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Investigation on the application of by-product steam in iron ore sintering: performance and function mechanism

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Abstract: The combustion-supporting effect of steam to coke breeze in sintering has the potential to improve sinter quality and reduce pollutants emissions**.** The results show that increasing the by-product steam injection concentration(0.32-0.47vol%) and prolonging the injection time(5min) within a proper range(10-15min) can improve sinter quality. 2.13kgce/$t_{\text{-sinter}}$ of the fuel consumption was decreased by reducing coke breeze usage from 5.60% to 5.45% under the recommended parameters, with 15.16% decrease of CO in sintering waste gas. By comparing experimental data with thermodynamic calculations, although the reaction between CO and steam can reduce CO emission and generate H_2, steam tends to react with coke breeze to generate H_2 and CO(react at 674°C), and OH radical produced by H_2 which can reduce the activation energy of CO oxidation reaction is the key to reducing pollutant emissions. The application of steam injection technology, excluding the equipment modification and steam injection cost of $300,000, can achieve a profit of $737491.2 per year. Therefore, low-carbon and cleaner iron ore sintering production can be realized through applying by-product steam.

Keywords: iron ore sintering; steam injection; energy saving and emission reduction; mechanism analysis

1 Introduction

Whether in social development or military fields, steel is an indispensable resource for human beings (Denton2014), but the steel industry is the third-largest consumer of fossil fuels, accounting for about 5% of the world's greenhouse gas emissions (Chen et al.2014), and also emits a large number of harmful gases such as NOx and SO_2 (Kristin et al.2015). According to the statistics of the World Bank, the top 10 countries with GDP consumed 80 billion tons of energy in terms of oil equivalent and released 21.82 billion tons of CO_2 (2014), China's steel industry accounted for 15% of China's total energy consumption (Cheng et al.2017). To achieve sustainable development, the United States will reduce CO_2 Emissions from US Steel Consumption by 70% by 2050 (Ryan et al.2020), China has also committed to reducing CO_2 emissions by 60-65% by 2030 in the Paris Agreement (He et al.2018), and most steel mills in India

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can cut their energy consumption by half (Haider et al.2021). Affected by environmental protection, carbon reduction technologies are also advancing rapidly (Mao et al.2021; Yang et al.2021).

China's iron and steel industry, which uses sinter as the main raw material for making iron, is facing the most stringent environmental requirements. The country has required the steel industry to meet the ultra-low emission standard (PM < 10mg/m^3, SO_2 < 35mg/m^3, NOx < 50mg/m^3) by 2020 (2017), which is a stricter emission standard than the European and American. Sintering is the first high-temperature process in steel production, the dust (Pal2019), SO_2 and NOx emissions account for 35.4%, 67% and 51.1% of the total process emissions (Cai et al.2021). At present, China mainly adopts end-control technology to treat gas pollutants. But it is can not meet the current environmental protection requirements through the above means. In addition, China pays more and more attention to the treatment of COx, the proportion of CO in the sintering flue gas with a mass concentration much higher than NOx and SO_2 is 0.4~1% (Wang and Zhang.2020).

Sintering gas pollutants mainly come from fuel combustion. Scholars have studied and numerically simulated the fuel combustion of iron ore sintering. With thermal power industry or generally fixed bed fuel combustion is different (Hobbs et al.1993; Pugh et al.2017), fuel in sintering material layer is scattered distribution, generally accounts for only 3-5% of total material weight, and most of the solid carbon particles are wrapped by inert ore materials. The combustion regularity of fuel is between monomer char combustion and char layer combustion, which belongs to heterogeneous reactions (Fernandez et al.2017). Fan et al.(2021) studied the relationship between ignition and low-carbon sintering and found that prolongation of ignition time can reduce fuel consumption and pollutant emission. Toda et al. believed that sintering mixture at high temperature would form melt, which would reduce the diffusion efficiency of oxygen in the material layer, affect the fuel combustion rate, and make it easier to generate CO (Hideo and Kimio1984). Zhu et al. (2006) found that the CO content in flue gas was related to the amount of coke powder. With the increase of the amount of coke powder, there was a reducing atmosphere around the coke powder particles and it was easy to form CO . Li et al. (2020) found in their study that CO would be oxidized to CO_2 by NO on the reduced surface of the reduced calcium ferrite. Gan et al.(2016) found that CO and NOx emissions could be reduced by performing fuel pellets during sintering, which was achieved by covering the fuel with quicklime and controlling the fuel surface atmosphere. It can be seen that the emission of CO in the sintering process is related to the combustion rate and the fuel surface atmosphere, but the combustion rate is related to the sintering rate and the high temperature retention time of the fuel layer, which should not be changed. If the fuel combustion efficiency is improved by changing the fuel surface atmosphere in the fuel layer, the emission of CO can not only be reduced, the heat released by the oxidation of CO can also be used to increase the temperature of the feed layer. It is beneficial to improve the quality of sintered minerals.

In the field of coal burning, fuel combustion has been studied deeply. Although it is very different from sintering conditions, some technologies are worth referring to. Buhre et al.(2005) studied the oxygen-coal combustion system. By using pure oxygen and circulating flue gas to control the temperature and heat flow distribution, the fuel combustion efficiency can be improved and NOx emissions can be significantly reduced. An analysis of pressurized coal burners by Hong et al.(2009) showed that high pressure can improve energy efficiency. Oxy-steam combustion is a promising next generation oxy-fuel combustion technology. Wang et al. studied the effect of steam concentration on the combustion process of oxy-steam. At low steam concentration, the decomposition of H_2O molecules is conducive to the formation of C(O) on the particle surface and the conversion to CO and new active sites, which can accelerate the reduction rate of NO at high temperatures (Wang et al.2019). Li et al.(2012)

used PFR model to simulate the reduction path of NO by H_2O and CO, showing that CO is the key to the generation of H free radical and the reduction of NO when the [H_2O] is less than 1%.

It is unreasonable to use pure oxygen or change the pressure in the sintering process of iron ore, the use of pure oxygen will greatly increase the production cost, while the pressure of sintering directly affects the sintering speed and the quality of sintered minerals. There have been many studies on the application of circulating flue gas. Li et al.(2014) showed through experiments that circulating flue gas would concentrate SO_2 in flue gas and achieve higher removal efficiency. Fan et al.(2019) calculated the composition of circulating flue gas and established a fine circulation mode. The emissions of NOx and SO_2 can be reduced by 28.6% and 8.15% without worsening the sintering index. Steam is seldom used in sintering. Pei et al.(2018) analyzed the influence of sintering surface steam spraying technology, and the results showed that steam can reduce CO emissions and increase fuel combustion efficiency, but the specific performance and emission reduction mechanism needs to be further studied.

In this paper, the influence of steam injection on sintering performance was studied, and the appropriate injection system was determined. In addition, HSC software was used to analyze the possible reaction after the addition of steam, the mechanism of CO emission reduction was analyzed. Suggestions were put forward for the practical application of steam spraying sintering technology. The research results will provide effective support for the wide application and improvement of the technology in steel sintering plants.

2 Materials and methods

2.1 Raw material properties

The raw materials used in the test included iron-containing materials, fluxes (dolomite, limestone and quicklime) and coke breeze. Table 1 shows the chemical compositions of raw materials and their proportions. As can be seen from Table 1, the iron contents of mixed iron ores decided the final iron content in the sinter product, while the fluxes were used to adjust the basicity (CaO/SiO_2 mass ratio) and MgO of sinter to 1.80 and 1.80%. Table 2 shows the ultimate and proximate analyses of coke breeze, the fixed carbon and calorific value of which were 82.71% and 28.69MJ·kg^{-1}.

Table 1

Chemical compositions and LOI of raw materials

Raw materials	Chemical composition/%						LOI/%
	TFe	SiO_2	CaO	MgO	Al_2O_3	FeO	
Mixed iron	62.42	6.05	0.21	0.32	0.96	9.63	3.82
Dolomite	0.55	1.70	32.10	18.04	0.20	0.14	45.58
Limestone	0.53	3.45	54.58	0.57	0.26	.0.17	40.69
quick lime	0.10	1.02	80.52	3.19	0.18	0.02	8.10
Sinter returns	56.68	5.67	10.58	2.06	1.66	9.41	0.10
Blast furnace returns	57.00	5.17	10.52	2.11	1.59	8.54	0.48
Coke breeze	1.40	6.03	0.80	0.18	3.94	0.05	86.24

LOI: loss on ignition

Table 2

Industrial analysis of coke and its element content analysis results

Components	Proximate analysis /%			Calorific value / (MJ/kg)	Ultimate analysis /%				
	V	A	FC		C	H	O	N	S
Value	3.44	13.76	82.80	28.69	83.68	2.00	1.02	0.75	0.22

V: volatile matter, A: ash content, FC: fixed carbon

2.2 Test methods

2.2.1 Sintering test

A laboratory sintering cup with a size of Φ180×700 mm was used to simulate the practical sintering process, as shown in Fig. 1. Sinter materials are mixed as shown in Table 3. The composition of sinter material is represented by external distribution. Since the return fines need to be constant, sintering returns and blast furnace returns are used as external distribution materials for the convenience of calculation.

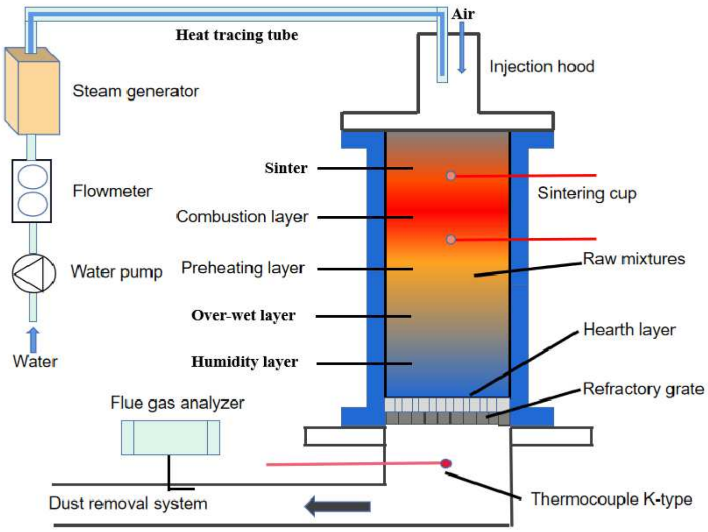

Fig. 1 Schematic diagram of steam injection sintering test research device

Table 3

Composition ratio of sinter material

Components/%	Coke breeze	Mixed iron	Dolomite	Limestone	quick lime	Sinter returns	Blast furnace returns	∑
Value	5.60	77.17	5.71	7.02	4.50	18.00	12.00	130

After manual blending, the raw materials were granulated using a drum of Φ600×1400 mm, with a speed of 15 r/min for 4min. Add 80% of the total water during the mixing process, and the rest was added to the granulating process. Add 1kg hearth and then charging the granulated mixture. Igniting at 5kPa for 1 min (ignition temperature is 1050°C) and sintering at 10kPa. The main evaluation indexes of sintering included sintering speed, productivity, yield and tumbler index.

Sintering speed is the ratio of sintering height to sintering time, as shown in formula (1). (ν: Sintering speed, mm/min; H: The height of the sintering layer without the thickness, mm; t: Sintering time, which means the time interval from ignition to the maximum temperature of the exhaust gas, min.) In this paper, H=680mm.

$$\nu = \frac{H}{t} \tag{1}$$

The productivity is the output index of sinter per unit time and per unit area, as shown in formula (2). (γ: Productivity, t/(m^2h); S_S: Quality of sinter with particle size greater than 5mm, kg; D: Diameter of sintering cup, mm.) In this paper, D=180mm.

$$\gamma = 7.65 \times 10^4 \frac{S_S}{D^2 t} \tag{2}$$

The yield is the proportion of sinter with the size of 5mm or more after screening, as shown in formula (3). (η: Yield, %; S_0: Quality of sinter without hearth, kg.)

$$\eta = \frac{S_S}{S_0} \times 100\% \tag{3}$$

And the tumbler index represents the strength of sinter, as specified by ISO3271(2007), as shown in formula (4). (TI: Tumbler index, %; m_1: The quality of sinter with particle size greater than 6.3mm after drum, kg; m_0: The quality of sinter added to the drum, kg.) In this paper, m_0=7.5kg.

$$TI = \frac{m_1}{m_0} \times 100\% \tag{4}$$

Fig. 1 shows that in the sintering process, the flue gas temperature is tested by a thermocouple installed in the flue gas pipeline and the composition of the flue gas was analyzed by a portable infrared flue gas analyzer (Madur Photon) consisting of two units, a Photon II flue gas analyzer and a PGD-100 flue gas preprocessor.

2.2.2 Steam Injection Method

Moving the injection hood above the sintering cup to spray steam on the sintering surface. The steam was generated by the LEP-800 liquid evaporator of Nanjing Boyun-Pass Instrument Technology Co., LTD., and the amount of water is controlled by the attached BT101L flow intelligent peristaltic pump (driver BT101L, pump head YZ15). To prevent condensation of steam before injection, an electric tracing tube is connected between the outlet and the injection hood. The temperature of tracing tube is set at 150 °C. Two thermocouples are set 100mm and 300mm away from the material surface to detect the temperature change of the material layer after spraying steam.

In this paper, different injection schemes were adopted to explore the influence of injection concentration, injection time and injection interval on sintering index and pollutant emission. According to the industrial application, four groups of different steam injection time schemes were studied (the initial injection time was set as 10min, and the injection concentration was set as 0.6%, which means 1 m^3 of air contains 0.006 m^3 of steam), as shown in Fig. 2.

Although several sintering plants in China have tested steam injection technology in industry, the optimal strategy has not been explored in the technology, and there is still a great possibility of improvement. Bai et al.(2020) studied steam sintering technology at China Anyang Iron and Steel Co., Ltd., and found that compared to early injection, steam injection 7min after ignition had a better sintering index (1min ignition). However, Huang et al.(2019) installed 7 injection pipes (within No. 7-14 bellows) in the industrial test, and the injection time range was 10~20min for sintering, and the sinter yield increased by 2%. As shown in Fig. 2, according to industrial application, 10min after ignition was taken as the starting time of steam injection, and four different injection schemes were set to explore the optimal strategy.

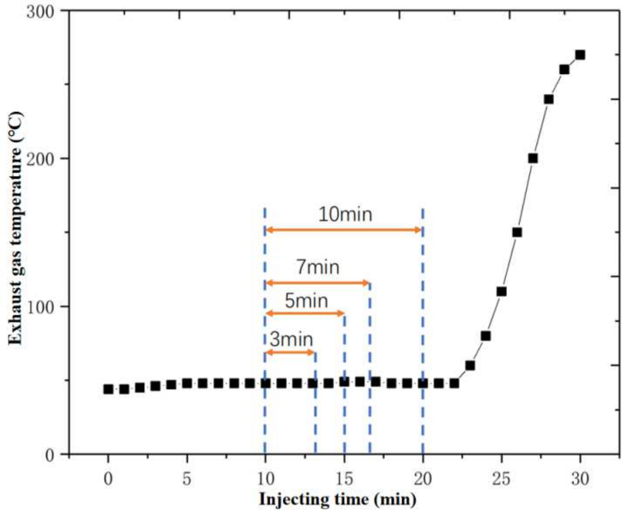

Fig. 2 Steam injecting schemes during sintering process

2.2.3 Calculation Method

In this paper, HSC Chemistry was used to evaluate the possible reactions in the sintering process after the addition of steam, mainly to calculate the Gibbs free energy of each reaction. Based on the sintering time of 10~15min, the sintering temperature can reach more than 800℃, the steam and free radicals are defined as gaseous states.

3 Results and discussion

3.1 Effect of steam injection on sintering performance

3.1.1 Effect parameters on sintering quality

Fig. 3 gives the influence of steam injection time on sintering index, where the steam injection concentration is 0.6%. When the injection time increased from 0 min to 5min, the productivity, tumbler index and yield all showed an increasing trend, from 1.38t/(m^2h), 65.37% and 70.70% to 1.46t/(m^2h),65.64% and 71.67%. Prolonging the injection time further, sintering index showed a decrease. Therefore, the recommended injection time is 5min.

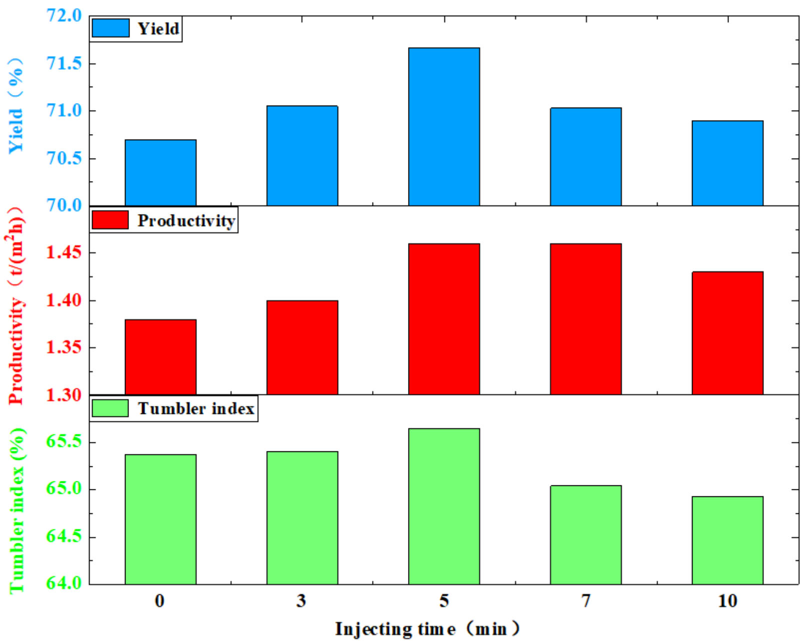

Fig. 3 Influence of injection time on sintering index

Fig. 4 gives the influence of steam injection concentration on sintering index, where the injection time is 5min and the injection interval is 10-15min. When the steam injection concentration increased from 0 to 0.32%, the sintering indexes improved. When increasing the concentration further to 0.47%, sintering indexes were improved slightly, while the tumbler index dropped by 2.17% compared with the base case when increasing the concentration to 0.6%. Therefore, the recommended injection concentration is 0.32~0.47%.

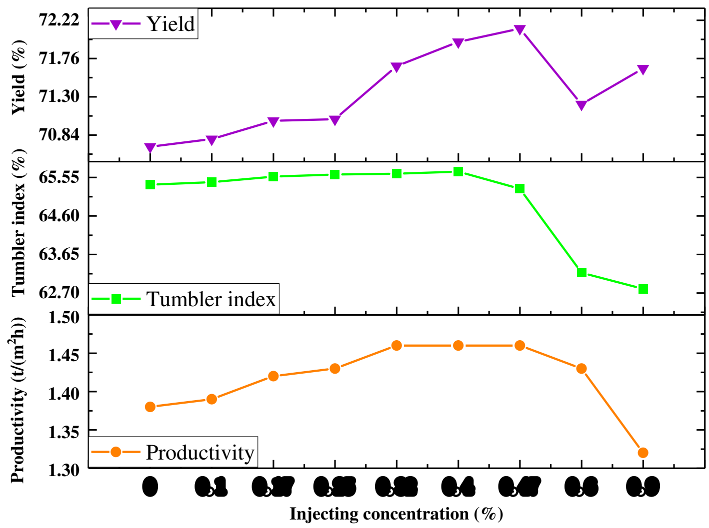

Fig. 4 Influence of injection concentration on sintering index

Fig. 5 gives the influence of steam injection interval on sintering index, where the injection time and concentration were 5min and 0.6%. It can be found that compared with the base case, the optimal injection interval is 10-15min, under which the sintering indexes can be improved to a greater extent. It should be mentioned that when injecting the steam in the earlier stage, such as 5-10min and 8-13min, the sintering index presented a dropping tendency. Therefore, the appropriate steam injection system is 0.32~0.47% of injection concentration, 5 min of injection time, 10~15min of injection interval.

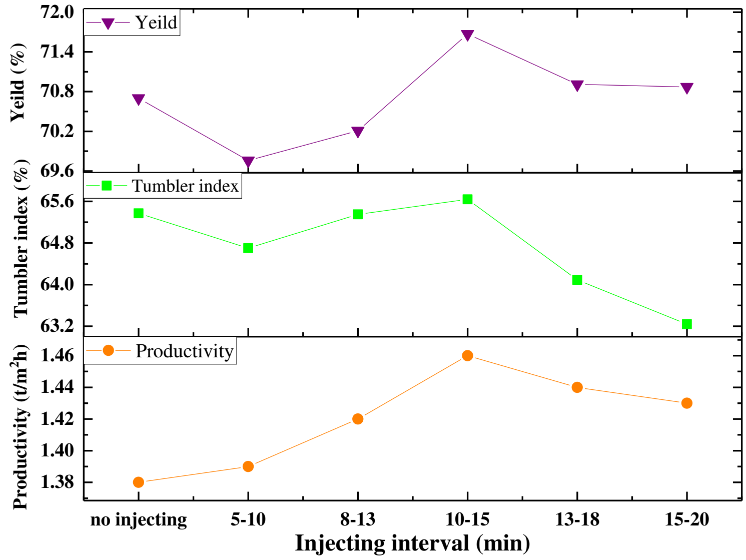

Fig. 5 Influence of injection interval on sintering index

3.1.2 Effect on coke consumption and CO emission

The sintering index obtained under the optimal parameters was better than the base level. Under the recommended injecting conditions, the influence of steam injection on proper coke breeze rate was studied, as shown in Fig. 6. It can be obtained that the coke breeze content can be reduced from 5.6% to 5.45%, without affecting the sintering indexes, and the fuel consumption can be reduced by 2.13 kgce/t-sinter.

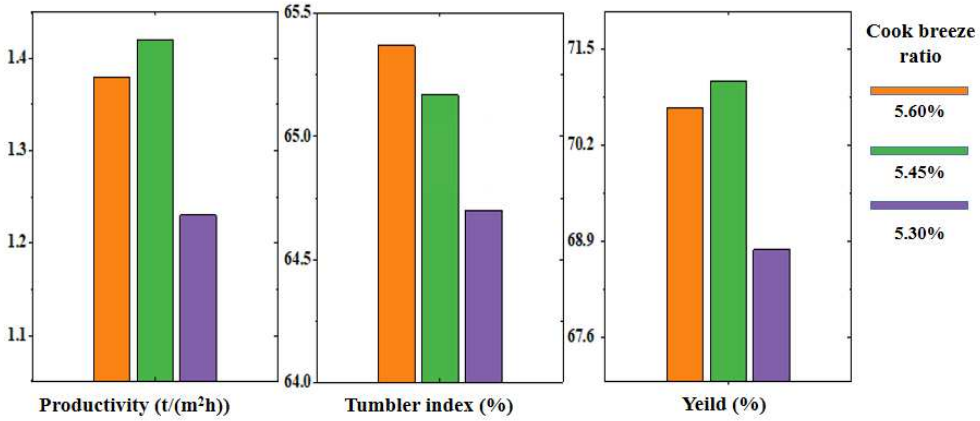

Fig. 6 Influence of steam injection on sintering indexes with different coke breeze contents

Under the recommended steam injection time and intervals, the influence of steam injection concentration on CO emission was studied, and the results were shown in Fig. 7. With the increase of steam concentration, CO emission concentration appeared an obvious decrease. Compared with the base case, when the injecting concentration was 0.40%, the average CO emission concentration in the interval obviously drops from 11690mg/m^3 to 9918mg/m^3, with a decrease of 15.16%. With the further increase of 0.90% of steam concentration, the average CO emission concentration in the interval decreases as high as 3435mg/m^3, with a decreasing proportion of 29.38%. As can be seen from Fig. 7, when the steam concentration increases, the CO emission reduction rate increases gradually slowly, combined with the research data, the CO emission reduction rate obtained between 0.4 and 0.6% steam concentration is effective.

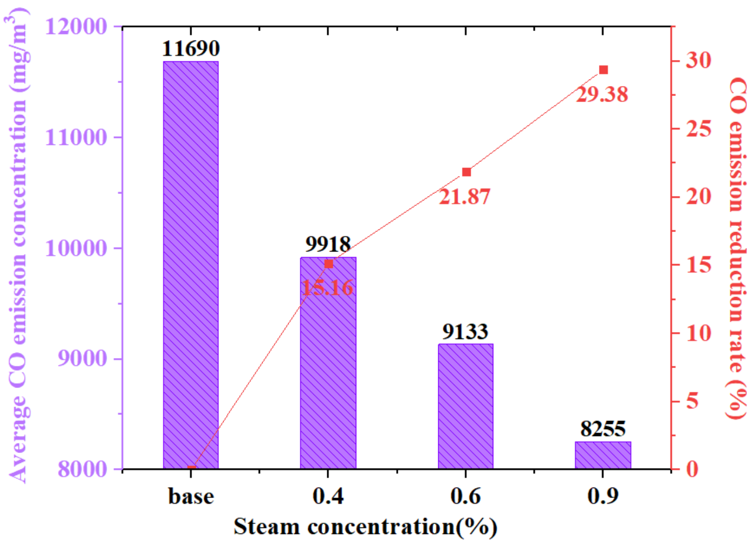

Fig. 7 Effect of injection concentration on CO emission

3.2 Function mechanism of steam injection during sintering process

3.2.1 Influence mechanism on sinter quality

Fig. 3 and Fig. 4 shows with the increase of steam injection concentration and time, the sintering index was improved, the potential reason can be described that the specific heat capacity of steam was larger than the air (Escudero et al.2021), which was conducive to the heat transfer of the sintered layer, the addition of an appropriate amount of steam promoted the combustion of fuel. When the concentration of injection was 0.32~0.47% and the injection time was 5min, the indicators were improved, but when the concentration exceeded 0.6% or the injection time exceeded 5min, it would have adverse effects. Heat transfer occurred when steam passed through the sintered layer and then reached the combustion layer. In addition, the excessive concentration of the injection has a great influence on the combustion temperature of the fuel (Li et al.2020), and the steam also carries a lot of heat when it finally enters the flue gas, increasing the heat loss. Fig. 8 shows the temperature curves of the material layer at 100mm and 300mm after spraying steam (0.40% steam concentration), it shows spraying steam in 5-10 minutes will not only reduce the maximum temperature of the upper sintered bed (58℃ reduced) but also shorten the high temperature retention time (more than 800℃), spraying steam in 10-15 minutes can accelerate the temperature rise and increase the maximum temperature of the middle-sintered bed by 15℃.

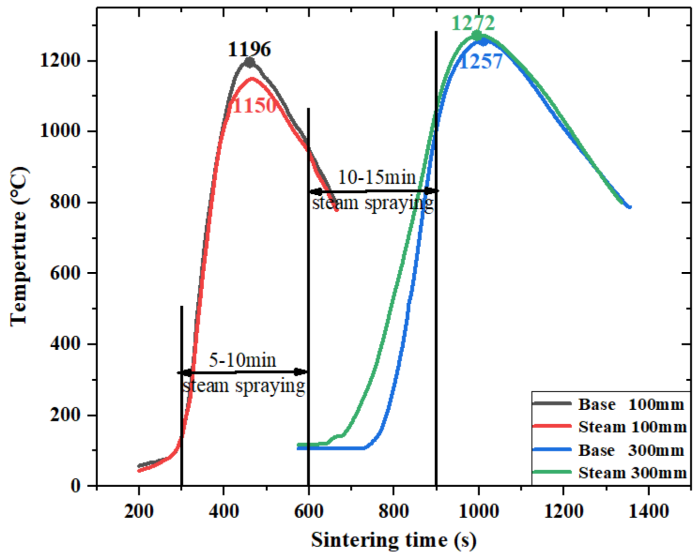

Fig. 8 Influence of spray steam at different time on temperature of sintered bed

Fig. 5 shows during the steam injecting interval of 10-15min, sintering indexes all reached an improvement while injecting steam in the earlier sintering stage worsened the sintering performance. Fig. 9 shows the curve of the flue gas composition (CO, CO_2, O_2, NOx) when steam is injected during the interval of 5-10min. It can be obtained that CO, CO_2 and NOx of the sintering flue gas were all dropped and O_2 content is increased, which indicates that the fuel combustion in the sintered layer deteriorates in 5-10min. At early, the upper layer accumulates less heat, which presented lower highest temperature and duration (Pei et al.2018). Since the temperature of the steam is far lower than the combustion layer, physical heat absorption occurs when steam is close to the combustion layer, and chemical heat absorption occurs after steam reaction ($C+H_2O=CO+H_2$, heat absorption reaction), which causes adverse effects on the sintering of the upper layer, this agrees with the experimental results (As shown in Fig. 8).

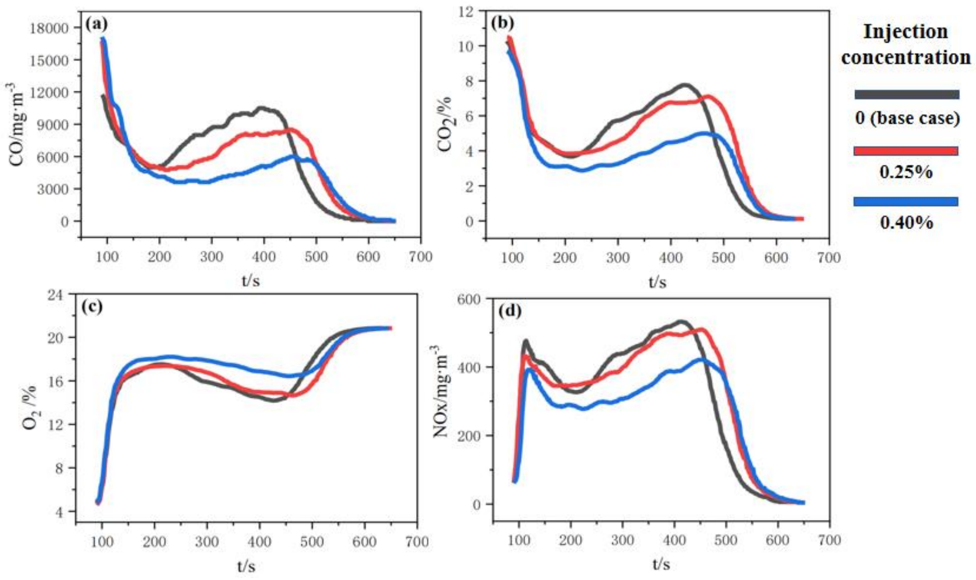

Fig. 9 Emission characteristics curve of sintering flue gas at different injection concentrations

3.2.2 Influence mechanism on CO reduction

For the carbon-oxygen reaction system, a new reaction path occurred after injecting steam, which exerted an influence on the flue gas composition, as shown in Fig. 10. Fig. 10(a) and (b) show the reaction path of the carbon-oxygen system without and with steam injection. It can be seen that after injecting steam, the thermodynamics aspect to reduce CO emissions through $CO + H_2O$ □$CO_2 + H_2$. In the combustion layer, steam reacted with coke breeze to generate hydrogen. In addition, the diffusion coefficient of steam molecule was higher (Wang et al.2013), and the contact area with coke breeze was larger, which promoted the combustion of coke breeze and improved the combustion efficiency of coke breeze through the reaction $C+H_2O \rightarrow CO_2+H_2$.

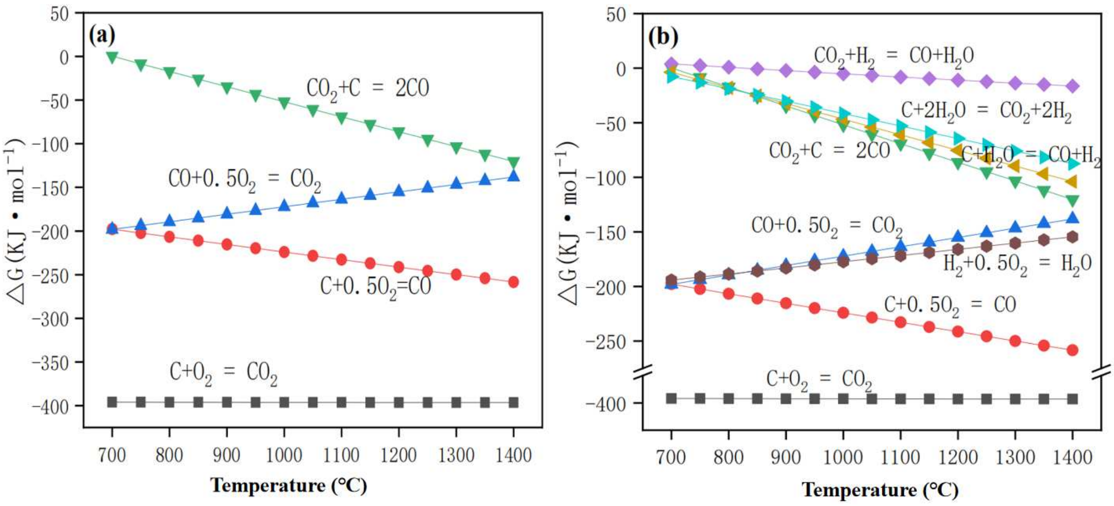

Fig. 10 Changes of reaction pathways after water vapor addition

After injecting steam in the sintering, the combustion reaction formula of coke breeze can be expressed as (Zhang et al.2016):

$$C+(\alpha)O_2 + (\beta)H_2O \rightarrow 2(1-\alpha)CO + (2\alpha-1)CO2 + (\beta)H_2O$$

In the formula, the value of α is between 0.5 and 1, and the burning efficiency of coke breeze is expressed by the ratio of $CO_2/(CO+CO_2)$.

Yukihiro (1980) studied CO_X concentration at different positions on the surface of coke breeze particles during combustion, as shown in Fig. 11. It can be seen that at 900 ºC, the CO concentration on the surface of coke breeze is about 6%, and the CO_2 concentration is about 17%. At this time, the combustion efficiency of coke breeze is 74%, and α is 0.87. When 1mol C is burned, 0.87mol O_2 is required to participate in the reaction.

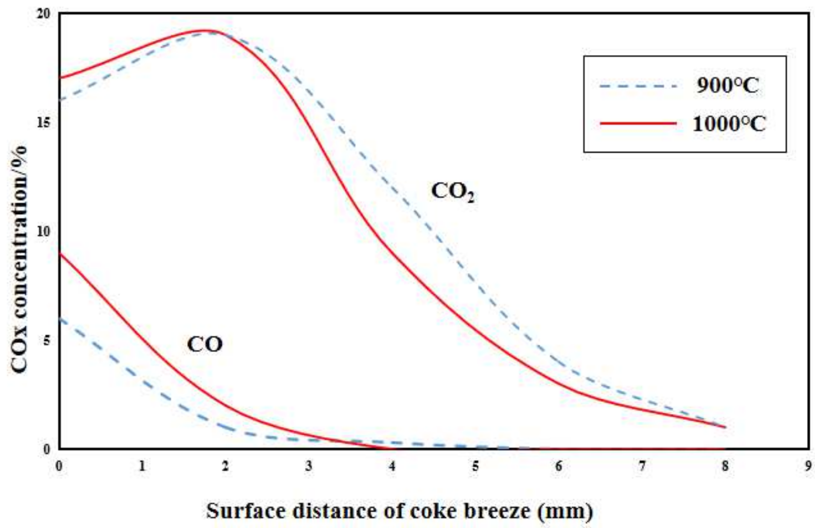

Fig. 11 CO_X concentration at different distances of coke breeze surface(Yukihiro et al.1980)

The mechanism of the above reaction is an exothermic reaction, so temperature has a great influence on this reaction. Under the conditions of 0.87mol of oxygen (74% combustion efficiency) and 0.50% of steam concentration, the effect of temperature on CO emission reduction was investigated, as shown in Fig. 12. Increase the temperature from 700°C to 1400°C, the CO emission decreased from 2514 mg/m^3 to 950 mg/m^3. That is not conducive to the forward reaction, the results and analysis are consistent.

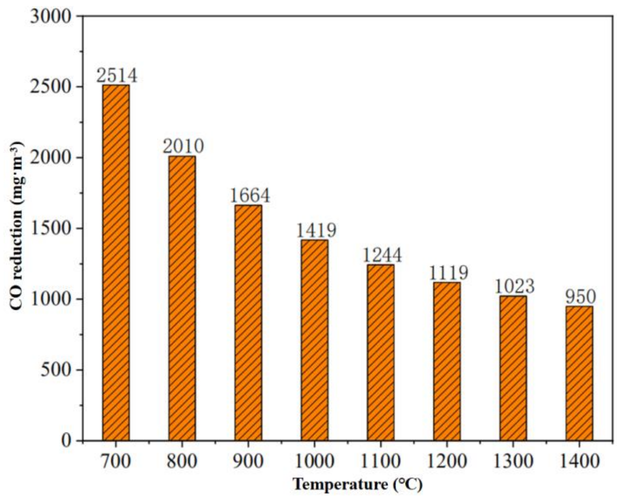

Fig. 12 Effect of temperature on CO emission reduction

However, during sintering process, the temperature is not stable or uniform and can be as high as 1350°C or higher. It can be analyzed that the O_2 content in the sintering flue gas was maintained at 14% and 7% oxygen was consumed in the sintering process, which is only equivalent to the normal concentration of oxygen in 1/3 of the air. Therefore, the maximum CO emission reduction concentration calculated theoretically is 838mg/m^3(at 700°C), which is quite different from the CO emission reduction when the steam injection concentration is 0.40% (Fig. 7 shows 1772mg/m^3). Therefore, it can be speculated that the presence of steam can reduce CO emissions, but the reaction products produced by steam in sintering are the key factor.

According to Fig. 13, in the presence of (OH), CO would react with it to generate (H) and CO_2. However, there are many views on the generation pathway of (OH) and (H). Zhang et al.(2010) believed that high concentration of steam would react with volatiles/tar in gas phase to form (H) radicals. Li et al.(2012) suggested that (H) and (OH) were produced by the decomposition of steam. Through thermodynamic analysis, it is very difficult to decompose steam at high temperature, and the concentration of steam sprayed in sintering is very low, so it is difficult to refer to the above viewpoints. As can be seen from Fig. 13, when the temperature is higher than 674℃, H_2 will be continuously generated, which means that (OH) will also be continuously generated. Compared with the decomposition of steam at high temperature, it is a more reasonable speculation to regard H_2 as the source of (OH).

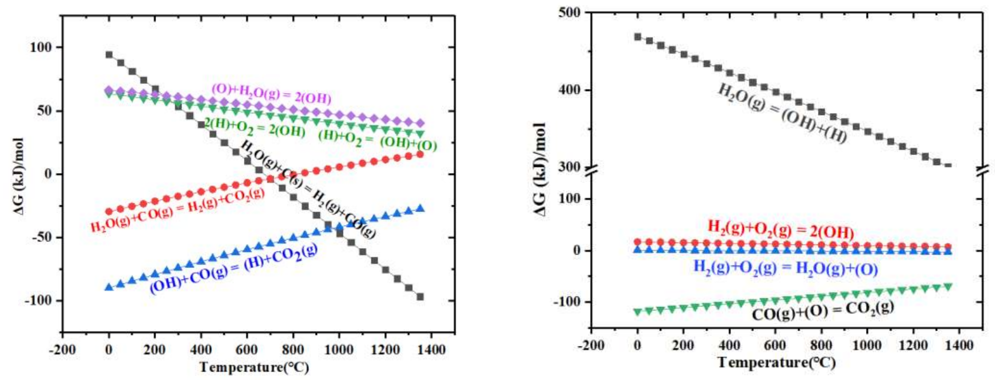

Fig. 13 Thermodynamic analysis of sources of free radicals

In the sintering process, oxygen is sufficient, but due to the limitations of the technological process and the generation of high-temperature melt, oxygen is difficult to reach the surface of coke powder, and there is a local reducing atmosphere around the coke powder. Compared with oxygen, steam diffuses more rapidly in the sinter bed, which can improve the combustion atmosphere of coke powder and at high temperatures, it reacts with C to produce hydrogen, H_2 and O_2 produce not only (OH) but also (O), and both of these free radicals oxidize CO, thereby reducing CO emissions. The reaction formula is as follows:

$$H_2O(g) + C = H_2(g) + CO(g) \text{ (High temperature spontaneous process)}$$

$$H_2(g) + O_2(g) = 2(OH)$$

$$H_2(g) + O_2(g) = H_2O(g) + (O)$$

$$(OH) + CO(g) = (H) + CO_2(g)$$

$$(O) + CO(g) = CO_2(g)$$

From the above analysis, CO production will be inhibited after steam injecting in the sintering process, and CO emission will be affected by two factors. Fig. 14 is the schematic diagram of the reaction mechanism.

1) At high temperature, CO produced by incomplete combustion of coke breeze will react with steam to produce CO_2 and H_2 ($H_2O(g) + CO(g) = H_2(g) + CO_2(g)$), by calculation, this pathway cannot occur spontaneously at temperatures higher than 800℃, so this is not the main way to reduce CO emission.

2) When the temperature is higher than 674℃, steam reacts with coke breeze to form H_2, which reacts with O_2 to form (OH) and (O). These two free radicals will rapidly oxidize CO, which is the key to reduce CO emissions.

3) Both reactions can occur between 674°C and 800°C. Considering that the temperature interval is less than 30 seconds during the sintering heating process, it is considered that the reaction tends to proceed in 2) as the temperature increases.

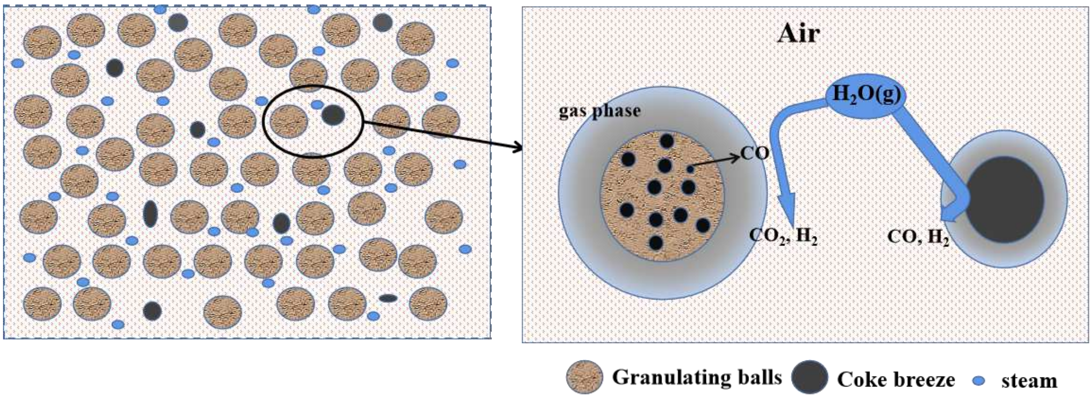

Fig. 14 Mechanism diagram of CO emission reduction by steam

3.3 Further Discussion and Recommendations on Industrialization

During the sintering process, the CO emitted from incomplete combustion of coke breeze can be reduced through steam injection. However, the high temperature region is constantly changing from top to bottom, only by injecting steam in a suitable area can desirable emission reduction effect be achieved.

In industrial production, steam can be preheated by the hot sinter, according to the temperature curve of the sintered layer (Fig. 8), it can be seen that the highest temperature and high temperature retention time of the upper sintered layer are worse than those of the middle and lower layers, so it is not suitable for low-temperature steam injection. It is better to inject steam when the combustion layer reaches the middle of the sintering layer, where the hot sinter layer has the ability to heat the steam to a higher temperature. After steam reaches the high temperature area, it can react with C to generate H_2, and it's going to form (OH) and (O), which releases heat of reaction. Due to the addition of extra heat, the sintering energy consumption and pollutant emissions can be reduced through reduce the ratio of coke breeze.

In industrial application, the influence of steam temperature, the height of the injecting device from the sinter surface and the pressure of injecting should be considered comprehensively. However, this study provided effective production and operation parameter guidance for steam injecting in iron and steel sintering plants.

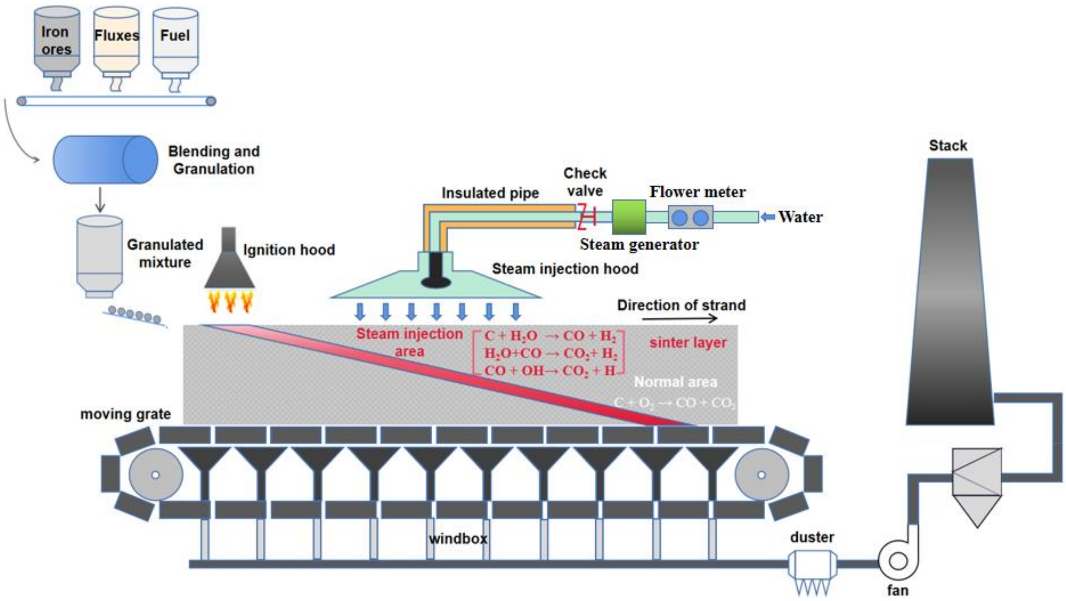

Fig. 15 Schematic diagram of practical application of steam injection in iron and steel sintering plant

Fig. 15 is a schematic diagram of the actual application of steam injection in iron and steel sintering plants. Steam injection device should be installed in the middle of sintering machine, the flowmeter control injection concentration, steam is produced by the industrial recovery wastewater after heating and atomization, water can be heated to 150°C by a heating device or preheating device, the injection device is highly controllable and covers the sintering surface. Industrial reclaimed wastewater mainly includes rolling, steelmaking and coking wastewater, etc.

At present, most iron and steel enterprises have established water circulation systems to treat and recycle the iron and steel industrial wastewater. In addition, the injection device can also be used for gas injection after modification, and better sintering effect can be achieved by exploring an appropriate coupling injection system.

On this basis, the energy consumption of sintering can be reduced by 2.13kgce/$t_{-sinter}$, in the sintering plant in China, the annual production of a 360m^2 sintering machine is approximately 3.2 million tons, and the coal price is $108.2 / ton, the annual economic benefit is estimated at $737491.2, excluding the cost of equipment modification and steam injection of approximately $300,000, the profit increased by $437491.2 in the first year. In short, the method is simple and easy to implement, the steam injection device not only has low cost and low risk but also can bring a profit of $737491.2 per year. It is a technology worth popularizing and applying.

4 Conclusion

(1) The influence of steam injection on sintering indexes is found: during sintering process, increasing the steam injection concentration and prolonging the time will improve the sintering indexes, the recommended value is 0.32~0.47% of injection concentration, 5 min of injection time, 10~15min of injection interval.

(2) The application of steam injection technology reduces the content of coke breeze and fuel consumption. The ratio of coke breeze can be reduced from 5.60% to 5.45%, the average emission concentration of CO was reduced by 1772 mg/m^3, with a decrease of 15.16%, the emission of CO_2, NO_x can be reduced when all the indexes of sinter are guaranteed.

(3) When $T<800$°C, steam will react with CO to generate H_2 and CO_2, when $T>674$°C, steam tends to react with coke to generate H_2, and then generate (OH) and (O) radicals, which can rapidly oxidize CO at high temperature.

(4) With the application of steam injection technology, excluding the equipment modification and steam injection cost of $300,000, the profit can be increased in the first year by reducing solid fuel consumption by 2.13kgce/$t_{\text{-sinter}}$, and the annual profit is $737491.2.

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

Chen Xuling is in charge of project management. Fan Xiaohui proposed conceptualization. Gan Min and Zhou Haoyu are in charge of project supervision. Ji zhiyun mainly provides methodology, funding acquisition, writing review and editing.Li Haorui and Lai Ruisi investigated samples from the project.. Wu Yufeng is mainly responsible for verification, formal analysis and writing-preliminary draft preparation. Zhao Yuanjie is responsible for data management. Zhang Rongchang controls resources. All authors read and approved the final manuscript.

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