Influence Factors on PM$_{2.5}$ and PM$_{10}$ Emissions in Iron Ore Sintering Process

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Influences of factors on PM$_{10/2.5}$ (particulate matters less than 10/2.5 μm in aerodynamic) emission in iron ore sintering process have been investigated using a lab-scale sinter pot. Research findings show that increasing moisture content contributes to decreasing the emission concentration of PM$_{10/2.5}$ due to the stronger scrubbing effect of over-wetted layer; increasing coke breeze rate would increase the generation of PM$_{10/2.5}$ since more trace elements are volatilized and conversed into particle phase. Prolonging granulation time can improve the mechanical strength of granules and also restrain the removal of volatile trace elements to particulate matter, which enables to reduce PM$_{10/2.5}$ emissions. The utilization of recycling materials remarkably enhances PM$_{10/2.5}$ emissions for more fine particles (<10/2.5 μm) are brought in and more volatile trace elements are entrained into particulate matters. Taking sintering indexes into consideration, applying recycling materials wisely or adding solid sorbents serve as more prospective approaches than merely regulating process parameters. This information is able to guide the development of in-bed controlling techniques for reducing PM$_{10/2.5}$ emissions.

KEY WORDS: iron ore sintering; influencing factors; PM$_{10/2.5}$ emission and controlling.

1. Introduction

PM$_{10/2.5}$ (particulate matters less than 10/2.5 μm in aerodynamic) have become one of the main atmospheric pollutants. Due to its typical small size, PM$_{2.5}$ has been regarded as the inhalable particles, while PM$_{2.5}$ can even go directly to the alveoli of the lungs. Since their huge specific surface area, PM$_{10/2.5}$ easily become the carrier of diverse toxic chemicals like heavy metals, metalloids, PAHs, PCDD/Fs, etc., which are adverse to the healthy life of human beings.

Iron & Steel industry is an important emitter of atmospheric particulate matters. In the whole steelmaking line, sintering process is the main emitter of atmospheric pollutants including gaseous COx, SOx, NOx, etc., and particulate matters. Previous research showed that particulate matters emitted from sintering process account for about 45% of the total amount of the whole steelmaking process. Besides, PM$_{10}$ and PM$_{2.5}$ can account for more than 80% of the escaped particulate matters after electrostatic precipitators. Therefore, reducing the emission concentration of PM$_{10/2.5}$ in iron ore sintering is of great significance in integrated steelworks. Indeed, current research pointed out that using moving electrodes, high-quality filter bag, hybrid particulate collector like electro-bag compound duster, etc. are prospective approaches to realize efficient removal rate of PM$_{10/2.5}$. However, these end-of-pipe approaches need to add extra investment for equipment modification and operation. In-bed controlling techniques like regulating operation parameters or material structures seem to be of greater competitiveness.

Previous research upon the factors influencing particulate matter emission mainly focused on how they affected the emission of total dust or coarser-grained particulate matters (>10 μm). Unfortunately, there is no report mentioned about how process parameters and raw materials influence the emission of PM$_{10/2.5}$. The finding results in our previous research have revealed the emission rules of PM$_{10/2.5}$, and its chemical composition during the whole sintering process, and this research was carried out to understand the factors influencing the emission of PM$_{10/2.5}$, with the purpose of guiding the development of in-bed controlling techniques. Four factors including moisture content, coke breeze rate, granulation time and recycling materials were studied.

2. Materials and Methods

2.1. Properties of Raw Materials

The chemical compositions and percentages of mixed iron ores, fluxes (limestone, dolomite and quicklime), coke breeze, return fines, which are the dispensable raw materials for producing sinter with TFe of 56.24%, SiO$_2$ of 4.98%, MgO of 2.03% and basicity of 1.72, are given in Table.
Table 1. Chemical compositions of raw materials and their percentages (mass%).

| Ore types         | Mixed iron ores | Limestone | Dolomite | Quicklime | Coke breeze | Return fines |
|-------------------|-----------------|-----------|----------|-----------|-------------|--------------|
| aTFe              | 58.88           | 0.60      | 0.40     | 0.20      | 2.32        | 56.24        |
| SiO₂              | 4.57            | 0.83      | 0.70     | 3.90      | 6.20        | 4.98         |
| CaO               | 0.95            | 53.90     | 34.29    | 79.62     | 0.91        | 8.60         |
| MgO               | 0.55            | 1.57      | 18.80    | 1.28      | 0.20        | 2.03         |
| Al₂O₃             | 2.14            | 0.52      | 0.34     | 0.99      | 4.34        | 2.38         |
| S                 | 0.059           | 0.013     | 0.000    | 0.051     | 0.960       | 0.100        |
| P                 | 0.020           | 0.003     | 0.004    | 0.003     | 0.001       | 0.017        |
| TiO₂              | 0.094           | 0.005     | 0.000    | 0.011     | 0.200       | 0.088        |
| K₂O               | 0.075           | 0.062     | 0.024    | 0.010     | 0.144       | 0.061        |
| Na₂O              | 0.039           | 0.008     | 0.023    | 0.012     | 0.138       | 0.033        |
| Pb                 | 0.012           | 0.000     | 0.000    | 0.000     | 0.001       | 0.008        |
| Zn                 | 0.035           | 0.004     | 0.002    | 0.002     | 0.004       | 0.024        |
| bLOI              | 5.98            | 42.73     | 45.85    | 14.18     | 83.20       | 0.00         |
| Percentage/%      | 63.63           | 3.22      | 5.28     | 3.87      | 4.00        | 20.00        |

1. TFe: Total iron content; bLOI: loss on ignition at 950°C in air

1. Mixed iron ores are Fe-rich materials, while fluxes are Ca-rich and Mg-rich for dolomite, and only Ca-rich for limestone and quicklime. Coke breeze is the common solid fuel during sinter making, the main part of which is fixed carbon due to the higher LOI. Fe and Ca comprise the main components of return fines. Apart from their main components, trace elements like S, P, Ti, K, Na, Pb, etc. are widely distributed in these raw materials.

Table 2. Comparison between typical common iron ores and recycling materials in chemical compositions (mass%).

| Ore types         | TFe  | SiO₂ | CaO   | MgO | Al₂O₃ | K₂O | Na₂O | Pb | Zn |
|-------------------|------|------|-------|-----|-------|-----|------|----|----|
| Iron ore-1        | 55.89| 4.95 | 0.20  | 0.15| 2.83  | 0.134| 0.009| 0.006|    |
| Iron ore-2        | 59.74| 7.78 | 0.09  | 0.07| 1.66  | 0.012| 0.003| 0.005|    |
| Recycling materials | 43.57| 10.10| 6.64  | 0.78| 1.88  | 2.678| 1.238| 0.174| 1.830|

Table 3. Chemical compositions and grain size of kaolin.

| Chemical composition (mass%) | Average grain size (µm) |
|------------------------------|-------------------------|
| Al₂O₃ | SiO₂ | CaO | MgO | FeO₃ | K₂O | Na₂O | TiO₂ | 43.42 | 52.45 | 0.06 | 0.38 | 0.21 | 0.34 | 0.51 | 0.21 | 6.03 |

1.2. Experimental Methods

A lab-scale sinter pot of depth 700 mm and diameter 180 mm was applied to simulate industrial-scale sinter-making process, which was schematically described in Fig. 1. During the process, raw materials given in Table 1 were well-mixed according to their proportions, with prescribed proportion of water added. The mixture was then charged into a drum for granulating fine-grained materials into granules. After that, the granules were fed into the sinter pot. After feeding, the solid fuel in the surface layer was initially ignited by a natural-gas-fuelled ignition hood, and the combustion front moved downward with the support of a downdraught system. The whole sintering process started from the ignition point to the burning through point at which the flue gas had reached its maximum temperature that recorded by a K-type thermocouple. For each individual sampling case, a low-pressure cascade impactor (Model WY-1, China) was used to collect particulate matter from flue gas, as shown in Fig. 1.

The particulate matter (PM) samples were collected by Whatman QMA Quartz fiber filters with the help of the low-pressure cascade impactor, which was able to segregate PM into 0.7–1.4 µm, 1.4–2.5 µm, 2.5–3.6 µm, 3.6–5.0 µm, 5.0–6.9 µm, and 6.9–10 µm according to their aerodynamic diameter. The accumulation of PM within size range 0.7–2.5 µm, 0.7–10 µm were selected to reflect the properties of PM_{2.5} and PM_{10} respectively. For guaranteeing the effectiveness of PM samples, isokinetic sampling is the prerequisite. To achieve this goal, the real-time linear velocity of flue gas is calculated on the basis of real-time flue gas flow and the dimension of the flue. This information serves as the guidance to adjust the linear velocity of sampling,
thereby making linear velocity of gas flue and sampling equal. After sampling, the mass concentration of PM with different diameters was calculated in Eq. (1). After that, the upper part of particles with size range 0.7–2.5 μm was removed from the filter using a scalpel for further analysis. As the sampled particulate matters were practically difficult to be completely removed from the filter, the following elemental analysis of PM2.5 must be considered as tendency.

\[ C_p = \frac{m_t - m_0}{Q_t} \]  \text{(1)}

Where \( C_p \) is the mass concentration of PM, mg/m³; \( m_t \) is the mass of fiber filter after sampling, mg; \( m_0 \) is the mass of fiber filter before sampling, mg; \( Q_t \) is total volume of flue gas during the whole sampling process, m³.

The elemental composition of PM2.5 was analyzed by energy dispersive XRF (X-Ray Fluorescence: EAGLE III, America). Additionally, the concentrations of trace elements like K, Na, Pb, Sn etc. in raw mixtures and sinter was examined by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES Optima 30, Jobin Yvon, France). Detailed analytical steps could be described as ground samples with size range of −0.074 μm were dissolved by acid digestion with aqua regia added to fluorhydric acid (4 mL HCl, 4 mL HNO₃ and 2 mL HF). After that, solutions were heated at 120°C for 9 h, and then made up to 25 mL with 2 mL boric acid and 13 mL pure water. Finally, ICP-AES was used to analyze targeted trace elements. Equation (2) was used to calculate the removal rate of trace elements.

\[ \eta = \left( 1 - \frac{c_{m_s}}{c_{m_r}} \right) \times 100\% \]  \text{(2)}

Where \( \eta \) is the removal rates of K, Na, Pb etc., mass%; \( c_s \) and \( c_r \) are the concentration of K, Na, Pb etc. in sinter and raw mixtures respectively, mg/kg; \( m_s \) and \( m_r \) are the total mass of sinter and raw mixture for each case, kg.

In this investigation, the influences of four variable factors including moisture content, coke breeze, granulation time and recycling materials on PM10/2.5 emissions were studied, and their levels were given in Table 4. When researching the influences of recycling materials, the proportion of iron ore-1 and iron ore-2 that shown in Table 2 were changed to reach the targeted proportion of recycling materials.

3. Results and Discussion

3.1. Influences of Operation Parameters on PM10/2.5 Emissions

3.1.1. Influences of Moisture Content

Influences of moisture content on emission property of PM10/2.5 are investigated under the condition of coke breeze rate 4.0%, granulation time 4.5 min, with no recycling materials added. Results are presented in Fig. 2, where can be found that increasing moisture content shows the tendency to reduce the emission of PM10/2.5. As clearly observed from Fig. 2(a), when increasing moisture content from 7.0% to 7.5%, particulate matters with different diameters all achieve a decrease, and increasing the moisture content further to 8.0–8.5% contributes to reducing their emissions to a greater extent. More direct information can be found in Fig. 2(b), from which it can be seen that increasing the moisture content from 7.0% to 8.5%, the emission concentration of PM10, PM2.5 are reduced from 75.7 mg/m³, 45.5 mg/m³ to 19.6 mg/m³, 9.3 mg/m³ respectively.

Over-wetted layer serving as a wet scrubber for the flowing gases and then remove particulates was the widely accepted mechanism for the effects of moisture content. For further understanding this mechanism, the influence of moisture content on the properties of over-wetted layer was studied. The method to achieve the changes of moisture content in sinter bed can be described as a sudden stop was conducted during the middle sintering process, and liquid nitrogen was added through the top of sinter pot to cool the whole sinter bed immediately. After that the mixture under

| Factors                          | Levels |
|----------------------------------|--------|
| Moisture content (mass%)         | 7.0    |
|                                  | 7.5    |
|                                  | 8.0    |
|                                  | 8.5    |
| Coke breeze rate (mass%)         | 3.76   |
|                                  | 4.0    |
|                                  | 4.24   |
| Granulation time (min)           | 2.5    |
|                                  | 4.5    |
|                                  | 6.5    |
| Recycling materials (mass%)      | 0      |
|                                  | 5      |
|                                  | 10     |

| Table 4. Variable factors and their levels for pot test. |
|---------------------------------------------------------|
| Factors | Levels |
|---------|--------|
| Moisture content (mass%) | 7.0 | 7.5 | 8.0 | 8.5 |
| Coke breeze rate (mass%) | 3.76 | 4.0 | 4.24 | / |
| Granulation time (min) | 2.5 | 4.5 | 6.5 | / |
| Recycling materials (mass%) | 0 | 5 | 10 | / |
the sinter layer was divided into several parts with an interval about 50 mm to test the moisture content, and relative results are given in Fig. 3. As can be found that increasing the moisture content in raw mixture would enlarge the over-wetted area, which stands for the area where the moisture content in sinter bed is higher than the base level. Larger over-wetted area means stronger scrubbing effect of over-wetted layer. When PM_{10/2.5}-bearing flue gas flows through the over-wetted layer, larger over-wetted area is able to capture more particles on the wet surface of granules or condensed water droplets.

3.1.2. Influences of Coke Breeze Rate

Influences of coke breeze rate on the emission property of PM_{10/2.5} are studied under the condition of moisture content 7.5%, granulation time 4.5 min, with no recycling materials added, and the results are given in Fig. 4. As shown in Fig. 4(a), increasing coke breeze rate tends to increase the emission concentration of particulate matters with different diameters. The emission concentration of PM_{10}, PM_{2.5} can be increased from 11.0 mg/m^3, 25.3 mg/m^3 to 31.3 mg/m^3, 60.9 mg/m^3 respectively when improving the coke breeze rate from 3.76% to 4.24% (Fig. 4(b)). The effects of coke breeze rate on PM_{10/2.5} also show similar property to the reports on total dust and coarser particles.\textsuperscript{14,15} The rate of coke breeze has a direct impact on the temperature and atmosphere during the sintering process, and Fig. 5 gives the temperature of sinter bed 200 mm below the top of the sinter pot. As can be clearly found that the temperature of sinter bed reaches an increasing rise with the coke breeze rate increased from 3.76% to 4.24%, and the highest temperature in sinter bed is increased from 1 222°C to 1 317°C. Increasing bed temperature has the function to increase the volatile of trace elements like K, Na, Pb, Sn etc. The volatile of these components can form the precursors of PM_{10/2.5} as have found by Bool and Yao.\textsuperscript{17,18} The removal rates of K, Na, Pb, and Sn with the increase of coke breeze rate during sintering process are given in Fig. 6. Obviously, increasing coke breeze rate from 3.76% to 4.24% would enhance

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**Fig. 2.** Influences of moisture content on emission property of PM_{10/2.5}. (a) Influences on emission concentration of particulates with different diameters; (b) Influences on total emission concentration of particulates.

**Fig. 3.** Influences of moisture content on over-wetted area.

**Fig. 4.** Influences of Coke breeze rate on emission property of PM_{10/2.5}. (a) Influences on emission concentration of particulates with different diameters; (b) Influences on total emission concentration of particulates.

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**Fig. 5.** Temperature of sinter bed 200 mm below the top of the sinter pot.
the removal rates of K, Na, Pb and Sn simultaneously. For further confirm this results, the influences of coke breeze rates on chemical compositions of PM$_2.5$ are given in Table 5. When increasing coke breeze rate from 3.76% to 4.00%, the contents of K, Na, Pb, and Sn reach an increase, and the contents of which reach a further increase with improving coke breeze rate to 4.24%. This phenomenon agrees with the improved removal rates of K, Na, Pb and Sn, which also serves as a better explanation to the effects of increasing coke breeze rates.

3.1.3. Influences of Granulation Time

The influences of granulation time on emissions of PM$_{10/2.5}$ are investigated with keeping moisture content at 7.5%, coke breeze rate at 4.0% and no recycling materials added. As can be found in Fig. 7(a), with prolonging granulation time, the mass concentration of particulate matters with different diameters achieves a drop. Figure 7(b) demonstrates that increasing granulation time from 2.5 min to 6.5 min contributes to decreasing the emission concentration of PM$_{10}$, PM$_{2.5}$ from 65.8 mg/m$^3$, 39.4 mg/m$^3$ to 23.6 mg/m$^3$, 12.6 mg/m$^3$ respectively. It is well-known that granules comprise adhesive fines (raw materials $<$0.5 mm) and nuclear particles (raw materials $>$0.5 mm). Prolonging granulation time helps to improve the mechanical strength of granules, which therefore makes adhesive fines tightly adhered and not easy to drop from the surface during the sintering process. This effect of granulation time was also proposed by Ball, while the focus of which mainly aimed to the formation of total dust. Additionally, prolonging granulation time also has an influence to the removal of volatile trace elements to flue gas, which is the precursors of PM$_{10/2.5}$ as have been stated above. Tight linkage between fines particles not only restrict their drop, but makes the mass transfer of K, Na, Pb, Sn, etc. to flue gas.

Table 5. Influences of coke breeze rate on chemical composition of PM$_{2.5}$.

| Elements | Coke breeze rate (mass%) |
|----------|--------------------------|
|          | 3.76 | 4.00 | 4.24 |
| O        | 18.03 | 12.18 | 10.45 |
| Fe       | 14.73 | 9.30  | 5.04  |
| Ca       | 3.33  | 1.83  | 0.48  |
| Al       | 2.22  | 1.00  | 1.14  |
| Si       | 2.47  | 1.26  | 1.44  |
| K        | 21.69 | 25.84 | 27.99 |
| Na       | 3.04  | 3.70  | 1.89  |
| Pb       | 6.75  | 9.32  | 13.01 |
| Sn       | 0.38  | 3.77  | 6.34  |
| S        | 3.04  | 2.31  | 2.07  |
| Cl       | 23.91 | 29.50 | 30.06 |

Fig. 5. Influences of coke breeze rate on the temperature of sinter bed.

Fig. 6. Influences of coke breeze rate on removal rates of K, Na, Pb and Sn.

Fig. 7. Influences of Granulation time on emission property of PM$_{10/2.5}$. (a) Influences on emission concentration of particulates with different diameters; (b) Influences on total emission concentration of particulates.
the comprehensive effect of which may serve as the explanation of the reduced emission concentration of PM$_{10/2.5}$ when prolonging granulation time.

### 3.2. Influences of Recycling Materials on PM$_{10/2.5}$ Emissions

The influences of utilizing recycling materials on PM$_{10/2.5}$ emissions have been studied under the condition of moisture content 7.5%, coke breeze rate 3.76%, and granulation time 4.5 min, the results of which are given in Fig. 8. As can be clearly seen from Fig. 8(a), the application of recycling materials can significantly increase the mass concentration of the part of particles less than 2.5 µm in diameter. Especially when adding 5% recycling materials, the emission concentration of particles with diameter of 1.4 µm is increased from 18.0 mg/m$^3$ to 86.8 mg/m$^3$. Figure 8(b) shows more obvious results, when adding recycling materials to 5–10%, the emission concentration of PM$_{10}$ and PM$_{2.5}$ all obtained remarkable rise. When improving the proportion of recycling materials from base case to 10%, the emission concentration of PM$_{10}$ and PM$_{2.5}$ reaches an enhancement from 54.5 mg/m$^3$, 24.5 mg/m$^3$ to 168.1 mg/m$^3$, 134.3 mg/m$^3$ respectively.

Obviously, adding recycling materials plays an important role in the formation of PM$_{10/2.5}$, especially the PM$_{2.5}$. For revealing the potential mechanism of how recycling materials increases the emission concentration of PM$_{10/2.5}$, the size distribution of recycling materials is examined, which is shown in Fig. 9. It is not hard to observe that recycling materials contain a part of fines less than 10 µm, and even less than 2.5 µm, the volume percentage of which is 16.33%, 5.30% respectively. Taking the structure of granules into consideration, this part of fine particles distributes on the surface of granules, which therefore has the potential to escape from granules to flue gas.

Apart from that, another more important source of increased PM$_{10/2.5}$ is the conversion of trace elements from recycling materials. As have been introduced in section 2.1, the contents of K, Na, Pb and Zn is much higher than them in common iron ores (Table 2). Table 6 gives the influences of applying recycling materials on chemical compositions of raw mixtures, where can be seen that the contents of K, Na, Pb and Zn are increased with the proportion of recycling materials rising. According to the reports in coal combustion field, the particles formed from the volatile-condensation process of K, Na, Pb, etc. typically have a diameter less 2.5 µm and even 1 µm. Therefore, increased volatile elements have a considerable influences on the emission of PM$_{2.5}$, while exert marginally influences on the formation of particle between 2.5 µm and 10 µm. This is the reason for the slight changes of particles between 2.7 µm and 10 µm. For further verifying that more volatile elements enter into the fine particles, the chemical composition of PM$_{2.5}$ are examined, and the results are given in Table 7. As can be observed that, for the base case where no recycling materials

![Fig. 8](image-url) **Fig. 8.** Influences of adding recycling materials on emission property of PM$_{10/2.5}$. (a) Influences on emission concentration of particulates with different diameters; (b) Influences on total emission concentration of particulates.

![Fig. 9](image-url) **Fig. 9.** Size distribution of recycling materials.

### Table 6. Influences of recycling materials on chemical compositions of raw mixtures (dry base).

| Schemes            | Chemical compositions (mass%) |
|--------------------|--------------------------------|
|                    | TFe  | SiO$_2$ | CaO  | MgO  | Al$_2$O$_3$ | S    | P    | TiO$_2$ | K$_2$O | Na$_2$O | Pb    | Zn    | LOI  |
| Base case          | 48.82 | 4.33    | 7.46 | 1.76 | 2.06        | 0.100| 0.017| 0.088   | 0.076  | 0.041   | 0.010 | 0.029 | 13.20 |
| 5% recycling materials | 48.38 | 4.32    | 7.46 | 1.75 | 2.11        | 0.121| 0.019| 0.096   | 0.140  | 0.056   | 0.018 | 0.105 | 13.64 |
| 10% recycling materials | 47.94 | 4.32    | 7.46 | 1.74 | 2.16        | 0.143| 0.020| 0.105   | 0.205  | 0.071   | 0.024 | 0.182 | 14.08 |
is added, PM$_{2.5}$ contains higher part of non-volatile elements like Fe, Ca, Al, Si, etc., and the contents of K, Na, and Pb account for 25.84%, 3.70%, and 9.32% respectively. After adding 5% recycling materials, the mass percentages of Fe, Ca, Al, and Si drop remarkably, while the content of K achieves a considerable increase to 38.21% with the content of Cl increased from 29.50% to 41.29% as well. Additionally, the effect for the case of using 10% recycling materials is the same. Also, it can find that the content of Na in PM$_{2.5}$ is decreased. Since the contents of K reaches a considerable increase due to its higher removal ratio than Na, the dilution effect of K probably serves as the potential explanation for this phenomenon. However, compared with base case, it is easy to find that the total amount of Na in PM$_{2.5}$ is increased if taking the mass concentration of PM$_{2.5}$ and the content of Na in PM$_{2.5}$ into consideration comprehensively. Therefore, though the content of Na is decreased, its emission amount still gets a rise with recycling material added.

### 3.3. Further Discussion and PM$_{10/2.5}$ Controlling Suggestions

According to the finding results stated above, improving moisture content, keeping lower coke breeze rate, and prolonging granulation time contribute to controlling the emission concentration of PM$_{10/2.5}$ at a relatively low level. However, achieving optimum sinter quality and quantity is the prerequisite of adjusting process parameters. The influences of moisture content, coke breeze rate and granulation time on sintering indexes are studied, and the results are shown in Table 8. Taking sintering speed, yield, tumbler index and productivity into consideration comprehensively, the optimum moisture content, coke breeze rate and granulation time are 7.50%, 4.00% and 4.5 min respectively, where optimum sinter quality and quantity can be achieved. However, optimum levels of process parameters can guarantee desirable sintering indexes, while it is hard to keep the emission concentration of PM$_{10/2.5}$ at the lowest level as analyzed above. Consequently, there exists obvious limitation to realize the efficient control of PM$_{10/2.5}$ through adjusting the levels of process parameters. Using recycling materials is the widely applied strategy for most of the iron & steel corporations for realizing lower production cost.$^{24,25}$ Taking the significant influences of recycling materials into account, using recycling materials reasonably into sintering is an important question for the sake of both low-cost production and environmental protection. Removing volatile components like K, Na, Pb, etc. in advance or restraining the conversion of volatile matters into flue gas may be a feasible approach.

During coal combustion process, kaolin was widely regarded as an efficient solid sorbent to control PM$_{10/2.5}$ emissions.$^{26,27}$ On the basis of this information, the influences of adding kaolin on emission property of PM$_{10/2.5}$. (a) Influences on emission concentration of particulates with different diameters; (b) Influences on total emission concentration of particulates.

### Table 7. Influences of recycling materials on chemical composition of PM$_{2.5}$.

| Elements | Proportion of recycling materials (mass%) |
|----------|-----------------------------------------|
|          | 0  | 5  | 10 |
| O        | 12.18 | 4.11 | 2.24 |
| Fe       | 9.30 | 0.34 | 0.23 |
| Ca       | 1.83 | 0.10 | 0.06 |
| Al       | 1.00 | 0.32 | 0.39 |
| Si       | 1.26 | 0.41 | 0.49 |
| K        | 25.84 | 38.21 | 37.21 |
| Na       | 3.70 | 1.49 | 1.13 |
| Pb       | 9.32 | 9.20 | 10.77 |
| S        | 2.31 | 1.80 | 1.68 |
| Cl       | 29.50 | 41.29 | 44.83 |

### Table 8. Influences of process parameters on sintering indexes.

| Parameters | Levels | Sintering speed (mm·min$^{-1}$) | Yield (mass%) | Tumbler index (mass%) | Productivity (t·m$^{-2}$·h$^{-1}$) |
|------------|--------|---------------------------------|---------------|-----------------------|-----------------------------------|
| Moisture content (mass%) | 7.00 | 22.80 | 69.89 | 65.07 | 1.35 |
| Coke breeze rate (mass%) | 7.50 | 25.50 | 72.53 | 65.60 | 1.60 |
| Granulation time (min) | 8.00 | 25.98 | 71.54 | 64.80 | 1.56 |
|             | 8.50 | 24.08 | 71.08 | 64.33 | 1.41 |
|             | 3.76 | 25.50 | 68.10 | 64.80 | 1.48 |
|             | 4.00 | 25.50 | 72.53 | 65.60 | 1.60 |
|             | 4.24 | 25.34 | 74.81 | 62.67 | 1.58 |
|             | 2.5  | 25.19 | 71.23 | 65.33 | 1.48 |
|             | 4.5  | 25.50 | 72.53 | 65.60 | 1.60 |
|             | 6.5  | 25.19 | 71.03 | 64.00 | 1.46 |
ences of adding kaolin on the emission concentration of particulate matters for the case of adding 10% recycled materials were investigated. The dosage of kaolin is calculated based on the mass of recycled materials. From Fig. 10(a) it could find that adding kaolin was effective to reduce the mass concentration of the particle matters with different diameters, especially for the particles with diameter less than 2.5 μm. As was observed in Fig. 10(b), adding 1% kaolin was able to reduce the mass concentration of PM10 and PM2.5 from 168.1 mg/m3, 134.2 mg/m3 to 66.0 mg/m3, 43.5 mg/m3 respectively. The influences of kaolin on PM10/2.5 emission reduction were widely known as kaolin characterized porous structure, which contributed to adsorbing the vapors or submicron particles and therefore reduced the generation of PM10/2.5 from the head.26,27 However, adding 2% kaolin would increase the emission of PM10 and PM2.5 compared with the case only adding 1%. This phenomenon was possibly resulted from the entrance of the fine kaolin particles into flue gas. However, more work will be done in the future to deeply elucidate the functional mechanism of kaolin in reducing PM10/2.5 during sintering process, and more efficient controlling measures will be exploited.

4. Conclusions

The effects of four factors including moisture content, coke breeze rate, granulation time, and recycling materials on PM10/2.5 emissions have been investigated, and the conclusions can be drawn as follows.

(1) Increasing moisture content and prolonging granulation time is able to reduce the emission concentration of PM10/2.5, while increasing coke breeze rate would increase the emission concentration of PM10/2.5.

(2) Compared with the influences of process parameters, adding recycling materials remarkably enhances the emission concentration of PM10/2.5 for more fine particles (<10/2.5 μm) are brought in and more volatile trace elements are entrained into particulate matters.

(3) Depending merely on regulating process parameters to reduce the emission of PM10/2.5 exists an obvious limitation after taking sintering indexes into consideration. Applying recycling materials wisely and adding solid sorbents are prospective approaches to realize efficient PM10/2.5 reduction.

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