MECHANICS OF PARTICLE TRAPPING AND MAINTENANCE IN MICRO-SCALE FLUID VORTICES

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ABSTRACT

We describe a mechanism for maintenance of particle orbits inside microscale laminar vortices. Particles 'trapped' in the fluid vortex self-assemble into equilibrium positions where larger particles occupy orbits closer to the vortex center. We investigated the contribution of several fluidic forces that may play a role in particle maintenance, including centrifugal force, Saffman lift force and shear gradient lift force. We found that the orbit characteristics of the particles were independent of density, and determined that the shear gradient lift force is mainly responsible for stable trapping. This has significant implications in designing devices for predictable vortex trapping systems by simply modifying the shape of the velocity field.

KEYWORDS

Laminar Microvortices, Fluid Inertia, Inertial Microfluidics

INTRODUCTION

Particle trapping in fluid microvortices have been explored for various biological applications [1]. However, there is little empirical evidence in explaining the behavior and mechanism of particle trapping in microvortices. Recently, we introduced a novel phenomenon in which particles and cells can be selectively trapped within and released on demand from microscale fluid vortices that form when inertial effects become important [2]. While the approach was successful in capturing cancer cells, the current device design is limited to a trapping size cut-off of approximately 15 µm. In order to improve our understanding of particle trapping in microvortices, we developed a model of the capture process which takes into account two critical steps: i) selective particle entry into microvortices from the main flow [2] and ii) particle maintenance within microvortices following entry. Upon investigating particle maintenance, we unexpectedly identified that shear-gradient lift alone can create defined orbits for particles within microvortices, suggesting it is a key component responsible for stable trapping.

EXPERIMENT

The microvortex trapping system consists of a simple straight microchannel with an expansion-contraction region which creates two fluid vortices on each side of the channel at finite Reynolds Numbers (Fig. 1A). Particles of various densities greater or less than water were injected into the vortex trap and tracked with a high-speed microscope and MATLAB software. A 'trapped' particle orbits in the vortex with a stable trajectory (Fig. 1A,B). Particles self assemble within the vortex where larger particles occupy orbits closer to the vortex center. Particles experience rapid changes in velocity while orbiting in the vortex with faster velocities near the channel center (Fig. 1C).

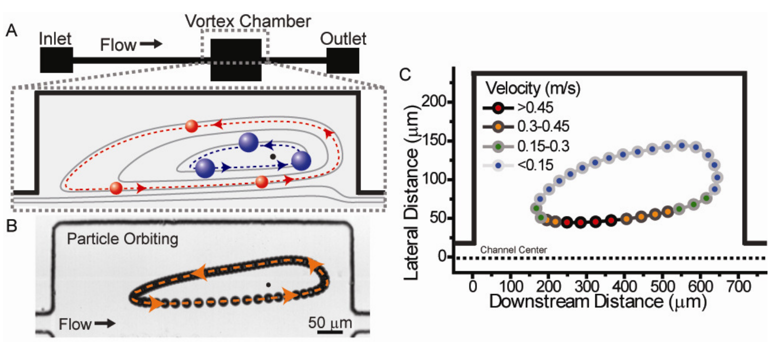

Figure 1: Particles Orbit in Stable Trajectories in Laminar Microvortices. (A) Schematic of microfluidic device with a straight channel consisting of an expansion-contraction region where particles are passively trapped in the vortex chamber. (B) Time-lapse high-speed image of an orbiting glass particle. Elapsed time is ~6.1ms. (C) Particles experience rapid changes in velocity while orbiting in the vortex: faster velocities near the channel center.

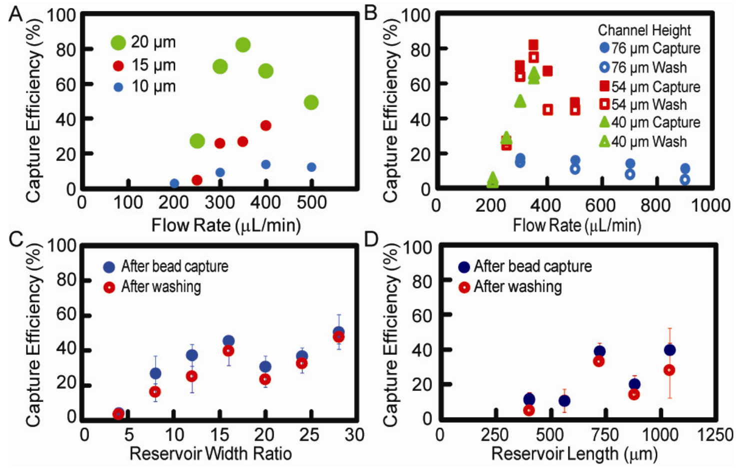

Figure 2: Dependence of Capture Efficiency on Geometrical Parameters and Flow Conditions.. (A) Size-dependence of particle trapping with H=54µm. Effective trapping observed above 15µm and flow rates of 300µL/min. (B) Effect of H and Q on particle trapping. Effective trapping observed at H≤54µm. Stability of trapping increases with lower heights (C,D) Effect of reservoir width ratio over main channel width and reservoir length on particle trapping. Effective trapping observed at reservoir ratio of 15 and length of 720µm.

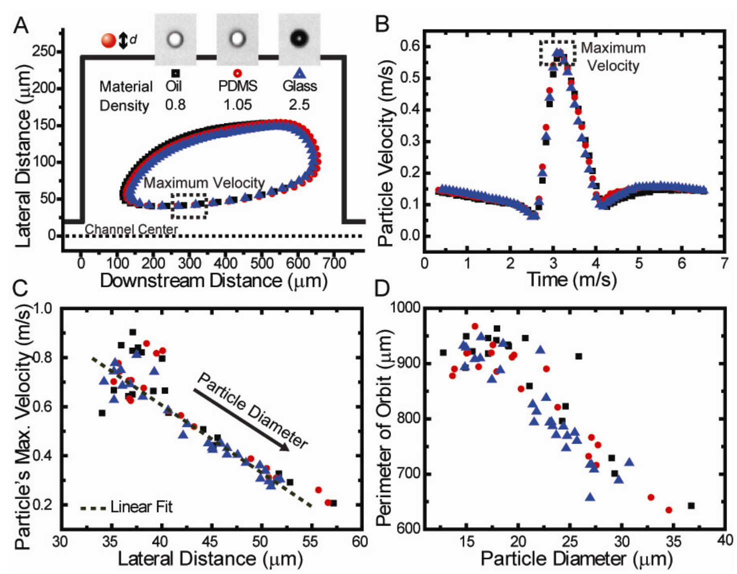

Figure 3: Orbit Characteristics are Independent of Particle Density. Using same-sized particles of different densities, oil droplets (0.8g/cm³), PDMS beads (1.03g/cm³) and glass beads (2.6g/cm³), no significant difference was found between (A) orbit size, (B,C) maximum velocity, or (D) orbit perimeter. These results demonstrate that the centrifugal force is not a dominant factor in particle maintenance.

RESULTS AND DISCUSSION

The efficiency of trapping depends in a complex fashion on system parameters (Fig. 2A-D). We found that optimal trapping was observed for particles above 15µm, a channel height of H=54µm, reservoir width ratio of 15 and reservoir length of 720µm (Fig. 2A-D). More importantly, we found that the vortex trapping depended on system parameters non-linearly. For example, trapping did not monotonically increase with reservoir width ratio, displaying a local minimum in trapping at a ratio of 20. These behaviors were not explained with our previously developed model describing entry and maintenance in vortices.

To better understand particle maintenance, we evaluated several potential hydrodynamic forces acting on single particles in microvortices: shear gradient lift force, Saffman lift, and centrifugal force [2,3]. First, we experimentally demonstrated that particles with densities different than the suspending fluid ($\rho_{\text{oil droplets}}$=0.8g/cm^3, $\rho_{\text{PDMS beads}}$=1.03g/cm^3 and $\rho_{\text{glass beads}}$=2.6g/cm^3 versus ρ_{fluid}=1g/cm^3) follow similar orbital trajectories and velocities (Fig.3A-D). This behavior emphasizes that Saffman lift and centrifugal force do not lead to an outward directed force that is responsible for particle escape.

Thus, the dominant mechanism responsible for both inward and outward directed forces that create stable particle orbits is the shear-gradient lift force, Fs, (Fig. 4A-C) dependent on the local second derivative of the velocity and inertia of the fluid in microfluidic systems [4]. Particle velocities (measured from experimental results) mapped over the fluid velocity profiles at two channel heights (H=13, 27μm) show that stable orbits correspond to inflection points in fluid velocity, where the shear-gradient and corresponding force changes sign (Fig. 4B,C). This insight gives improved intuition for developing far-ranging particle trapping applications by modifying the shape of the velocity field for more predictable vortex trapping systems.

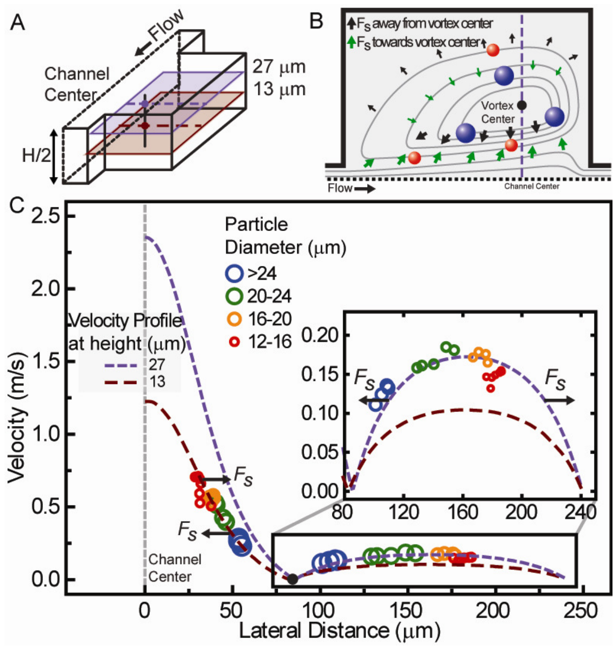

Figure 4: Shear Gradient Lift Force (F_S) Alone Can Result in Stable Orbits of Particles in Vortices. (A,B) Schematics of microvortex chamber used in numerical simulation where the velocity line profile (dashed-line) was extracted at H=27μm, 13μm. (B) Schematic showing direction of F_s pointing away and towards the vortex center. (C) Particle velocities (experimental) plotted over fluid velocity line profiles. Particles closer to the channel center experience higher velocity and occupy equilibrium positions closer to the wall (H=13μm) while particles closer to the channel wall are slower with equilibrium position at H=27 μm.

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