Study on Agglomeration of Ultrafine Droplet Particles by Acoustic Air-jet Generators

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Abstract. Acoustic agglomeration is a potential technology for fine particle pretreatment, but the high energy consumption restricts its industrial application. In order to develop a reliable sound source with low energy consumption, acoustic air-jet generators with frequencies ranging from 3 kHz to 8 kHz are adopted to study on the agglomeration effect of ultrafine droplet particles. The influences of frequency, flow rate and initial particle concentration on agglomeration efficiency are experimentally investigated. The results show that the acoustic frequency is a crucial factor for the agglomeration efficiency. The agglomeration efficiency of ultrafine droplet particles is higher than 55% at an optimal frequency of 6 kHz. The probability of collision between droplets increases with the increase of the initial mass concentration, which favors aerosol agglomeration. Moreover, it is shown that the sound pressure level increases with the increase of flow rate of compressed air.

1. Introduction
Generally, numerous industrial mist droplet aerosols could not be captured effectively, which induces some drawbacks in environmental pollution and waste of valuable substance. For example, the limestone-gypsum wet flue gas desulphurization technology is widely applied in coal-fired power plants for its unique advantages in low input costs, stable operation, and high desulfurization efficiency. However, it should be noted that the coal-fired gas is usually water-saturated through the wet desulfurization process. Commonly, the gas without proper treatment is considered to be an unneglectable reason for “gypsum rain” or acid rain, resulting in environmental pollution. The conventional particle filtering devices are inefficient for retaining particles smaller than 20 μm[1]. Moreover, the device will be clogged or corroded with the reason of water pressure, flue gas velocity, the cycle of backwashing, and so on. Therefore, we urgently need to find a reliable and effective technology to remove the droplet particles quickly.

Acoustic agglomeration is an aerosol preconditioning process in which intense sound waves promote relative motions and collisions of aerosol particles. It can significantly turn smaller aerosol particles into larger ones to enhance the performance of conventional filtering devices. A lot of theoretical works have been done on acoustic agglomeration by scholars all over the world. The process of acoustic agglomeration is complex but scholars think orthokinetic interaction[2] and acoustic wake effect[3, 4] play an important role in acoustic agglomeration. Orthokinetic interaction is based on the fact that different size particles enter the sound field at different rates, leading to the relative movement of them[5]. Small
particles will stick to big particles after relative movement and collisions and turns into larger ones. The acoustic wake effect is based on the disturbance of particles toward the flow field which results in a low-pressure wake behind the particles. If the other particles travel in this acoustic wake, it moves towards to the leading one with accelerated motion in a reduced resistance flow field. As a consequence, the two particles converge within a short time and eventually collide.

Acoustic agglomeration technology is mainly used in flue gas pretreatment which can promote the dust removal efficiency of fine particles and reduce the emission of PM$_{2.5}$ [6]. And this technology has been used in airport de-icing to improve the visibility [7]. It is also applied to the recovery of sulfuric acid aerosol particles and sodium carbonate particles in sulfuric acid plants and paper mills [8]. Electrically driven transducer is widely applied in the experiments of acoustic agglomeration by scholars in domestic and overseas because of its convenient adjustment. Based on this, the experts got a lot of experimental results. Guangxue Zhang [6] studied the agglomeration experiment of coal-fired fly ash and investigated that the best agglomeration frequency of the fly ash particles was 1400-1600 Hz which was verified by simulation. Michael Volk [9] noticed the best agglomeration frequency of carbon aerosol particles is 3 kHz by exploring its behavior in the sound field. The frequency of 20 kHz is the better selection than 10 kHz for fluidized bed smoke [10]. Guangxue Zhang [11] performed an experimental investigation of acoustic agglomeration with the initial concentration and found that the acoustic agglomeration efficiency had a positive correlation with initial particle concentration. Yubo Kang [12] collected aerosol particles with a diameter of less than 100nm from combustion and studied the effect of acoustic agglomeration on it. And then, he obtained the same result as Guangxue Zhang. Shuangquan Hou [13] experimented to disperse the water mist with low frequency sound waves, and the result showed that the low frequency sound waves with high sound intensity can promote the agglomeration effect of sound waves on water mist. Ph. Capéran [14] studied ethylene glycol mist by two different frequencies of sound field, and found that the agglomeration rate is positively correlated with the square of acoustic amplitude. In addition, some scholars have added “additives” to the sound field in order to obtain better agglomeration efficiency. Jie Wang [15] added seed particles to the coal-fired fly ash aerosol, which promoted the agglomeration efficiency by 15.5%. Guangxue Zhang [16] significantly improved acoustic agglomeration of fine particles by droplet spray.

At present, sound energy in experimental study of acoustic agglomeration is converted from electromagnetic energy. Significant agglomeration efficiency obtained by the laboratory studies, but the low electro-acoustic conversion efficiency of transducer cannot be ignored. It requires a lot of energy, and the equipment is easy to be damaged in high temperature environment, which limits its industrial applications. Therefore, it’s necessary to develop reliable high-power sound sources suitable for industrial environments. Comparatively speaking, the air sound conversion efficiency of acoustic air-jet generators can reach 80% [17] and it can adapt to the hostile environments which is an appropriate industrial sound source. There exist high-power acoustic air-jet generators at present. Such as the hooter, whose sound produced by the compressed air blowing the reed or the film vibrates, the siren cuts the airflow quickly by the rotating body to make the air vibrate and produce the sound, and the Hartmann whistle uses the impact of airflow on the periodic variation of the cavity. So the use of acoustic air-jet generators for acoustic agglomeration is almost the only feasible technical path to promote the technology to industrial application. However, there are no experimental reports on the use of acoustic air-jet generators for acoustic agglomeration up to now.

In this paper, the agglomeration experiment system of acoustic air-jet generators was built to study the influence of several key factors (acoustic frequency, flow rate of generators, and initial concentration of aerosol) on the agglomeration efficiency of ultra-fine droplets, which can provide reference for the industrial application of acoustic air-jet generators.

2. Experimental setup

2.1 Experimental systems and equipment
The experimental system is shown in Figure 1. The main body of the agglomeration chamber is a
cylindrical structure made of organic glass with an inner diameter of 100 mm and a length of 700 mm. The small hole near the bottom serves as the inlet for compressed air. The agglomeration chamber has a high transmittance which allows most of the light to pass through. And the bottom is a rigid reflecting surface, which can effectively reflect the sound waves and promote the utilization efficiency.

The ultrafine droplets produced by the ultrasonic atomizer pass through the agglomeration chamber under the action of a vacuum pump. The air pump supplies the compressed air to the acoustic air-jet generators which emits a SPL (sound pressure level) of up to 135 dB. The ultrafine droplet particles agglomerate under the continuous action of the sound pressure of the intense SPL of the acoustic air-jet generators, and the measurement is performed after the working condition is stable.

2.2 Features of the acoustic air-jet generators
The cylindrical acoustic air-jet generator is showed in Figure 2. The inlet of compressed air is on the top of acoustic air-jet generator, and an annular nozzle, formed by the round baffle and the wall, is located on the middle part. Moreover, the resonance chamber is located between the bottom and the annular nozzle and serves as the place to generate sound. The compressed air accelerates through the annular nozzle and rapidly enters the chamber which produces impact force. The center baffle added into the device connecting the round baffle with the bottom to enhance the support and improve the vocal efficiency.

The main frequency of the air-jet generators is determined by its cavity depth and diameter. Six different air-jet generators with frequencies ranging from 3 to 8 kHz designed according to the empirical formula (1). The SPL in the agglomeration room can reach 135 dB when the flow rate driven by the sound source exceeds a certain value, which can meet the requirements of experiment for high SPL.
where \( c \) is the speed of sound, \( L \) is the depth of the resonance chamber, and \( d \) is the diameter of the device.

The results of spectrum analysis of the air-jet generators are shown in Figure 3. It can be seen that the sound is strong at the design frequency. Taking Figure 3 (a) as an example, it can be seen that the SPL of the sound source exceeds 120 dB at a frequency of about 3 kHz, and there is also a distinct peak at the frequency of 6 kHz (twice as the fundamental frequency), but its SPL is only 80 dB, which is far lower than the frequency of 3 kHz. In summary, the main SPL of the acoustic air-jet generator is concentrated on 3 kHz.
2.3 Calculation of the agglomeration efficiency

The ultrafine droplet particle concentration is obtained by the light transmittance test method. The light is from the laser with a power of 60 mW and a wavelength of 650 nm, and the ultrafine droplet particle transmissivity \( T_a \) was calculated based on the attenuation of the laser beam, given by

\[
T_a = \frac{I_a}{I_0} \times 100\%
\]

where \( I_a \) is the light intensity through the ultrafine droplet particle when the sound wave acted, and \( I_0 \) is incident light intensity.

In order to eliminate the effect of compressed air dilution, a comparative test was added. The light intensity of the mixed compressed air and ultrafine droplet particles was measured, and the new light transmittance \( T_0 \) was obtained. The calculation formula is as follows:

\[
T_0 = \frac{I_{a'}}{I_0} \times 100\%
\]

where \( T_0 \) is the light transmittance of the ultrafine droplet particles in the agglomeration chamber with only compressed air acted, and \( I_{a'} \) is the light intensity when the only equal flow of compressed air flows through particles.

According to Lambert-beer’s law, the relationship between the transmittance of aerosol particles and the volume fraction of the particles gained by Manoucheri\(^{[19]} \), based on this, the agglomeration efficiency \( (\eta) \) was calculated by

\[
\eta = 1 - \frac{V_a}{V_0} = 1 - \frac{\ln(T_a)}{\ln(T_0)}
\]

where \( V_a \) is the volume fraction of ultrafine droplet particles in the agglomeration chamber under the action of sound waves, and \( V_0 \) is the volume fraction of the ultrafine droplet particles in the agglomeration chamber when only the equal flow compressed air is passed.

3. Results and discussion

3.1 Tests of Acoustic air-jet generators and ultrafine droplet particle

The particle size distribution of the ultrafine droplets was measured by the FA-3 impactor (with a sampling range from 0.43 \( \mu \)m to 10 \( \mu \)m). The equipment has an aluminum alloy disc with a decreasing order of eight-stage orifice diameter and a filter plate. The measured particles are pumped into the
device by the air pump, and the air velocity will increase as the size of the nozzle decreases. Different sizes of particles will impinge on the corresponding acquisition board with the action of inertia, and the submicron level particles are finally captured by the filter. Every stage of the acquisition board can be weighted to obtain the particle mass of each stage.

The mass data in 10 min was extracted from the ultrafine droplets by the impactor at a sampling speed of 10 L/min, and the mass data was processed to obtain the particle size distribution map of the ultrafine droplets as shown in Figure 4. It can be seen from the distribution map that the particle size of the ultrafine droplet particles is between 1-10 \( \mu \text{m} \), and the fine ultrafine droplets particles whose diameters are below 4 \( \mu \text{m} \) accounted for the main specific gravity.

![Figure 4. Particle size distribution of ultrafine droplet particles.](image)

Figure 5 shows the relationship between the SPL and air flow or air pressure. It can be seen that the SPL of air-jet generators increases with the bigger air flow. And the SPL of six air-jet generators can reach 125 dB, some well-performing devices even get the high SPL of 130 dB. Different devices correspond to different frequencies of sound waves, and the SPL is changed by adjusting the air flow.

![Figure 5. Effect of flow and pressure on SPL.](image)

(a) The effect of air pressure on SPL.  
(b) The effect of flow on SPL.

3.2 Influence of frequency sound on agglomeration effect

Figure 6 shows the agglomeration effect of an aerosol under the effect of frequency which is from 3 kHz to 8 kHz with the mass concentrations of 100 g/m³. Six types of air-jet generators were used in the acoustic agglomeration, and the experimental result shows that, comparing to the other frequencies, the air-jet generator of 6 kHz has the most significant effect on enhancing the agglomeration efficiency, even if at different flow rates. A reduction of 56% in total number concentration is gained by 6 kHz.
under the flow rate of 58 L/min, which is obviously greater than the elimination efficiency of 45% by 8 kHz.

As mentioned above, the acoustic agglomeration is mainly based on the orthokinetic interaction and the acoustic wake effect. The ultrafine droplet particles of different sizes correspond to their optimal frequencies under the agglomeration by the movement in the same direction, and the agglomeration efficiency will be reduced by the deviation from the optimal frequency. Moreover, the ultrafine droplet particles under the action of the sound field are also subjected to the entrainment of sound waves, which will regularly reciprocate under the action of the sound waves. And the entrainment effects of different particle sizes are different which causes a speed difference between the particles, eventually the collision of particles. Theoretically, there should be an optimal agglomeration frequency to achieve the optimal agglomeration effect. And the optimal frequency of aerosol agglomeration gained by equation (5).

$$f_{op} = \frac{9\sqrt{3} \eta}{4\pi\rho_p a^2}$$

where \( \eta \) is the gas viscosity coefficient, \( \rho_p \) is the density of the particles, and \( a \) is the radius of the particles.

![Figure 6. Effect of frequency on agglomeration efficiency.](image)

3.3 Influence of initial concentration on agglomeration
The gas flow rate is fixed at 75 L/min, exploring the influence of initial concentration sound on agglomeration. The result shows that the acoustic agglomeration efficiency has a positive correlation with initial particle concentration. The initial particle concentration increased from 18 g/m3 to 64 g/m3, and the agglomeration efficiency of the 3 kHz increased from 25% to 52%. At the same time, we can find that it is obvious to improve the agglomeration effect by the increase of initial concentration for the low concentration particles.

The initial concentration represents the number of particles in the unit volume. The initial concentration was positively correlated with the number of particles and negatively correlated with the relative distance between particles. And it improves the probability of collision between the ultrafine droplet particles under the action of sound waves. The aggregates will play the role of collecting core in the sound field because of their big volume and mass. It will easily collide with small particles and adsorb them on the surface, which promote the agglomeration efficiency [20].

In the numerical calculation of aerosol particles, the agglomeration kernel function is often used to describe the probability of collision between two particles, defined as the occurrence of unit time between two particles per unit volume and unit particle number density. The function can be expressed as
where $K_{ij}$ is the agglomerated kernel function between particle i and particle j, $f$ is the acoustic frequency, and $d_i$ and $d_j$ represent the diameters of the two particles.

The number of particle agglomeration per unit time can be expressed by equation (7):

$$dN = K_{ij} \times N'_i \times N'_j$$

where $dN$ represents the number of agglomerations in two particles per unit time, the particle number concentration of particle i and particle j are represented by $N'_i$ and $N'_j$.

3.4 Influence of the air flow rate on agglomeration

In this experiment, the air flow of the air-jet generators will dilute the concentration of the ultrafine droplet particles, and it also determines the SPL. Therefore, the influence of the gas flow rate on the agglomeration efficiency is important. Figure 8 shows the effect of air flow rate on agglomeration efficiency when acoustic waves are applied at different frequencies. It can be seen from the Figure 8 that at various acoustic frequencies, the acoustic agglomeration efficiency has a positive correlation with air flow rate. It is worth noting that at the condition of $3 \, \text{kHz}$, with the increase of gas flow rate, the growth rate of agglomeration efficiency is significantly higher than that of other conditions. This is because the frequency spectrum is shifted to $6 \, \text{kHz}$ as shown in the Figure 3(a) with the flow rate increased, which significantly improves the agglomeration efficiency.

As can be seen from Figure 4(b), the SPL becomes larger as the flow rate increases and the gas medium in the agglomeration chamber also oscillates. The ultrafine droplet particles will oscillate accordingly because of the viscous force of the gas. Compared with small particles, the large particles whose inertial are large will be slightly affected by this. Relative motion occurs in the particles, and then they collide into the aggregates.

Agglomeration volume is the collision area of the large particles with the small particles in orthokinetic interaction, which is viewed as cylindrical region. The agglomeration volume is related to the diameter and amplitude of the particles size, specifically expressed as

$$V_{ij} = \pi \left(\frac{d_i + d_j}{2}\right)^2 \times \frac{u_0}{\omega} \mu_{ij}$$

where $V_{ij}$ represents the volume of the agglomerate, $d_i$ and $d_j$ are the diameter of the two particles respectively, $u_0$ is the amplitude of the medium vibration, and $\omega$ is the angular frequency, $\mu_0$ indicating the relative carrying coefficient of particle i and particle j.
The sound agglomeration efficiency has a positive correlation with SPL, but the high SPL also represents the high intensity energy, and the energy consumption increases sharply with the increase of the SPL. Moreover, after the SPL reaches a certain level, the increase of the SPL slows down. The income and high energy consumption are not proportional. Therefore, the relationship between energy consumption and agglomeration efficiency should be coordinated to obtain the best economic benefits in industrial applications.

![Figure 8. Effect of flow on agglomeration efficiency.](image)

4. Conclusions
In this experiment, the agglomeration experimental system was built to verify the effect of air-jet generators on agglomeration of ultrafine droplets. The effects of acoustic frequency, initial concentration and compressed air flow rate on agglomeration efficiency were studied.

1. In this experiment, the ultrafine droplets have the highest agglomeration efficiency at the frequency of 6 kHz, and the agglomeration efficiency of the other five frequencies is significantly lower, indicating there is a direct relationship between the agglomeration efficiency and frequency of the sound wave.
2. In the range of the initial concentration of ultrafine droplets from 40 g/m3 to 140 g/m3, the collision efficiency between the particles increases with the increasing of initial concentration, and the agglomeration effect is significantly improved.
3. Similar to sound pressure level, agglomeration is enhanced as the compressed air flow rate increases. Stronger relative action is gained by the increasing flow rate, and it also favors the vibration amplitude of particles, increases the collision probability between particles which cause the significant improvement in the sound agglomeration effect.

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