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Inhomogeneous acoustofluidics: how does medium inhomogeneity impact acoustic streaming in microscale?

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1. Introduction

Boundary-driven Rayleigh streaming in a homogeneous fluid has been extensively studied, and plays an important role in the manipulation of particles in microscale acoustofluidics. On the other hand, in fluids of spatially inhomogeneous density and compressibility in a standing wave field in microfluidic systems, a novel acoustic body force is created, resulting in relocation and stabilization of inhomogeneities[1, 2)]. This new phenomenon enables iso-acoustic focusing using which the acoustic impedance of cells can be measured[1)]. We would like to show here that acoustic streaming can be significantly suppressed in inhomogeneous medium by experimental observations, which enables manipulation of submicrometer particles.

2. Theoretical Background

The origin of the acoustic body force $\boldsymbol{f}_{\mathrm{ac}}$ acting on the inhomogeneous fluid is the nonzero divergence in the time-averaged acoustic momentum-flux-density tensor $\langle\Pi\rangle$[2)],

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

Here, $\langle\boldsymbol{\Pi}\rangle$ is provided by the products of the first-order acoustic field p_1 and $\boldsymbol{v}_1$,

$$\langle\boldsymbol{\Pi}\rangle = \langle p_2\rangle\boldsymbol{1} + \langle\rho_0\boldsymbol{v}_1\boldsymbol{v}_1\rangle, \qquad (2a)$$

where the time-averaged, second-order mean Eulerian excess pressure $\langle p_2\rangle$ takes the form

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

on the slow hydrodynamic time scale τ was derived in Ref. [2] in terms of spatial variations in the fluid parameters of density ρ_0 and compressibility κ_0,

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

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.

3. Materials and Methods

The experiments were performed using a long straight microchannel of length L = 24 mm, width W

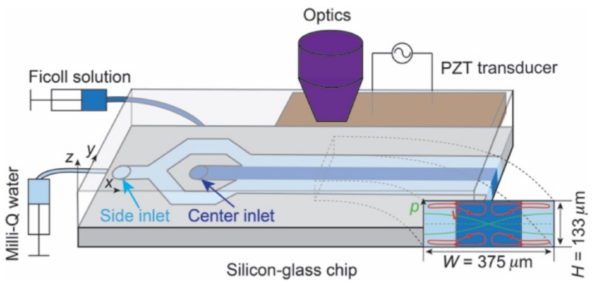

Fig. 1 Sketch of the acoustofluidic silicon chip (gray) sealed with a glass lid, which allows optical recording (purple) of the tracer bead motion (red trajectories) in the channel cross section of width W = 375 μm and height H = 133 μm. A Ficoll solution (dark blue) is injected in the center and laminated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

= 375 μm, and height H = 133 μm in a silicon-glass chip with an attached piezoelectric transducer, as sketched in Fig. 1. A laminated flow of Milli-Q water and 10% Ficoll PM70 solution was injected to form a concentration gradient with the denser fluid at the center. General defocusing particle tracking (GDPT)[3)] was used to record the motion of 0.5 μm-diameter polystyrene tracer beads. At time τ = 0 s, the flow was stopped, and the GDPT measurements (10 fps) were conducted with the transducer driven at 1.6 $V_{\mathrm{p\text{-}p}}$ voltage and the frequency swept from 1.95 to 2.05 MHz in cycles of 10 ms to produce a standing half wave across the width with energy density $E_{\mathrm{ac}} \approx 31.4$ J m^{-3}. For each set of measurements, the particle motion was recorded for 200 s to observe the evolution of the acoustic streaming. The experiment was repeated 16 times to improve the statistics.

4. Results

The streaming evolution is shown in Fig. 2 for the inhomogeneous Ficoll-water solution. At early times (τ = 35 s), the streaming is greatly suppressed in the bulk, and the four streaming rolls are confined to the walls with an asymmetric pattern. As time evolves (τ = 105 s), the streaming rolls grow toward homogeneous steady-state Rayleigh streaming, but the asymmetric pattern is

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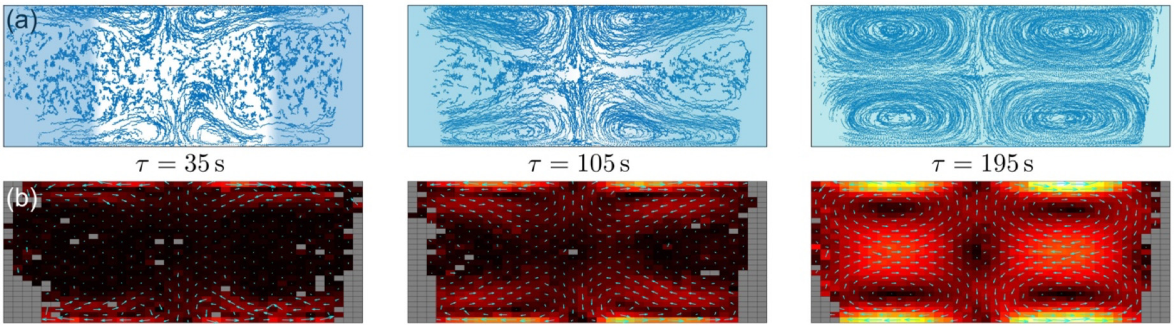

Fig. 2 The acoustic streaming observed in the vertical *y-z* cross section at time τ = 35, 105, and 195 s using the 10% Ficoll PM70 at the center and Milli-Q water at the sides. (a) Experimental particle positions (blue points) with a color plot of the solute concentration. (b) Color plot of the streaming velocity amplitude from 0 μm/s (black) to 45 μm/s (white) overlaid with a vector plot (cyan). Spatial bins with no data points are excluded (gray). Reproduced with permission from Ref. [5].

still apparent. At later times (τ = 195 s), the streaming pattern is identical to that of a homogeneous system as diffusion and advection have homogenized the system. The streaming suppression is due to the competition between the boundary-induced streaming stress and the inhomogeneity-induced acoustic body force, which has been discussed both theoretically and experimentally in our recent papers[4, 5].

The suppression of streaming in inhomogeneous medium provides clear potential for manipulating the particles below the cross-over size in acoustophoresis. Conventional acoustophoresis separate particles based on the particle size, since acoustic radiation force scales with the cube of the particle radius. As the particle size decreases, the Stokes drag force induced by the streaming becomes dominant, and the particle motion mainly follows streaming and hence the separation based on the time-of-flight focusing to the pressure nodal plane due to radiation force is not possible (upper row in Fig. 3). When inhomogeneous medium is applied, the majority area of the channel becomes streaming-free, thus most of the particles below the cross-over size can still be focused to the pressure nodal plane (lower row in Fig. 3)[6]. We have performed the separation of three types of bacteria (diameters all below 1 μm) from lysed blood in inhomogeneous medium, which is not possible in homogeneous acoustophoresis[7].

5. Conclusions

In this work, we show that acoustic streaming can be greatly suppressed in inhomogeneous fluids at early times due to the competition between the viscous boundary-induced streaming stress and the inhomogeneity-induced acoustic body force. We further prove this novel phenomenon can be used for manipulating the particles below the cross-over size in conventional homogeneous acoustophoresis.

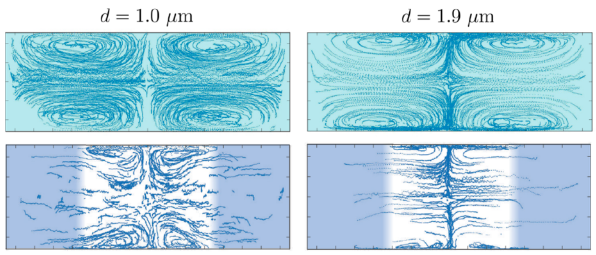

Fig. 3 Experimental particle trajectories in homogeneous (upper row) and inhomogeneous (lower row) mediums observed in the vertical *y-z* cross section at time τ = 5 s for particles with diameters d = 1.0 and 1.9 μm. In this study, 2.5% Ficoll PM70 was used to create homogeneous medium, while Milli-Q water (side stream) and 5% Ficoll PM70 (center stream) were used to create inhomogeneous medium.

In the conference, we will also show our latest findings regarding creating inhomogeneity in acoustofluidic devices using different approaches, which leads to completely different flow fields.

References

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