Ultrasonic collection of particles at an air/liquid interface

Priscilla Rogers*, Ian Gralinski* & Adrian Neild* a)
*Department of Mechanical and Aerospace Engineering, Monash University, Vic 3800, Australia

Summary Ultrasonic actuation is demonstrated as a method for producing ordered particle clustering at the free surface of a liquid volume. The particles are shown to collect within the liquid at the pressure nodes of the resonant ultrasonic standing wave used, or at specific locations on the liquid/air interface. The proportion of particles collected at each of the two locations is related to the particle size. Closer inspection reveals that the mechanism is attributed to acoustic radiation forces and streaming.

INTRODUCTION

The ability to handle particles and cells in suspension is a requirement for many lab-on-a-chip applications [1]. Ultrasound has proven to be an effective method of achieving this, resulting in collection in lines [2], grids [3] and sorting of particles [4] within closed systems. In the presence of an air/liquid interface, particles can still be collected in the fluid bulk [5]. However, little work has been conducted regarding collection at the interface. At low acoustic frequencies, Falkovich et al. [6] showed that the surface displacement collects hydrophobic and hydrophilic particles at the antinodes and nodes, respectively. Li et al. [7] have shown particle island formation due to the excitation of low frequency subharmonics in a system driven by ultrasonic surface acoustic waves. In this work, we demonstrate the collection of particles at the surface using ultrasonic effects alone.

METHODS

The experimental device is depicted in Fig 1. It consists of a rectangular fluid chamber excited by a piezoelectric transducer. The AC signal is applied to a strip electrode at a frequency that is determined through experimentation to yield a resonant ultrasonic standing wave. Suspensions of silica particles (1, 3.5 and 5 μm) in deionised water were deposited in the open chamber, creating the air/liquid interface.

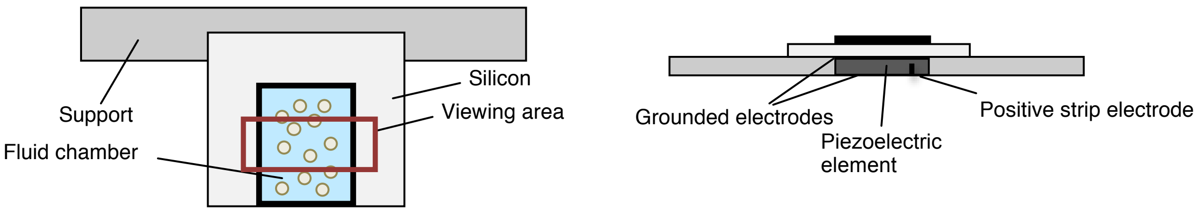

Figure 1: The experimental device is shown from the top (left) and side (right).

RESULTS

Figure 2 shows the collection of different sized particles over time. Interestingly, within the nodal line interspacing, particle clustering on the surface is observed. The smallest particle type preferentially clusters on the surface (Fig. 2a), while the largest particle type exhibits considerably less clustering, preferring to collect at nodal lines within the bulk.

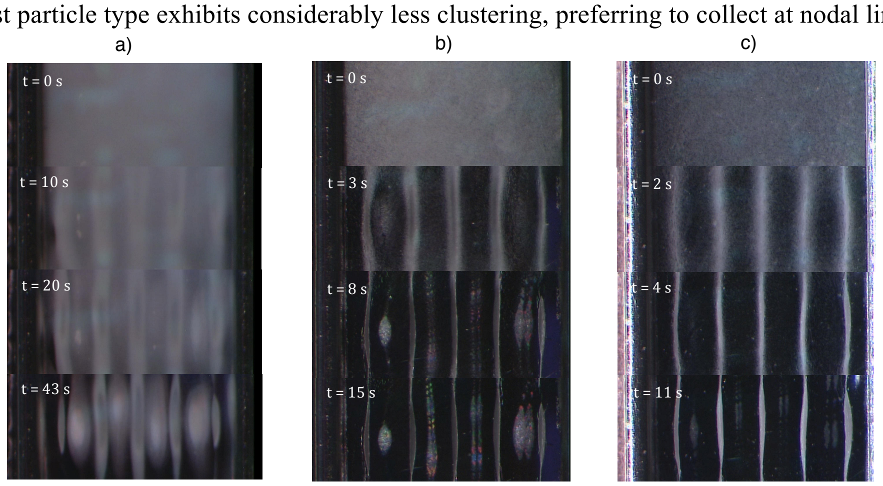

Figure 2: The collection of a) 1, b) 3.5 and c) 5 μm silica particles at both nodal lines within the bulk, and clusters on the free surface.

---

a) Corresponding author. Email: adrian.neild@monash.edu.

To understand the collection mechanisms, we first examine the acoustic radiation force. Gor'kov [8] derived that the force potential is given by:

$$\langle U \rangle = V\left(\frac{1}{2}\frac{\langle p^2 \rangle}{\rho c^2} f_1 - \frac{3}{4}\rho \langle v^2 \rangle f_2\right).$$

Here, $\langle p^2 \rangle$ and $\langle v^2 \rangle$ are the time averages pressure and fluid particle velocities, $f_1 = 1 - \left(\rho c^2 / \rho_s c_s{}^2\right)$ and $f_2 = 2(\rho_s - \rho)/(2\rho_s + \rho)$, ρ is the density, c is the speed of sound, where the subscript s refers to particle properties as opposed to fluid properties, and V is the volume of the particle. In most cases, the force potential causes the collection of particles at the pressure nodes, where the pressure time average is the dominant term. By modelling the pressure field, which occurs across the chamber, in Comsol Multiphysics, we are able to predict the locations at which particles collect. By modelling a fluid volume in 2D with a hard wall boundary on the lower and side surfaces, and a soft (pressure release) boundary on the upper (air/liquid) boundary, the resultant force potential is shown in Fig. 3. The effect of the soft upper boundary is that the pressure is approximately zero at this location. The lower surface nodes and antinodes are established due to the resonant excitation.

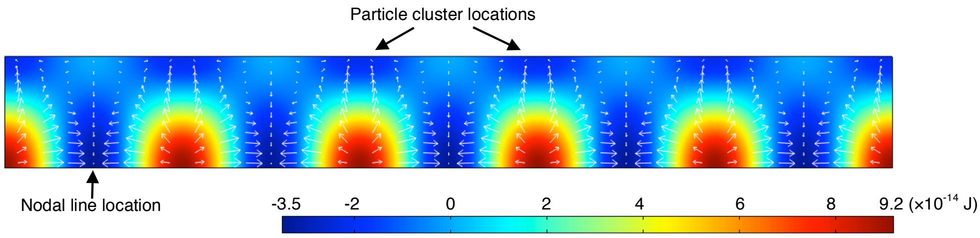

Figure 3: The force potential is plotted across the fluid chamber. Particles collect within the bulk of the fluid at nodal lines, as well as at potential minima located on the free surface.

It is clear from the radiation force model that the cluster locations on the free surface are in the interspacing of the nodal lines, verifying the experimental observations. However, it now becomes necessary to explain why smaller particles prefer to cluster. If the radiation force, scaling with particle volume, was the only contributing force, larger particles would simply arrive at their final destination faster, regardless of location. As such, we postulate that the acoustic streaming, arising from second order effects, plays an increasingly larger role on smaller particle behaviour. As the drag force is proportional to particle radius, the role of streaming is greater for smaller particles than for larger ones. We believe that it is this acoustic streaming that aids the migration of smaller particles to the upper surface.

CONCLUSIONS

Particle clustering at the air/liquid interface has been demonstrated using purely ultrasonic techniques. Whilst the particles cluster at radiation force minima, it is the increased role of acoustic streaming (and decreased role of the radiation force) on smaller particles that causes increased clustering on the free surface. This technique can potentially be used for manipulation of particles intended for self-assembly and creating monolayers with controlled shapes.

References

[1] S. Haeberle, R. Zengerle, Microfluidic platforms for lab-on-a-chip applications, *Lab on a Chip*, **7**:1094–1110, 2007.

[2] A. Neild, S. Oberti, F. Beyeler, J. Dual, B. J. Nelson: A micro-particle positioning technique combining an ultrasonic manipulator and a microgripper, *J. Micromech. Microeng.*, **16**:1562-1570, 2006.

[3] S. M. Hagsater, T. G. Jensen, H. Bruus, and J. P. Kutter, Acoustic resonances in microfluidic chips: full-image micro-PIV experiments and numerical simulations, *Lab Chip* **7**:1336-1344, 2007.

[4] F. Petersson, A. Nilsson, C. Holm, H. Jonsson, T. Laurell, Continuous separation of lipid particles from erythrocytes by means of laminar flow and acoustic standing wave forces, *Lab Chip*, **5**:20-22, 2005.

[5] S. Oberti, A. Neild, R. Quach, J. Dual, The use of acoustic radiation forces to position particles within fluid droplets, *Ultrasonics* **49**:47-52, 2009.

[6] G. Falkovich, A. Weinberg, P. Denissenko, S. Lukaschuk, Surface tension: Floater clustering in a standing wave , *Nature*, **435**:1045–1046, 2005.

[7] H. Li, J. Friend and L. Yeo, Microfluidic colloidal island formation and erasure induced by surface acoustic wave radiation, *Physical Review Letters*, **101**: 084502, 2008.

[8] L. P. Gor'kov, Concerning the forces acting on a small particle in an acoustic field in an ideal fluid, *Dokl. Akad. Nauk SSSR* **140**:88-91, 1961.