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Ultrasonic removal of coarse and fine droplets in air

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ABSTRACT

It has been a big challenge to effectively collect coarse and fine droplets from the air by compact and light equipment. In this report, a novel strategy of collecting coarse and fine droplets from the air, which employs an ultrasonic field in an air gap between a flat radiation surface and reflector, is demonstrated. Coarse and fine droplets (PM2.5-10 and PM2.5) can be effectively collected onto the reflector's surface when the air gap thickness is proper. The radiation surface works in a flexural vibration mode at 56.9 kHz, and the collected droplets may form concentric rings and irregular shape on the reflector's surface. Analyses show that both the acoustic streaming and acoustic radiation force contribute to the collection.

1. Introduction

Collection of PM2.5-10 (particulate matter with aerodynamic diameter larger than 2.5 μm and equal to or less than 10 μm, defined as coarse particles) and PM2.5 (particulate matter with aerodynamic diameter equal to or less than 2.5 μm, defined as fine particles) [1] in air has potential applications in air cleaning for limited space, air quality monitoring and protection, etc. Major existing methods of collecting particulate matter in air include high-efficiency particulate air (HEPA) filtering [2], electrostatic precipitating [3–6] and dielectrophoresis technology [7,8].

The HEPA technology uses the HEPA filters to filtrate air as the air with micro/nano droplets and particles is pumped through the filters. However, the life of most HEPA filters is only about 8–12 months, causing the inconvenience maintenance. Moreover, particles screened by the filters may block the filters, causing a sharp drop of the filters' efficiency and the 2nd pollution. Electrostatic precipitators or collectors have been commonly used to capture or control airborne dust and fine particles in indoor air cleaning systems and industries [3]. They use corona dischargers to charge incoming aerosols and collect these charged aerosols by electrostatic forces [4]. The instruments are very effective, and purified air in them has low pressure-drop. However it is well known that corona dischargers produce too many oxides of nitrogen and ozone, which are harmful to environment and human health [5,6]. Also, the use of high voltage makes the system bulky and heavy. The dielectrophoresis effect refers to the neutral matter's motion caused by polarization effects in non-uniform electric field. The dielectrophoresis force is determined by the magnitude and polarity of the charges induced in a dielectric particle by the electric field with a large spatial gradient [7,8]. Air cleaning process based on dielectrophoresis only occurs in the area with a large enough electric field gradient, which usually occurs near the electrode. This limits the particle collecting area and scaling up capability of the dielectrophoresis based devices. Compact, environmentally friendly and energy-efficient air-cleaning instruments are desired, especially for the applications in vehicles, rooms, planes, spacecrafts, etc., which have limited working space.

Airborne ultrasound may be used to agglomerate fine particles in air by using the linear and nonlinear effects of power ultrasound [9–11]. One major progress in this field is the successful development of an acoustic aerosol preconditioning system for the fumes from a 0.5 MWt fluidized bed coal combustor, by Gallego-Juarez et al. [11]. The system is 5 m long, and fit for medium and large-scale acoustic agglomeration and precipitation process. Applications such as small-scale air cleaning of the indoor environment, vehicle interior, and aircrafts, usually require the equipment of compact structure and light weight. Although the ultrasonic or piezoelectric equipment has the merits of compact structure and light weight, the research on working principle and device structure of ultrasonic air cleaning in small-scale is still very scarce. In this paper, an ultrasound based strategy of collecting coarse and fine droplets (PM2.5-10 and PM2.5) from air, with a very simple and relatively compact device structure, is demonstrated. Droplets in an air gap between a transducer's radiation surface and reflector can be effectively collected onto the reflector's surface when the air gap's thickness is proper. The effects of working time and vibration

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displacement on collected droplet mass are also measured and clarified. Analyses show that both the acoustic radiation force and acoustic streaming in the working ultrasonic field contribute to the collecting process.

2. Experimental method

Fig. 1(a) shows the device for collecting PM2.5-10 and PM2.5 droplets from the air. In the experiments, it is placed in a sealed box (250 mm× 250 mm×200 mm) filled with smoke composed of coarse and fine droplets. The device is composed of a piezoelectric transducer and silicon reflector, which are parallel to each other as shown in Fig. 1(b). Ultrasonic field in the air gap between the radiation surface and reflector is used to collect the droplets from the air.

In the transducer, two piezoelectric rings with opposite polarization directions are aligned and pressed together between two aluminum covers by a bolting structure, as shown in Fig. 1(b). The outer diameter, inner diameter and thickness of each piezoelectric ring are 30 mm, 12 mm and 5 mm, respectively. The diameter of the radiation surface is 4.5 cm, and the reflector has the same diameter as that of the radiation surface. The electromechanical quality factor Q_m, piezoelectric coefficient d_{33}, and relative dielectric constant $\varepsilon_{33}{}^T/\varepsilon_0$ of the piezoelectric rings are 2000, 325×10^{-12} m/v and 1450, respectively. Fig. 2(a) shows the frequency response of the transducer driven by 50 V_{p-p}, which is measured by a laser Doppler vibrometer (POLYTEC PSV-300 F). Fig. 2(b) and (c) shows the measured mode patterns at 48.0 kHz and 56.9 kHz, respectively. It is seen that the radiation surface works in a piston vibration mode at 48.0 kHz, and flexural vibration mode at 56.9 kHz. Our experiments indicate that the flexural vibration mode has a better collecting effect. Thus 56.9 kHz is used as the working frequency in this work.

Smoke produced by smolder of a joss stick is used in the experiments. The droplet diameter distribution is measured by a laser granularity analyzer (Winner 318, Jinan Winner Particle instruments Stock Co., Ltd.), and the result is shown in Fig. 3. It is seen that PM10 is the major particulate matter in the experimental smoke, and PM2.5 shares about 50% in the PM10 droplets in terms of particle number. The smoke is composed of coarse and fine droplets which are made of sugar, nicotine, starch, amino acid, polyphenols and protein [12,13].

Under the conditions that the transducer is in resonance (56.9 kHz), and working voltage and time are 100 V_{p-p} and 15 min, respectively, it is observed that droplets in the air gap can be collected onto the reflector's surface when the air gap thickness L is 1.58 mm, 3.00 mm and 5.89 mm, respectively. Fig. 4 shows the images of the particulate matter which deposits on the reflector's surface. It is seen that there are two types of deposit patterns, depending on the air gap thickness. At L = 1.58 mm, droplets collected onto the reflector's surface form a series of concentric rings. The inner rings are more regular and have clearer boundaries than the outer rings. At L = 3.00 mm and 5.89 mm, the deposit patterns are not regular and contains a mixture of spots

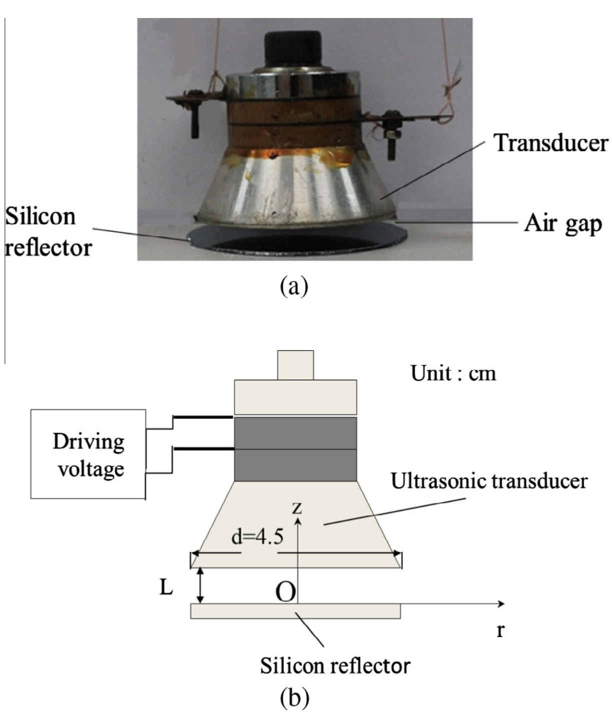

Fig. 1. A device for collecting droplets in smoke in a testing box. (a) Photo. (b) Schematic diagram.

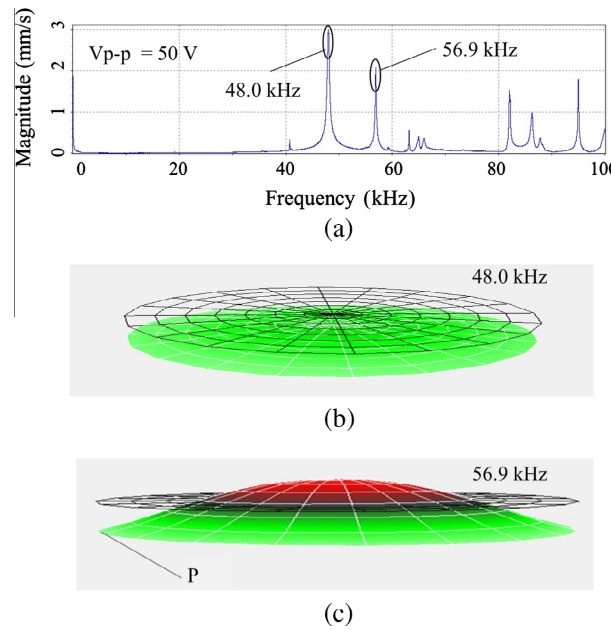

Fig. 2. Frequency response of the ultrasonic transducer. (a) Vibration magnitude vs. working frequency. (b) Vibration mode at 48.0 kHz. (c) Vibration mode at 56.9 kHz.

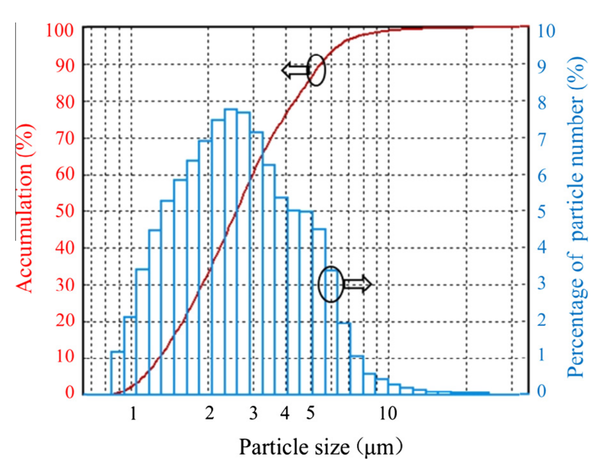

Fig. 3. Diameter distribution of particles in the smoke. The measurement range of the Winner 318A is from 0.1 μm to 323 μm, and the average for ten measurements is used.