Experimental verification of fine particle emission reduction based on acoustic agglomeration for steel sintering flue gas

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Abstract. The sintering flue gas in steel production has the characteristics of large discharge capacity, fine size, high temperature, corrosion and fluctuation of working conditions, and is the primary control object of PM$_{2.5}$ emission source. Traditional dust removal technologies and equipment are difficult to achieve efficient collection of fine particles. In order to quantitatively study the effect and regularity of high intensity sound waves on fine particles, the online acoustic agglomeration test system was built by using high-power pneumatic source and wave tube with abrupt section. The high intensity standing wave field of 140 to 150 dB was generated in the wide frequency range between 50 Hz and 2 kHz by the acoustic resonance synthesis, and interference from compressed airflow was avoided by the acoustic-flow separation module. Variation of the sintered flue gas PSD was obtained under different sound intensities and frequencies. Data analysis shows that the high concentration condition can greatly reduce the operation time and energy consumption. Under the action of high intensity acoustic waves with a fundamental sound pressure level of 87.3-161.8 dB and duration of 3 s, the measured PM$_{2.5}$ removal efficiency is 16%-92%, and the optimal frequency is near 800 Hz. This paper verifies the feasibility of acoustic agglomeration (AA) in the treatment of sintering flue gas, and provides a theoretical reference and technical basis for the development of PM$_{2.5}$ real-time emission control device for steel production.

1. Introduction
The control of PM$_{2.5}$ emission reduction is the focus of air pollution control in recent years. As an important pillar industry of the national economy, iron and steel industry is also a big 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]. Among them, the fine particles in the sintering process come from mineral melting, burning debris, fine ash particles, and the broken fine mineral particles that are not fully burned, etc. The concentration of PM$_{2.5}$ particles produced before dust removal is $10^6$ 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 emission in
sintering process is relatively dominant and is the primary control object of PM$_{2.5}$ emission source in the steel industry.

The discharge of sintering head and tail is characterized by high temperature, large emission, high corrosivity, fine particle size and fluctuation of working conditions, etc. Although dust removal facilities with high purification efficiency are adopted, it is difficult to realize the efficient collection and ultra-low emission of PM$_{2.5}$. Fine particle agglomeration technology is a promising development direction of steel emission control. 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.

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. In the experiment, increasing sound intensity significantly improved emission reduction efficiency. Liu jianzhong et al. [5] completed the flue gas agglomeration experiment in traveling-wave tube with different frequencies, sound intensity and initial particle characteristics. Chen houtao et al. [6] applied low-frequency strong sound waves to fine particles of coal burning in fluidized bed, and the mass concentration of particles under 10 $\mu$m decreased by 92.5%. In the recent numerical model established by zhang optics et al. [7], orthokinetic interaction and acoustic wake effect with modified collision efficiency are considered. In order to clarify the relationship between the optimal acoustic parameters and aerosol particle size distribution, zhou dong et al. [8] obtained experimental data on the influence of different particle size and frequency on monodisperse aerosol concentration.

In order to improve the emission reduction efficiency of acoustic agglomeration industry and reduce operational energy consumption [9], 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 [10-13]. Yan jinpei et al. [10,11] proved that the removal efficiency of fine particles could be effectively improved by steam phase transformation and adding specific wetting agents.

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, and then carried out in-factory test verification based on the high intensity pneumatic source and acoustic resonance synthesis. The resonant frequency of the agglomeration tube is set equal to the optimal frequency of multi-dispersed aerosol agglomeration to improve emission reduction efficiency and reduce sound power consumption under the resonance state. Through the comparison and analysis of the acoustic field characteristics and the data of sintering flue gas agglomeration effect, the optimal working conditions and emission reduction rules are clarified.

2. 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.

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:

\[
    u_{ij} = \frac{\eta_i \cos(\omega t - \phi) - \eta_j \cos(\omega t - \phi)}{1 + (\omega \tau_p)^2}
\]

(1)

Where, \(U_a\) is the amplitude of air vibration velocity, \(\omega\) is the angular frequency of sound wave, \(\eta\) is the entrainment coefficient, describes the ratio of particle to air vibration velocity amplitude, and \(\phi\) 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 \(\tau_p\):

\[
    \eta = \sqrt{1 + (\omega \tau_p)^2}
\]

(2)

Relaxation time

\[
    \tau_p = \frac{\rho_p d^2}{18 \mu}
\]

(3)

Where, \(\rho_p\) and \(d\) are particle density and diameter, and \(\mu\) 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. The optimal agglomeration frequency of the aerosol composed of two sizes of particles is

\[
    \omega_{opt} = \frac{1}{\sqrt{\tau_p \tau_{ji}}} \cdot \frac{1}{1 + (\omega \tau_p)^2}
\]

(4)

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:

\[
    K_{ij} = \frac{1}{4} \pi d^2 u_{ij}
\]

(5)

From (1), (2), (3) and (5), the expression of the kernel function of the agglomeration mechanism of orthokinetic interaction can be obtained as follows:

\[
    K_{ij} = \frac{1}{2} U_a (d_i + d_j)^2 \frac{\omega |\tau_{ij} - \tau_{ji}|}{\sqrt{1 + (\omega \tau_{ij})^2} \sqrt{1 + (\omega \tau_{ji})^2}}
\]

(6)

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 monodisperse 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.

3. Test system of online agglomeration effect in steel plant

Agglomeration effect of the real flue gas in the steel plant was tested under the action of sound wave. The test layout in the plant is shown in figure 1. 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.

**Figure 1.** Composition of the online agglomeration effect system for real sintered flue gas in steel plant including flue gas extraction (right figure).

**Figure 2.** Demonstration of the AA system based on acoustical resonator: (a) a loudspeaker array generates sound waves; (b) a high frequency siren is used to increase the source level.

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). In the test, the high pressure air compressor drove the sound source, forming a high intensity standing wave field in the test system. Under the extraction of the speed regulating fan, the flue gas of high temperature was extracted from the flue between the sintering section and the conventional dust removal device. The flue gas entered from the side entrance of the test system, and in the process of flowing through the test system, fine particles form aggregates under the action of sound waves. Then it flows out from the side exit of the test system, and re-injects into the plant flue under the action of induced fan. Because the particle size test equipment cannot directly measure the flue gas with high concentration and high temperature, it needs to be cooled, dried, and diluted before the test.

The experimental system of AA of flue gas [16] includes flue gas generation 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 a high sound intensity, high purity waveform and shock wave avoidance environment to improve agglomeration efficiency and reduce energy consumption. Through the integration of data monitoring and control equipment such as adjustable structure, SPL, particle concentration and PSD test devices, the process feedback control is realized to adapt to the smoke with different characteristics. Through the design of pipe series silencer, wall sound insulation and sound absorption, the leakage of strong sound waves can be reduced.

The flue gas with a volume flow rate of about 5 L/s is stably provided. The flow speed is below 0.5 m/s and the corresponding agglomeration time is greater than 3 seconds. The concentration of the flue gas is about $10^4$-$10^6$ particles per cm$^3$, and the mass concentration is about several hundred mg per m$^3$. Outlet of the aerosol generator is connected with the inlet of the agglomeration chamber.

The agglomeration effect is independent of sound intensity. The pneumatic source is composed of air compressor, high frequency siren and frequency control module. The high frequency siren has good frequency response in the range of 50 Hz to 2.0 kHz. The siren is coupled to the conical horn to radiate high intensity sound waves into the downstream chamber (figure 2). The horn inlet and outlet diameters are 0.1 m and 0.25 m, respectively, and the length is 0.2 m. 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 1.5 m and the side length is 0.1 m, while the length of the latter is 0.5 m and the side length is 0.3 m. 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. The separated gas stream is discharged from an exhaust port near one end of the siren. One could use the adjustable piston located at one end of the narrow tube to change the length of the chamber and sequentially modify the resonance frequency of the whole system. Sound frequency and intensity inside the agglomeration chamber can be adjusted by the source and air compressor. Compared with the classical uniform tube, the introduction of two stage standing wave tube may help to improve the performance of AA. Nonlinear effects such as acoustic saturation, shock wave formation have influence on the high intensity sound field and may sequentially reduce the agglomeration efficiency. As higher resonance frequencies of the tube are not the integral multiplies of the fundamental one, strong nonlinearity can be avoided at the resonance state for the two stage tube.

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.
4. Results and analysis

4.1. Acoustic characteristics in the agglomeration tube

The time-domain signals at the measurement points in the agglomeration tube was recorded at different sound frequencies and then Fourier transform was performed to obtain the frequency response corresponding to the fundamental frequency. The frequency response results of the SPL in the tube show a certain fluctuation, and the measured SPL value at different frequencies are quite different. Due to the acoustic-flow separation plate with a certain amount of sound insulation, most of the frequencies correspond to the fundamental frequency are below 140dB. The design of the geometry of the tube system is not conducive to transmitting low frequency signals, so that the sound intensity below 600 Hz is low, and the SPL value varies between 80 and 132 dB.

Keeping the sound frequency constant, continuously adjusting the axial length of the agglomeration tube, the SPL recorded by the microphone changes periodically. When the tube reaches resonance state, the SPL value reaches a maximum value. SPL value of the fundamental frequency and the corresponding tube length during the adjustment were recorded. Figure 3 shows the spectrum results during the resonance adjustment. It can be seen that the acoustic energy is concentrated on the fundamental frequency and the second harmonic components. Figure 4 shows the SPLs recorded at the measurement points when the tube is adjusted to the resonance state. The SPL results vary from 87.3 to 161.8 dB under different sound frequencies. Among them, the corresponding values of about 700 to 800 Hz, 1200 to 1400 Hz, and 1700 Hz are relatively high, which varies from 140 to 150 dB. Frequencies below 600Hz and 900 to 1100Hz have lower SPL values between 120 and 130dB.

It can be seen in figure 4 that relative to the results of the fixed tube length (dotted line in the figure), a SPL gain of 5-15 dB was obtained by the piston adjustment. After the resonance adjustment, the SPL

![Figure 3. Time-frequency analysis results during tube length adjustment at different sound frequencies.](image-url)
values corresponding to the fundamental frequency at most working conditions are higher than 140 dB, and the values at half of the working conditions are higher than 150 dB. Among them, a thinner acoustic-flow separation plate is adopted to obtain a higher sound intensity, and all frequency response curves have similar trends. Below 500 Hz, the acoustic intensity in the tube is weak. The maximum value in the frequency response curve is around 700 to 800 Hz. A small value of sound pressure exists around 1000 Hz.

Figure 4. Maximum SPL corresponding to the fundamental frequency in the agglomeration tube during the adjustment of the tube length at different sound frequencies.

4.2. Fine particle removal efficiency as a function of sound intensity and frequency
The air blower was adjusted to make the flow velocity of smoke in the agglomeration tube about 0.5 m/s, so the maintain time of the smoke can reach to 3 to 5 seconds in the high intensity acoustic field. The particle size test range is 0.2 to 42.9 microns, and the channel number in the range is 98. During the test, a particle size spectrometer and a diluter were installed downstream of the agglomeration tube. The flue gas characteristics reached stability within 3 minutes after the flue gas circulation system was turned on. Then, after applying acoustic 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 5 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 800 Hz, 850 Hz), the removal efficiency of fine particles is better.

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 5, figure 6 shows the PM$_{2.5}$ agglomeration efficiency under different frequencies and intensities recorded 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.

![Figure 5. Comparison of smoke PSD and initial particle size distribution under different frequencies of high intensity sound waves.](image)

![Figure 6. Changes of PM$_{2.5}$ agglomeration reduction efficiency in sintered flue gas under different frequency and intensity sound waves.](image)

4.3. Particle size distribution characteristics and frequency control

The in-plant experimental results show that for medium-concentrated flue gas, a few seconds of high-intensity acoustic wave can achieve an ideal agglomeration efficiency. This is somewhat different from the theoretical analysis in section 2 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.
5. 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.

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 agglomeration effect of sintered flue gas was tested in a wide frequency band of 50 Hz to 2 kHz and a high intensity standing wave field above 140 to 150 dB. The experimental results show that there is a preferred frequency in the dominant smoke, which is about 800 Hz. High intensity conditions are conducive to improving the reunion 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 experimental research in this paper verified the feasibility of acoustic agglomeration in the treatment of sintered flue gas. There is a significant difference between the actual measurement results and the simulation results in terms of acoustic operation time. 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, improving emission reduction efficiency, and industrial application feasibility.

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References

[1] G. Zhang, Study on emission characteristics of particulate matter in iron and steel enterprises, master thesis, Northeastern University, 2015.

[2] J. H. Ma, Study on the characteristics of particulate emissions from typical production processes
of iron and steel enterprises, master thesis, Southwest University, 2009.

[3] Y. J. Wang, Experimental research on PM$_{2.5}$ production and discharge characteristics of sintering machine in steel plant, master thesis, Hebei University of Technology, 2015.

[4] G. Yao, B. Zhao, X. L. Shen, Experimental study and numerical analysis of the acoustic agglomeration effectiveness of inhalable particles of burned coal, Journal of Engineering Thermal Energy and Power. 21(2006) 175-178.

[5] J. Z. Liu, G. X. Zhang, et al, Experimental study of acoustic agglomeration of coal-fired fly ash particles at low frequencies, Powder Technology. 193(2009) 20-25.

[6] H. T. Chen, X. L. Shen, W. L. Liu, et al, “Experimental study on acoustic agglomeration of fine particles from coal combustion,” International Conference on Digital Manufacturing & Automation. Guangzhou, China. 2010.

[7] G. X. Zhang, J. Z. Liu, J. H. Zhou, et al., A theoretical model and experimental verification on the influence of frequency on acoustic agglomeration of coal-fired fly ash, Proceedings of the CSEE. 29(2009) 97-102.

[8] D. Zhou, Z. Y. Luo, M. S. Lu, et al., Acoustic agglomeration experiments of monodispersed aerosol, Journal of Zhejiang University. 51(2017) 358-369.

[9] J. Wang, G. X. Zhang, J. Z. Liu, et al., Effect of seed particles on acoustic agglomeration efficiency, CIESC Journal. 62(2011) 355-361.

[10] J. P. Yan, L. Q. Chen, L. J. Yang, Agglomeration removal of fine particles at super-saturation steam by using acoustic wave, CIESC Journal. 65(2014) 3243-3249.

[11] J. P. Yan, L. Q. Chen, L. J. Yang, Experimental study on promotion of coal combustion fine particles acoustic agglomeration removal by using wetting agents, Journal of Fuel Chemistry and Technology. 42(2014) 1259-1265.

[12] D. G. Ma, W. Q. Lin, Q. Q. Zheng, et al., Pretreatment based on combined effect of acoustic agglomeration and atomization and its application in air filtration, Chinese Journal of Environmental Engineering. 9(2015) 2353-2358.

[13] G. X. Zhang, Y. J. Zhu, T. T. Zhou, et al., Improve acoustic agglomeration of fine particles by droplet spray, CIESC Journal. 68(2017) 864-869.

[14] G. X. Zhang, Theoretical and experimental research on acoustic agglomeration of coal-fired fly ash aerosol, PHD thesis, Zhejiang University, 2010.

[15] Song Limin, Modeling of acoustic agglomeration of fine particles, PHD thesis, The Pennsylvania State University, 1990.

[16] Y. Zhao, C. X. Dong, Z. F. Tian, Experimental research of PM$_{2.5}$ removal from coal combustion by acoustic agglomeration in a standing wave tube with abrupt section, Proceedings of the CSEE, 38(2018) 6021-6028.