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Aerosol manipulation through modulated multiple acoustic wavepackets with a pair of resonators

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ABSTRACT

In general, the aerosols mixed in air medium can be regularly manipulated by means of the interactions between the aerosols and the acoustic field. The manipulable properties of aerosols can be engineered through geometric parameter and acoustic resonance condition of the underlying device. The aerosols manipulated by modulated multiple acoustic wavepackets (MAWP) in acoustic resonance condition is proposed and demonstrated in this paper, whose application belongs to an efficient aerosol removal technique. The experimental results indicated that the removal efficiency of aerosols was mainly influenced by the different harmonic order. The technique and process proposed in this paper was feasible for industrial application. The MAWP is modulated by means of the synthetic standing wave field at the resonant frequency 1.268 kHz. The aerosol manipulation processes through MAWP consist of the aerosol shift, collision aggregation and deposition between the dot and the anti-neck of a single wavepacket. As a visual inspection confirming standing wave, the processes may also be applied in modulating the MAWP simultaneously. The manipulation efficiency can be increased due to the increase of wavepacket amount under the same operating conditions. The acoustic radiation force causes shift and accumulation of aerosol in waveguide and the secondary radiation force enhances collision aggregation and deposition thereof. The initial number concentration of particles <2.5 μm (resp. larger than 2.5 μm) was about 517,488 $1/cf^3$ (resp. 51,918 $1/cf^3$). Under the action of these forces, the aerosols in waveguide were aggregated and deposited onto the inner wall of waveguide. At the end of experiment, the final number concentration of particles <2.5 μm (resp. larger than 2.5 μm) is about 59,096 $1/cf^3$ (resp. 392 $1/cf^3$). The $PM_{2.5}$ content of aerosols used in experiment is about 91%. The removal coefficients are larger than 85%. The deposition stripe distribution shows the specific pattern associated with a wavepacket. The surface of the stripe particles is covered with the uniform small hollows (~105.7–177.7 nm), and plenty of nanoscale particles (~13.66–16.55 nm) are grown around the surface of small hollows. It may be possible to develop a new way for large scale and batch aerosol processing to apply to the prospective emission control of industrial aerosols.

1. Introduction

Currently, aerosol removal equipment to remove numerous small aerosols such as $PM_{2.5}$ presents the major challenge caused by aerosols generated from the industrial combustion [1]. The aerosols mixed in air can be regularly manipulated by acoustic standing wave (ASW) via the interaction process between aerosols and acoustic field [2–10]. The progress of aerosol removal technique might be benefitted from the acoustic-related researches on different aspects such as [2–25].

In the field of the manipulation of ASW on aerosols, the main consideration is the increase of the collision possibility under the interaction between the acoustic wave and particles, named as acoustic aggregation [2–5,11–18]. During the collision progress, numerous small particles become larger particles due to the particle interaction [11,12]. The large particles can be removed in the next stage by the traditional removal equipment [13,14]. This application enhances the removal efficiency of the traditional equipment [13,15]. Based on this mechanism, many important studies have been carried out through selective acoustic parameters, such as sound pressure and frequency. For example, Liu et al. [2] studied an obvious removal for the coal-fired fly ash particles, <10 μm, in a study-scale cylindrical tube induced by the high sound pressure 147 dB and low frequency 1.4 kHz. Chen et al. [3] studied an obvious decrease for the ultrafine particles of 0.023 μm–10 μm in diesel engine exhaust caused by the sound pressure 161.5 dB and frequency 1 kHz. Chen H. et al. [4] found in particular acoustic environment of the sound pressure 142 dB and frequency 1.6 kHz, the coupled acoustic and electric fields can cause the penetration efficiency down lowest to

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4.4% for fine particles, 0.03 μm–2.5 μm, from coal combustion. Besides, the acoustic field combined with the turbulence field [5], the nonlinear acoustics [6] and the fibrous media [7], respectively are considered as the efficient aerosol removal techniques. However, the efficient aerosol removal technique based on this method needs further study [8].

Other important researches are the acoustic manipulation [8–10] and levitation [19–21] for particles in air, whose primary consideration is the acoustic radiation force [22] between nodes and anti-nodes of ASW field. Based on this mechanism, Karpul et al. [8] suggested an acoustic device to filter carbon particles of size 1 μm from the burning of fossil fuels and biomasses. Andrade et al. [19] constructed a non-resonant acoustic levitator used for practically separating polystyrene particles in the space distance 10 cm at an appropriate frequency ~23.7 kHz. Weber et al. [20] suggested a levitator to acoustically levitate the liquid or solid drops of 1 mm–3 mm at the resonant frequency ~22 kHz and maximum sound pressure 160 dB. This levitator was used for material measurement on low temperature liquid droplets.

In the current study, the advantage of multiple acoustic wavepackets (MAWP) on aerosol manipulation is rarely noticed. In our previous study [10], it was found that the structure factors of acoustic field were important to achieve the macro manipulation for numerous aerosols between nodes and anti-nodes in finite space. This means that the driving forces behind the aerosols shift, collision aggregate and deposition should be well understood. This paper focuses on MAWP modulated by synthetic standing wave and demonstrates that the aerosol can be manipulated by MAWP. The manipulation focuses on the aerosols shift, collision aggregation and deposition controlled by MAWP. Further, it is appropriate to explore the possible aerosol manipulation using MAWP as a kind of efficient aerosol removal technique, which is the objective of this paper.

2. Experiment and method

2.1. Experimental device

This device (Fig. 1) consists of two opposing Helmholtz resonator source (HRS) and one cylinder resonant waveguide used as the aerosol vessel [23]. HRS is composed of speaker and Helmholtz resonator and emits the acoustic wave with the single resonant frequency. Two identical HRS as a parity-time operator [26] are installed on the two ends of the waveguide to realize time-space symmetry of synthetic standing wave in waveguide. The synchronal acoustic waves are pumped into the aerosol vessel to provide energy consumption for manipulating aerosols and compensating the loss from waveguide. In terms of the HRS, some important advantages about this device can be searched from the relative important studies [23–25]. In the device, all of the component natural frequencies and geometric parameters should satisfy the resonance similarity condition as follows.

$$(nc_0/(2L_n))^2 = (c_0{}^2/4\pi^2)(\pi d_e{}^2/4)/(l_e + 0.73d_e)/(l_t\pi d_t{}^2/4) = f^2 \tag{1}$$

where c_0 is the acoustic velocity in air; d_e, l_e is the geometry parameters of neck tube; l_t, d_t is the geometry parameters of cavity; f is the harmonic frequency of waveguide equal to the Helmholtz resonance frequency of HRS; n is harmonic order; L_n is the length of waveguide corresponding to the n order harmonic. Eq. (1) indicates that the frequency relationship to the geometry parameters of HRS and waveguide is complex [10]. The resonant property of the device is engineered through the underlying geometric parameters.

Besides, in the previous studies such as [2–6,8,12–14], the frequency of acoustic wave has been verified as one important factor to achieve the optimal aerosol manipulation in the acoustic field. The natural frequencies of all acoustic cavities should be of a given initial parameter. The relation between the harmonic number n and waveguide length L_n is directly given by using Eq. (1) while all the parameters except n and L_n are kept fixed. Note that the n should be integer. Accordingly, in this paper the important parameters are as following, $n = 7$, $L_n = 978$ mm, $d_e = 8$ mm, $l_e = 5$ mm, $d_t = 35$ mm, $l_t = 9$ mm, $f = 1.268$ kHz. The quarter-wavelength of acoustic wave is 67 mm, the inner diameter d_c of waveguide is 35 mm, and the waveguide material is transparent plexiglass.

2.2. Method

The measure system (Fig. 2) consists of the acoustic sensors for the sound pressure measurement, the *PlantTower* particle counter for testing the aerosol number concentration and the aerosol size distribution and the CCD camera for recording the aerosol manipulation effect. The axial direction of waveguide is the specified axis. The total of 54 test points are uniformly arranged in the waveguide along the axis x. The test points x_i of the sensors are arranged depend on the anti-nodes (AN) and nodes (N) of synthetic standing wave field. For example, the test point x_{27} is the anti-node position in the middle of the waveguide, x_{26} and x_{28} are the positions 15 mm away from x_{27}, x_0 and x_{54} are arranged 10 mm away from each end. The experiment is carried out at

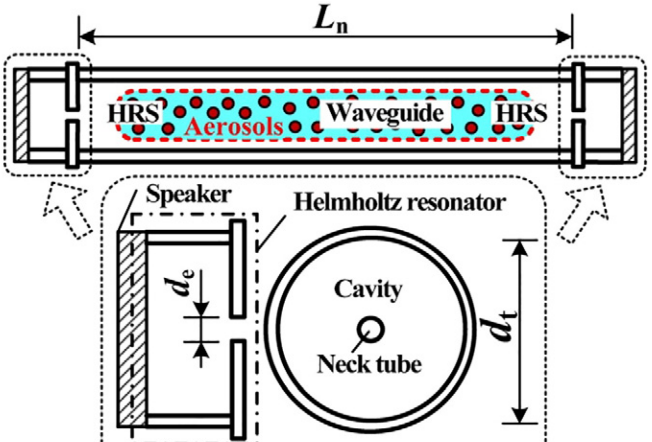

Fig. 1. Schematic diagram of the experimental device.

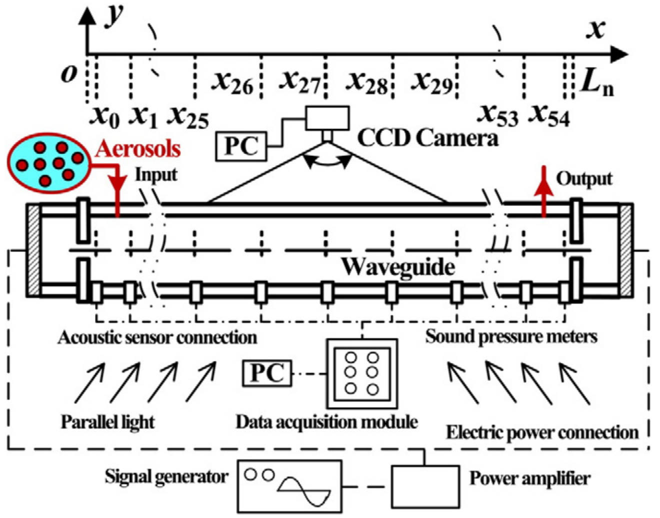

Fig. 2. Schematic diagram of method for measure system and experimental devices.