Experimental study of acoustic agglomeration and fragmentation on coal-fired ash

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Abstract. As the major part of air pollution, inhalable particles, especially fine particles are doing great harm to human body due to smaller particle size and absorption of hazardous components. However, the removal efficiency of current particles filtering devices is low. Acoustic agglomeration is considered as a very effective pretreatment technique for removing particles. Fine particles collide, agglomerate and grow up in the sound field and the fine particles can be removed by conventional particles devices easily. In this paper, the agglomeration and fragmentation of 3 different kinds of particles with different size distributions are studied experimentally in the sound field. It is found that there exists an optimal frequency at 1200 Hz for different particles. The agglomeration efficiency of inhalable particles increases with SPL increasing for the unimodal particles with particle diameter less than 10 μm. For the bimodal particles, the optimal SPLs are 115 and 120 dB with the agglomeration efficiencies of 25% and 55%. A considerable effectiveness of agglomeration could only be obtained in a narrow SPL range and it decreases significantly over the range for the particles fragmentation.

1. Introduction

With the rapid economic development, air pollution has drawn a widely public attention [1]. As one of the main kinds of air pollution, particulate pollution is mainly caused by fossil fuel combustion, automobile exhaust, cement, iron and steel manufacturing and other industrial activities [2]. At present, the efficiency of conventional dust removal devices for large particles with particle diameter more than 10 μm (PM10) is high, however, the efficiency of removal fine particles with particle diameter less than 10 μm, especially less than 2.5 μm (PM2.5) is low. For example, as the most widely used dust removal device, electrostatic precipitator (ESP) can capture 99% large particles with particle diameter more than 10 μm, but for PM2.5 the efficiency is not high. In order to solve this problem, some scholars make the improvements on conventional dust removal devices to make fine particles agglomerate and grow up before entering conventional dust removal devices [3].

Acoustic agglomeration is a potential pretreatment technique [4]. Particles with different particle size distributions (PSDs) vibrate under different amplitudes in the sound field [5]. Relative motion between particles increases the collision probability. After a short time of colliding and agglomerating, the particle size distributions shift from smaller to larger sizes and the number and concentration of fine particles reduce. There are many advantages using acoustic agglomeration as pretreatment technology, such as simple structure, low cost, strong adjustability. This study is significant not only

for large coal-fired power plant boilers, but also for small and medium coal-fired industrial boilers and heating boilers.

Since the 1930, scholars have done lots of experimental research and numerical simulation on fine particles acoustic agglomeration, however, the conclusions are not totally consistent because of complex mechanisms and different experiment conditions. There are two main theories of mechanisms: orthokinetic interaction and hydrodynamic interaction. Orthokinetic interaction is that particles with different particle size distributions vibrate under different amplitudes due to inertia effect, which makes particles with different particle size distributions collide and agglomerate [6]. Hydrodynamic interaction can explain why the particles with the same size distributions can agglomerate [7]. There are 2 main factors frequency and sound pressure level (SPL) in acoustic agglomeration. Fahnoe used sound wave from 800 Hz to 5000 Hz to agglomerate NaCl aerosol with the average particle diameter of 1 µm and found the agglomeration efficiency increasing by adding steam [8]. Scott used sawtooth wave instead of sinusoid to agglomerate ZnO aerosol and it indicated that sawtooth wave was better [9]. Wang Jie used 1000~1800 Hz sound wave to agglomerate coal-fired ash with the particle diameter from 0.1~10 µm and found the optimal frequency at 1400 Hz [10]. Overall the investigated operating conditions are different, most particles are less than 10 µm [11-12]. However, large particles and fine particles are coexistent in actual coal-fired ash. The size range of coal-fired ash is 0~200 µm and most of particles usually present bimodal state in particles size distribution.

In this study, we dealt with the 3 kinds of particles with different particle size distributions to analyze the effects of removal efficiency Frequencies and SPLs were investigated to find the optimized condition for acoustic agglomeration.

2. Experimental method

2.1. Experimental setup

Figure 1 shows the experimental system, which consists of sound source, agglomeration chamber, particle feeding system, aerosol sampling and measurement system, dust removal device system. The agglomeration chamber was made of a vertical plexiglass with an inside diameter of 100 mm, a length of 1500 mm and wall thickness of 10 mm to obverse conveniently. The upper end of the agglomeration chamber was connected with a sound source, the lower end was connected with a sampling pool and dust removal device system. The acoustic source system consists of a computer, high power amplifier (MTC-300, Ma Safety Signal Co. Ltd., China) and high-power sound source (TD-300, Ma Safety Signal Co. Ltd., China). The commercial software SpectraLAB can issue different frequencies of sound waves with frequency from 0~6000 Hz and the SPL can be controlled by the high power amplifier. Sound-absorbing sponge was placed on the bottom of the agglomeration chamber in order to prevent the reflection.

Feeding system was composed of fan (SF-5), flowmeter and micro-feeder (DF-100, Dongfu Co. Ltd., China). In the experiment, particles were were mixed with air before into agglomeration chamber. The experimental feeding amount was 4.6 g/min to achieve required concentration of 20 g/m^3. The flow rate of the aerosols was 14 m3/h to ensure residence time of 3s. The experiments were carried out at 20 °C and RH 30%.
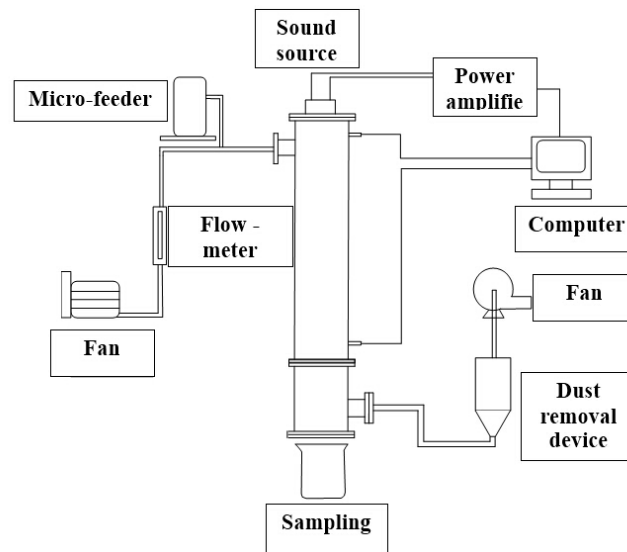
Figure 1. Schematic diagram of experimental facilities.

2.2. Particle size distribution

Three kinds of particles, named as particle α, particle β and particle γ, were studied to investigate the relationship between agglomeration efficiency and particles size distribution. The sizes and distribution of particles were analysed by Malvern laser particle size analyser (Mastersizer 3000) with measuring range 0~1000 μm. Figure 2 shows the analysis results of 3 size distributions of particles. The particles size ranges of α, β, γ were 0~10, 0~140, 0~170 μm. The average diameters were 1.885, 32.671 and 40.654 μm. The particles α were unimodal with peak at 2.555 μm. The particle β and γ were bimodal with peaks at 2.555, 65.285 μm and 25.169, 78.995 μm. Initially, particle size distribution of particles β and γ were bimodal, however, the size range and peak were different. In general, the particle size of particles γ were larger than particle β.
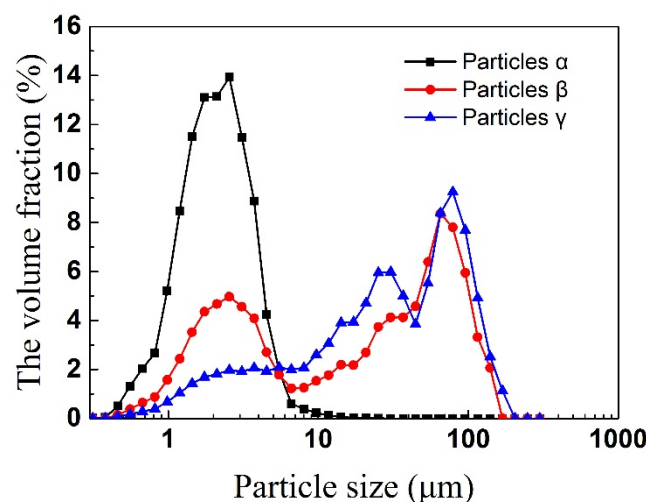

Figure 2. 3 Particles initial size distributions.

Agglomeration efficiency, η used to evaluate the agglomeration rate in this study, can be calculated by Eq. (1).

$$\eta = \frac{N_0 - N_1}{N_0} \times 100\%$$ (1)

Where N_0 and N_1 are the volume fraction of the aerosol at the initial stage and after agglomeration, respectively.

3. Results and discussion

3.1. Influence of acoustic frequency on agglomeration efficiency
To investigate the influence of acoustic frequency on agglomeration efficiency, acoustic frequency varies from 800 Hz to 1800 Hz, the other conditions are SPL 140 dB, resistance time 3s, initial concentration 20 g/m^3.
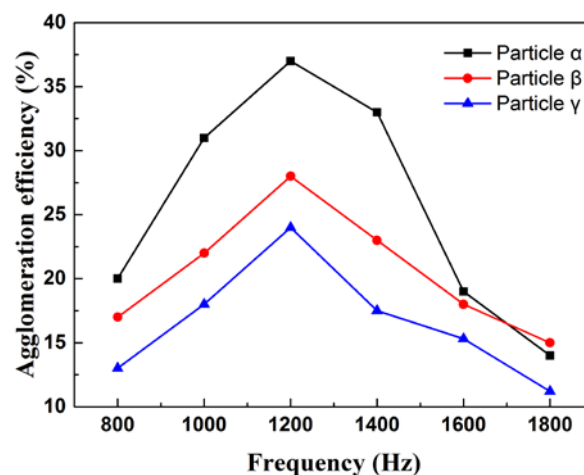

Figure 3. Agglomeration efficiency of particles at different frequencies.

Figure 3 shows the results of this experiment. We can see that the agglomeration efficiency increases with the frequency increasing and then decreases and each optimal frequency is same. In the sound field, particle size distribution of fine particle is the main factor affecting entrainment coefficient. Entrainment coefficient is small for fine particle and large for big particle because of the inertia. A higher relative entrainment coefficient means a larger relative motion between different particles. The larger relative motion promotes the probability of collision and it is positive for agglomeration. For coal-fired ash, the inertia effect of particles below 10 μm, especially 2.5 μm is small and these particles directly affect the optimum frequency of agglomeration.

3.2. Influence of SPL on agglomeration efficiency
Figure 4 shows the influence of SPL on agglomeration efficiency at 1200 Hz and a residence time of 3 s. For the unimodal particles α, It can be seen that agglomeration efficiency increases with the increasing of the SPL. The agglomeration efficiency reaches 38% at 140 dB. To get a considerable agglomeration efficiency, the SPL is required to 140 dB at least for the unimodal particles. It can be seen generally, with the increasing of the SPL, the agglomeration efficiency increases. When the SPL is 150 dB or higher, the agglomeration efficiency can be 50% to 60%.

However, the agglomeration efficiencies of bimodal particle is different from the unimodal particle. The agglomeration efficiencies increase first and then decrease with the increasing of SPL for particle

β and γ. The agglomeration efficiencies of particles β and γ can be 57% and 25% at 120 dB and 115 dB. The initial concentration of the particles is one of the important factors affecting the agglomeration efficiency. The volume fraction of particles below 10 μm is 40% for particles β, about twice as much as particles γ so that agglomeration efficiency of particles γ is lower than particles β.
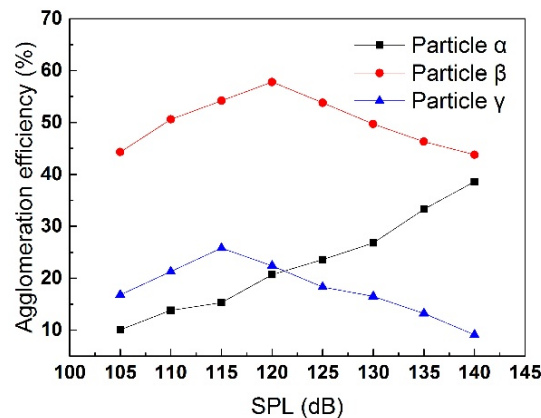

Figure 4. Agglomeration efficiency of particles at different SPLs.
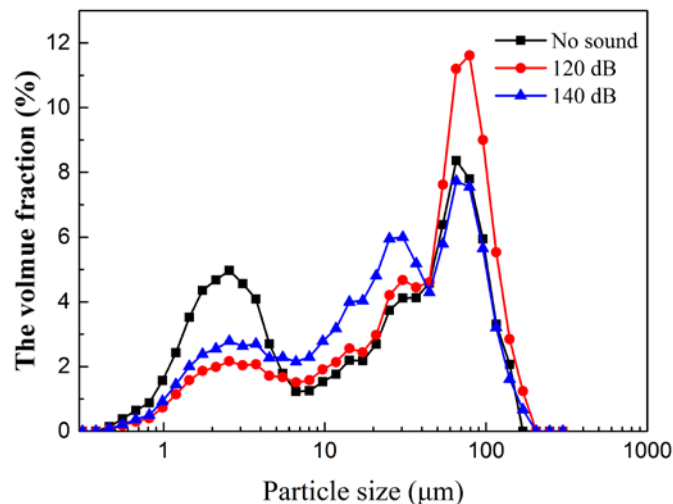

Figure 5. Particle β size distribution at different SPLs.

For the unimodal particles α, the agglomeration efficiency is high at high SPL because the sizes of most agglomerated particles are still less than 20 μm. However, the agglomeration efficiency of the bimodal particles β and γ are different. Figure 5 shows the particles β size distribution at different SPL. The particles around the second peak at 60 μm act as the agglomeration nucleus and the fine particles are agglomerated to the large particles with the size 60~120 μm at 120 dB. However, the amount of particles with the size 60~120 μm is close to the initial and the amount of particles with the 20~30 μm increases at 140 dB. It means the agglomerated particles with 60~120 μm are fragmentation at 140 dB. The particles around 20~30 μm act as the new agglomeration nucleus and fine particles restart to agglomerate at 140 dB. Although it still trends to agglomeration, the agglomeration efficiency at 140 dB is far less than at 120 dB.

4. Conclusions

This paper briefly introduced the experiment and studied the influence of acoustic frequency and SPL with different particles. It is indicated that agglomeration efficiency is sensitive. A considerable effectiveness of agglomeration could only be obtained in a narrow frequency range and it decreases significantly beyond the range. The optimal frequency in this paper is 1200 Hz. The agglomeration efficiency of inhalable particles increases with SPL increasing for the unimodal particles with particle diameter less than 10μm. However, there exists an optimal SPL for bimodal particles, which in this article is about 120 dB. If SPL is higher, the agglomeration efficiency will decrease because of agglomerated particles fragmentation.

Acknowledgement

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