increased from upstream to downstream, and the *MQI* rose with the same pace. Thus, the *MQI* can really reflect the trend of sinter yield. Therefore, *MQI* was adopted to characterize the sinter strength at different charcoal substitution rates since *MQI* can reflect more comprehensive information and had a closer trend with sinters yield in this paper.

Figure 12 shows influence of substitution rate on *DTMT*. Figure 13 shows the influence of substitution rate on local and average *MQI*. It was observed that, local *MQI* increased with the rise of charcoal substitution rate in the beginning, then decreased after charcoal substitution rate exceeded 60%. The increase of *MQI* was easy to accept due to the increase of calorific heat input, as shown in

Table 5. However, at the same fixed carbon input and even higher calorific heat input, *MQI* decreased sharply at high charcoal substitution rate, such as 80% and 100%. This is interesting and important to understand charcoal sintering behaviors. In this paper, the phenomena could be explained from the views of heat generation and utilization performances in sintering bed.

There is a general agreement that at the temperature above than 727 °C, CO is the main product formed at the coke-gas interface [29]. From the temperature-time profile of sintering bed, local temperature rose very rapidly from room temperature to 727 °C. Thus, the main reactions can be approximately described by Eq. (4a) and Eq. (4b). At the solid fuel surface, carbon is oxidized to CO. Then the formed CO is further oxidized to CO₂ in bulk gas. Partial pressure of O₂ in bulk gas is the key factor for oxidization of CO, which determines the combustion efficiency. Figure 14 shows the average O₂ concentration of waste gas at different charcoal substitution rates. The results indicated that at low substitution rates, O₂ concentrations were almost unchanged, except the ending time of sintering process. However, O₂ concentrations in waste gas decreased obviously at high substitution rates (80% and 100%). Lower O₂ concentration would lead to more production of CO in the sintering process, decreasing combustion efficiency. This is a reasonable explanation of lower peak temperature, *DTMT* and *MQI* from the view of heat generation.

In filtration combustion, there exist two types of travelling fronts: heat transfer front and reaction front [30]. Heat transfer front and reaction front propagate independently with their own speeds. Two typical travelling regimes are reaction leading and heat transfer leading, as shown in Figs. 15(a) and

15(b). According to the filtration combustion theory, heat accumulation effect reaches to the maximum when the speeds of heat transfer front and reaction front are the same [31], as shown in Fig. 15(c). Iron ore sintering process is a typical example of filtration combustion in its industrial application [32]. Similarly, the heat utilization efficiency will reach to the maximum when the *HTFS* is equal to *FFS*. After some simplifications, the simple expression [3] was adopted in the present study to obtain the *HTFS* for evaluating the matching performance of *HTFS* and *FFS* in the engineering applications. The gas heat capacity and density were taken as average values over the range of temperatures. Air flowrate was the average value measured by flowmeter (at ambient temperature) during the sintering process. The sinter density was measured five times using pycnometer. The adopted sinter density was the average value. The detailed values adopted in Eq. (3) are presented in Table 6. The comparison of *HTFS* and *FFS* at different charcoal substitution rates is presented in Fig. 16. The differences of *HTFS* and *FFS* at 20%, 40% and 60% charcoal substitution rates were -2.92%, -0.92% and 4.46%, respectively. This meant the heat utilization performances were quite perfect. However, the differences of *HTFS* and *FFS* suddenly increased to 12.41% at 80% charcoal substitution and 29.87% at 100% charcoal substitution. Great differences between *HTFS* and *FFS* weakened the heat accumulation effect in high temperature layer, resulting in the deteriorated peak temperature, *DTMT* and *MQI*.

According to the above analysis, the influencing mechanism of substitution rate on heat generation and utilization performance in sintering bed was clarified. As the higher intrinsic reactivity and larger specific reaction area of charcoal, combustion rate in sintering bed accelerated with the increase of charcoal proportion. At low charcoal substitution rate, sinter strength (*MQI*) can be maintained or even enhanced due to the increased calorific heat input from 20% to 60% charcoal substitution. However,

sinter strength was badly weakened after substitution rate exceeded 60%. The main causes were the deteriorated combustion efficiency and heat utilization efficiency.

With stricter emission control regulations, controlling NO_x emission in iron ore sintering has been paid much more attention in recent years. The concentration-time profiles of NO_x in waste gas at different charcoal substitution rates are shown in Fig. 17. It can be observed that, concentration of NO_x reduced with the increase of charcoal proportion. As a result, introducing charcoal into sintering process was very helpful to reduce the emission concentration of NO_x .

5. Discussion

According to the above investigation, commercial charcoal is a wise choice for alternative fuel to partially replace coke breeze in iron ore sintering. Charcoal has much larger specific surface area and higher intrinsic reactivity than those of coke breeze, which is helpful to increase sintering speed. On the other hand, it results in poorly organized combustion at larger fuel-gas interface with limited O_2 supply. Beyond that, the damaged matching performance between *FFS* and *HTFS* at high substitution rate weakens the heat utilization efficiency in the sintering bed. Consequently, organizing combustion reasonably and avoiding excessively high combustion rate should be the primary concerns in charcoal sintering. Increasing the size of charcoal particles and optimising charcoal particles distribution to reduce reaction area are the traditional methods. Coating passivation layer on the charcoal surface is also an effective method to organize charcoal combustion efficiently. As for the low O_2 partial pressure during sintering process, it should be noted that only injecting O_2 to the subjected area may have little effect on improving combustion efficiency, because combustion is still poorly organized since both of solid fuel and CO oxidization rates increase simultaneously at the O_2 enrichment condition.

Producing sinters of suitable quality at the lowest fuel rate, lowest emission and highest productivity is the ultimate goal of most operations. Calorific heat input in the sintering bed increases as the rise of charcoal substitution rate. It is suggested that sintering strength even deteriorates at high charcoal proportion, which means more fuel rate is needed to maintain suitable sinters strength. Therefore, operators have to balance the CO₂ emission, sinter quality and energy consumption in charcoal sintering. Considering the cost and flexibility, it is promising to solve the problem by simultaneously applying gaseous fuel injection [25] and partial charcoal substitution techniques, as shown in Fig. 1 (step 3). The injection of gaseous fuel will create a secondary combustion area above the solid fuels burning area, which enables to produce high strength sinters at higher charcoal substitution rate and lower fuel consumption.

6. Conclusions

In order to reduce the CO₂ emission in sintering process, this paper focused on applying commercial charcoal, with extensive source and low cost, in iron ore sintering process. Sintering tests were performed at different charcoal substitution rates keeping other parameters unchanged. The primary fuel was coke breeze with 20%, 40%, 60%, 80% and 100% substitution of fixed carbon input with charcoal. Firstly, the intrinsic reactivity and microstructures of charcoal and coke were compared with the help of thermogravimetric analysis and SEM. Secondly, flame front and sintering performance were characterized on the basis of temperature-time profiles. Thirdly, the deteriorated sintering performance at high substitution rate was explained from the view of combustion and heat utilization efficiencies.. The main findings were summarized as follows:

- (1) *FFS* increased from 23.94 mm·min⁻¹ at 20% charcoal substitution rate to 32.03 mm·min⁻¹ at 100%

charcoal. The acceleration of *FFS* with increase of charcoal proportion was mainly caused by its higher intrinsic reactivity and larger specific reaction area. After slight rise of at low substitution rate, peak temperature sharply dropped at 80% and 100% charcoal substitution.

- (2) Both *DTMT* and *MQI*, the indicators of sinter quality, reached to their maximum values at 60% charcoal substitution using equivalent fixed carbon substitution method. However, *DTMT* and *MQI* significantly decreased when charcoal substitution rate exceeded 60%. Besides, the emission concentration of NO_x reduced with the increase of charcoal proportion.
- (3) From the view of combustion efficiency, O_2 concentration reduced with the increase of charcoal proportion due to the higher consumption rate. Lack of O_2 supply would lead to the more incomplete oxidization product CO , resulting in low combustion efficiency. And from the view of heat utilization performance, obvious increase of *FFS* at 80% and 100% charcoal substitution damaged the matching performance of *FFS* and *HTFS*, which weakened the heat utilization performance in sintering bed. It is recommended to control the excessively high combustion rate to improve the sinter strength at high charcoal proportion.

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Table Captions

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Fig. 12 Influence of charcoal substitution rate on local and average *DTMT*

Fig. 13 Influence of charcoal substitution rate on local and average *MQI*

Fig. 14 Influence of charcoal substitution rate on O_2 concentrations

Fig. 15 Structure of the forward filtration combustion wave [30]

Fig. 16 Comparison of *FFS* and *HTFS* at different charcoal substitution rates

Fig. 17 NO_x concentrations at different charcoal proportions

Table 1 Summary of alternative fuels used in published work

No.	Author	Alternative fuel	Substitution principle	Substitution rate
1	Lovel [15]	Hard wood char	Equivalent mass	-
		Woody prickly		
		Red gum charcoal		
2	Ooi	Sunflower seed husks [16]	Equivalent heat	20%
		Charcoal 1 [17]		40%
3	Zandi [18]	Sunflower husks pellets	Equivalent total carbon	-
		Hazelnut shells		-
		Almond shells		-
4	Lu [19]	Red gum charcoal	Equivalent mass	50%
5	Gan [21]	Charcoal 2	Equivalent heat	40%
		Charred-straw		20%
		Molded-sawdust		15%
6	Oyama [25]	Liquefied natural gas	Equivalent heat	0.4%
		Propane		0.2%
		Carbon monoxide		1.2%

Table 2 Main parameters adopted in the experiments

Parameters	Sintering conditions
Ignition temperature (°C)	1100 ±10
Ignition time (s)	90
Ignition suction (kPa)	5
Sintering suction (kPa)	10
Basicity (CaO/SiO ₂) (kg·kg ⁻¹)	1.8

Table 3 Blending ratio of sinter mixture used in the experiments

Raw materials	VMS ore	WPF ore	Brazilian ore	Return fine	Hydrated lime	Coke
Mass fraction (%)	25.54	25.54	12.77	20.56	10.60	5.00

Table 4 Proximate analysis and heat value of coke breeze and charcoal

Parameters	Coke breeze	Charcoal
Proximate analysis		
Fixed carbon (ad)	74.06%	71.85%
Volatiles (ad)	5.20%	16.84%
Ash (ad)	20.40%	6.52%
Moisture (ad)	0.34%	4.76%
Calorific value (d)	25.03 MJ·kg ⁻¹	30.41 MJ·kg ⁻¹

Table 5 Comparison of calorific heat input at different substitution rates

Substitution rate (fuels mass basis)	Fixed carbon content (raw mix mass basis)	Calorific heat input (raw mix mass basis)
20%	3.70%	1.32 MJ·kg ⁻¹
40%	3.70%	1.38 MJ·kg ⁻¹
60%	3.70%	1.44 MJ·kg ⁻¹
80%	3.70%	1.50 MJ·kg ⁻¹
100%	3.70%	1.57 MJ·kg ⁻¹

Table 6 Main parameters used to estimate *HTFS* [3]

Parameters	ε	c_g	ρ_g	c_s	ρ_s	q_m
Unit	-	J·kg ⁻¹ ·°C ⁻¹	kg·m ⁻³	J·kg ⁻¹ ·°C ⁻¹	kg·m ⁻³	kg·s ⁻¹ ·m ⁻²
value	0.4	1140	0.353	920	4155	0.827

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Fig. 2 Schematic diagram of experimental system

(a) Microstructure of coke

(b) Microstructure of charcoal

Fig. 3 Microstructure of solid fuels

(a) Comparison of TG profiles between coke and charcoal

(b) Comparison of DTG profiles between coke and charcoal

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