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Improving acoustic agglomeration efficiency by addition of sprayed liquid droplets

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ABSTRACT

Acoustic agglomeration is a potential pretreatment technology for industrial flue gas to efficiently reduce particulate matter emission. However, the process requires a huge amount of energy input, which restricts its commercial industry application. In order to reduce the energy requirement, the spraying of liquid droplets into the aerosol is proposed in this study. It is thought that the droplets sprayed would improve the acoustic agglomeration process through two mechanisms: 1) increasing the adhesion factor due to the formation of liquid bridge forces between particles; and 2) as seed particles, which enhance the relative movement between particles and then increase the collision probability. The experimental results in this study show that the acoustic agglomeration efficiency can be greatly improved by up to 55% with the assistance of water spray droplets. It is also found that the influence of acoustic frequency on agglomeration efficiency basically remains unchanged regardless of the existence of spray droplets, and an optimum frequency corresponding to the highest agglomeration efficiencies exists. The only difference is that when frequency deviates from the optimum value, the agglomeration efficiency drops less sharply with the presence of the water spray than that without it. The agglomeration efficiency increases significantly with the increase of the liquid-gas ratio, up to 80% at liquid-gas ratios above 0.13. For pure acoustic agglomeration, the sound pressure level required for a 50% agglomeration efficiency is 146 dB, while the efficiency could achieve 55%–73% with water sprayed at only 140 dB, saving approximately three-quarters of energy consumption. The performance of two wetting agencies (SDS and TX100) in acoustic agglomeration is also tested, which could make a further increase of agglomeration efficiency by 5%–20% comparing to that using pure water. The results show that the optimum concentrations of SDS and TX100 solutions are 0.2% and 0.05%, respectively, corresponding to the minimum surface tension and contact angle.

1. Introduction

Fine particles suspended in the air, especially $PM_{2.5}$ (particles with aerodynamic diameters <2.5 μm), are seriously harmful to human health because their huge surfaces are concentrated with heavy metals, organics and viruses [1,2]. Particulate matter has been regarded as the major air pollutant in recent years in many countries [3,4]. Dust filters, including electrostatic precipitators, cyclone separators and baghouse filters, have been widely applied in industrial processes. However, the common problem is that these filters are inefficient for $PM_{2.5}$. For example, the total dust removal efficiency of an electrostatic precipitator can usually reach 97% to 99%, while it drops to 70% to 90% [5–7] for $PM_{2.5}$. As a result, a large number of fine particles are still emitted into the atmosphere in industrial processes despite the application of dust filters.

One possible way to increase the removal efficiencies of $PM_{2.5}$ is to pretreat the $PM_{2.5}$ particles by agglomerating them into larger ones before entering the dust filters [8]. Acoustic agglomeration is one of these pretreatment technologies. With the effect of sound, relative motion between particles is produced and their collision rate increases significantly. Once the particles collide, they are very likely to adhere together to form larger ones due to the van der Waals force, capillary force and electrostatic force. After the pretreatment of acoustic agglomeration, the $PM_{2.5}$ number concentration in an aerosol is normally reduced and the particle size distribution shifts towards a larger size. According to the experimental studies, $PM_{2.5}$ can decrease by >70% in an acoustic agglomeration process under appropriate operating conditions [9]. As a consequence, the $PM_{2.5}$ removal efficiency of the subsequent dust conventional filter followed can then be improved from 80% to 97% [10].

The acoustic agglomeration technology has been widely researched in recent decades. The optimum operating conditions, especially the optimum sound frequencies, have been obtained for various industrial flue

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gases. Experimental results have demonstrated that the optimum frequency is determined by the aerosol's initial size distribution, and it increases as the particle size decreases. For coal-fired flue gas, which contains submicron and micron particles, sound with frequencies of 1 to 3 kHz is favorable [9,11]. For exhaust gases of internal combustion engines containing nanometer particles, however, ultrasound with high frequencies of 10 to 30 kHz is more efficient [8,12]. In addition to experimental studies, several mechanisms of acoustic agglomeration have been proposed [13,14]. It is generally considered that the most significant mechanisms are orthokinetic interaction and hydrodynamic interactions [15]. Orthokinetic interaction is the dominant mechanism of acoustic agglomeration of dispersed aerosols [16]. According to this mechanism, particles of different sizes are entrained at different rates, defined as entrainment coefficients, into the oscillation motion of gas medium for their different inertias. The relative motion between big and small particles causes them to approach, collide and finally adhere together. The other important mechanisms, hydrodynamic interactions, are proposed to explain acoustic agglomeration of monodisperse aerosols [17]. In this process, orthokinetic interaction does not work due to the lack of relative motion between particles with the same size. Hydrodynamic interactions are those which produce particle interactions through the surrounding medium due to hydrodynamic forces and the asymmetry of the flow field around the particles [18]. Such mechanisms can take effect from distances larger than the acoustic displacements and are still available for the same sized particles.

Remarkably high agglomeration efficiency of fine particles using acoustic agglomeration technology has already been obtained in laboratories [9]. However, a high-intensity sound field with a sound pressure level (SPL) above 150 dB is typically required to produce efficient agglomeration in several seconds. A huge amount of energy is required to generate such a sound field at the required SPL and noise pollution is a by-product of the process. Thus the development of this technology into an industrial application is restricted. In order to achieve considerable agglomeration efficiency in a sound field of moderate intensity, some researchers proposed methods of adding external effects coupling with sound. The additions of external effects include seed particles with sizes larger than 20 μm [19], steam [12], and sprayed liquid droplets [20]. Steam and water are usually easy to obtain and are low in cost in most industry processes, which makes these methods more feasible for further industrial applications.

Sarabia [12,21] experimentally studied the effect of water vapor on the acoustic agglomeration of diesel exhaust nanometer particles at 21 kHz, and found that the presence of 6% humidity raised the agglomeration rate by up to 56%. In comparison, there was only an agglomeration rate of 25% without water vapor. Recently, Yan [22] studied the influence of steam on the acoustic agglomeration of coal-fired flue gas at 1800 Hz. The results showed that the removal efficiency of particles increased by nearly 50%, with the addition of steam at supersaturation degrees above 1.0. A removal efficiency of 70% was finally obtained with the combined effect of sound and steam at a SPL of only 130 dB.

Similar to steam, the addition of sprayed liquid droplets is also found to be effective to improve the acoustic agglomeration rate. Chen [23] researched the effect of water droplets on the acoustic agglomeration of coal-fired fly ash at 1000 Hz, and the agglomeration rate rose by 20%. Furthermore, sprayed liquid droplets of several kinds of wetting agents were added in the sound field to enhance the agglomeration rate, and it was indicated that the fine particle removal efficiency increased as the wettability of the wetting agent on particles was increased [22].

The method of combining a sound field and spray droplets has been proven to be more effective than pure acoustic agglomeration. It can reduce the energy consumption and has more application potential in various industrial processes. However, the published studies, which mainly compare the agglomeration rate with and without the addition of spray droplets, are insufficient and still preliminary. The influences of the main operating parameters, such as liquid-gas ratio, residence time, and sound frequency, have not yet been explored. In particular, frequency is one of the most important parameters for an acoustic agglomeration process, and previous theoretical and experimental studies have shown that an optimum frequency exists for a given dispersed aerosol [9–11,24,25]. But for the spray-assisted acoustic agglomeration, the influence of frequency still remains unknown.

In this paper, the mechanisms of improvement of acoustic agglomeration rates with the addition of sprayed liquid droplets are analyzed, and an experimental study is conducted to investigate the influences of the main operating parameters on the acoustic agglomeration process using coal-fired fly ash aerosols, with the addition of sprayed water droplets and two kinds of wetting agents.

2. Agglomeration mechanism with liquid droplets added

2.1. Adhesion factor increases with addition of spray droplets

In an acoustic agglomeration process, particles are entrained differently to oscillate by the effect of sound, which causes relative movement between them. Once they collide, it is possible for them to agglomerate together, but not every collision results in agglomeration. The probability of agglomeration when two particles collide is called the adhesion factor, ranging from 0 to 1 [26,27].

Without the presence of liquid droplets, particles in an aerosol adhere together mainly due to the van der Waals force which is relatively weak. As a result, the adhesion factor is generally low. It has been observed that the agglomeration efficiency dropped with the increase of SPL in a high intensity acoustic field, indicating that the van der Waals force was not strong enough to hold particles together when they collided [9,28]. However, with the addition of fine liquid droplets, the liquid bridge force becomes the main attraction force between particles, which is much stronger than van der Waals force [29]. Therefore, the liquid droplets added can greatly promote the adhesion factor and improve the agglomeration efficiency [30].

If the sprayed liquid could wet the solid particles in an aerosol, the agglomeration process would happen through four phases as shown in Fig. 1 [31]. At the beginning, the liquid wets the particles, and the particles collide with each other with the effect of sound, and they are most likely to adhere together to form bigger porous agglomerates due to the liquid bridges between them (state 1). With further contact with the liquid, the pore spaces in the porous state 1 agglomerates are filled with liquid until all the pore spaces are fully filled to form saturated agglomerates (state 2). Once the agglomerates are saturated, liquid bridges are created between them, and they continue to agglomerate to form even larger state 3 agglomerates with raspberry-like shapes. Then the particles in state 3 agglomerates rearrange themselves and become the final state 4 solid-liquid agglomerates.

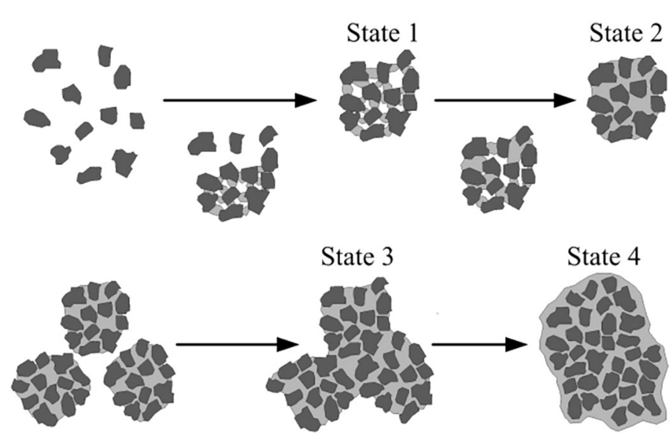

Fig. 1. Schematic representation of agglomeration between particles and droplets.