IOP Conference Series: Earth and Environmental Science

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To cite this article: Yun Zhao *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **508** 012003

IOP Conf. Series: Earth and Environmental Science **508** (2020) 012003 doi:10.1088/1755-1315/508/1/012003

Numerical simulation of acoustic agglomeration of fine particles in sintered flue gas of steel production

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Abstract. Fine particles in the sintering flue gas of steel production account for the vast majority, which is the primary control object of $PM_{2.5}$ emission sources. Traditional dust removal methods have low capture efficiency for fine particles below 1 micron. Previous research on acoustic agglomeration has focused on broad-spectrum smoke, and there is a lack of understanding of the agglomeration process of sub-micron narrow-spectrum case. Based on the zoning method, the time evolution data of particle size distribution (PSD) and agglomeration efficiency corresponding to different frequencies, sound pressure levels (SPLs), and particle concentrations under the sub-micron narrow-spectrum condition are calculated in this paper. The data analysis shows that the agglomeration efficiency of the fine particle dominated flue gas increases with the increase in the frequency of action. High sound intensity conditions are conducive to improving the agglomeration efficiency, and high flue gas concentration conditions can significantly reduce the emission reduction time and energy consumption. Compared with broad-spectrum flue gas, due to the small difference in particle size and movement speed, under the same action conditions, fine particles occupy a longer agglomeration time, and the required acoustic intensity is higher, which is not conducive to practical industrial applications. Therefore, after adding a small amount of large-size particles, the acoustic agglomeration of fine particles dominated smoke was studied. Theoretical analysis shows that the presence of a small number of large particles in the flue gas significantly enhances the agglomeration efficiency and reduces the time of action and the acoustic intensity. In-plant tests verified the feasibility of acoustic agglomeration in the real-time treatment of sintered flue gas and the advantage of adding a small amount of large particles. The test sound frequency range is 50 Hz to 2 kHz, the fundamental frequency SPL is 87.3 ~ 161.8dB, and the action time is within 3s. The measured $PM_{2.5}$ emission reduction efficiency is 16% ~ 92%, and the optimal frequency is about 800Hz.

1. Introduction

The control of $PM_{2.5}$ emission reduction is the focus of air pollution control in recent years. Iron and steel industry is a huge emitter of pollutants. Emissions from sintering, blast furnace and converter processes in typical steel production processes are concentrated in fine particles ranging from 0 to 2.5 microns [1]. The concentration of $PM_{2.5}$ particles produced before dust removal is generally 10^6 to 10^7

per cm^3, the peak is concentrated in the particle size range of 0.4 to 0.7 micron, and the mass concentration is 1000 to 1550 mg per m^3. Due to the poor collecting effect of dust remover on small particles, the concentration of $PM_{2.5}$ particles discharged after dust removal accounts for more than 99% of the concentration of PM_{10} particles. Therefore, fine particulate matter becomes the primary control object of $PM_{2.5}$ emission source in the steel industry.

Electrostatic precipitator is given priority to high temperature exhaust gas generated by smelting, which can handle 300 to 400 degrees of flue gas. High efficiency bag dust remover can be used for the treatment of dust-containing gas with large amount of smoke, dust production and temperature lower than 180 degrees. For particles larger than 1 μm, dust removal efficiency increases with the increase of particle size. Generally, particles below 1 μm are difficult to remove by traditional devices. Typical measured results of low-pressure particulate matter collection analyzer (ELPI)[2,3] show that the mass percentage of $PM_{2.5}$ in PM_{10} after conventional dust removal is about 85% to 84%. After the conventional dust removal process, the peak mass concentration is pushed towards the direction of small particles, and the PM_{10} discharged into the atmosphere is mainly composed of $PM_{2.5}$. Although dust removal facilities with high purification efficiency are adopted, it is difficult to realize the efficient collection and ultra-low emission of fine particles.

Fine particle agglomeration technology is a promising development direction of steel emission control. By applying electric field, sound field, magnetic field or adding chemical accelerator, agglomerate fine particles into large particles, so as to enhance the collection efficiency of fine particles in the conventional dust removal device. Considering the limitation of industrial emission reduction on real-time, agglomeration efficiency and cost, acoustic agglomeration has the advantages of short action time, remarkable effect, economy, and adaptability to harsh environment, etc., which is considered to have a good application prospect in the pretreatment of industrial fine particulate matter. The basic principle of acoustic wave agglomeration is to use high intensity sound field to increase the probability of contact and collision between particles of different particle sizes, and the particles will agglomerated into larger particles after collision. In a relatively short time (several seconds), the number of particles decreased significantly and the particle size increased significantly. In iron and steel production, $PM_{2.5}$ concentration can reach hundreds of mg per m^3 and PM_{10} concentration can reach several g per m^3, which is conducive to the implementation of efficient agglomeration process.

Recent studies have focused on acoustic agglomeration mechanism and testing in laboratory environment. Yao gang et al. [4] studied the agglomeration effect of inhalable particles from coal burning. Liu jianzhong et al. [5] completed the flue gas agglomeration experiment in traveling-wave tube with different frequencies, sound intensity and initial particle characteristics. In the recent numerical model established by zhang optics et al. [6], orthokinetic interaction and acoustic wake effect with modified collision efficiency are considered. In order to improve the emission reduction efficiency and reduce operational energy consumption [7], recent experimental studies explored the combination of spray or adding seed particles to change the interparticle force and increase the concentration, so as to achieve efficient agglomeration under low sound intensity [7-10].

The sintering flue gas of iron and steel satisfies the aerosol distribution dominated by fine particles, and the flue gas characteristics in the industrial field are quite different from those in the laboratory environment, which will significantly affect the acoustic agglomeration process and results. In order to clarify the feasibility of industrial treatment, this paper simulated and analyzed the agglomeration process of the flue gas dominated by fine particles under different parameters, determined the agglomeration rules and experimental parameters. Through the data comparison of sintering flue gas agglomeration, the optimal working conditions and emission reduction rules are clarified.

2. Acoustic agglomeration of typical sintering flue gas

2.1 Acoustic agglomeration mechanism

Multi-dispersed aerosol acoustic agglomeration is a complicated process. There are some classical acoustic agglomeration mechanisms, such as orthokinetic interaction, mutual radiation and acoustic wake effect,etc. Some theoretical analyses have adopted the quasi-steady state hypothesis, and most of them describe the particle attraction and acoustic wake effect in the equivalent jet flow based on the theoretical solutions of Stokes and Oseen steady state flows. The orthokinetic interaction mechanism is proportional to the velocity of the particle in the sound field. The hydrodynamic interaction is proportional to the square of the particle velocity. When the SPL is higher, the hydrodynamic interaction is significantly enhanced.

2.1.1. Orthokinetic interaction. Suspended fine particles in the sound field are excited or entrapped by sound waves, particles oscillate periodically with sound waves. Due to the difference in motion speed between suspended particles and surrounding medium, the oscillation speed of particles lags behind the acoustic vibration speed of the medium, so particles with different sizes in the sound field may collide with each other and become a agglomerator. Considering the aerosol composed of two sizes of particles , according to the classical entrapment collision theory, the relative motion velocity between particles is:

$$u_{ij} = U_a \left[\eta_i \cos\left(\omega t - \phi_i\right) - \eta_j \cos\left(\omega t - \phi_j\right) \right] \tag{1}$$

Where, U_a is the amplitude of air vibration velocity, ω is the angular frequency of sound wave, η is the entrainment coefficient, describes the ratio of particle to air vibration velocity amplitude, and ϕ is the phase difference between the two. The velocity of particles under the action of sound is related to the diameter of particles and the frequency of sound waves. In Stoke flow, the entrainment coefficient is determined by frequency and relaxation time τ_p:

$$\eta = 1 \Big/ \sqrt{1 + \left(\omega \tau_p\right)^2} \tag{2}$$

relaxation time

$$\tau_p = \frac{\rho_p d^2}{18\mu} \tag{3}$$

Where, ρ_p and d are particle density and diameter, and μ is viscosity coefficient. For the same acoustic frequency, the particle velocity decreases with the increase of particle diameter. For the same particle diameter, the particle velocity increases with the decrease of frequency. The velocity of particle movement at different frequencies varies greatly, and low-frequency sound waves are more likely to cause particle movement. The motion states of particles with different diameters are very different under the same frequency. Small particles have good following quality and the entrainment coefficient is close to 1, while large particles are not easy to be entrained.

It can be seen that frequency, sound intensity and particle size are the key factors influencing the agglomeration process. Frequency and particle size affect the relative motion of particles. With the increase of sound intensity, the relative motion between particles is enhanced, the collision probability and agglomeration efficiency are increased. The optimal frequency is inversely proportional to the particle size of particles.

The kernel function of acoustic agglomeration frequency is defined as the number of collisions between particles of different number concentration and two particle sizes per unit time. Kernel function of orthokinetic interaction agglomeration mechanism:

$$K_{ij}^{Or} = \frac{1}{4} \pi \left(d_i + d_j\right)^2 u_{ij} \tag{4}$$

From (1), (2), (3) and (4), the expression of the kernel function of the agglomeration mechanism of orthokinetic interaction can be obtained as follows:

$$K_{ij}^{Or} = \frac{1}{2} U_a \left(d_i + d_j\right)^2 \frac{\omega \left|\tau_{di} - \tau_{dj}\right|}{\sqrt{1 + (\omega \tau_{di})^2} \sqrt{1 + (\omega \tau_{dj})^2}} \tag{5}$$

According to the description of the orthokinetic interaction mechanism, the relative velocity of suspended particles with the same size is zero, and the kernel function of agglomeration frequency is also zero. This indicates that the mono-disperse particles cannot converge and collide with each other, which is not consistent with the reality. Therefore, it is not complete to adopt the classical orthokinetic interaction mechanism.

2.1.2. Mutual radiation pressure force. The mutual radiation of suspended particles in sound field is derived from Bernoulli's law. The density of the medium varies in different particles areas due to the action of sound waves. Assuming that the concentric line of the particles is perpendicular to the propagation direction of the incident sound wave, if the particles pass through the sound disturbance region, the relative flow area becomes smaller and the flow velocity is accelerated. As a result, the region between the suspended particles forms a low pressure area and the particles tend to attract each other. When the concentric line of particles is parallel to the direction of the incident sound wave, the relative flow area between particles increases, which slows down the flow velocity and increases the pressure, and the suspended particles tend to repel each other [10].

Mutual radiation pressure refers to the interaction between adjacent particles caused by the nonlinear effect of the original incident wave and the scattered wave. Based on the statistical method, Song[11] obtained the quantitative representation of the aggregation frequency function of mutual radiation acoustic agglomeration, and believed that the significant improvement of aggregation efficiency was related to the enhancement of mutual radiation interaction.

The kernel function of mutual radiation agglomeration mechanism can be expressed as:

$$K_{ij}^{Rp} = \pi(d_i + d_j)^2 \int_0^{\pi} h(u_{rji}) u_{rji} \sin\theta d\theta = \frac{\sqrt{3}\rho_0 U_a^2 d_i^2 d_j^2 (d_i + d_j)^2}{1152\pi\mu r^4} g_{ji} \tag{6}$$

Where, g_{ji} is the mutual radiation force function, u_r is the radial component of velocity, h is the step function, r is the distance between particles, θ is the included Angle between connecting line between particles and particle velocity of sound field.

2.1.3. Acoustic wake effect. The mechanism of acoustic wake is based on the asymmetry of the flow field around the suspended particles in Oseen (Re<10). When the moving velocity of particles and medium is different, a low-pressure wake area will be formed because of the disturbance difference of particles on the flow field before and after the particles. When the direction of the incident sound wave is consistent with the concentric line of the two particles, and it is assumed that both particles move to the left, a low-pressure wake zone is formed behind particle 1. If particle 2 is located in this low-pressure wake area, and suffers less fluid resistance than particle 1, the relative velocity of the two suspended particles will increase, and they are likely to collide with each other. Therefore, the acoustic wake effect is opposite to the mutual radiation effect.

The agglomeration of mono-disperse suspended particles can be explained by the mechanism of acoustic wake. In addition, the acoustic wake effect can be used as the refilling mechanism of the orthokinetic interaction.

The kernel function of acoustic wake agglomeration mechanism is expressed as:

$$\begin{aligned} K_{ij}^{We} = \frac{1}{4}\pi(d_i + d_j)^2 \Big| \frac{3U_a}{8\pi r}[d_i l_i + d_j l_j + \frac{U_a}{2\pi\upsilon}(d_i^2 l_i^2 + d_j^2 l_j^2)] - \frac{3\upsilon}{\pi^2 r^2}(d_i + d_j) \\ - \frac{9U_a}{64\pi r^2}(d_i^2 l_i + d_j^2 l_j) + \frac{3U_a^2}{16\omega r^2} l_i l_j (l_i q_i - l_j q_i)(d_i - d_j) \Big| \end{aligned} \tag{7}$$

Where l and q are respectively the slip coefficient and entrainment coefficient of suspended particles in Oseen flow region.

2.2 Agglomeration efficiency of fine particles

The analysis of fine particulate agglomeration effect requires the evolution data of flue gas PSD under the action of sound wave, which can be obtained by solving the aerosol dynamics equation. Because the van der Waals force between particles is strong, the aggregates formed are relatively solid, so the influence of the reverse agglomeration process, such as breakage and boundary loss, is often ignored in the study. The change in the number of particles with volume v over time should be:

$$\frac{\partial n(v,t)}{\partial t}=\frac{1}{2}\int_0^v \beta(v-w,w)n(v-w,t)n(w,t)dw-n(v,t)\int_v^\infty \beta(v,w)n(w,t)dw \tag{8}$$

Where, n(v,t) is the number density function based on particle volume of v, and β is the agglomeration frequency function. The basic idea of the partitioning method is to partition the particles in the aerosol according to the volume or particle size, and assume that the particles in a certain region have the same volume, so as to discrete the aerosol dynamics equation. The aggregation frequency function β_{ij} is expressed as K_{ij}, Smoluchowski equation describing aerosol particle size distribution change was obtained:

$$\frac{dn_k}{dt}=\frac{1}{2}\sum_{v_i+v_j=v_k} K_{ij}n_in_j-n_k\sum_i^\infty K_{ik}n_i \tag{9}$$

Where, n_i, n_j and n_k are the number and concentration of particles in the region of i,j,k . Equation (9) shows the relationship between the change rate of the number of suspended particles and the agglomeration kernel function. The variation of the number of suspended particles can be estimated and the effect of sound wave agglomeration of suspended particles can be qualitatively described by solving the discrete equation by numerical method.

It is assumed that the poly-disperse aerosol emissions from steel sintering meet the ideal lognormal distribution, which can be expressed by the following formula:

$$n(d_p)=\frac{N}{d_p\cdot\sqrt{2\pi}\cdot\ln\sigma_g}\exp\left[-\frac{(\ln d_p-\ln \bar{d}_p)^2}{2(\ln\sigma_g)^2}\right] \tag{10}$$

Where, N is the concentration of the total number of aerosol particles, σ_g is the geometric standard deviation, d_p is the diameter of particles, $\bar{d}_p$ is the geometric average diameter of particles, $n(d_p)$ is the function of the number and density of particles.

Based on formula (9) and zoning method, the agglomeration process was calculated for the sintered flue gas dominated by fine particles. Ideal lognormal distribution was used as the input of the initial flue gas distribution to study the influence of acoustic frequency, intensity, initial concentration on the PSD and agglomeration efficiency, so as to provide theoretical basis for in-plant verification and the selection of operating parameters.

Reference to the measured data of typical sintered flue gas, the particle density was set as 1400 kg per m^3, the minimum particle size in the logarithmic distribution was 0.2 μm, the maximum particle size was 1.25 μm, the geometric mean diameter was 0.55 μm, and the geometric standard deviation was 1.6. The collision efficiency is 1, and the number of group is 50. The simulated frequency variation ranges from 300 to 2000 Hz, the SPL ranges from 130 to 170 dB, and the initial concentration variation ranges from 1e4, 1e5, 1e6, and 1e7 per cm^3.

2.2.1 frequency of acoustic waves. The frequency of acoustic wave was set as 2kHz, the SPL was 150dB, and the initial particle concentration was 1e5/cm^3, and the changes of flue gas particle size distribution at different times were obtained as shown in figure 1. It can be seen that the number of fine particles decreases gradually with the increase of operation time. With the same increment of operation time, the decrease of fine particles near the initial moment is the greatest. With the increase of operation time, the agglomeration effect gradually approaches saturation. This is because the concentration of the total number of particles has decreased when the action time is longer, so the probability of particle collision and particle agglomeration efficiency decrease. Compared with the general distribution of smoke with wide spectral range, time required for the smoke that fine particles dominated greatly increases. This is because the size range of the latter particle is small, and the relative velocity difference between particles is small, which is not conducive to achieving the agglomeration quickly.

The initial flue gas parameters and SPL are kept unchanged, while the sound frequency is changed. Figure 2 shows the changes of flue gas PSD corresponding to the application of sound wave with different frequencies for 2000s. First, the effect of sound wave only changed the number and concentration of particles, while the change of frequency did not change the shape of PSD. Secondly, the optimum frequency exists under the condition of the distribution of wide spectral range. However, for the flue gas dominated by fine particles, the high frequency sound wave is beneficial to the improvement of agglomeration efficiency. With the increase of frequency, the particle size corresponding to the peak of number concentration decreases more.

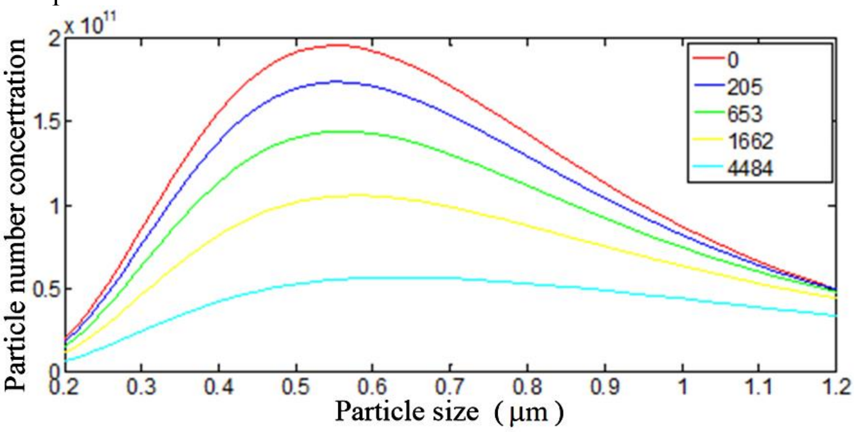

Figure 1. Particle size distribution at different times under the action of sound waves with frequency 2000Hz and SPL 150dB

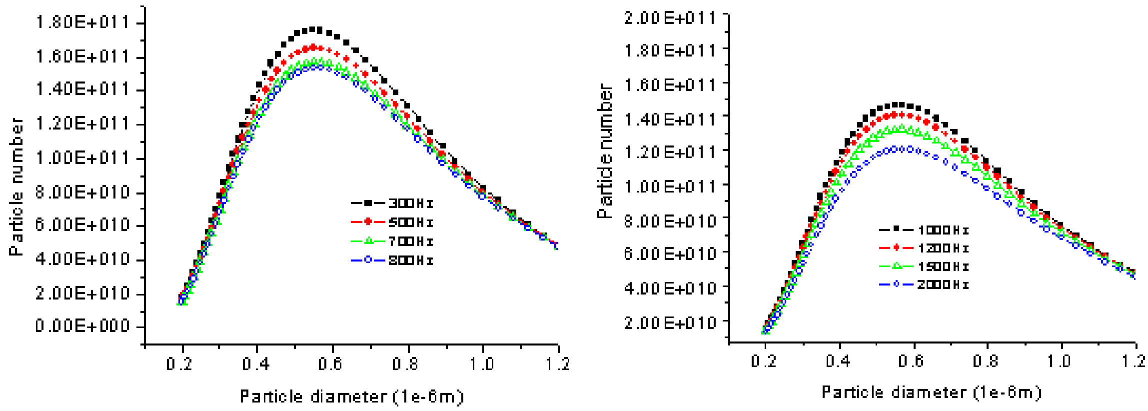

Figure 2. Particle size distribution corresponding to different frequencies under the SPL 150dB and fixed acoustic operation time (2000s)

The theoretical analysis results show that the agglomeration efficiency varies with the frequency, and there is an optimal agglomeration frequency. As the particle size of flue gas dominated by fine particles is similar， different to that of the theoretical analysis, the results are more similar to the situation of mono-disperse aerosol. The corresponding optimal frequency is not within the selected frequency range.

2.2.2 sound pressure level. The sound frequency was kept at the optimal frequency (2kHz) and the initial particle concentration was unchanged at 1e5/cm^3. The SPLs were 130, 140, 150, 160 and 170dB, respectively, to calculate the change of flue gas particle size with time during the agglomeration process.

Figure 3 shows the change of PSD with action time under 170dB. It can be seen that the number of fine particles decreases gradually with the increase of agglomeration time. Similarly, with the same increment of operation time, the number of particles at the initial time decreases the most, and the agglomeration effect gradually approaches saturation with the increase of time. Compared with figure 1, after the increase of sound intensity, the time required to achieve the same emission reduction effect is reduced to less than 1/6.

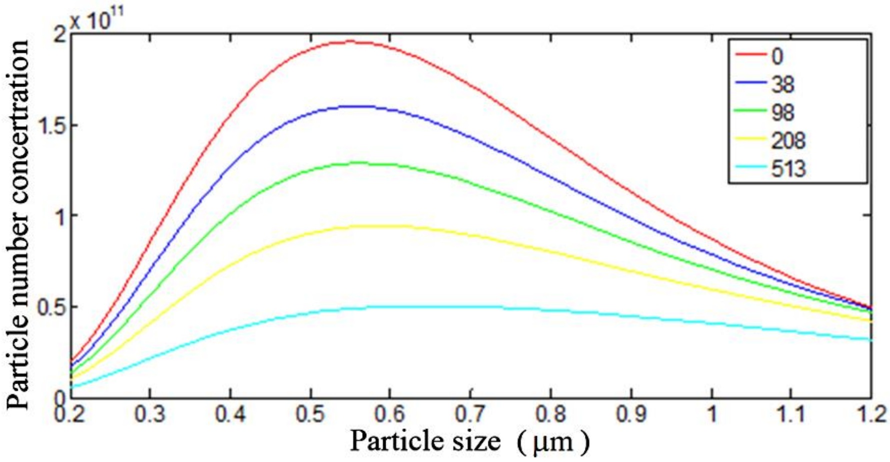

Figure 3. particle size distribution at different times under the action of acoustic waves with frequency 2000Hz and sound pressure level 170dB

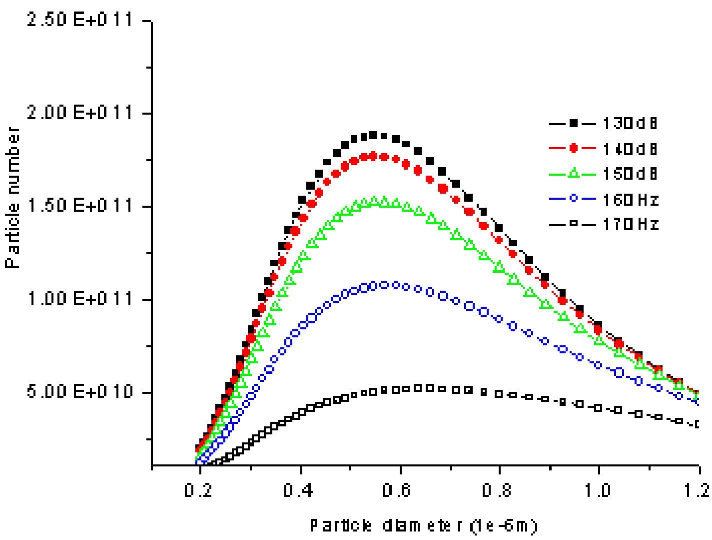

Figure 4. Particle size distribution corresponding to different SPLs at a fixed frequency of 2000Hz and fixed acoustic operation time （500s）

The effect of SPL on agglomeration efficiency of fine particles is significant. Figure 4 shows the PSD corresponding to different SPLs and the same operation time (500s). It can be seen that the agglomeration efficiency of fine particles increases rapidly with the increase of SPL. The change of SPL affects the time to achieve the same agglomeration effect, and the SPL does not have a big impact on the final PSD. Compared with figure 2, the efficiency of emission reduction increased from 30% to 70% under the condition of less action time. In figure 4, the increase interval of SPL is 10 dB, and the increase interval of corresponding sound pressure value increases gradually. Therefore, the increase value of emission reduction efficiency increases with the sound intensity. After the sound intensity is increased, it will take less time to achieve the same emission reduction efficiency.

2.2.3 initial flue gas concentration. The initial concentration of flue gas is the main influencing factor of agglomeration efficiency. High aerosol concentration is conducive to the efficient removal of fine particles in the lower intensity of acoustic wave and the shorter duration of operation, so as to improve the emission reduction efficiency and reduce energy consumption. The sound frequency was kept at the optimal frequency (2000Hz) and the SPL of medium intensity was kept at 150dB. Particle concentrations of 1e4, 1e5, 1e6 and 1e7 per cm^3 were respectively taken to simulate the agglomeration process of aerosols dominated by fine particles.

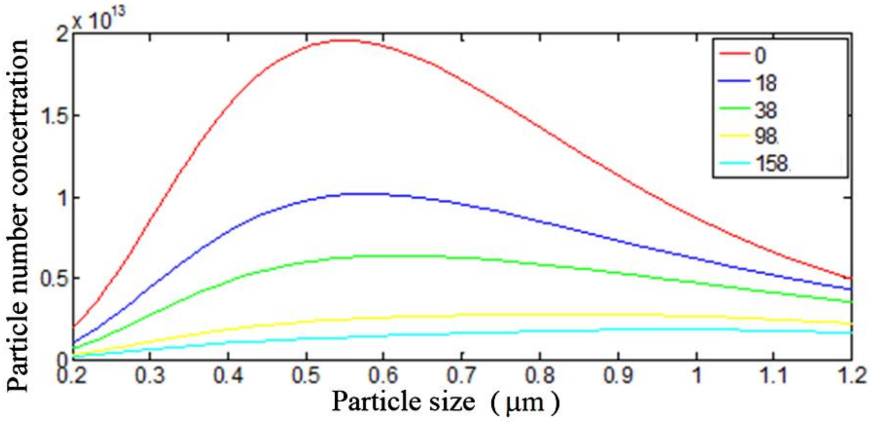

Figure 5. particle size distribution under the conditions of frequency 2000Hz, sound pressure level 150dB and initial concentration 1e7 /cm^3

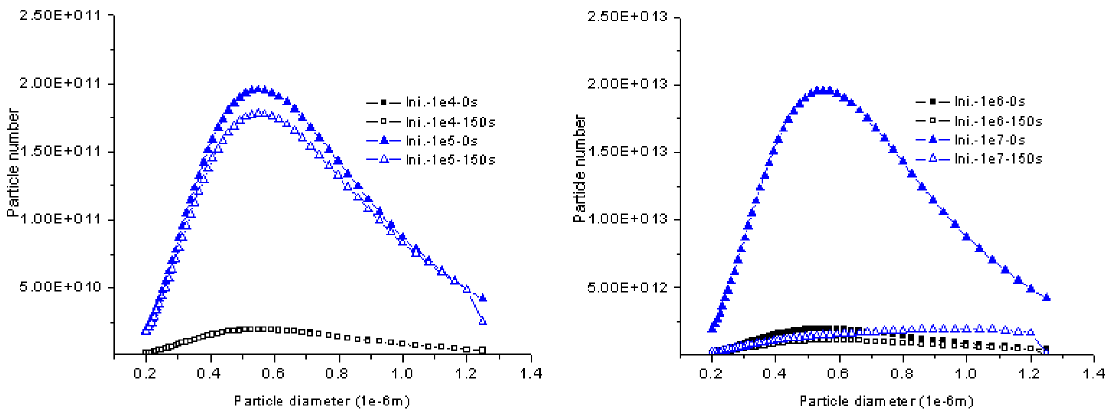

Figure 6. Particle size distribution changes before and after the acoustic exposure under different initial concentration conditions with fixed time of 150s and frequency 2kHz

Figure 5 shows the change of flue gas PSD under the condition of initial concentration of 1e7 per cm^3 at different action times. Compared with figure 3 and figure 1 (initial concentration of 1e5 per cm^3), it can be seen that when the concentration and acoustic intensity are low, it takes hundreds or even thousands of seconds to achieve the desired effect of fine particulate emission reduction. However, in the case of high initial concentration, the number of fine particles decreases rapidly with the increase of agglomeration time, and the time required to achieve a similar emission reduction efficiency or particle number ratio drops from several hundred seconds to around ten seconds.

In order to visually compare the effect of initial concentration, figure 6 shows the changes of PSD under different initial concentrations before and after acoustic agglomeration at the same operation time (150s). It can be seen that under the condition of short exposure time, only when the initial concentration is high, the medium intensity sound wave can achieve a relatively ideal emission reduction efficiency.

2.2.4 agglomeration process with shorter action time and better emission reduction efficiency. The actual industrial application shall take particle removal efficiency, operation time and economy into consideration, and the relatively ideal agglomeration time shall be several seconds to meet the needs of real-time processing, and the SPL shall not exceed 160dB to reduce energy consumption.

It can be seen that the initial smoke concentration has an important influence on the action time required for agglomeration. When the initial aerosol concentration is high and the sound intensity of the action is high, the ideal removal effect of fine particles can be achieved with only a few seconds to tens of seconds. For the typical single-peak logarithmic particle size distribution of flue gas, from the perspective of practical application, theoretical calculation has confirmed that the acoustic agglomeration has the emission reduction performance to meet the practical application demand under the condition of high aerosol concentration.

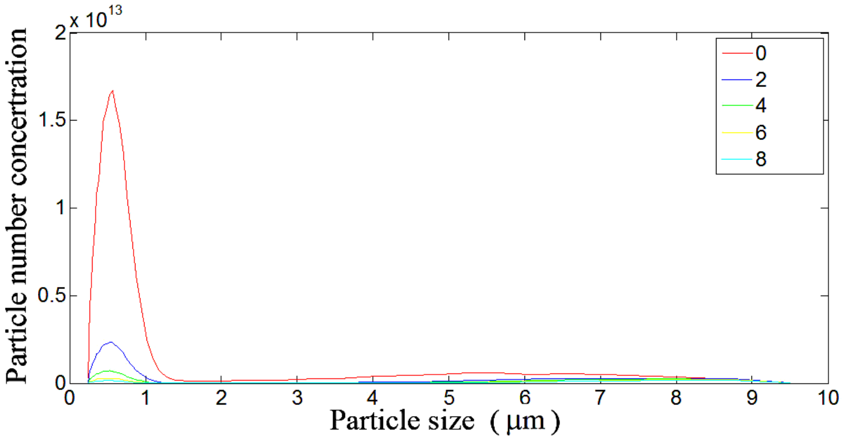

Figure 7. Flue gas PSD before (figure 5) and after adding a small amount of large particles at a 2 kHz, SPL 150 dB, and initial concentration of 1e7p / cm^3.

The in-plant experimental results show that for medium-concentrated flue gas, a few seconds of high-intensity acoustic wave can achieve a ideal agglomeration efficiency. This is somewhat different from the theoretical analysis of this paper. The reason is that the classic sintered flue gas does not contain large particles. To verify the effect of the presence of a small number of large particles, the measured initial PSD was used as an input to re-simulate the agglomeration process.

Maintaining a frequency of 2kHz, a medium-intensity SPL of 150 dB, and a particle concentration of 1e7 p / cm^3 are used in the simulation. Figure 7 compares the change in the PSD of the flue gas with or without the addition of large particles over time. It can be seen that the smoke containing only sub-micron particles needs an action time of more than one hundred seconds to achieve the ideal agglomeration, and a small amount of large particles only needs 2 to 4 seconds to achieve a similar effect. The addition of large particles greatly improves the agglomeration efficiency of fine particles or can significantly reduce energy consumption for emission reduction.

3. Test system and results of online agglomeration effect in steel plant

Agglomeration effect of the real flue gas in the steel plant was tested in high intensity acoustic field. The test layout in the plant is shown in figure 8. A certain amount of flue gas samples were extracted from the flue gas duct of the plant, and an acoustic agglomeration test system was used to record the PSD of flue gas and the effect of $PM_{2.5}$ agglomeration emission reduction under different intensity and frequencies.

The on-line agglomeration effect system consists of high pressure air source, sound wave agglomeration test system, speed regulating fan, sound field and particle size test equipment and test pipeline circuit. The sintering section with higher concentration of flue gas was selected as the pilot location (figure 1, right). The experimental system of AA of flue gas[12] includes flue gas extration system, high intensity sound generation system, sound field test system, standing wave tube, particle size test system and exhaust gas treatment system. The design of high sound resonance synthesis, air sound separation, plane wave retention and other aspects provides high sound intensity, high purity waveform and shock wave avoidance environment to improve agglomeration efficiency and reduce energy consumption.

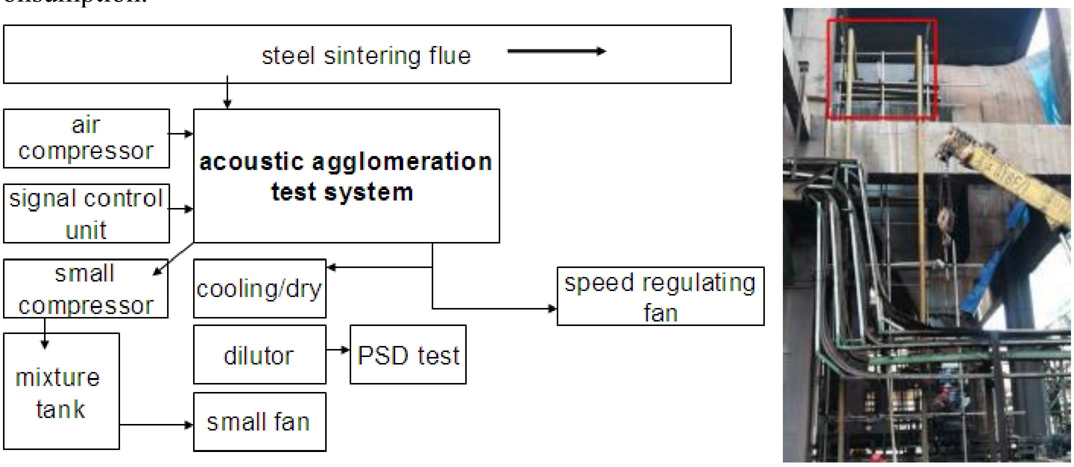

Figure 8. Composition of the online agglomeration effect system for real sintered flue gas in steel plant including flue gas extraction (right figure).

The flue gas with a volume flow rate of about 5 L/s is stably provided. The flow speed is below 0.5m/s and the corresponding agglomeration time is greater than 3 seconds. The high frequency siren has good frequency response in the range of 50 Hz to 2.0 kHz. The sound field test system is composed of three high intensity microphones (B&K 4941) which is located equally along the flow direction by the side of the agglomeration chamber. Sound signal is recorded by the B&K 3050 system.

The standing wave tube with square and abrupt section is composed of a narrow tube and a wide tube. The length of the former is 1.5m and the side length is 0.1m, while the length of the latter is 0.5m and the side length is 0.3m. The narrow tube is designed as the agglomeration chamber and the wide tube is called the coupling chamber. As the compressed air used to drive the siren has influence on the fine particle agglomeration, an acoustic penetration board is installed in the middle section of the coupling chamber to achieve the sound-flow separation. Sound frequency and intensity inside the agglomeration chamber can be adjusted by the source and air compressor.

The particle size test system is composed of an aerosol spectrometer (TOPAS LAP-322), a 1:100 diluter and the fine particle sampling apparatus. It is connected with the outlet of the chamber. The former is used to measure the aerosol’s particle size distribution before and after the treatment of sound waves and the latter is used to take the mass value of small particles with diameter between 2.5 and 10 μm. During the test, the flue gas characteristics reached stability within 3 minutes after the flue gas circulation system was turned on. Then, after applying acousitc sonication for 1 minute, the particle size test was started. The test settling time was 10 seconds, and the test recording time was 40 seconds. Finally, the cumulative average PSD results within 40 seconds were given.

Figure 9 shows the comparison of the particle distribution in the flue gas under different frequencies and intensities. It can be seen that the initial smoke PSD presents a bimodal distribution, most of the particle sizes are below 1 micron, and the flue gas also contains a small number of large particles of 3 to 10 microns. The highest number of particles is about 0.5 to 0.6 microns. Sound waves with different frequencies and intensities have certain effects on the agglomeration of fine particles. The number of particles below 1 micron decreased significantly. The number of particles increased slightly between 1 and 3 microns. Affected by gravity settlement, the number of large particles above 3 microns decreases significantly under the action of sound waves. The emission reduction varies greatly with different working conditions. Under the action of sound waves with higher SPLs and lower frequencies (such as 800Hz, 850Hz), the removal efficiency of fine particles is better.

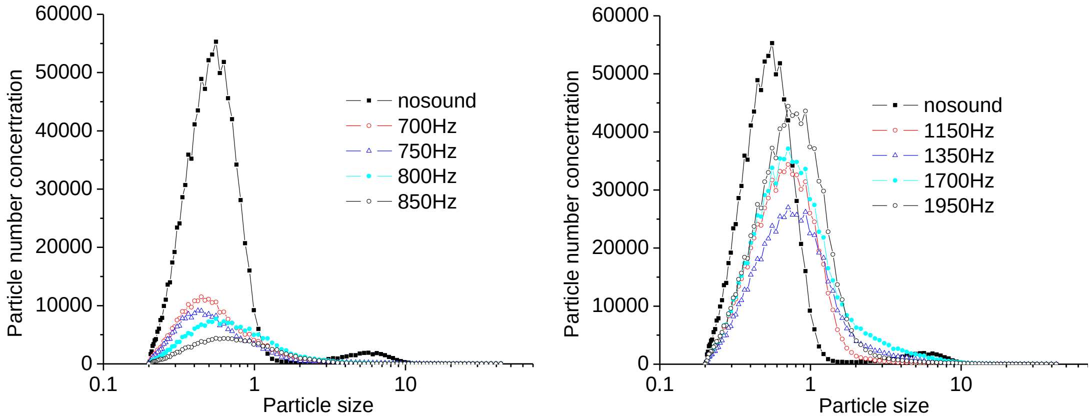

Figure 9. Comparison of smoke PSD and initial particle size distribution under different frequencies of high intensity sound waves.

The relative change in the number of particles below 2.5 microns before and after action of sound is defined as the $PM_{2.5}$ agglomeration efficiency. According to the statistics of the PSD data in figure 9, the $PM_{2.5}$ agglomeration efficiency was calculated under different frequencies and intensities in multiple tests, and the corresponding efficiency change range for different frequencies is 16% to 92%. It can be seen that near 800Hz where the SPL is higher, the removal efficiency can reach more than 90%. In the same high frequency band with higher SPL, the removal efficiency has decreased significantly. This shows that the frequency is still an important factor for the agglomeration process.

4. Conclusion

The sintering flue gas produced by steel has the characteristics of large emission, high concentration, and submicron fine particles dominate, and it is difficult to achieve ultra-low emission standards using traditional dust removal methods.

Firstly, the agglomeration of fine particles in sintered flue gas was studied based on the zoning method. Through the simulation of the agglomeration process of fine particles, it can be seen that the flue gas concentration is high. It is mainly composed of fine particles below 1 micron, and lacks larger particles to participate in collision and agglomeration. When the frequency is low, it takes tens of seconds or even longer to achieve a better reduction effect, and the real-time nature of the removal is lost. The collision and agglomeration of fine particles are more likely to occur under the action of high-frequency sound waves. At the same SPL, as the frequency increases, the required operation time decreases significantly. At the same frequency, as the SPL increases, the time required for the same reduction effect is significantly reduced. When the SPL is 160dB and the frequency is 2kHz, the ideal real-time reduction effect is achieved. For the condition that pure fine particles are dominant, it cannot meet the requirements of high emission reduction efficiency and low energy consumption.

On-line agglomeration test of sintered flue gas in steel plant was carried out based on high-power pneumatic source and abrupt cross-section tube. The experimental results show that there is a preferred frequency in the dominant smoke, hich is about 800 Hz. High intensity conditions are conducive to improving the removal efficiency, and high concentration conditions can greatly reduce the time and energy consumption of emission reduction. The fundamental frequency sound pressure level is 128.6-161.8 dB, and the high intensity sound action for several seconds can achieve $PM_{2.5}$ emission reduction efficiency of 37%-92%.

The simulation and experimental research in this paper verified the feasibility of acoustic agglomeration in the treatment of sintered flue gas. Further analysis shows that the large-size particulates present in the sintered flue gas have a significant effect on improving the agglomeration efficiency, which is beneficial to reducing operating energy consumption and improving emission reduction efficiency.

Acknowledgments
This work was financially supported by Hunan Provincial Key R&D Project (No. 2017SK2322).

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