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Aerosol manipulation by acoustic tunable phase-control at resonant frequency

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ABSTRACT

The aerosols regularly manipulated by modular platform of acoustic tunable phase-control at resonant frequency 2.6427 kHz are demonstrated in this paper. In order to make full of the superimposition of multiple waves in non-uniform two dimension acoustic standing wave field, the modular platform is composed of the square cavity and the two pairs of symmetric acoustic sources with Helmholtz resonators. The modular platform allows that the effective volume of cavity is 32.8 (length) × 32.8 (width) × 5 (height) cm^3 and also the tunable acoustic phase-control is realized by proposed two different phase modes named π-mode phase and 0-mode phase. The ranges of the aerosol size distribution and the aerosol concentration are 0.08 μm–1 μm and 51.6–93.3% (Opacity), respectively. The experimental temperature remains at 298 K. Results indicate that the platform causes perfect nonuniform two-dimension acoustic standing wave field. Under the condition of π-mode phase, the manipulation is better than that under 0-mode phase; the characteristic length of X-pattern for displaying the manipulation is half-wavelength larger than quarter-wavelength acquired in one-dimension acoustic standing wave field. The major areas to remove aerosols are 39 cm^2 under π-mode phase and 9.7 cm^2 under 0-mode phase. The phase is an important parameter for impacting the manipulation of aerosols. For explaining the difference of manipulation under the two phase conditions, the relative structural factors of acoustic field are found and considered as the intermediate variables from acoustic tunable phase to aerosol manipulation. Especially, the large neck for the shape of sound pressure nodes might cause weak interaction between aerosols and acoustic field and further result in the unexhaustive manipulation.

1. Introduction

Aerosol manipulation in acoustic standing wave (ASW) field can achieve the regular motion of aerosols in a finite space. This regular motion plays the significant role in the process of aerosol removal.

Recently, there are different experiments to study the aerosol behaviors in ASW field, in order to manipulate the aerosol removal more efficiently [1–5]. Frequency and sound pressure as the important characteristic parameters of ASW field have been verified acting as the significant factors to impact the effect of an acoustic field on aerosol manipulation. Enough high sound pressure (140 dB [1], 120 dB [3]) and appropriate frequency (1.4 kHz [1], 1.416 kHz [3]) are essential to acquire an obvious manipulation effect. However, the study on the aerosol manipulation by the phase acting as one characteristic parameter of ASW field is rare, which is one objective of this paper.

In the aspects of particle manipulation by ASW about phase within liquid (water [6,7] generally selected), the significant study on the phase-control has been done currently. One thing they [6,7] mostly focused on is the microscopic scale of set-up such as micro-channel. Besides, Raeymaekers et al. [8] studied the macro scale patterns [8] about particle manipulation using bulk acoustic wave in water. However, the physical characters of particle environment for liquid and gas respectively are obviously different such as the acoustic velocity, the viscosity, the density, etc. At the same time, the acoustic source is a piezoelectric transducer for producing high frequency (740 kHz [6], 91 MHz [7]) acoustic wave in water. Utilizing the plate [6,8] and the cylinder [8] for the types of conventional piezoelectric transducer can transmit directly satisfactory acoustic wave into water. Conversely, when used to manipulate particles in air, the conventional piezoelectric transducer needs to be improved based on the acoustic impedance match between transducer and air, for example the additional radiation plate and mechanical amplifier used in the device of Juan et al. [4]. Therefore, without special improvement for the device, the conventional acoustic source cannot produce enough high sound pressure used for aerosol manipulation at the relative low frequency like 1.4 kHz in air medium.

Other relative important researches are the acoustic manipulation [9] and levitation [10–12] of micro- and macro scale particles in gas. Karpul et al. [9] designed industrial acoustic filters to manipulate

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particles, and showed the advantage of optimizing operating and structure factors of acoustic filter on achieving better manipulation. They studied respectively two kinds of different particles, radiuses of 1 μm for graphite and 1 mm for polystyrene foam. Weber et al. [10] constructed an acoustic levitator to achieve levitating liquids at resonant frequency ~22 kHz. Their particle diameter is in the range of 1–3 mm. Daniele et al. [11] designed an acoustic macro platform for levitating a steel sphere of 5 mm in air using ASW of 25 kHz. Therefore, it is appropriate that we study the effect of the phase of ASW on the aerosol manipulation at low resonant frequency, especially in macroscopic cavity. In terms of the industrial occasions for flue gas emission from coal and oil combustion, the amount of emission for aerosols is usually huge [13]. When applying the aerosol manipulation in ASW field to remove aerosols in these occasions, the design and manufacture of the huge cavity to achieve optimal acoustic resonance is also the one of challenges.

On the other hand, among the current studies, one dimension ASW field is prior selected for the establishment of ASW field by one acoustic source and reflective plate [4,14] or by two symmetric acoustic sources [15,16]. However, two-dimension ASW field has potential advantage making full of the superimposition of multiple waves and such research has been developed. In some studies [4,6,17] the two-dimension ASW field is formally two dimensional in space, but such ASW field can be equal to one dimension ASW field because of the uniform distribution along the direction perpendicular to the propagation of acoustic wave. In fact, such two-dimension is only the extension of one dimension ASW field in plane, and it still belongs to the scope of one-dimension in nature. In contrast, the nonuniform two-dimensional ASW field (NTASWF) is rarely used for aerosol manipulation, which is another objective of this paper.

When carrying out the aerosol manipulation in NTSAWF, however, how to control the interaction between aerosols and two dimension ASW field becomes a significant topic on the interaction between aerosols and acoustic field environment of their existing. This paper demonstrates that the aerosol moving behavior can be regularly manipulated by modular platform of acoustic tunable phase-control in NTASWF at 2.6427 kHz of a low frequency.

2. Experiment and method

2.1. Experimental set-up

The modular platform of acoustic tunable phase-control consists of two types of modules, one horizontal square cavity and two pairs of symmetric acoustic sources, showed by Fig. 1. The square cavity is made up of Perspex plate of thickness 5 mm and its volume is 32.8

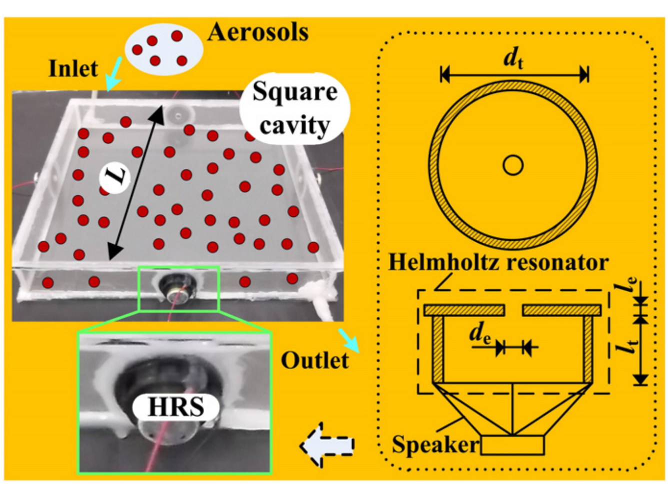

Fig. 1. Schematic diagram of setup.

(length) × 32.8 (width) × 5 (height) cm^3. Four same power acoustic transducers are arranged on the four sides symmetrically against to the center point of square cavity. Two acoustic transducers of each pair are opposing each other, and constitute symmetric acoustic sources of a pair with respect to the center point. These acoustic sources have same center frequency. The acoustic source is the type of acoustic streaming, named as Helmholtz resonator source (HRS) [16,18]. Helmholtz resonator source is composed of electromagnetic speaker and Helmholtz resonator. HRS operating at Helmholtz resonance frequency (HRF) can produce great acoustic wave of similar single frequency [18]. Such acoustic wave can satisfy the requirement of sound pressure when manipulating aerosols by acoustic tunable phase-control. In order to realize the resonance of modular platform and cause suitable NTASWF, the working frequency of acoustic source is equal to the HRF and to the five order harmonic frequency of square cavity.

The structural parameters of modular platform satisfied the following formula [16,19]

$$(nc/(2L))^2 = (c^2/4\pi^2)\left(\pi d_e^2/4\right)/(l_e + 0.73d_e)/\left(l_t\pi d_t^2/4\right) = f^2, \tag{1}$$

where $n = 5$ is the five order harmonic order of square cavity; L is the length of square cavity; c is the acoustic velocity of air; $d_e = 8$ mm, $l_e = 5$ mm, $d_t = 35$ mm & $l_t = 2$ mm are the geometric parameters of Helmholtz resonator; and f is HRF equal to 2.6427 kHz in our study, and equals the center frequency of acoustic source.

Eq. (1) is a similarity condition for resonance. According to this similarity condition, the geometric size (length and width) of the square cavity can be larger. For example, a smaller f, satisfying the geometric parameters d_e, l_e, d_t, l_t, corresponds to a longer L, or an appropriate larger n, satisfying the positive odd integer (the even integer has not been verified [16]), corresponds to a longer L. In order to avoid the generation of the ASW field in the direction of height, the height of square should also be less than half-wavelength. This constraint ensures the production of NTASWF only in the plane of length–width. Therefore, under the constraint of Eq. (1) and the height constraint, the influence of the setup dimension amplified on acoustic tunable phase-control can be neglected [16]. It must be pointed out that such method has not been suggested in previous study.

The sound pressure, p, radiated from the acoustic sources is $p_m^\varepsilon = p_a \exp(i(\omega t + \psi_m^\varepsilon))$, here, p_a and ω are respectively the amplitude and angular frequency of sound pressure, t is the time, the phase $\psi = \pi$ or 0 represents the contrary (π) and same (0) to the vibration directions of the symmetric acoustic sources (note that using the inversion of the two vibration directions [16] does not produce the general phase achieved by Kun et al. [20], and the study on how to improve the method to achieve the general phase for our proposed set-up has not been carried out), the subscript $m = 1$ or 2 represents the two sources of the each pair of symmetric acoustic sources, the superscript $\varepsilon = 1$ or 2 represents the two pairs. Acoustic tunable phase-control can be realized through the tunability of contrary and same phase between acoustic waves radiated from the each pair of symmetric acoustic sources. Therefore, the acoustic tunable phase-control in this paper is equivalent to two different phase modes, π-mode phase and 0-mode phase. The foundation of this classification is based on the tunability for the phase of the each pair of symmetric acoustic sources [16]. Using the phase of ψ_m^ε, the two modes can be expressed as

$$\begin{bmatrix} (\psi_m^\varepsilon)_{\pi\text{-mode}} \\ (\psi_m^\varepsilon)_{0\text{-mode}} \end{bmatrix} = \begin{bmatrix} \left(\left(\psi_m^1\right), \left(\psi_m^2\right)\right)_{\pi\text{-mode}} \\ \left(\left(\psi_m^1\right), \left(\psi_m^2\right)\right)_{0\text{-mode}} \end{bmatrix} = \begin{bmatrix} (0,\pi), (\pi,0) \\ (0,0), (0,0) \end{bmatrix}. \tag{2}$$

It must be pointed out that according to the right side of Eq. (2), there also have other modes, such as [(0, π), (π, 0)], [(π, π), (π, π)], [(0, π), (0, 0)]. Due to the symmetry of square cavity, [(0, π), (π, 0)] and [(π, π), (π, π)] is the same as [(0, π), (π, 0)] and [(0, 0), (0, 0)],