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Suppression of acoustic streaming by the inhomogeneity-induced acoustic body force

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Suppression of acoustic streaming by the inhomogeneity-induced acoustic body force

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Rayleigh streaming in a homogeneous fluid has been extensively studied, and plays an important role in the manipulation of particles in microscale acoustofluidics. In this work, the acoustic streaming is investigated in a glass-silicon microchannel as it evolves in fluids made inhomogeneous in density and compressibility (or speed of sound) by the addition of solute molecules. It is found that the streaming is greatly suppressed in the bulk, due to the competition between the boundary-induced streaming stress and the inhomogeneity-induced acoustic body force. The streaming rolls are initially confined to a narrow region close to the walls, then expand from the walls into the bulk as the inhomogeneity is smeared out by diffusion and advection, and finally the homogeneous state is reached. The efficient suppression of streaming enables manipulation of submicron particles using acoustophoresis.

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1. INTRODUCTION

Acoustic streaming is a steady flow that arises in a fluid medium interacting with sound waves. This phenomenon has been classified into two categories based on its formation mechanisms. One mechanism is the acoustic energy dissipation in viscous boundary layers, where the velocity of oscillating fluid decays to match the velocity of the boundary.[1,2] This so-called boundary-driven Rayleigh streaming typically appears when sound waves propagate near walls or suspended objects. The other mechanism is the spatial attenuation of acoustic waves in the bulk of the fluid, which results in a time-averaged net force in the same direction of the wave propagation.[3] This type of streaming is called Quartz wind or bulk-driven Eckart streaming, which is generally observed in large systems where the length scale of wave propagation is much longer than the wavelength. Both categories play important roles in various areas in acoustics, and hence have been extensively stuidied. Recent studies of acoustic streaming spread to microscale particle manipulation using acoustic waves,[4,5] where in most acoustofluidic systems Rayleigh streaming is the case due to the small size of the devices compared to the wavelength of the sound wave. In acoustofluidic devices using ultrasonic standing wave, suspended microparticles are subject to both acoustic radiation force and the Stokes drag force from the acoustic streaming, the relative magnitude of the two forces depends on the size of the microparticles and the material of the solvent. When the size of microparticles is below a critical value, the motion of microparticles is dominated by acoustic streaming, which in most cases hinders the manipulation of sub-micrometer particles.

Recent discovery has found that acoustic force density can be created in fluids of spatially inhomogeneous density and compressibility in a standing wave field in microfluidic systems, resulting in relocation and stabilization of inhomogeneities.[6–8] This novel phenomenon enables iso-acoustic focusing using which the acoustic properties of cells can be measured.[7] Furthermore, the presence of the acoustic force density in fluids with density gradient greatly suppresses the acoustic streaming.[9] The finding of the streaming suppression opens up a new possibility to manipulate sub-micrometer particles, and hence should be investigated in more detail. In this paper, we extend the study of acoustic streaming to fluids made inhomogeneous in both density and speed of sound by the addition of solute molecules, and investigate its evolution in a rectangular glass-silicon microchannel.

2. THEORETICAL BACKGROUND

The origin of the acoustic force density $\boldsymbol{f}_{\mathrm{ac}}$ acting on the inhomogeneous fluid is the nonzero divergence in the time-averaged acoustic momentum-flux-density tensor $\langle \boldsymbol{\Pi} \rangle$,[8]

$$\boldsymbol{f}_{\mathrm{ac}} = -\boldsymbol{\nabla} \cdot \langle \boldsymbol{\Pi} \rangle. \tag{1}$$

Here, $\langle \boldsymbol{\Pi} \rangle$ is provided by the products of the first-order acoustic field,

$$\langle \boldsymbol{\Pi} \rangle = \langle p_2 \rangle \mathbf{1} + \langle \rho_0 \boldsymbol{v}_1 \boldsymbol{v}_1 \rangle, \tag{2a}$$

$$\langle p_2 \rangle = \frac{1}{4}\kappa_0 |p_1|^2 - \frac{1}{4}\rho_0 |\boldsymbol{v}_1|^2, \tag{2b}$$

on the slow hydrodynamic time scale τ was derived in Ref. 8 from a divergence in the time-averaged acoustic momentum-flux-density tensor induced by continuous spatial variations in the fluid parameters of density ρ_0 and compressibility κ_0,

$$\boldsymbol{f}_{\mathrm{ac}} = -\frac{1}{4}|p_1|^2 \boldsymbol{\nabla}\kappa_0 - \frac{1}{4}|\boldsymbol{v}_1|^2 \boldsymbol{\nabla}\rho_0. \tag{3}$$

Here, p_1 and $\boldsymbol{v}_1$ are the acoustic pressure and velocity field, respectively, assumed to be time-harmonic first-order perturbations of the hydrodynamic degrees of freedom.

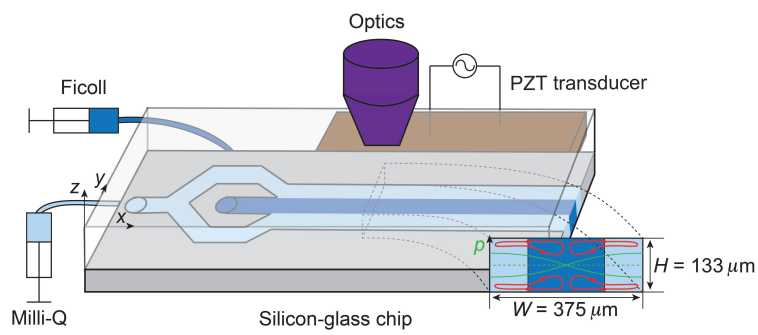

Figure 1: Sketch of the acoustofluidic silicon chip (gray) sealed with a glass lid, which allows optical recording (purple) of the tracer bead motion (red trajectories) in the channel cross section of width $W = 375\,\mu m$ and height $h = 133\,\mu m$. A ficoll solution (dark blue) is injected in the center and laminated by pure water (light blue). The piezoelectric transducer (brown) excites the resonant half-wave pressure field p_1 (inset, green) at 2 MHz.

3. MATERIALS AND METHODS

The silicon chip consists of a straight channel of length $L = 40$ mm, width $W = 375\,\mu$m, and height $h = 133\,\mu$m. The chip was sealed by a pyrex lid using anodical bonding, and a lead zirconate titanate (PZT) transducer (Dimensions, PZT26, Ferroperm Piezoceramics, Denmark) was bonded underneath. The channel possesses two inlets and two outlets with trifurcation at both ends. The density modifier used for this study was Ficoll (PM70, GE Healthcare Biosciences AB, Uppsala, Sweden), of which three mass concentrations (1%, 5%, and 10%) were prepared by dissolving in Milli-Q water.

Polystyrene beads with a nominal diameter of 0.49 μm (Molecular Probes, Thermo Fisher Scientific, Waltham, MA, USA) were suspended in the solutions as tracer particles. The motion of the tracer particles was recorded using a general defocusing particle tracking (GDPT) technique. GDPT is a single-camera particle tracking method in which astigmatic images are employed by using a cylindrical lens. An unique defocused elliptical shape of a spherical particle in depth coordinate can be provided in such a system, which enables robust three-dimensional tracking of particle motion in microfluidic systems.[10]

A laminated flow of two liquids was injected to form a concentration gradient, see Fig. 1. At time $\tau = 0$, the flow was stopped, and the GDPT measurements were conducted with the PZT transducer driven at the frequency swept from 1.95 to 2.05 MHz in cycles of 1 ms to produce a standing half-wave across the width. The applied voltages (ranging from 1.6 to 1.8 V peak-to-peak voltage) varied when different liquids were injected, in order to obtain similar energy density (E_{ac} = 52 Pa) in the channel. For each set of measurements, the particle motion was recorded for 200 s to observe the evolution of the acoustic streaming. The measurement was repeated at least 16 times to improve the statistics.

4. RESULTS AND DISCUSSION

Examples of the particle positions and the color plot of their velocity in the inhomogeneous fluids at $\tau = 35\,s$, $\tau = 105\,s$, and $\tau = 195\,s$, and in homogeneous fluid are shown in Fig. 2. We find that the streaming rolls are confined close to the channel wall at early times, which is not the case in homogeneous medium. The streaming suppression is due to the competition between the boundary-induced streaming stress and the inhomogeneity-induced acoustic force density.[9] The suppressed streaming rolls exhibited asymmetry along both horizontal and vertical planes of the channel, with a larger vortex size near the center as compared to the sides. As time evolves, the fluid is homogenized due to diffusion and advection, and at 195 s the streaming pattern is similar to the homogeneous case.

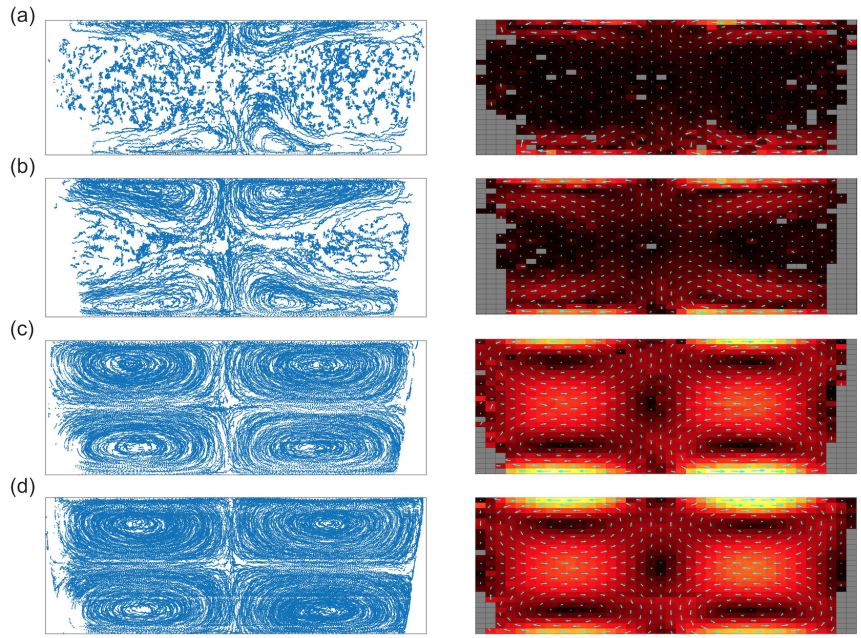

Figure 2: Acoustic streaming in the inhomogeneous fluids at (a) τ = 35 s, (b) τ =105 s, and (c) τ = 195 s, and (d) acoustic streaming at homogeneous fluid. Column 1 shows experimental particle positions (blue points). Column 2 shows experimental streaming velocity field (velocity amplitude $|v| = 0$ μm/s, black, $|v| = 45$ μm/s, white) with the arrows (cyan) indicating the direction. Spatial bins with no data points are excluded (gray)

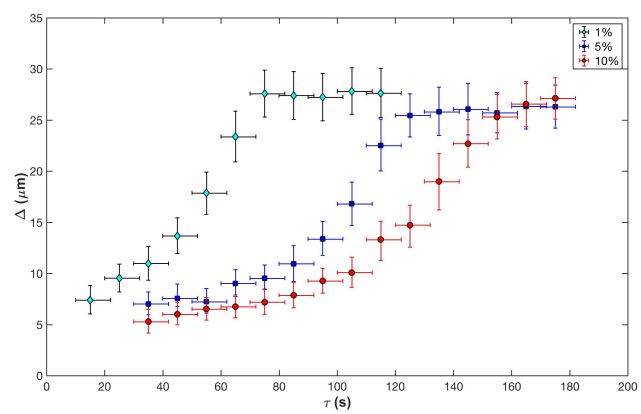

Figure 3: Measured Δ as functions of τ with 1%, 5%, and 10% Ficoll solutions.

A dynamic length scale Δ of the streaming vortex size is introduced, which is defined as the distance between the top or the bottom wall to the position where the streaming velocity amplitude $|v| = 0$ at $y = \frac{1}{4}W$ or $y = \frac{3}{4}W$. The evolution of the streaming is characterized by Δ in different Ficoll solutions, as shown in Fig. 3. The breakdown of Δ occurs at early times as the concentration of Ficoll solutions decreases. With low concentration, the initial gradients of density and compressibility are weak, resulting in small acoustic force density. Hence, the Δ with small concentration is larger than that with high concentration at the same τ. The streaming rolls expand from the walls into the bulk as the inhomogeneity is smeared out, and finally become the same as homogeneous streaming , indicated by the same level of Δ at late times.

5. CONCLUSION

In this study, the acoustic streaming in fluids made inhomogeneous in density and compressibility is experimentally investigated. The results clearly show the suppression of acoustic streaming in the bulk of fluids with inhomogeneity with an asymmetric shape, due to the competition between the boundary-induced streaming stress and the inhomogeneity-induced acoustic body force. The streaming rolls grow as the fluids become homogenized due to the diffusion and advection, and the breakdown of the suppressed streaming is related to if the acoustic force density generated by the gradients of density and compressibility is sufficiently strong. The efficient suppression of streaming enables manipulation of submicron particles using acoustophoresis.

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