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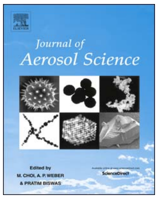

Modeling and experimental study on acoustic agglomeration for dust particle removal

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ABSTRACT

The acoustic agglomeration has been admitted to be one of the effective ways for dust particle removal. In this study, a modified model for acoustic agglomeration of aerosol particles has been studied. The proposed model is featured by its full consideration of collision efficiency among aerosol particles with different sizes. Plus, the segmentation model for the acoustic agglomeration chamber has been established to investigate the process of particle agglomeration in the presence of sound field. An experimental system has been built to validate the model. Experimental results manifest that the model proposed in this study performs very well in depicting the process of acoustic agglomeration of aerosol particles. The model is then employed to investigate the influential factors that affect the collision efficiency between particles, including particle size, acoustic frequency and sound pressure level (SPL). Meanwhile, agglomeration effectiveness along the gas flow in the agglomeration chamber is investigated as well by the model. The work will contribute to the development of acoustic agglomeration for aerosol particle removal.

1. Introduction

Micron and submicron particulate emissions linked with the flue gas of fossil fuel combustion have been admitted to be a serious problem of environmental pollutions. These particles particularly PM2.5 (which is defined as a group of particles whose diameters are less than or equal to 2.5μm) suspend in the air for a long time, and they have been proved to be of potential health hazard for they often become the carriers of various viruses and bacteria which easily enter into human body through breath. Although many technologies have been developed for particle removal such as electrostatic precipitators, high-efficiency filters and so on, they are still of low efficiency for the PM2.5 removal. Thus, it is necessary to develop an aerosol agglomeration method which can cause micro-particle to coagulate and help improve the PM2.5 removal efficiency of current particle removal technologies (Ostro & Chestnut, 1998).

The method of acoustic agglomeration, which is recognized as one of the promising technologies of aerosol agglomeration, has been focused on by many researchers (Mednikov et al., 1965; Shaw et al., 1979; Cheng, Lee, Berner, & Shaw, 1983; Capéran, Somers, Richter, & Fourcaudot, 1995; Hoffmann & Koopmann, 1996; Hoffmann,1997, 2000; Ezekoye et al., 1999; Gallego-Juárez et al., 1999; González, Elvira, Hoffmann, & Gallego, 2001; González, Gallego-Juárez, & Riera, 2003; Sarabia et al., 2000; Sarabia et al., 2003; Dong, Lipkens, & Cameron, 2006; Sheng et al., 2006; Liu et al., 2009; Milcamps, Dommelen, Stigter, Vanderleyden, & Bruijn, 2013; Yuen et al., 2014; Liao et al., 2015). The fundamental principles of acoustic agglomeration can be illustrated as follows: the

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Nomenclature

C	Cunningham slip factor
d	Diameters of particle m
f	Acoustic frequency Hz
F_x', F_y'	Component Force kg m/s^2
k_B	Boltzmann constant J/K
K^{AW}	Kernel function of acoustic wake m^3/s
K^{BRO}	Kernel function of Brownian agglomeration m^3/s
K^{HY}	Kernel function of hydrodynamic interaction m^3/s
K^{OR}	Kernel function of orthokinetic agglomeration m^3/s
K^{TOT}	Total kernel function m^3/s
A, L, h, q	Intermediate variables
l	Distance between two particle m
m_F	Mass of particle kg
N	Number concentration of aerosol particles m^{-3}
r	Polar radius m
SPL	Sound pressure level dB
t_R	Relaxation time s
t	Residence time s
T	Temperature K
u_0	Amplitude of vibration velocity m/s
u_x, u_y	Components of gas velocity m/s
u_x', u_y'	Components of particle velocity m/s
V	Volume m^3
x, y	Horizontal and vertical direction in the plane coordinates

Greek symbols

ε	Collision efficiency
ψ	Removal efficiency
ρ_p, ρ_g	Density of particles and mixed gas medium kg/m^3
θ	Polar angle rad
τ	Time s
η	Fluidic viscosity coefficient kg/(m s)
μ_p	Carrying coefficient
ν_g	Sound velocity m/s
μ_g	Slip coefficient
ω	Angular frequency rad/s
φ	Phase… rad

propagation of sound waves results in the relative motion of aerosol particles and increases the collision probability among particles; once the particles collide with each other, the smaller particles will tend to grow into larger ones, and the newly-formed particles continue to agglomerate with the others, which ultimately brings about a continuous growth of aerosol particles. The most important mechanisms of acoustic agglomeration documented in the literature mainly include the mechanism of orthokinetic collision (Cheng et al., 1983; Mednikov & Larrick, 1965), hydrodynamic interaction (González et al., 2001, 2003; Hoffmann & Koopmann, 1996; Wang, 2012; Zhang, Liu, Wang, Zhou, & Cen, 2012) and Brownian agglomeration (Otto & Fissan, 1998; Otto, Fissan, Park, & Lee, 1999).

The mechanism of orthokinetic collision, which was firstly summarized by Mednikov et al. (1965), has been recognized as the main mechanism of acoustic agglomeration (Liu et al., 2009). It concerns refilling model and collision efficiency model of particles. According to the refilling model, the smaller particles outside of one specific 'volume' constantly enter into the 'volume' to supplement the disappearing particles which have been agglomerated into the larger ones, and this makes the agglomeration process sequential. The collision efficiency is defined as the proportion of the smaller particles that can collide with the larger particles inside a specific 'volume'. In the conventional model of orthokinetic agglomeration, the collision efficiency was often assumed as 1.0, but the actual collision efficiency will be lower than 1.0. Cheng et al. (1983), Temkin (1994) have made investigations on the collision efficiency, but they did not provide the calculation method; Nakajima and Sato (2003) have found that the collision efficiency is pretty low for the sub-micron particles; in the study by Dong et al. (2006), the Stokes number was employed to estimate the collision efficiency without considering the effect of acoustic field.

In this paper, a modified model for the acoustic agglomeration of aerosol particles is developed based on the previous models (Ezekoye & Wibowo, 1999; Hoffmann, 1997; Sheng & Shen, 2006; Zhang, 2010). The highlight of the proposed model in this study is that the collision efficiencies among the aerosol particles with different sizes are fully considered into the discrete equations describing the process of aerosol agglomeration in the presence of sound field, and the spatial variations during the aerosol agglomeration are also taken into account. Meanwhile, an experimental system has been designed for the model validation. Afterwards, the model is then employed to make a parametric study on the acoustic agglomeration of aerosol particles.

2. Model development

Aerosol dynamics in the agglomeration chamber can be simulated through the group method (Temkin, 1994; Zhang, 2010). Assuming that the collision should happen based only on the growth of particles without considering the influence of aggregate fragmentation, the equation for calculating the change of number concentration with time can be described as follows:

$$\frac{\partial c_k}{\partial t} = \frac{1}{2}\int_0^k K_{ij} c_i c_j di - c_k \int_k^\infty K_{ik} c_i di \tag{1}$$

where, c_k is the number concentration of particle k; k, i, j represent particles with different sizes, respectively; K_{ik} are agglomeration kernels, which represent collision times between particle i and particle j in per unit time and per unit number concentration.

To solve the aerosol dynamic equation, Eq. (1) needs to be discretized for the convenience of numerical calculation, and thus the discrete form called Smoluchowski function is applied to replace Eq. (1), which can be written as follows (Sheng & Shen, 2006):