Large volume flow rate acoustophoretic phase separator for oil water emulsion splitting.

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Efficient separation technologies for multi-component liquid streams that eliminate waste and reduce energy consumption are needed. Current technologies suffer from high cost of energy, use of consumables, fouling, and limited separation efficiency of micron-sized particles. We propose a novel platform technology consisting of a large volume flow rate acoustophoretic phase separator based on ultrasonic standing waves. The acoustic resonator is designed to create a high intensity three dimensional ultrasonic standing wave resulting in an acoustic radiation force that is larger than the combined effects of fluid drag and buoyancy, and is therefore able to trap, i.e., hold stationary, the suspended phase. The action of the acoustic forces on the trapped particles results in concentration, agglomeration and/or coalescence of particles and droplets. Heavier than water particles are separated through enhanced gravitational settling, and lighter particles through enhanced buoyancy. A first prototype consists of a 2" by 1" flow chamber driven by a single 1" by 1" transducer at 2 MHz, with flow rates of 30 L/hr, and measured oil separation efficiencies in excess of 95%. A second prototype is designed to further scale the system to flow rates of 150 L/hr. [Supported by NSF SBIR 1215021 and NSF PFI:BIC 1237723]
INTRODUCTION

Efficient separation technologies for multi-component liquid streams that eliminate waste and reduce energy consumption are needed. Current technologies suffer from high cost of energy, use of consumables, fouling, and limited separation efficiency of micron-sized particles. We propose a novel platform technology consisting of a large volume flow rate acoustophoretic phase separator based on ultrasonic standing waves. The technology has the potential to be economic, efficient, sustainable, and environmentally benign. Ultrasonic standing waves are used to trap, i.e., hold stationary, the secondary phase particles in a fluid stream. This is achieved when the acoustic radiation force exerted on the particles is stronger than the combined effect of fluid drag and buoyancy force. The action of the acoustic forces on the trapped particles results in concentration, agglomeration and/or coalescence of particles and droplets. Heavier than water particles are separated through enhanced gravitational settling, and lighter particles through enhanced buoyancy. A combination of experimental results and computer modeling is used to investigate the fundamental interaction between the piezo-electric transducer and the acoustic field with the goal of maximizing the acoustic trapping potential. The novel acoustophoretic separation technology provides for a cheaper and lower cost of energy separation of multi-component phase mixtures, especially for micron-sized particles.

First, we discuss modeling of the acoustic radiation force acting on suspended particles. A combination of numerical models is used to calculate the acoustic radiation force in a two-dimensional approximation. Then, we describe the design of an acoustophoretic oil-water emulsion splitting system. We conclude by discussing experimental results obtained on the acoustophoretic oil-water emulsion system.

COMPUTATION OF ACOUSTIC RADIATION FORCE

Acoustic Radiation Force Theory

A particle suspended in a flowing fluid passing through an acoustic standing wave experiences three primary forces: the fluid drag force, the gravitational/buoyancy force, and the acoustic radiation force. When the opposing forces in each direction are balanced, the particle is in equilibrium and will effectively be trapped by the ultrasonic standing wave. For small particles, the drag force is given in Eq. (1).

\[
\vec{F}_D = 4\pi\mu R_p \left( \vec{U}_f - \vec{U}_p \right) \left[ 1 + \frac{3}{2} \mu \right] \left[ \frac{1}{1 + \mu} \right]
\]

(1)

Here \( \vec{U}_f \) and \( \vec{U}_p \) are the fluid and particle velocities, \( R_p \) is the particle radius, \( \mu_f \) and \( \mu_p \) are the dynamic viscosities of the fluid and particle, and \( \mu \) is the ratio of dynamic viscosities. The buoyancy force is given by Eq. (2), where \( g \) is the gravitational constant and \( \rho_f \) and \( \rho_p \) are fluid and particle densities, respectively.

\[
\vec{F}_B = \frac{4}{3} \pi R_p^3 \left( \rho_f - \rho_p \right) g \vec{k}
\]

(2)

For a particle to be trapped in the ultrasonic standing wave, the force balance on the particle must be zero, and therefore an expression for the required lateral acoustic radiation force \( \vec{F}_{LRF} \) in the flow direction can be found, given by: \( \vec{F}_{LRF} = \vec{F}_D + \vec{F}_B \). For a particle of known size and material properties and for a given flow rate, this equation can be used to estimate the minimum lateral acoustic radiation force that is required for particle trapping.

Gorkov’s formulation is used to calculate the acoustic radiation force acting on a suspended particle in a two-dimensional acoustic field. Gor’kov developed an expression for the acoustic radiation force applicable to any sound field. The primary acoustic radiation force \( \vec{F}_A \) is defined as a function of a field potential \( U \),

\[
\vec{F}_A = -\nabla U, \quad \text{and} \quad U = V_0 \left[ \frac{1}{2} \rho_f c_f \left( \vec{v}_f(x,y,t) \right) \cdot \vec{f}_1 - \frac{3}{4} \rho_f \left( \vec{v}_f(x,y,t) \right) \cdot \vec{f}_2 \right]
\]

(3)

with \( \vec{f}_1 \) and \( \vec{f}_2 \) the monopole and dipole contributions defined by

\[
\vec{f}_1 = 1 - \frac{1}{\Lambda^2}, \quad \text{and} \quad \vec{f}_2 = \frac{2(\Lambda - 1)}{2\Lambda + 1}
\]

(4)
p(x,y,t) is the acoustic pressure and \( \nu(x,y,t) \) is the fluid particle velocity, \( \lambda \) is the ratio of particle density \( \rho_p \) to fluid density \( \rho_f \), \( \sigma \) is the ratio of particle sound speed \( c_p \) to fluid sound speed \( c_f \), \( V_o \) is the volume of the particle, and \( <> \) indicates time averaging. All calculations assume harmonic acoustic wave propagation. The acoustic radiation potential can then be expressed as:

\[
U = V_o \left[ \frac{p_{ rms}^2(x,y)}{2\rho_f c_f^2} f_1 - \frac{3\rho_f V_{ rms}^2(x,y)}{4} f_2 \right]
\]

(5)

**Numerical Model and Results**

COMSOL multiphysics software is used to predict the acoustic standing wave field in the acoustic separation device based on two-dimensional approximations of the device. The resulting acoustic pressure and velocity fields are then used to calculate the acoustic radiation force acting on a suspended particle. The COMSOL simulations typically involve the use of three different physics modules to arrive at realistic predictions of the acoustic standing wave field. A piezo-electric module is used to simulate the piezo-electric drivers that are used to generate the ultrasonic waves. The water layer is modeled as pressure acoustics. The surrounding structures of the device are modeled as linear elastic layers. The piezo-electric transducer is driven by a particular voltage at a fixed frequency, which generates displacements and results in the generation of acoustic waves. The acoustic pressure and velocity are then used to calculate the acoustic radiation force acting on a suspended particle. Figure 1 shows the geometry of a multi-physics computer model consisting of a 1 MHz PZT-8 piezo-electric transducer, 1” wide and 0.08” thick, in an aluminum top plate (0.125” thick) in a 1” deep water channel terminated by a steel reflector plate (0.180” thick). The model can include a wear plate or other transmission layer between the transducer and water. This model reflects an acoustic separator device, which has a 1”x1” flow cross section and in which the acoustic beam spans a distance of 1”. The depth dimension, which is 1”, is not included in the 2D model.

![FIGURE 1. Schematic of the modeled geometry for the two-dimensional numerical computations.](image)

A numerical simulation experiment was run to demonstrate typical results obtained with this method. The transducer was driven at 10V and a frequency sweep calculation was done to identify the various acoustic resonances. Results are shown for an acoustic resonance frequency of 960 kHz. The acoustic radiation force is calculated for an oil droplet with a radius of 5 micron, a density of 880 kg/m³, and speed of sound of 1700 m/s. Water is the main fluid with a density of 1000 kg/m³, speed of sound of 1500 m/s, and dynamic viscosity of 0.001 kg/ms. Figure 2 shows the acoustic pressure amplitude in the fluid. The field at 960 kHz is that of a primarily planar standing wave field with a pressure amplitude of 450 kPa. Figure 3 shows the lateral (horizontal) acoustic radiation force on the right and axial (vertical) component on the left.

A first important conclusion from Figure 3 is that the relative magnitude of the lateral acoustic radiation force component (7e-13N) is significantly smaller than the magnitude of the axial component (2e-11 N) of the radiation force, indicating that for a primarily planar standing wave, the lateral force component is at least an order of
magnitude smaller than the axial component. This result confirms what other authors have mentioned in the literature.\textsuperscript{2-4} When one is interested in designing devices with high lateral trapping forces, it is necessary to design standing wave fields that have higher gradients of the acoustic field parameters in the lateral direction, thereby resulting in larger trapping forces, as explained by Gor'kov's formula. Trapping at higher flow velocities can also be obtained by increasing the applied power to the transducer. Another conclusion is that at the frequency shown, the trapping forces associated with this particular trapping mode extend across the entire flow channel, thereby enabling capture of oil droplets across the entire channel width.

\textbf{FIGURE 2.} Acoustic pressure amplitude (Pa) of the acoustic standing wave field calculated at a frequency of 960 kHz. Horizontal and vertical axes represent distance in the channel (m).

\textbf{FIGURE 3.} Axial (left) and lateral (right) component of the acoustic radiation force (N) at a frequency of 960 kHz. Horizontal and vertical axes represent distance in the channel (m).
ACOUSTOPHORETIC OIL WATER EMULSION SPLITTING SYSTEM

Experiment Design and Setup

The experimental setup comprises three main components, as shown in Figure 4, i.e., an emulsion system loop, the acoustic phase separation system, and the electronic driver and controls. The emulsion system contains a reservoir for the emulsion, a metering pump to add oil to the water, and a centrifugal pump to shear the oil and create the emulsion. The acoustic system contains a flow inlet, the acoustic separation system, a flow outlet, and a collector for the separated oil. The electronic drive system consists of a function generator, RF amplifier, and piezoelectric transducer. LabVIEW is used to create an electronic control system and determines relevant parameters such as electrical power absorbed and impedance of the transducer.

![Figure 4. Schematic of experiment setup, consisting of the emulsion system loop, the acoustic phase separation system, and the electronic driver and control.](image)

Acoustophoretic Oil-Water Separator Design

The small scale system has a flow cross section of 1”x2”, is able to support flow rates in excess of 500 ml/min, is driven by a single 1”x1” 2 MHz PZT-8 piezoelectric transducer and requires about 15-20W of power to generate the ultrasonic standing wave necessary to trap the oil droplets. Computational Fluid Dynamics computations were used to make sure that the inlet of the system resulted in plug flow in the acoustic system.

A typical experiment consisted of making a motor-oil in water emulsion by metering sufficient oil in the 80 gallon water reservoir to make a 1000 ppm emulsion. Measurement of oil droplet size indicated that the average droplet size is about 5 micron. The emulsion then enters the acoustic separation system through the fluid inlet at the top of the system, as shown in Figure 5, flows at the specified flow rate through the acoustic separation system in a vertically downward direction, and exits the system through the flow outlet at the bottom of the unit. During a typical experiment, oil is collected for a 30 min period. When the acoustic system is operational, the oil droplets are trapped in the standing wave, coalesce to larger droplet sizes, until buoyancy becomes the dominant force at which
point the droplets float out of the acoustic standing wave upward into the oil collector, thereby separating the oil droplets from the water stream. Oil separation efficiencies are determined by a combined measurement of the amount of oil collected in the separator and the concentration of oil in the outflow.

FIGURE 5. Schematic of the acoustic phase separation system, showing the flow inlet, the oil collector, and the acoustic standing wave section.

Results

The first experiment was designed to investigate the effect of transducer shape on oil separation efficiency. A 1”-round PZT-8 2MHz transducer and a 1”x1” PZT-8 2MHz square transducer were used in this study. Otherwise the experiment was run at identical conditions. Table 1 shows the results.

<table>
<thead>
<tr>
<th>Transducer Shape</th>
<th>Test Duration (min)</th>
<th>Capture Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round</td>
<td>45</td>
<td>59</td>
</tr>
<tr>
<td>Square</td>
<td>30</td>
<td>91</td>
</tr>
</tbody>
</table>

The results indicate that the square transducer provides better oil separation efficiencies than the round transducer, which is explained by two facts, (1) the square transducer provides better coverage of the flow channel with acoustic trapping forces, and (2) the round transducer only provides strong trapping forces along the centerline of the standing wave. Further experiments then involved the use of square transducers only.

A second study involved a careful investigation of the effect of the acoustic resonance frequency on the oil separation efficiency. The experiment thus consisted of repeating the experiment at four consecutive acoustic resonance frequencies; all close to the transducer resonance frequency. The conditions at all excitation frequencies were identical otherwise, i.e., an experiment duration of 30 min, a 1000 ppm oil concentration, a flow rate of 500 ml/min, and an applied power of 20W.
Figure 6 shows an example of the separated oil collected in the graduated cylinder, located at the top of the system. Table 2 summarizes the findings from this experiment. An important conclusion is that the oil separation efficiency of the acoustic separator is directly related to the particular acoustic resonance frequency that is excited. Almost a threefold difference in oil separation efficiency is measured between resonance peak 1 and 4. A second conclusion, useful for scaling studies, is that the tests indicate that capturing 5 micron oil droplets at 500 ml/min requires 10 Watts of power per square-inch of transducer area per 1” of acoustic beam span. The main dissipation is that of thermo-viscous absorption in the bulk volume of the acoustic standing wave.

**TABLE 2.** Oil separation efficiency of a 1000 ppm motor-oil in water emulsion at four consecutive acoustic resonance frequencies at a flow rate of 500 ml/min, test duration of 30 min, and a power of 20 W.

<table>
<thead>
<tr>
<th>Resonance Peak</th>
<th>Capture Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91</td>
</tr>
<tr>
<td>2</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>58</td>
</tr>
<tr>
<td>4</td>
<td>37</td>
</tr>
</tbody>
</table>

Figure 7. Photograph of trapped oil droplets (left) and acoustic pressure field (right).
The comparisons between numerical and experimental results are excellent and demonstrate the accuracy of the models. Figure 7 shows a photograph of the trapped oil droplets in the standing wave on the left side, and the calculated acoustic pressure field on the right side. Both experiment and model show identical features. Oil droplets were trapped in the standing wave well outside the fluid volume defined by the transducer area, indicating an acoustic field with strong trapping forces. Trapping forces outside of the main acoustic standing wave seem to stem from diffraction effects of the edges of the transducer.

CONCLUSION

A novel acoustophoretic phase separation system has been presented. The system consists of a flow inlet, an oil collector, and an acoustophoretic separation section based on an ultrasonic standing wave. Oil droplets are trapped in the acoustic standing wave, which results in continuous accumulation of oil droplets, coalescence of droplets to larger size, and ultimately separation of the larger oil droplets by buoyancy forces. Experiment results show excellent separation efficiencies of a stable motor-oil in water emulsion for a prototype design based on a flow cross section of 1"x2", flow rates of 500 ml/min, power levels of 20 W, and a frequency of 2 MHz. The proposed technology for multi-component liquid streams offers the potential for a separation technology that eliminates waste and reduces energy consumption.

Numerical models have been developed to predict the acoustic field in the acoustic separation devices and the resulting acoustic radiation force acting on suspended particles. The agreement between numerical results and experimental observation is very good.

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