THE PHYSICS AND TECHNOLOGY OF ULTRASONIC PARTICLE SEPARATION IN AIR

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Abstract

A potential application of ultrasound is the separation of small particles from a moving airborne aerosol. Previous studies have shown that it is feasible to extract small particles from a moving stream of water. The thermodynamic and transport properties of the suspension fluid control the mechanisms available for separation, the forces that can be exerted, and the practical dimensions of ultrasonic airborne particle separators. Fundamental models exist that allow comparison of electrostatic and piezoelectric transduction in general for ultrasonic particle separation. Finite element studies show that allowance for slight curvatures in flow channel geometry can increase achievable acoustic pressures. We describe analyses and experiments that consider these factors for ultrasonic particle separation in air. The potential performance of ultrasonic separation in air is then compared to competing inertial technologies.

Introduction

In the interest of public health, it desirable to have the capability to determine the nature of small particles in suspended in air. The particles may be inorganic materials or biological pathogens harmful to humans. These particles range in size from 10μm to less that 1μm in diameter. A crucial problem is caused by the fact that only a few particles may be necessary to cause harm, thus increasing the difficulty in their detection. Consequently, it is of prime interest to monitor large volumes of air quickly, and extract the few particles that may be dangerous for later analysis. For example, consider a room of dimensions 6m×6m×3m. Suppose a device samples the air at a rate of 100 liter/min through a cross section of 4cm×4cm, which would imply an average air flow velocity through the cross-section area of 1 m/s. It would take 18 hr to completely sample the air in this room! Inertial and filtration technologies are commonly used at the present to sample small particles suspended in air [1]. An alternative approach is the application of ultrasonic radiation force to separate small particles from the airstream.

Acoustic radiation force has been successfully applied in the past to concentrate small particles in a moving stream of water. Recent developments have demonstrated feasibility, and have validated basic models that describe the design and behaviour of this type of device [2,3].

The present paper describes the application of this technology to the design of ultrasonic separators that are intended to separate small particles from a moving air-stream.

Design Considerations

We consider the physical limitations for ultrasonic separation of airborne particles by exploring the reference design shown in Figure 1. A suspension of particles in air, an airborne aerosol, enters a rectangular channel from the left, and flows to the right. It is assumed that the air flow is laminar, with velocity $U(z)$. An ultrasonic transducer of width $2b$ is flush-mounted to one wall of the channel. The transducer vibrates as a rigid plane at circular frequency $\omega=2\pi f$, were f is the frequency in Hz. The walls of the channel are separated by one-half wavelength, or $\lambda/2$, were $\lambda=c/f$ is the ultrasonic wavelength, and c is the speed of sound in air.

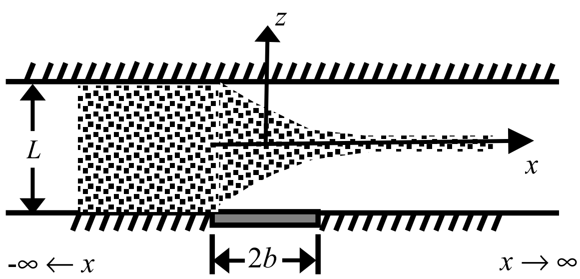


Figure 1. Ultrasonic particle concentrator.

A simple model for particle movement in front of the projected area of the ultrasonic transducer is

$$\frac{4}{3}\pi a^3 \rho_p \ddot{z} = F_z(x,z) - 6\pi\mu a \dot{z}\,,$$
$$\frac{4}{3}\pi a^3 \rho_p \ddot{x} = F_x(x,z) + 6\pi\mu a\left(U(z) - \dot{x}\right) \qquad (1,2)$$

where F_z, F_x are the acoustic radiation forces in the z and x directions respectively; a, ρ_p are the particle radius and density, μ is the shear viscosity of the suspension medium, and x,z measure the position of the particle as it passes the ultrasonic transducer. A model for radiation force that assumes perfect collimation of the ultrasonic standing wave and accounts for the particle compressibility [4] is

$$F_z = -\frac{2\pi^2 p^2 a^3}{\lambda \rho c^3} F_o \sin\left(\frac{4\pi}{\lambda} z\right), \quad F_o = \frac{\zeta + (2/3)(\zeta - 1)}{1 + 2\zeta} - \frac{1}{3\zeta\sigma^2}, \tag{3}$$

and F_x=0. In this expression ρ, c are the density and sound speed of the suspension fluid; ς, σ are the ratios of the particle density and sound speed relative to those of the suspension fluid, and p is the acoustic pressure amplitude. A model for radiation force that includes the effect of viscous shear and thermal conduction at the particle boundary has been developed by Doinikov [5]. This model includes an additional physical dependence of the radiation force on the viscous penetration depth $\delta=(2\mu/\rho\omega)^{1/2}$.

The model for particle movement (1,2) illustrates several physical differences between ultrasonic separators designed to work with air as the suspension medium and those designed to separate particles from water. At a given frequency, the wavelength in air is 4.73 times shorter than in water. Since transducer alignment becomes difficult with narrow channels [6], and narrow channels limit overall flow-through rates, ultrasonic separators designed for air as the suspension medium are in practice limited to lower frequency. Since air is a tenuous acoustic medium, the particle compressibility effect is always absent from the radiation force. In air, the particle compressibility coefficient F_o (3) becomes F_o=5/6, and particles are moved to the pressure nodes of the standing acoustic wave of the channel. For particles in water, the compressibility effect may lead to different results. Consider the compressibility effects of Lucite and soft rubber in water. The compressibility coefficient F_o for Lucite (density 1200 kg/m^3, sound speed 2650 m/s) and soft rubber (density 950 kg/m^3, sound speed 1050 m/s) [7] in water are F_o=0.303 and F_o=-0.400 respectively. For soft rubber in water, the coefficient is less than zero and the particles will collect at the pressure anti-nodes. The coefficient F_o=5/6 is greater than zero for both materials in air, which means that particles will collect at pressure nodes. Generally speaking, particles will always collect at pressure nodes when air is the suspension medium, and that may not be the case when water is the suspension medium. Experimental observations with biological particles in water [2] indicate that the mechanical properties of these particles are such that they collect at pressure nodes in water. Finally, the radiation force in actuality may be influenced by viscous shear and thermal conduction at the particle boundary, as predicted by Doinikov [5]. In this circumstance, a controlling parameter is the viscous penetration depth δ. Given equal wavelengths, the viscous penetration depth in air is approximately 8.5 times that in water.

Required Sound Pressure Levels

An estimate for the acoustic sound pressure amplitude required for particle separation in a moving fluid can be derived by assuming that the particle moves to a pressure node at an average velocity in the same time as it passes the ultrasonic transducer. The maximum transverse velocity $\dot{z}_{\max}$ attained by a particle can be computed from (1) to be

$$\dot{z}_{\max} = \frac{5\pi}{18} \frac{p^2}{\mu \rho c^2} \frac{a}{\lambda} a, \tag{4}$$

where it has been assumed that ς, σ→∞ as would be the case when air is the suspension medium. Assuming that a particle moves a maximum distance of λ/4 at a speed of (1/2) $\dot{z}_{\max}$ in a direction transverse to fluid flow in the same time that it passes a transducer of width 2b at an average fluid velocity $\bar{U}$, one can determine by equating these times that the required sound pressure amplitude is

$$p = \frac{\lambda}{a} \sqrt{\frac{9\bar{U} \mu \rho c^2}{10\pi b}}. \tag{5}$$

For example, given a particle of diameter 2a=7 µm, a frequency of 50 kHz, a transducer width 2b=32.5 mm, and a fluid flow velocity of $\bar{U}$=10 cm/sec, this expression predicts a required sound pressure amplitude of 159 dB re 20 µPa. At 50 kHz, the channel depth of λ/2 would be approximately 3.4 mm. Numerical integrations of particle motions using the more general model (1,2) shows that this estimate is slightly conservative, but is useful because it transparently reveals the physics. As would be expected, a designer would favor a short wavelength, and secondly, a wide transducer. When air is the fluid medium, the wavelength is limited by practical channel width.

Requirements on Transduction

A further consideration is the channel wall displacement amplitude required to generate the acoustic field in the separation channel. A simple estimate can be made of the required displacement amplitude of a transducer mounted in the channel wall. Using an expression for the pressure field in a closed cavity one-dimensional cavity, the maximum pressure amplitude at resonance is

$$p = \rho c u \frac{2Q}{kL}, \tag{6}$$

where u is the channel wall velocity amplitude, $k=n\pi/L$ is the nominal wavenumber at the n^{th} λ/2 resonance. For an ultrasonic separator, Q is a quality factor that includes absorption within the fluid, at the channel walls, and losses associated with acoustic waves that propagate away from the transducer area.

Substituting the pressure (6) into (5), and replacing the velocity amplitude u with $2\pi fx$, were x is the displacement amplitude of the transducer, one obtains an expression for the required displacement amplitude

$$xQ = \frac{n}{4c}\frac{\lambda^2}{a}\sqrt{\frac{9\bar{U}}{10\pi b}\frac{\mu}{\rho}} \,. \qquad (7)$$

In our experience, quality factors of Q~200 are achievable for airborne particle concentrators [8]. An example calculation using f= 50 kHz, $\bar{U}$ =10 cm/sec, $2a$=7 μm, $2b$=32.5 mm, and Q=200 gives a required wall displacement amplitude of 264 nm.

Incidentally, the formula (7) predicts that the transducer displacement amplitude requirements for particle concentration in air can be much more formidable than would be the case for water as the suspension medium. If it is assumed that the particle compressibility is such that $\varsigma, \sigma \to \infty$, and equal average velocity $\bar{U}$, quality factor Q, acoustic wavelength λ, and transducer width $2b$, the expression (7) predicts that the required ratio of required wall amplitude x_a for air as the suspension medium to x_w for water as the suspension medium yields

$$\frac{x_w}{x_a} = \frac{c_a}{c_w}\sqrt{\frac{\mu_w}{\mu_a}\frac{\rho_a}{\rho_w}} \,. \qquad (8)$$

This ratio turns out to be $x_w/x_a \approx 0.056$, which means that roughly 18 times more wall displacement would be required when air is the suspension medium for a similarly sized ultrasonic separator.

Transduction Technologies

There are two practical transduction choices for excitation of the standing ultrasonic wave in the separation channel; piezoelectric and electrostatic. Piezoelectric transduction has been exclusively used when the suspension medium is water, while we have reported on the use of electrostatic transduction when the suspension medium is air [9].

When piezoelectric transduction is used for ultrasonic separation, a layer model may be used to predict performance [10]. In the application of this model to ultrasonic separators, one layer consists of the piezoelectric transducer, another layer is assigned to the fluid channel, and the other layers model the other structural components.

To evaluate the suitability of piezoelectric transduction in ultrasonic separators designed to separate particles from a moving air-stream, we adopt a very simplified version of the layered piezoelectric resonator model. We assume that the piezoelectric transducer is stress-free at the back $z=-(L_t+L/2)$, that the reflector surface at $z=L/2$ is rigid, and that the fluid pressure on the transducer does not affect its motion. The last assumption is reasonable because it has been reported that the cavity resonance of the fluid layer is decoupled from the resonances of the elastic solid layers [3]. With these assumptions, a three-port model [11] of the piezoelectric layer at low frequency reduces to

$$x = \frac{1}{2}\frac{d_{33}}{2\left(d_{33}^2/\varepsilon_{33}^T\right)-1}V \,, \qquad (9)$$

where V is the applied voltage, d_{33} is the piezoelectric stress constant, and $\varepsilon_{33}{}^T$ is the dielectric permittivity at constant stress. In this model, the elastic acoustic wavelength λ_e and half-wavelength frequency $f_{\lambda/2}$ are

$$\lambda_e = \frac{1}{f\sqrt{\rho_t s_{33}^D}} \,, \; f_{\lambda/2} = \frac{1}{2\pi L_t\sqrt{\rho_t s_{33}^D}} \,, \qquad (10,11)$$

where ρ_t and $s_{33}{}^D$ are the mass density and elastic compliance at constant electric displacement for the piezoelectric material. With these assumptions, an estimate of the stress T in the piezoelectric layer is given by

$$T = -\frac{d_{33}}{1-(\varepsilon_{33}^T/2d_{33}^2)}\frac{V}{s_{33}^E L_t} \,, \qquad (12)$$

where $s_{33}{}^E$ is the compliance of the piezoelectric material at constant electric field.

It is instructive to estimate the performance of piezoelectric transduction as would be applied to ultrasonic separation of particles in airborne aerosols. We assume a transducer thickness L_t of L_t=3 mm. Using a density of ρ_t=7500 kg/m^3 and elastic compliance of $s_{33}{}^D$=8.99(10)$^{-12}$ m^2/N [11] for PZT-5H, and a frequency of 50 kHz, the elastic acoustic wavelength is λ_e=77.0 mm. The half-wavelength frequency for the transducer thickness is $f_{\lambda/2}$=641.9 kHz. Given the properties for PZT-5H d_{33}=593(10)$^{-12}$ C/N, $\varepsilon_{33}{}^T$=30.1(10)$^{-9}$ F/m, $s_{33}{}^E$=20.7(10)$^{-12}$ m^2/N [11], and an applied voltage amplitude V=1000 Volts, expressions (9,12) give a displacement amplitude x=185 nm, or 0.185 nm/V, and stress of $|T|$=15.5 MPa. This stress is near the ultimate tensile strength of commercially available piezoelectric materials. For example, it is our understanding that the ultimate dynamic tensile strength of type APC 841 [12] material is 20 MPa. Use of thicker piezoelectric elements, or composite arrangements [13] to reduce the operating stress would result in transducers that far exceed the dimensions of the air-stream flow channel, and would lead to impractical size for the overall device. Given the channel wall displacements required for separation, it is apparent that piezoelectric transduction may have limited application for ultrasonic separation in airborne aerosols.

An alternative to piezoelectric is electrostatic transduction. A commercially available electrostatic transducer is manufactured by Polaroid [14]. This transducer is of the roughened backplate category [15], and has a broad resonance peak near 50 kHz.

This is the transducer that we have employed in our past feasibility measurements.

The capability of electrostatic transduction in general can be analyzed using a model that has been developed for electrostatic transducers that use micro-machined backplates [16]. Small ridges, of height h and separation distance w are deposited on the backplate, as shown in Figure 2. A model of this type of transducer takes the form

$$(j\omega)mu + \frac{s}{(j\omega)}u - \frac{V_p^2\varepsilon_o}{(j\omega)x_o^3}u = -\rho c u\frac{2Q}{kL} + \frac{V_p\varepsilon_o}{x_o^2}V\,, \qquad (12)$$

where u is the velocity amplitude of the transducer diaphragm, m and s are equivalent mass and stiffness; V_p, and V are the polarization voltage, and applied voltage amplitude; x_o is the average diaphragm separation from the backplate after application of the polarization voltage V_p, ε_o is the dielectric permittivity of free space, and a harmonic response proportional to $e^{j\omega t}$ has been assumed. Details for calculation of the parameters m and s are contained in Ref. 16, and they have been normalized to the transducer area here. In the model (12), the pressure of the fluid in the channel has been included because it has been our experience that electrostatic transducers are not stiff enough to be decoupled from fluid in the channel, even if it is air.

An example calculation showing the diaphragm displacement amplitude $x=|u/j\omega|$ of an electrostatic transducer used in an ultrasonic separator designed for airborne aerosols is shown in Figure 3. In this computation, the dimensions for the transducer were ridge height h=5 µm, ridge separation w=400 µm, a 5µm thick diaphragm made from metallized polyethylene terephthalate (Mylar), and polarization voltage V_p=400 Volts. A total quality factor Q=200 was assumed for the fluid channel cavity. Two curves are contained on the graph shown in Figure 3. The solid and dashed line show the diaphragm displacement amplitude per volt computed from (12) with and without an account for the fluid pressure on the diaphragm respectively. Two conclusions are evident. First, the fluid pressure in the channel can significantly affect the performance of the transducer. Secondly, the displacement amplitude per volt possible with an electrostatic transducer is much higher than what could be expected from a piezoelectric transducer.

Channel Geometry

Ultrasonic particle separators employ resonant amplification between channel walls to achieve high sound pressure levels in the flowing fluid. Most commonly, the channel is rectangular or cylindrical in shape. In these designs, some of the acoustic energy generated by the ultrasonic transducer propagates

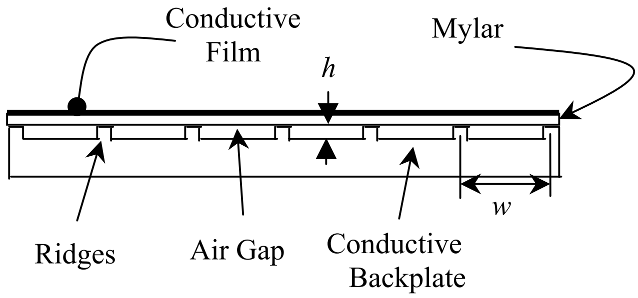


Figure 2. Electrostatic ultrasonic transducer design.

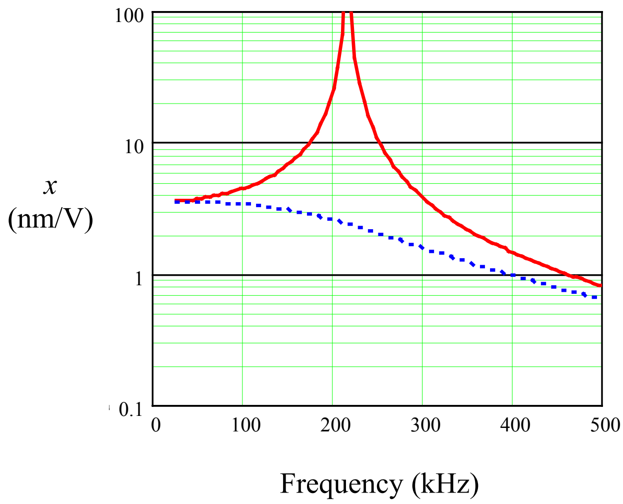


Figure 3. Performance of electrostatic transducer.

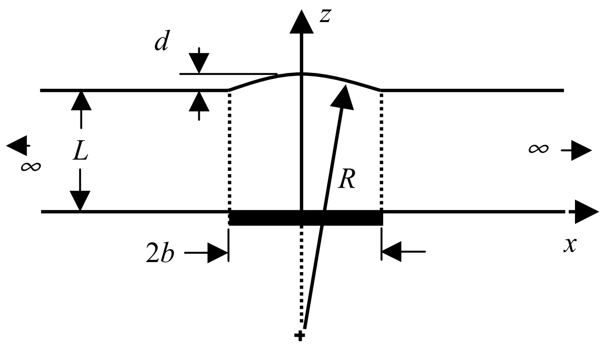


Figure 4. Geometry of shaped channel.

away from the standing wave field, and lowers the achievable sound pressure amplitude. One way to increase the achievable sound pressure amplitudes in the separation channel is to modify the shape of the reflecting wall of the channel directly opposite the ultrasonic transducer. This strategy has been adopted by designers of acoustic levitators [17].

We have explored the design of a curved reflecting surface to be machined into one wall of a rectangular separator channel. A sketch of such an arrangement is shown in Figure 4. This sketch shows a curved surface, of depth d, in the reflecting wall of the channel. The surface extends only to the edges of the ultrasonic transducer, and has a radius of curvature R given by

$$R = d\left[\frac{1}{2}\left(\frac{b}{d}\right)^2 + 2\right]. \qquad (13)$$

A finite element analysis was used to determine the acoustic pressure in the channel with curved reflectors of varying depth d. A Perfectly Matched Layer (PML) [18] was employed to account for acoustic waves that propagated away from the standing wave field directly in front of the transducer.

Two example computations of acoustic pressure amplitude in a channel with a curved reflecting wall are shown in Figure 5. In these computations, a transducer width $2b$=28.57 mm, channel width L=3.4 mm, transducer velocity amplitude u=2.95 mm/s, and frequency f=50 kHz were used. A relaxation time of τ=12.42ns was included in the wave equation model to account for absorption within the body of the fluid and channel walls. In Figure 5a, the reflector was planar and a maximum pressure amplitude of 124 Pa was observed. In Figure 5b, the normalized depth of the curved reflector $d^*=d/L$ was 16%, and a maximum pressure amplitude of 320 Pa was observed. The presence of a curved reflector of this depth resulted in a factor of 2.58 increase in acoustic pressure amplitude. Our computations further show that a respectably large gain in acoustic pressure amplitude can be obtained using a reflector of surprisingly small normalized depth d^*.

Comparison of Ultrasonic and Inertial Particle Separation

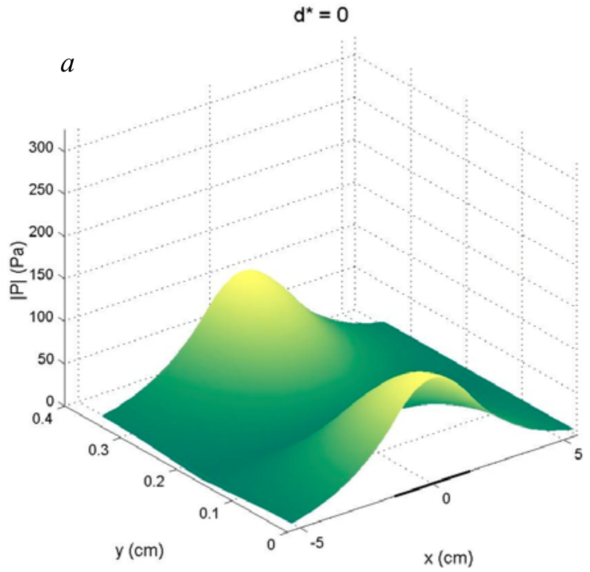
An independent measure of the efficacy of ultrasonic separation of airborne particles may be obtained by comparing its performance to inertial separation technologies. To make this comparison, we consider the schematic model for inertial separation shown in Figure 6. An airborne aerosol is forced through a curved channel of nominal curvature r at an average fluid flow velocity U. A simple model for particle motion transverse to flow at steady state is

$$\frac{4}{3}\pi a^3 \rho_p \frac{U^2}{r} = -6\pi\mu a \dot{z}_I , \qquad (14)$$

where $\dot{z}_I$ is the particle velocity transverse to the fluid flow direction, and a subscript I has been added to denote that the velocity is caused by particle inertia. Solving for $\dot{z}_I$ from (14) above, and comparing to $(1/2)\dot{z}_{\max}$ for ultrasonic separation, one obtains the ratio

$$\eta = \frac{\dot{z}_I}{(1/2)\dot{z}_{\max}} = \frac{8}{5\pi}\frac{\rho_p\left(U^2/r\right)}{\left(p^2/\rho c^2 \lambda\right)}, \qquad (15)$$

a



b

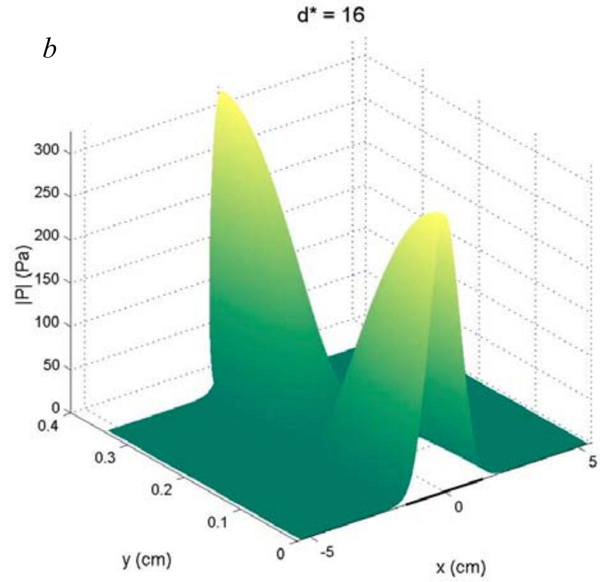


Figure 5. Acoustic pressure amplitude in channel.

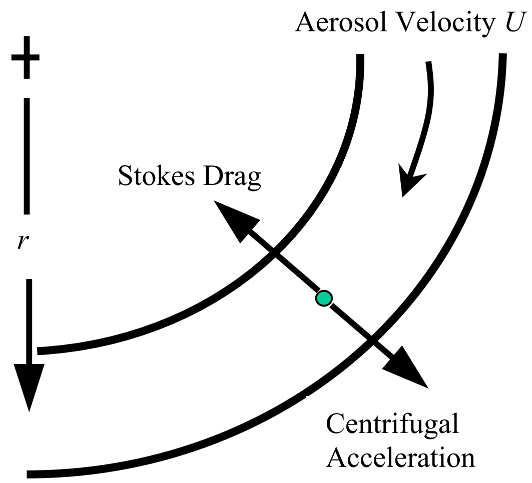


Figure 6. Geometry for inertial separation.

where η is a representative measure of the "efficacy" of inertial separation compared to ultrasonic separation. This expression shows that the comparison is independent of particle diameter, assuming the radiation force model (3).

An application of this comparison ratio is shown in Figure 7. In this computation, the radius of curvature was assumed to be r=10 mm, and the average fluid flow velocity U was set to U=100 cm/s, closer to the flow velocities that are encountered in commercial inertial separation devices. The particle density was assumed to be that of water, ρ_p=1000 kg/m^3. Figure 7 shows that at frequencies of 100 kHz, 300 kHz, and 1MHz, sound pressure levels of 165 dB, 160 dB, and 155 dB would be required for ultrasonic particle separation in air to be competitive with inertial technologies. For r=1mm, these sound pressure levels would increase by 20 dB. At 500 kHz, the channel width L would become very small. For ultrasonic separation to become competitive, it is apparent that sound pressure levels in excess of 160 dB are required to achieve practical flow rates and channel size.

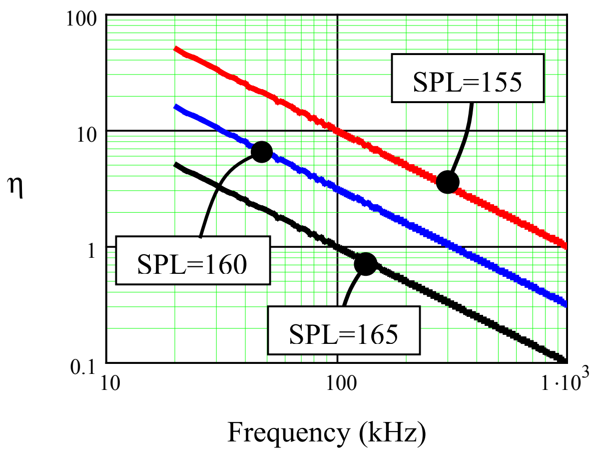


Figure 7. Ratio of inertial to radiation force velocity.

Experiments

Our research group has performed several measurements over the past years to validate quantitative models that predict particle motion in an ultrasonic separator designed to concentrate particle in an airborne aerosol. Our first efforts used a rectangular channel, approximately L=6.86 mm in width, operating nominally at 50 kHz. At this frequency, the channel width was one-wavelength wide, so that two pressure nodes were present. A Polaroid electrostatic transducer was used to excite the ultrasonic standing wave. An ultrasonic humidifier was used to generate water droplets, which served as the particles. A laser sheet was shined into the fluid channel during operation, so that particle motions could be observed, sound pressure level in the channel was measured with a calibrated microphone, and the air flow velocity was determined using a hot-wire anemometer. The apparatus is described in detail in Ref. 9. The measurements showed that particles did indeed collect at the pressure nodes, but we did not have great confidence in our estimation of droplet size.

Recently, we have changed our apparatus to allow the ultrasonic separation of glass spheres from a moving air-stream. An example visualization of the flow of glass spheres, of poly-disperse diameters ranging from 1μm to 10μm is shown in Figure 8. The measured air-flow velocity in the center of the channel was 10 cm/sec, and the sound pressure level at the channel wall directly opposite the transducer was 150 dB re 20μPa. The degree of particle movement while

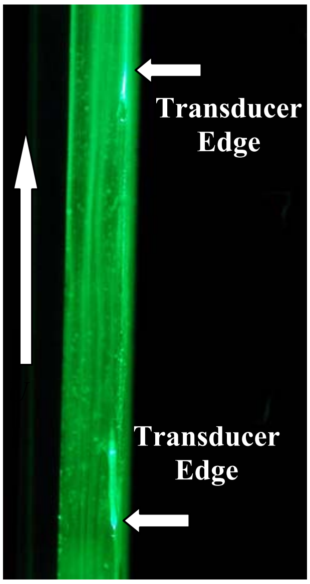


Figure 8. Experimental flow visualization of glass spheres in air-stream.

in front of the transducer was consistent with the predictions of the simple model (1,2) for particle motion. However, we have noticed that the apparent position of the collected streams do not agree with the expected locations of the pressure nodes.

Conclusions

The application of acoustic radiation force to the separation of small particles from a moving air-stream was assessed. Acoustic pressure amplitudes in excess of 160 dB re 20 μPa are required for practical separation rates. Piezoelectric transduction appears to lack the capability to generate the necessary sound pressure amplitudes, while electrostatic transduction may be suitable. Finite element models show that it may be possible to increase sound pressure levels in the separation channel in excess of 6dB if a slight curvature is formed in the reflecting wall of the air-stream channel.

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