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Combined effect of acoustic agglomeration and vapor condensation on fine particles removal

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HIGHLIGHTS

- The combined effect of acoustic agglomeration and vapor condensation.
- Fine particles are effectively captured in the coupling fields.
- High removal efficiency is obtained in a low intensity acoustic.
- Sound pressure level has a significant affect on the efficiency.
- Removal effects depend on supersaturation degree in acoustic field.

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ABSTRACT

A novel preconditioning process using the combined effect of acoustic agglomeration and vapor condensation for fine particles removal with high efficiency was presented. The effect of operation parameters on the enlargement and removal of fine particles were investigated experimentally. Particle size distribution and number concentration with and without external fields were measured by Electrical Low Pressure Impactor (ELPI). The results showed that the stage removal efficiency of fine particles was about 10–23% by acoustic agglomeration only with sound pressure level (SPL) of 150 dB. However, it was significantly improved by the combined effect of acoustic agglomeration and vapor condensation, reaching up to 53–80% with a SPL of 150 dB and supersaturation degree (S) of 1.2. Fine particle entrainment factor in acoustic field increased with the supersaturation degree, as well as the removal efficiency. While the supersaturation degree was lower than 1.0, the removal efficiency was extremely low, and increased slightly with the supersaturation degree. However, removal efficiency increased with the supersaturation degree rapidly when the supersaturation degree was higher than 1, which was improved by about 50% as the supersaturation degree increased from 1.0 to 1.4. The coupling external fields cannot be formed when the supersaturation degree was lower than the critical one, resulting in low removal efficiency. Removal efficiency was increased substantially to 63% in the supersaturation degree of 1.2, even in a low SPL of 130 dB. It indicates that high removal efficiency can be obtained in the combined effect of acoustic agglomeration and vapor condensational growth even in low intensity acoustic field.

1. Introduction

Fine particles have recently gained much attention because of their relevance with the deposition of toxic components and serious public health concern [1,2]. Continuous increasing consumption of energy leads to more and more inhalable particulate matter emissions [3,4]. Consequently, large quantity of fine particles was emitted into the ambient air, and they have been regarded as the major air pollutant in cities. The separation of fine particle has become important because of increasing clean air demands. However, the efficient separation of fine particles is difficult and expensive. They can be efficiently separated with conventional devices, if they are first enlarged by means of a preconditioning technique. Such preconditioning process can be the agglomeration effect or heterogeneous condensational growth of vapor on the surfaces of fine particles.

Acoustic agglomeration is considered to be a useful technique for fine particles removal. High-intensity sound wave enforces the relative motion among fine particles to produce efficient

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Nomenclature

A	acoustic wave amplitude
C	Cunningham correction coefficient
d_a	average particle diameter, μm
d_p	particle diameter, μm
F	resultant force of particles, N
F_p	pressure gradient force, N
F_v	Stokes viscous force, N
f	acoustic frequency, Hz
I	sound pressure level, dB
k	Boltzmann constant, $J \cdot K^{-1}$
K_c	kinetic coefficient
p	sound pressure, Pa
r	particle radius, μm
S	supersaturation degree
S_{cr}	critical supersaturation degree
T	gas temperature, K
u	air amplitude velocity, $m \cdot s^{-1}$
u_p	particle velocity, $m \cdot s^{-1}$
U_o	air velocity amplitude
U_p	particle velocity amplitude
V_w	embryo volume, m^{-3}
μ_g	gas dynamic viscosity, Pa·s
λ_a	molecular mean free path, m
λ	acoustic wave length, m
ω	angular frequency of acoustic wave, $rad \cdot s^{-1}$
τ	relaxation time of the particle, s
ρ_p	particle density, $kg \cdot m^{-3}$
σ_{eg}	interfacial tensions of the embryo-gas, $N \cdot m^{-1}$

collisions. Several theoretical descriptions for aerosol particle dynamics in acoustic fields have been investigated [5–8]. Experimental studies and numerous computational simulations have indicated that acoustic agglomeration significantly shifted the particle size distribution, from smaller to larger sizes in an acoustic field and reduced the particle number concentration [9–16]. But high value of sound pressure level (SPL) was needed to achieve a considerable removal efficiency of fine particles. Recently, the combined effect of acoustic wave with other external field was investigated [17,18], which showed that the removal efficiency of fine particles could be improved by the coupling effect of gas jet and acoustic wave or adding seed particles in acoustic field [19,20]. Therefore, the combination of acoustic wave with other external field is considered to be a novel preconditioning process for particle separation.

High particle agglomeration efficiency with low sound pressure level was required for acoustic agglomeration application. Investigations showed that heterogeneous condensation of water vapor with fine particles acting as nucleation centers was an effective method for particle growth [21–27]. The condensational growth and removal of submicron particles were confirmed, but high water vapor consumption to achieve the high supersaturation degree (defined as the ratio of the partial pressure of water vapor to its equilibrium vapor pressure) was the key problem [28,29]. Particles agglomeration and condensational growth could be achieved when supersaturation water vapor was introduced into an acoustic wave field. Under the combined effect of acoustic wave and vapor condensation, fine particles agglomeration and condensational growth occurred simultaneously. The agglomeration of fine particles by acoustic wave was useful for the condensational growth of supersaturation vapor on the surfaces of fine particles. On the other hand, the difference of aerosol size between fine particles and new born droplets promoted the particles collision and agglomeration in the acoustic field.

Although the acoustic agglomeration and condensational growth have been extensively investigated, the combined effect of acoustic agglomeration and vapor condensational growth has not been elucidated. The aim of this study is to contribute to the fundamental knowledge of the coupling effect of acoustic agglomeration and vapor condensation. Water vapor was introduced into the acoustic agglomeration chamber to form the coupling external fields. The effects of operation parameters on fine particle removal were investigated experimentally in the coupling intensification effect of acoustic agglomeration and vapor condensation.

2. Experiment sections

2.1. Experimental setup

The schematic experimental design is shown in Fig. 1. The experimental setup comprised a fluidized bed aerosol generator, a buffer chamber, an acoustic agglomeration chamber and a settling chamber. Fine particles from coal fired were generated used a fluidized bed aerosol generator with a gas flow rate of 50 L/min. The flue gas then passed through a buffer chamber, in which an electric heater and water vapor adding device were located. Water vapor was generated by an electric water vapor generator (LB-7.5D, Lanbao Co. Ltd., China). Fine particles were enlarged in the acoustic agglomeration chamber. A settling chamber with a length of 350 mm, width of 200 mm and height of 150 mm was used to separate the grown particles. At the exit of the settling chamber, an Electrical Low Pressure Impactor (ELPI, Dekati Co. Ltd., Finland) was employed to measure particle size distribution in real time with and without external fields. The ELPI was described in detail previously (www.dekati.fi). A brief description about the ELPI is given here. ELPI is suitable for application where a wide size rang and fast response times are required. The gas sample containing the particles is first sampled through a unipolar corona charger. The charged particles then pass into a low pressure impactor with electrically isolated collection stages. The impactor operating principle is based on particle size classification according to the aerodynamic diameter of the particles. The sampling flow rate is 10 LPM and the measuring size range is 0.023–9.314 μm of aerodynamic diameter.

The supersaturation degree achieved in the acoustic agglomeration chamber was controlled by the flue gas temperature and water vapor addition. According to the flue gas temperature and humidity detected at the outlet of buffer chamber, the supersaturation degree and temperature needed in the acoustic agglomeration chamber, the amount of water vapor required in the experiment was first calculated. Then the mass flow rates of vapor and gas temperature were regulated by the vapor mass flow meter and heater.

A sampling gas stream was withdrawn from main gas stream and diluted when it was routed into the ELPI. Since the sampling gas stream contained high moisture, vapor might condense on the sampling pipe and the impact plates of ELPI. To avoid the condensation of water vapor, the sampling gas was heated and diluted with particle free and hot dry air (dilution ratio was well defined of 8.18:1) prior to entering the ELPI measurement system. Heat