Size-dependent particle migration in acoustically-driven three-dimensional vortices

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When a microbubble's interface is forced to oscillate at certain frequencies, the surrounding liquid experiences comparable displacements in comparable time scales as the interface does. Observing the liquid at longer time scales, a net flow can be distinguished which has been commonly known as steady streaming [1] or *microbubble streaming*; in this particular case.

In order to observe such a flow, solid particles behaving as flow tracers are typically seeded in the liquid. However, particles in the system might not always perfectly follow the streamlines in the vortical structures generated by the bubble's oscillations. Wang et al. [2, 3] noticed that a very important factor to decide whether a particle follows a streamline in the vicinity of the bubble is its size. As rigid particles cannot penetrate the bubble surface, they are forced to switch to another streamline due to their finite size when they come close enough. This steric-based particle migration mechanism explained their experiments and was used to perform size-sensitive particle sorting and trapping [2, 3]. Recent experimental and theoretical results have shown that additional effects related with the particle inertia should also be relevant for the particle migration [4, 5].

Most results in the literature have assumed that microbubble streaming generated by semi-cylindrical-shaped bubbles is essentially a two-dimensional phenomenon. Recently, Marin et al. [6] showed that the confinement along the bubble's axis gives rise to an unexpected three-dimensional flow (see Fig. 1). This was confirmed by Rallabandi et al. [7] using an asymptotic model which could reproduce the same particle trajectories as in the experiments. Although Marin et al.'s experiments were performed using finite-sized particles (2-µm-diameter particles), considering the good comparison with the computed streamlines, it can be concluded that such particles followed faithfully the streamlines and could be considered as flow tracers.

The aim of this talk is to show how the characteristic toroidal trajectories that tracers follow in *m*icrobubble streaming are modified as the particle size increases up to 1/3 of the bubble radius. Our results show a robust size-sensitive particle positioning along the semi-cylindrical bubble's axis. Since different particle sizes also show very different migration time scales, this phenomenon can be used to precisely separate, filter or locate particles in a microchannel in precise 3D positions according to their size (see Fig. 2). As this phenomenon cannot be studied with classical optical arrangements, we use a defocusing-based particle tracking method (General Defocusing Particle Tracking) [8] to obtain the three-dimensional position of the particles and their trajectories.

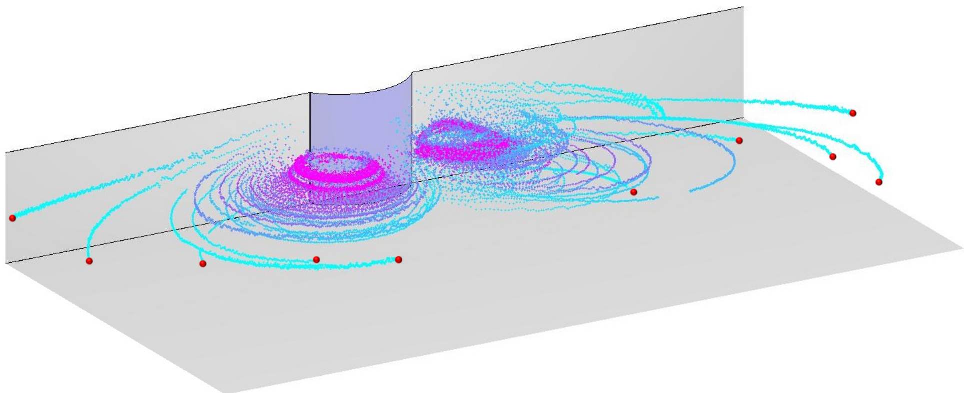

FIG. 1. Three-dimensional trajectories of 5-µm-diameter particles in two acoustically-driven microbubble streaming vortices. Color code is related with time: particles start the experiment (in cyan) homogeneously distributed over the channel and end up in smaller orbits (or loops) at the end of the experiment (in purple). Their final trajectory has a well defined orbit and a z-position, where they remain as long as the bubble is acoustically actuated.

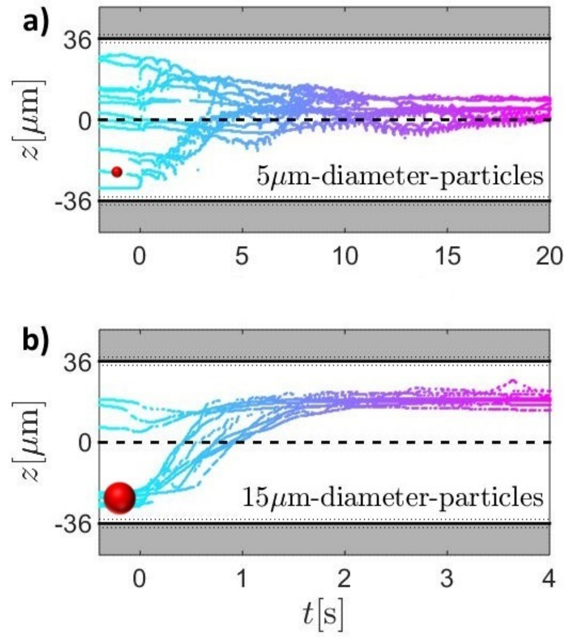

FIG. 2. Z-Position of 5 and 15-µm-diameter particles as a function of time as they migrate inside a bubble streaming vortex. Once the particles pass the perigee for the first time (closest position to the bubble's interface, set to $t = 0$), they migrate to a certain z-position. A red circle illustrates the size of the particle. **a)** Z-position for 5-µm-diameter particles: migration occurs within $\sim$10 seconds towards $z = 5 \pm 5\,\mu m$. **b)** z-position for 15-µm-diameter particles: migration occurs within $\sim$2 seconds towards $z = 20 \pm 5\,\mu m$.

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