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Review

Experimental study of acoustic agglomeration and fragmentation on coal-fired ash with different particle size distribution

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ABSTRACT

As the major constituent of air pollution, inhalable particles, especially the fine particles are inflicting great harm on human health due to their small particle size and absorption of hazardous components on them. However, the current conventional devices used for removing these particles suffer from low removal efficiency. Acoustic agglomeration is considered as a very effective pre-treatment technique for removing fine particles. Fine particles can agglomerate and grow to form large particles in the sound field, which can be easily removed by conventional particle removing devices. In this paper, the acoustic agglomeration and fragmentation of three different kinds of particles with different size distributions were experimentally studied. The fragmentation of agglomerates was calculated using the agglomerates forces. It was found that the particle size distribution and the volume fraction of fine particles affected the agglomeration efficiency. For unimodal particles having a narrow size range, higher the sound pressure level (SPL), greater was the agglomeration efficiency. However, there existed the optimal SPLs at 115 dB and 120 dB with 25% and 55% agglomeration efficiency (respectively) for bimodal particles with a wide size range. A desirable agglomeration could only be obtained in a narrow SPL range, while the agglomeration efficiency decreased significantly over the range due to the fragmentation of agglomerates. The fragments of agglomerates started to agglomerate again, though the new agglomerates were smaller than the previous agglomerates obtained at higher SPL. The spraying of water droplets can improve the agglomeration efficiency while avoiding the fragmentation of agglomerates for the bimodal particles with a wide particle size range.

Contents

1. Introduction

With the rapid economic development, air pollution has drawn significant public attention [1]. As one of the major air pollution types, particulate pollution is mainly caused by fossil fuel combustion, automobile exhaust, cement, iron and steel manufacturing, and other industrial activities [2–5]. Inhalable particles (PM10), especially the fine particles (PM2.5), are reported to be significantly harmful to human health and environment [6]. Fine particles (PM2.5) can contain large number of hazardous materials, including heavy metals, organics and viruses, and can be transported deeper into alveolar even into the capillaries due to their ultra-small aerodynamic diameter [7]. The conventional particle removing devices, such as electrostatic precipitators, cyclone separators and bag filters, suffer from low removal efficiencies and high cost. However, this can be improved, if a particle pre-treatment technique is employed before they are removed.

Acoustic agglomeration is considered as a very effective pre-treatment technique for removing fine particles [8]. High-intensity

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sound wave promotes the relative motion of particles due to different amplitudes. After colliding and agglomerating, the particle size distributions shift from small to large sizes, and the number and concentration of fine particles are reduced. Acoustic agglomeration was first proposed by Patterson in 1931, with the finding that the fine particles in sound field would enlarge [9]. Subsequently, various experimental studies, numerous computational simulations and theoretical works had indicated that particles with small size distributions shifted to the large size distributions. Orthokinetic interaction is the theory first proposed by Mednikov and widely recognized as the main mechanism for the change in size distribution [10]. It can explain the agglomeration of particles with different sizes, however fails to explain the agglomeration of particles having the same size [11]. Therefore, the hydrodynamic interaction mechanism was proposed to describe the agglomeration of particles having the same size [12,13]. However, the results from experimental studies published in literature are not consistent [14]. The differences in experimental conditions result in different values of various factors, such as the frequency, and sound pressure level (SPL). Fahnoe used sound waves from 800 Hz to 5000 Hz to agglomerate NaCl aerosol with the average particle diameter of 1 μm, and found that the agglomeration efficiency increased after the addition of steam [15]. Scott used sawtooth wave instead of the sinusoid to agglomerate ZnO aerosol, and found that the sawtooth wave was better than the sinusoidal [16]. Volk studied the effects of frequency, sound pressure level, initial concentration and residence time using carbon black aerosol with the particle diameter of 0.1–1 μm, and determined the peak efficiency at 3000 Hz and 120 dB [17]. Shaw compared the low frequency (1–3000 Hz) with high frequency (10–20 kHz), and showed that low frequency was better for the agglomeration of particles because of severe sound attenuation in high frequency [18]. Komarov utilized Zn with the particle diameter of 0.1–80 μm at 1173 K, and found that the optimal frequencies were 210 and 991 Hz with the efficiency values of 50% and 60%, respectively [19].Wang used 1000–1800 Hz sound wave to agglomerate coal-fired ash with the particle diameter of 0.1–10 μm, and found that the optimal frequency was 1400 Hz [20]. Besides, many scholars improved the acoustic agglomeration by combining it with other methods, such as the vapor condensation [21].

Overall, many scholars have done extensive research on the particles with the size of <10 μm [22,23], and showed the effectiveness of sound waves. However, in the actual industrial practice, fine particles having the size of <10 μm coexist with large particles. For example, the size of most coal-fired ash particle is 0–200 μm, which presents bimodal distribution of particles with peaks at 0–10 μm and 20–80 μm. The positions of peaks are different due to the differences in combustion conditions and types of coal. There is little research on effect of sound waves on the agglomeration of particles having a large particle size distribution. Moreover, unlike small particles, when acoustic pressure force, gravity, and other external forces are greater than the agglomeration force, large particles are fragmented [24,25].

Against this background, in this paper, the effects of SPL and particle size distribution on the acoustic agglomeration and fragmentation were investigated. The force analysis was performed on the agglomerates to explain their fragmentation. The spraying of water droplets can promote the agglomeration efficiency, and prevent the fragmentation of agglomerates. It is expected that the results would shed some light on the use of sound waves in treating particles in various industrial applications.

2. Experimental

Fig. 1 shows the schematic of the experimental setup, which consists of the sound source, agglomeration chamber, particle feeding system, aerosol sampling and measurement system, and dust removal system. The agglomeration chamber was made of a vertical plexiglass with the internal diameter of 100 mm, length of 1500 mm and wall thickness of 10 mm. The upper end of the agglomeration chamber was connected to the sound source, while the lower end was connected to the sampling pool and dust removal system. The acoustic source system consisted 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 computer controlled power amplifier can generate sound waves with the frequency varying from 0 to 6000 Hz and maximum SPL at 140 dB. Furthermore, a sound-absorbing sponge was placed at the bottom of the agglomeration chamber to prevent reflection. It was found that the attenuation of SPL along the agglomeration chamber was <1 dB, and therefore, was neglected in the current study.

The feeding system was composed of a fan (SF-5; Shunfu Co., Ltd., China), a flowmeter and a micro-feeder (DF-100; Dongfu Co., Ltd., China). During the experiments, particles were mixed with air before entering the agglomeration chamber. The feeding rate was 4.6 $g \cdot min^{-1}$, while the concentration was 20 $g \cdot m^{-3}$. A spraying nozzle was placed at the entrance of agglomeration chamber to spray water droplets with the size of 30 μm. The flow rate of aerosols was maintained at 14 $m^3 \cdot h^{-1}$ to ensure the residence time of 3 s. The experiments were carried out at 20 °C and relative humidity (RH) of 30%.

Three kinds of particles, namely the α particle, β particle, and γ particle, were studied to investigate the relationship between the agglomeration efficiency and the particles size distribution. Coarse particles were removed using a cyclone with the cut-off diameter of 10 μm prior for α particles. The β and γ particles were the original coal-fired ash particles. The sizes and distribution of particles were analysed using Malvern laser particle size analyser (Mastersizer 2000). Fig. 2 shows the results of size distribution of three types of particles. The particle size ranges of α, β, and γ particles were 0–10, 0–140, and 0–170 μm, respectively. The average diameters were found to be 1.885 (α particles), 32.671 (β particles) and 40.654 μm (γ particles) for the three types of particles. The α particles were unimodal with the peak at 2.555 μm. The β and γ particles were bimodal with peaks at 2.555 and 65.285 μm, and 25.169 and 78.995 μm, respectively. In comparison, the range of particle size for α particles (0–10 μm) was narrower than those for β (0–140 μm) and γ (0–170 μm) particles. Furthermore, the particle size distributions of β and γ particles were bimodal, although the size ranges and peaks were different for both the classifications.

3. Theoretical analysis

In the sound field, the forces on particles are complex and consist of gravity, drag force, van der Waals force, acoustic pressure force, and liquid bridge force. The particle will vibrate and the vibration lags behind the carrier medium. According to the acoustic entrainment theory and acoustic theory, the particle's motion is represented by Eq. (1) [26].

$$u_p = \mu_p u_0 \sin(\omega t - \varphi) \tag{1}$$

where u_p is the velocity amplitude of particle, u_0 is the velocity amplitude of the gas medium, ω is the angular frequency of sound wave, and μ_p is the particle entrainment coefficient, which is given by Eq. (2) [27].

$$\mu_p = \frac{1}{\sqrt{1+\omega^2 {\tau_d}^2}} \tag{2}$$

where τ_d is the particle's dynamic relaxation time, and is given by Eq. (3) [28].

$$\tau_d = \frac{\rho_p d^2}{18 \nu \rho_g} \tag{3}$$

where ρ_p and ρ_g are the densities of particle and gas medium, respectively, ν is the kinematic viscosity, and d is the diameter of particle.

According to Eq. (1) and Eq. (2), the particles vibrate in the sound field. In the sound field, the particle size distribution of fine particles is the main factor influencing the entrainment coefficient. The entrainment