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Acoustic separation of submicron solid particles in air

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ABSTRACT

The use of ultrasound to continuously separate submicron particles suspended in air is investigated in a rectangular channel with adjustable height. An electrostatic transducer is used to generate a standing wave in the 50–80 kHz frequency range and the particles experience forces within the acoustic field causing them to concentrate at the pressure nodes. To assess the effect of several key design parameters on the separation efficiency, a simple method based on light scattering is implemented to provide information on the particle concentrations as a function of position in the channel. The images acquired are processed to yield a separation efficiency metric that is used to evaluate the effect of acoustic, flow and geometrical parameters. The results show that, in qualitative agreement with theoretical models, the maximum separation efficiency increases with the pressure amplitude of the sound wave. The separation efficiency is also linearly proportional to the standing wave frequency, when it is varied between 50–80 kHz. On the other hand, the effect of the average fluid velocity is less pronounced than expected, suggesting that in our channel separation is not limited by the interaction length between the acoustic field and the suspended particles. The effect of the parallelism of the reflector relative to the transducer is also investigated.

1. Introduction

The separation of particles suspended in a gas is a problem relevant for a wide range of scientific and industrial applications. It is the subject of a sustained research effort aimed at developing and improving practical means for the concentration, sorting and removal of particles from gases. Currently, several mature industrial techniques are available to perform these tasks, including cyclones, electrostatic precipitators (ESP), scrubbers and filters based on porous elements. However, each have limitations such as the potential for clogging, the generation of liquid waste, reduced capabilities in harsh environments and for the handling of submicron particles [1–3]. Typically these techniques have a cut-off size, below which the particle removal efficiency significantly drops. For instance with filters relying on flowing the suspension through a porous material, the capture efficiency will obviously be low for particles smaller than the pore size. In this case, targeting smaller particles comes at the cost of an increased pressure drop. Other techniques such as ESPs can also be specifically designed to maximize submicron particle removal, with up to 90% capture efficiency [4], but this requires high energy input and results in the formation of ozone.

During the last few decades, microfluidics applications have benefited from the development of acoustically mediated techniques for the manipulation of particles, droplets and bubbles in liquids. This approach does not require the introduction of a physical barrier or of chemical additives for the separation of particles [5]. It is also able to sort particles according to their size [6] or other physical properties such as compressibility and density [7]. Techniques developed in the liquid phase can potentially be adapted to gaseous media [8]. Acoustic separation of particles suspended in air, especially submicron particles, has received limited attention and only a few works are addressing this problem experimentally. For instance, the investigations of Budwig et al. [9] and Anderson et al. [10] are limited to the separation and fractionation of particles several microns in diameter suspended in a gaseous flow. This motivates the present experimental investigation to study the effects of acoustic, flow and geometrical parameters on the separation efficiency of submicron solid particles suspended in air.

The paper is divided as follows: First, the theory behind the phenomenon under investigation is briefly explained. Then, the experimental setup and the data acquisition technique used are introduced. The effects of different parameters on the separation efficiency are then presented, including the pressure amplitude, the frequency of the standing wave, the average flow velocity and the parallelism of the channel walls. These results are followed

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by a brief discussion highlighting the implication for the design of practical acoustic separation systems.

2. Theory

The acoustic forces on a particle suspended in a fluid have been studied extensively since the first observation of particle separation in a standing wave by Kundt and Lehmann [11]. King [12] was the first to derive a comprehensive theoretical formula for the acoustic radiation forces on a rigid sphere in a plane standing wave. Several other studies further developed his initial formulation to include compressible spheres [13] and the effect of viscosity [14,15]. The particles suspended in an ideal 1D acoustic standing wave experience two forces from this field: the primary radiation force (PRF), generated by the interaction of a particle with the primary field, and the secondary radiation forces (SRF), originating from the energy scattered by the other suspended particles [16]. The PRF is by far the dominating force [17], and the SRF will accordingly not be considered in this study. In a standing wave, the PRF can be divided in two components: axial and transverse relative to the direction of the wave propagation. The axial component is responsible for the displacement of particles to the nodes or anti-nodes of the standing wave. The transverse component packs the particles closer together in the direction normal to the wave propagation [18]. The equation for the axial PRF [13] shown in Eq. (1) states that the acoustic force is proportional to the particle volume V_p and to the square of the pressure amplitude (p_a). The acoustic contrast factor $\Phi(\beta,\rho)$ depends on both the particle density ρ_p and its compressibility β_p in relation to the carrier fluid properties (ρ_f, β_f). The wave number k is defined as $\frac{2\pi}{\lambda}$, where λ is wavelength, x is the distance from a pressure node.

$$F_{ax} = \left(\frac{\pi V_p p_a^2 \beta_f}{2\lambda}\right)\Phi(\beta,\rho)\sin(2kx) \tag{1}$$

$$\Phi(\beta,\rho) = \frac{5\rho_p - 2\rho_f}{2\rho_p + \rho_f} - \frac{\beta_p}{\beta_f} \tag{2}$$

It should be noted here that the sign of the acoustic contrast factor sets the direction of the acoustic force either towards the pressure nodes or antinodes. Generally, solid particles suspended in air or aqueous media are moved to the pressure node, while gas bubbles in aqueous media are moved towards pressure antinodes [18].

3. Experimental setup

To assess the effect of a large number of parameters on acoustic separation efficiency, a versatile separation channel, a quick diagnostic technique and a suitable evaluating metric were implemented. These are presented in the following section.

3.1. Acoustic separation channel

A simple flow-through acoustic particle separator was built to study the effect of flow and acoustic parameters on the separation efficiency of solid particles suspended in air. The experimental setup is presented schematically in Fig. 1. The separation channel has a rectangular cross section, 30 mm wide, with transparent sidewalls to allow optical access to the acoustic region. An electrostatic broadband transducer (SensComp, Open face 600) is flush-mounted into the bottom wall, generating a standing wave across the channel height. The transducer can be operated in the 40–100 kHz range, generating sound pressure amplitudes up to 154.5 dB (re 20 μpa), measured using a type 4138 1/8″ Brüel and Kjaer pressure field microphone. A function generator (TG1000, TTi Ltd.) produces a sinusoidal signal for the transducer input. The signal is then shifted to positive values and amplified to 400 V peak-to-peak.

The separation channel is designed with a variable height (H), adjustable from 0 to 20 mm to yield standing waves of different frequencies. In the present study, the investigated range was 50–80 kHz, which corresponds to a channel height of 6.86–4.28 mm. The roof is manually positioned with micrometer screws at both ends while guided vertically by four supporting rods. The displacement of both extremities of the reflector is also measured optically from images captured using a digital camera, providing a resolution of 90 pixels/mm. From the measured value of the channel height, a baseline standing wave frequency is determined. The excitation frequency is then scanned around this baseline to identify the optimum resonance in the channel by visualization of the particle separation in the standing wave.

The velocity of air through the channel is regulated by a flow controller (Teledyne Hastings HFC-202), connected to a clean compressed air supply. The flow is conditioned upstream of the separation region in a stabilization chamber consisting of three rows of fine grids followed by a diffuser to ensure a Poisuille-type velocity profile over the transducer. The flow is seeded using a fluidized bed with TiO_2 solid particles (LaVision GmbH) with reported nominal diameter of 300 nm, density of 3900–4200 kg m^{-3} with negligible compressibility [19]. The seeder used is based on a design by Willert and Jarius [20,21], consisting of a cylinder with a porous metal plate glued to the bottom with clean air supplied from below. Solid particles located above the porous plate are entrained by the airflow when the drag force exceeds their weight. The size distribution of submicron particles was characterized using a Scanning Mobility Particle Sizer (SMPS, TSI 3080/3010), revealing possible agglomeration in the seeder as the size distribution is broad, centered at approximately 460 nm, and extends to large sizes, as shown in Fig. 1b.

3.2. Data acquisition

Only a few investigations in the literature have attempted to quantify the efficiency of acoustic separation in air, typically relying on directly counting the number of particles after the separation region. Budwig et al. [9] employed an off-line visualization approach using a microscope to evaluate the size distribution of the particles settling in a chamber downstream of the separation region. In a work in progress by our group [8], a Scanning Mobility Particle Sizer (SMPS) is used to quantitatively measure the particle size distribution in real time in the channel with and without a sound source. This technique can provide very precise information, but it is complex and not very fast. To investigate the effect of a wide range of parameters on the acoustic particle separation efficiency, a simple, fast and reliable method is required.

For the results presented here, a technique based on light scattering (also described in [8]) is implemented. A thin laser sheet parallel to the flow direction is used to illuminate the region immediately upstream and downstream of the transducer. The light sheet is created by a diode laser and two plano-convex cylindrical lenses in Keplerian configuration and is inserted through the downstream opening, along the centerline of the channel. The entrained particles in the channel scatter light, which is captured by a camera (Nikon D7000) positioned orthogonally to the flow. The images are exposed for a sufficiently long time to provide a high signal-to-noise ratio. Consequently, individual particles are not resolved but rather their trajectories are integrated. The images acquired are then processed using Matlab to yield a metric that can be used to assess the effect of different parameters on the separation efficiency.

Examples of images acquired using this technique are presented in Fig. 2 showing a nearly uniform distribution of particles in the