Acoustic Resonator Aerosol Particle Separation

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INTRODUCTION

It has been shown in the past that the acoustic radiation pressure created by a standing wave in a closed chamber can be used to separate solid particles from a surrounding liquid medium. However, much less work has been performed using this principle to separate aerosol particles in gases. Here we use acoustic radiation pressure to separate 10-50µm water droplets entrained in moving air.

THEORETICAL MODEL

Figure 1 illustrates the resonator chamber, standing acoustic wave, and aerosol separation.

Figure 1: Resonator chamber

A simple model of the forces acting upon a particle of water as it passes through the acoustic field in the resonant chamber has been constructed as follows. We assume a one-dimensional, collimated acoustic field transverse to the mean flow direction, and consider only acoustic, drag, and gravitational forces.

The equations of motion for a particle passing through the acoustic field in the transverse and tangential directions to the mean flow are, respectively,

\[
\ddot{z} = \left( \frac{1}{4\pi^3 \rho_p^3} \right) \left( \frac{5\pi}{6} \left( \frac{p_1^2}{\rho_0 c^5} \right) \omega^3 \sin \left( \frac{4\pi}{k} z \right) - 6\pi \mu a \right) \tag{1}
\]

\[
\ddot{x} = \left( \frac{1}{4\pi^3 \rho_p^3} \right) \left( \frac{4\pi^3}{3} \rho_p \right) g + 6\pi \mu \left( \frac{1}{2\mu} \rho_0 g \left( L_z - z \right) - \dot{x} \right) \tag{2}
\]

where the variables are defined as

- \( a \) = particle radius [m]
- \( \rho_p \) = particle density [g/m³]
- \( \rho_0 \) = air density [g/m³]
- \( g \) = gravitational constant [m/s²]
- \( \mu \) = dynamic viscosity of air [g/ms]
- \( c \) = speed of sound [m/s]
- \( k \) = wavelength of standing wave [m]
- \( \omega \) = angular frequency of acoustic wave [s⁻¹]
- \( p_1 \) = sound pressure at boundary [Pa]
- \( z \) = coordinate transverse to mean flow [m]
- \( x \) = coordinate tangential to mean flow [m]
- \( L_z \) = chamber width transverse to mean flow [m]

Integrating equations (1) and (2) across the width of the acoustic field, the anticipated particle trajectories are illustrated in Figure 2.
Figure 2: Predicted particle trajectories

Note that Figure 2 is rotated 90° counterclockwise from the orientation given in Figure 1.

Figure 2 illustrates the predicted path of water particles as they enter the chamber from the left and exit on the right. Concentrated streams are expected at the nodes of the standing acoustic wave, which correspond to points of minimum pressure. Pressure gradients due to the standing wave are expected to give rise to particle motion transverse to the main flow toward the minimum pressure points.

EXPERIMENTAL METHODS

Figure 3 is a photo of the laboratory equipment used for this investigation.

Figure 3: Equipment setup

Resonator Design

The resonator chamber was constructed from aluminum stock with an adjustable width \( L_z \) of 4.7mm to 6.0mm. The depth \( L_y = 29.2 \)mm and the length \( L_x = 117.0 \)mm were held constant. Flow entered from the bottom and exited from the top. Figures 4 and 5 illustrate the resonator construction.

Figure 4: Resonator construction

Acoustic Resonator

Chamber - back & side views

Figure 5: Chamber detail

Acoustic Resonator

Chamber detail

The transducer, hereafter referred to as the piston, was removed of its cover screen and mounted flush with the inner wall of the chamber facing the \( z \) direction. A 3.2mm (1/8in) microphone port was located in the reflecting wall opposite the center of the piston.

Acoustic Excitation

The piston used for creating the acoustic wave was a Polaroid Series 600 electrostatic transducer designed for sonar range finding in photographic equipment. The piston consists of a 4.0cm diameter, gold-coated mylar film stretched over an oppositely charged rigid rough surface.
excited with an AC voltage between 20kHz and 100kHz, capacitive effects between the gold on the mylar and the rigid surface beneath cause the mylar to oscillate and produce an acoustic field as it pushes on the surrounding air.

Driving electronics consisted of an HP E3611A DC power supply, a Pico model 28VV1 DC-DC boost converter, an HP 33120A wave generator, and two homemade AC amplifier circuits containing an APEX PA12 Op-Amp and a custom-wound 20:1 transformer, respectively.

**Sound Pressure Measurements**

Sound pressure measurements were accomplished with a freshly calibrated Type 4138 ultrasonic microphone from Bruel & Kjaer. The sound pressure level (SPL) in decibels [dB] is calculated from

\[
SPL = 20 \log \left( \frac{p}{p_{ref}} \right) = 20 \log \left( \frac{V_{mic,RMS}/\text{Calib}}{20 \mu \text{Pa}} \right) \tag{3}
\]

where the calibration constant \( \text{Calib} = 0.932 \, \text{mV/Pa} \) was given by the manufacturer, and the output voltage \( V_{mic,RMS} \) was measured with an Agilent 54621A digital oscilloscope. The microphone’s transducer surface was mounted flush with the reflecting wall of the resonator chamber through the microphone port.

**Particle Entrainment**

The aerosol droplets were generated by a SunMark 1.7gal ultrasonic humidifier. The droplets exited the humidifier in a concentrated fog, which passed through a 24 x 20cm cylindrical plenum chamber, a 7.6cm throttle valve, and a 3 x 3 x 8cm flow straightening section before entering the resonator chamber.

**Particle Sizing**

Given the dynamic nature of the water droplet diameter due to the opposing mechanisms of agglomeration and evaporation, the particle size measurements contributed the greatest amount of uncertainty to the validation of our theoretical model. Particle size was measured using close-up digital images taken with a Nikon CoolPix 990 digital camera as the droplets were held stationary in the resonant chamber. Figure 6 is a photo of the water particles in the chamber.

\[
D_{\text{particle,actual}} = K_B \left( \frac{D_{\text{particle}}}{L_z} / \text{photo} \right) L_{z,\text{actual}} \tag{4}
\]

However, further investigation showed that pixel blooming caused particle size measurements to be overestimated. This is a phenomenon in which the electrons, representing the captured image inside the camera, bleed across pixel borders with high contrast. Therefore the uncertain blooming factor \( K_B \) was added to Equation (4).

An attempt was made to quantify the blooming factor using particles of a known size. Figure 7 is an image of 30µm polystyrene particles on a microscope slide, next to a machinist’s scale with 1/64” increments. The photo was taken at the Coolpix camera’s minimum focus distance of 2cm and maximum resolution of 1536 x 2048 pixels.

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**Figure 6: Water particles**

**Figure 7: 30µm polystyrene particles**
Counting the width of the particles in pixels and comparing to the 1/64" increments on the scale as in equation (4), the following data was collected:

<table>
<thead>
<tr>
<th>Actual size</th>
<th>Estimated size from photos</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 µm</td>
<td>26 µm</td>
</tr>
<tr>
<td>30 µm</td>
<td>103 µm</td>
</tr>
</tbody>
</table>

Pixel blooming tended to increase the apparent size of the particles by a factor between 2 and 5, varying with both laser intensity and focus. Thus particle size was the most uncertain measurement in these investigations.

**Velocity Measurements**

Velocity measurements were taken at a point 3.5 cm downstream of the center of the piston, and in the center of the width of chamber ($z = L_z/2$) with the sound pressure turned off. These measurements were accomplished using Laser Doppler Velocimetry (LDV) equipment from DISA and TSI.

To measure the velocity of the moving particles, the LDV uses crossed laser beams, which form a measurement volume containing a fringe pattern of light waves. As particles pass through the measurement volume, light is forward scattered into a photodetector cell at the frequency the particles are crossing the fringes. The measurement volume was 0.3 mm across, with a fringe spacing of $\Delta x = 3.03 \mu m$. The photodetector output an amplified signal to the DISA Type 55 N 21 Tracker, which in turn produced a voltage signal proportional to the frequency $f_T$ at which particles were crossing the fringes:

$$ f_T = \left( \frac{V_T}{10V} \right) f_{top}, $$

where $V_T$ is the voltage output from the tracker, and $f_{top}$ is the upper limit of the bandwidth in which the tracker is operating.

To help stabilize the signal, the tracker frequency was modulated by shifting the frequency one of the laser beams by $f_s$, so that the fringes were also moving at a constant velocity. This was accomplished with a model 9186A Frequency Shifter from TSI. The doppler frequency $f_D$ that the particles would cross the fringes if they were stationary can be found using

$$ f_T = |f_D - f_s| $$

If a shift frequency is chosen such that $f_s > f_D$, this becomes

$$ f_D = f_s - f_T $$

Using the known fringe spacing $\Delta x$ and combining equations 5-7, the velocity of the particles $U_x$ passing through the control volume can be calculated from equation 8:

$$ U_x = \left[ f_s - \left( \frac{V_T}{10V} \right) f_{top} \right] \Delta x $$

Thus the computed velocity of the particles was a function of $V_T$, $f_s$, and $f_{top}$.

**Flow Visualization**

The flow visualization photos were taken using the Nikon Coolpix 990 digital camera. The flow of particles were illuminated using a Coherent Innova 70 4W Argon Ion Laser operated at 514.5 nm wavelength. The laser was passed through a focusing lens and then a scattering lens, which produced a thin laser sheet before being projected into the resonant chamber.

**Separation Efficiency**

Image processing software was developed to provide a measure of separation efficiency. First, a box of pixels was selected that illustrated the span of the separated flow. The software then tallied numerical grayscale values for each column of pixels in the selected area. The results were then plotted as a histogram of total grayscale vs. width for the image. See Figure XX in the result section.

**RESULTS**

**Maximum Sound Pressure at Resonance Without Particle Flow**

The piston manufacturer recommended a nominal 300V_p-p driving voltage with 150V_bk bias offset at 50 kHz, so that the driving voltage ranged between 0-300V. The bias voltage created the piston pretension and the AC portion created the oscillation. The manufacturer also rated the pistons at 400V peak maximum.

The resonator was tuned for maximum sound pressure by adjusting the driving voltage and frequency until just before dielectric breakdown of the mylar occurred. It was found that the piston
manufacturer’s specifications could be exceeded, up to 600Vp-p and 300Vdc bias before breakdown. (See Equation (3)) When 600V maximum driving voltage was increased, the piston would begin to arc, damaging the gold film and reducing sound pressure. Table 2 lists the parameters that achieved maximum sound pressure.

Note that for a wavelength equal to one chamber width, where \( \lambda = L_z = c/f \), the predicted resonance for a 5.21mm wide chamber is 65912 Hz, very close to the frequency at which maximum SPL was found.

Table 2: Parameters for Maximum Sound Pressure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Bias Voltage</td>
<td>( V_{dc} )</td>
<td>300</td>
<td>V</td>
</tr>
<tr>
<td>AC Pk-Pk Voltage</td>
<td>( V_{p-p} )</td>
<td>600</td>
<td>V</td>
</tr>
<tr>
<td>Driving Frequency</td>
<td>( f )</td>
<td>65900</td>
<td>Hz</td>
</tr>
<tr>
<td>Microphone Output</td>
<td>( V_{mic,RMS} )</td>
<td>1.09</td>
<td>V</td>
</tr>
<tr>
<td>Chamber width</td>
<td>( L_z )</td>
<td>5.21</td>
<td>mm</td>
</tr>
<tr>
<td>Sound Pressure</td>
<td>SPL</td>
<td>155.34</td>
<td>( \beta )</td>
</tr>
</tbody>
</table>

**Harmonic Saturation**

As the driving voltage of the piston was increased, it was found that an increasing portion of acoustic energy was going into harmonic content and not contributing to sound pressure. The oscilloscope was also used for FFT analysis as illustrated in Figure 8.

Figure 8: Microphone Frequency Spectrum

As can be seen in Figure 8, the first harmonic at double the driving frequency contributed a component about 23 dB, or about 7%, of the total acoustic energy.

A series of tests were run in which the driving voltage was slowly increased and an FFT analysis was taken at each voltage level. It was found that the first harmonic component was growing faster than the fundamental with total SPL levels as low as 100 dB. Figure 9 illustrates the relationship between the fundamental and the first two harmonic components of the microphone signal as the driving voltage was increased. This shows that acoustic saturation was occurring.

Figure 9: Acoustic Saturation

**Resonance Shift due to Particle Flow**

It was found that the presence of water droplets in the chamber shifted the resonant frequency by approximately 1kHz. Although the microphone could not measure SPL in the presence of water droplets, a PZT pinducer, 1/10” diameter, was also used to quantify the SPL. First, resonance was found with the microphone while the humidifier was turned off. Then, the microphone was replaced with the pinducer and a time trace was recorded. Then the frequency was adjusted until the best visible separation was achieved. Figure 10 illustrates the change in the pinducer time trace between resonance without water droplets and the best separation with water droplets present in the chamber.
Particle Size

Using the technique for measuring particle diameter described above in Equation (4) and Figures (6) and (7), Table (3) shows the estimated particle size, which varies greatly upon the blooming factor.

Table 3: Estimated Particle Size Range

<table>
<thead>
<tr>
<th>Lz,actual</th>
<th>0.205 in</th>
<th>0.205 in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dparticle,photo</td>
<td>0.25 in</td>
<td>0.25 in</td>
</tr>
<tr>
<td>Lz,photo</td>
<td>11.00 in</td>
<td>11.00 in</td>
</tr>
<tr>
<td>Kf</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Dparticle,actual</td>
<td>23.7 µm</td>
<td>59.2 µm</td>
</tr>
</tbody>
</table>

Therefore, the best estimation using this technique to measure particle diameter indicated that they ranged between 20 and 60 µm, depending on the blooming factor. Note that an actual size distribution would also be expected.

Flow Visualization

The results of these experiments are summarized in Figures (11) and (12). Figure (11) illustrates the interior of the resonant chamber for three flow speeds, including velocity and sound pressure measurements. It is interesting to note that at low flow velocities, acoustic effects tended to cause the concentrated streams to shift slightly from the expected positions. See the left-hand photo of Figure (11). It is assumed that this was caused by the fact that the acoustic field was not truly collimated, but in fact leaked outward in the + and – x directions. At flow velocities approaching zero, this same effect was observed to produce stable vortices roughly the width of the chamber.

Figure 11: Resonant Chamber Flow Separation

Figure 12 illustrates the exit conditions at roughly the same velocities as those shown in Figure (11), as well as gray scale histograms showing the relative separation efficiency at each velocity. As expected, the histograms show that separation efficiency is inversely proportional to velocity.

Figure 12: Exit Flow Separation