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Improving acoustic agglomeration efficiency of coal-fired fly-ash particles by addition of liquid binders

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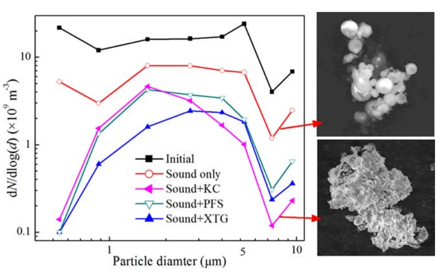
GRAPHICAL ABSTRACT



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ABSTRACT

Acoustic agglomeration is an efficient pretreatment technology for industrial flue gases, which can significantly improve their removal efficiency of conventional dust filters that follow. However, its two main shortcomings, i.e. high energy consumption and the breakage of aggregates, restrict its commercial application. In this paper, a novel method is proposed to overcome these shortcomings by addition of liquid binders. The mechanisms of acoustic agglomeration efficiency improvement by the addition of liquid binders are thought to be: 1) The binder droplets, acting as coarse seed particles, raise the agglomeration kernels based on both orthokinetic interaction and hydrodynamic interactions, thus increase the collision frequency of aerosol particles; 2) Liquid bridges and solid bridges between particles are formed in the presence of binder droplets, which are much stronger than van der Waals force to increase the adhesion factors and avoid the breakage of aggregates. The performance of three polymer binders: Xanthan Gum (XTG), Kappa Carrageenan (KC) and Polyferric Sulfate (PFS), is experimentally investigated. With addition of binders, the agglomeration efficiency reaches as high as 75–85% at an acoustic power of 2.5 W. In contrast, the agglomeration efficiency is only 60% under the same conditions with addition of water. The promotion effect of binders on agglomeration is found to be in the order of: XTG > KC > PFS. It is therefore concluded that the longer polymer chains and the higher viscosity of binders are more favorable for aerosol acoustic agglomeration. It is also found that the agglomeration efficiency becomes much less sensitive to the acoustic frequency change with addition of binders, comparing with the case without the addition of binders.

1. Introduction

Atmospheric particulate matter is produced in various industrial processes, such as coal combustion, cement production, steel manufacturing, and so on. Dust filters, including electrostatic precipitators and baghouse filters, have been widely applied and their total dust

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Nomenclature

C	Mass concentration of liquid binder
d	Particle diameter
e	Particle coefficient of restitution
F	Acoustic frequency
h	Thickness of the binder layer
h_a	Characteristic length of the particle surface asperity
$K_{i,j}$	Agglomeration kernel of particle i and j
$K_{i,j}^{ok}$	Agglomeration kernel of particle i and j based on the orthokinetic interaction
l_i	Slip coefficients of the particle i
m	Particle mass
N_0	Number concentrations of the aerosol at initial stage
N_a	Number concentrations of the aerosol after agglomeration
n_k	Number concentration of particles with size parameter k
P	Acoustic power
PSD	Particle size distribution of aerosol
SPL	Sound pressure level
St	Stokes numbers of particle
St^*	Critical stokes number of particle
t	Time
u_0	Inter-particle approach velocity
u_0^*	Critical collision velocity of particles
u_{ij}	Converge velocity of particle i and j
U_g	The amplitude of vibration velocity of gas medium
U_p	The amplitude of vibration velocity of particle

Greek letters

η	Agglomeration efficiency
λ	Liquid-gas ratio
μ	Entrainment coefficient of particles
μ_b	Viscosity of the liquid binder
μ_{ij}	Relative entrainment coefficient
μ_g	Dynamic viscosity of the gas medium
ρ_p	Particle density
τ_p	Particle relaxation time
ω	Angular frequency of sound

removal efficiency usually reaches 97–99% [1]. However, they are generally low-efficiency for removal of $PM_{2.5}$ (particles with aerodynamic diameters less than 2.5 µm). For example, the typical removal efficiency of electrostatic precipitators is only around 90% for $PM_{2.5}$ [2,3]. Consequently, a large number of fine particles are still emitted into the atmosphere in industrial processes despite the wide application of dust filters. The huge surfaces of these fine particles are usually concentrated with heavy metals, acids, organics and viruses, which makes them extremely harmful to human health [4,5]. In many countries, particulate matter has been regarded as the major air pollutant in recent years [6,7].

To improve the removal efficiency of $PM_{2.5}$, aerosol agglomeration technologies have been proposed as pretreatments to increase the particle sizes prior to entering the dust filters [8–10]. One potential agglomeration technology is acoustic agglomeration, which uses high-intensity sound field to enhance the collision rate of particles significantly. Once the particles collide, they are very likely to adhere together to form larger aggregates. As a result, after the pretreatment of acoustic agglomeration, the $PM_{2.5}$ number concentration in an aerosol will be dramatically reduced and the particle size distribution (PSD) shifts towards a larger size, which leads to a higher removal efficiency in the subsequent dust filter. The experimental results showed that the $PM_{2.5}$ concentration would decrease by about 70% in an acoustic agglomeration process under appropriate operating conditions, then the removal efficiency of the following dust filter could be improved from 90% to above 97%, approximately [11,12].

The acoustic agglomeration technology has been widely studied experimentally and theoretically in recent decades. The agglomeration efficiency was successfully increased to around 70% for coal-fired fly ash particles [13] and 60% for diesel exhaust gas [14]. The optimum operating conditions, especially the optimum sound frequencies, have been obtained for various industrial flue gases. The optimum frequency is thought to be determined by the aerosol initial size distribution, and it increases as the particle average size decreases. For coal-fired flue gases, which contain submicron and micron particles, sound with frequencies of 1–3 kHz is favorable [11,15]. For exhaust gases of internal combustion engines containing nanometer particles, however, ultrasound with high frequencies of 10–30 kHz is more efficient [8,14]. The orthokinetic interaction and hydrodynamic interactions are generally considered to be the most significant mechanisms for acoustic agglomeration [16,17]. In a sound field, particles with different sizes are entrained into the acoustic oscillation at different rates, which leads to the relative motion and collision between particles. This is the basis of orthokinetic interaction, which is usually proposed to explain the acoustic agglomeration of dispersed aerosols. The hydrodynamic interactions are produced through the hydrodynamic forces and asymmetry of flow field around the particles, and generally considered to be the dominant mechanisms for acoustic agglomeration of monodisperse aerosols [18,19].

Although considerable agglomeration efficiency of fine particles using acoustic agglomeration technology has already been obtained in laboratories and pilot-scale experiments [8], there are still some shortcomings which restrict its commercial industrial application. Firstly, a high-intensity sound field with a sound pressure level (SPL) above 150 dB is typically required to produce efficient agglomeration in several seconds of residence time [20,21]. In order to generate such a sound field at the required SPL, the energy consumption is very high and the noise pollution is a by-product of the process. Secondly, the experimental studies showed that the acoustic agglomeration efficiency usually had a limit. Further increase of SPL or residence time would not always improve the agglomeration efficiency [11]. This is because that the aggregate particles which consist of too many child particles tend to break up in the later stage of the agglomeration process due to the weak adhesive forces between particles [22]. Also, the increasing distances between particles make it more difficult for them to approach and collide, when the number concentration of the aerosol drops with the development of the agglomeration process.

In order to improve the acoustic agglomeration efficiency and reduce its energy consumption, some researchers proposed methods of adding external effects coupling with sound, such as steam [14], water spray [23] and wetting agents [20]. Sarabia et al. [14,24] experimentally studied the effect of water vapor on the acoustic agglomeration of diesel exhaust nanometer particles at 21 kHz, 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. Similarly, Yan et al. [25,26] studied the influence of steam on the acoustic agglomeration of coal-fired flue gas, which showed that the removal efficiency of particles increased by nearly 50% at supersaturation degrees above 1.0, and the removal efficiency was above 60% with the combined effect of sound and steam at a moderate SPL of only 130 dB. Zhang et al. [23] found that the acoustic agglomeration efficiency could be greatly improved up to 80% at liquid-gas ratios above 0.13, and the energy consumption was also greatly reduced. For pure acoustic agglomeration, the efficiency was 50% at a SPL of 146 dB, while it reached 73% with water sprayed at only 140 dB. Furthermore, sprayed liquid droplets of several kinds of wetting agents were added in